Essays on Environmental Cooperation and Trade

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A Thesis
in the Department
of
Economics

Presented in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy (Economics)
at Concordia University
Montreal, Quebec, Canada

May 2024

CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Dana Ghandour

Entitled: Essays on Environmental Cooperation and Trade

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (Economics)

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ABSTRACT

Essays on Environmental Cooperation and Trade

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This thesis investigates the relationship between environmental cooperation and trade within heterogeneous countries. Comprising three essays, the research delves into the impact of environmental damage heterogeneity on the stability of environmental coalitions in the presence of exogenous tariffs, the effect of environmental damage heterogeneity on the stability of environmental coalitions in the presence of endogenous tariffs, and the role of unilateral Carbon Border Adjustments (CBAs) in incentivizing environmental cooperation among heterogeneous countries.

The first essay employs a static three-country model to analyze the stability of international environmental agreements among heterogeneous trading partners. The study examines the trade-offs governments face in balancing the enforcement of emissions reductions through higher taxes against the potential consequences of noncooperation in the form of higher exogenous export tariffs. The main findings demonstrate that the grand coalition can be stable across various levels of heterogeneity, while underscoring the critical role of punitive tariffs in determining coalitional stability.

Building upon these insights, the second essay introduces an endogenous solution to the static three-country model, incorporating endogenous import tariffs. The research identifies conditions under which the grand coalition remains stable, showcasing environmental and welfare gains across varying levels of heterogeneity. The study reveals that as market sizes expand, the grand

coalition transitions from generating both environmental and welfare gains to primarily fostering only overall welfare gains.

The third essay shifts focus to the implementation of unilateral CBAs, exemplified by the European Union's Carbon Border Adjustment Mechanism. Investigating the effects of CBAs in a two-country trade model with different environmental damage parameters, the study assesses their impacts on global welfare and emissions. Novel considerations include the time sensitivity of CBAs, distinguishing between farsighted and myopic approaches, and exploring the potential for retaliation in myopic CBAs. Results show that farsighted CBAs can generate environmental and welfare gains under specific conditions, while myopic CBAs without retaliation offer potential avenues for cooperation.

Collectively, these essays contribute valuable insights into the intricate interplay of environmental cooperation and trade dynamics, shedding light on the challenges and opportunities presented by free-riding behavior, enforcement challenges, and environmental damage heterogeneity in the pursuit of stable environmental coalitions.

ACKNOWLEDGEMENT

As I reflect on the enriching journey of my Ph.D., I am compelled to express deep gratitude to the remarkable individuals who played pivotal roles in shaping this academic endeavor. First and foremost, I extend my sincere appreciation to Dr. Effrosyni Diamantoudi, my supervisor, for her instrumental role in facilitating this Ph.D. journey. Her friendly guidance, motivation, unwavering support, and extensive knowledge were invaluable at every stage of this thesis.

I specially appreciate the contributions of the External Examiner, Dr. Charles Seguin (Department of Economics, UQAM), the Chair of the Examining Committee, Dr. Rachel Berger (History), the Arm's Length Examiner, Dr. Huan Xie (Economics), and the Examining Committee members, Dr. Ming Li (Economics) and Dr. Eftichios Sartzetakis (Department of Economics, University of Macedonia). Their insightful comments and suggestions significantly enhanced the quality of this thesis.

I extend profound gratitude to the Graduate Program Directors, Dr. Szilvia Pápai (former), Dr. Damba Lkhagvasuren (former), and Dr. Christian Sigouin (current), as well as to the Department Chair, Dr. Jorgen Hansen, for their guidance throughout these years. Special thanks to Drs. Christian Belzil, Prosper Dovonon, Ming Li, Szilvia Pápai, and Huan Xie for their invaluable help and encouragement during my studies at Concordia. I also appreciate the continuous support from the former and current administrative staff, Elise Melancon, Melissa Faisal, Mary-Anne Jirjis, Emilie Martel, Kelly Routly, and Domenica Barreca.

Lastly, I extend my heartfelt gratitude to my daughters, Sarya, Ghayssa, and Rayana. Their warm love, unwavering patience, and endless support have been the cornerstone of my perseverance throughout this thesis. This accomplishment would not have been possible without their encouragement. Thank you all for being integral to this transformative experience.

…To my daughters, Sarya, Ghayssa, and Rayana

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INTRODUCTION

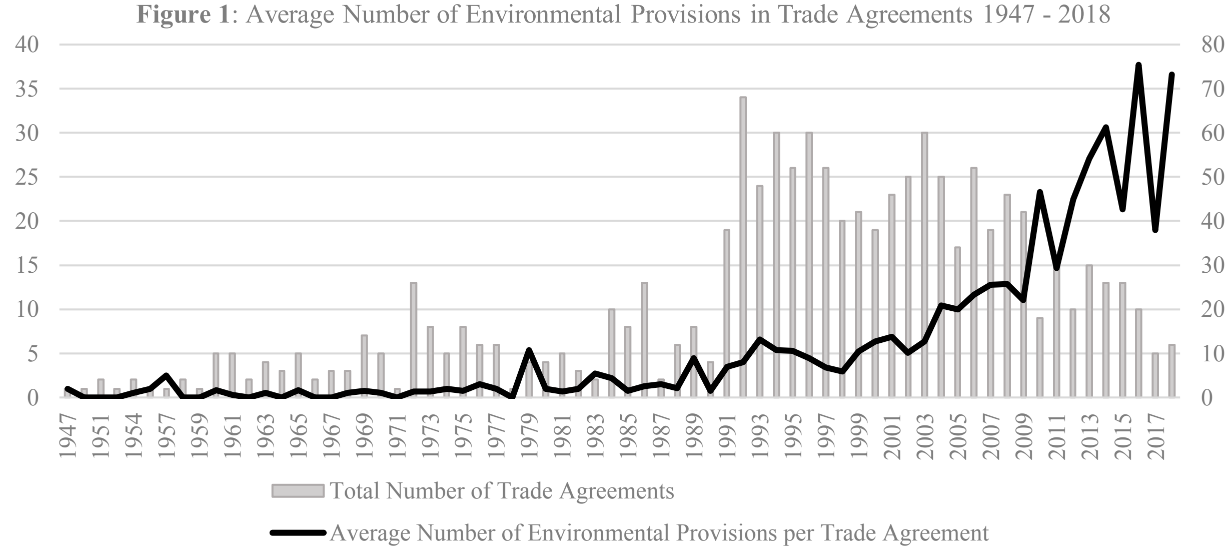
Transboundary pollution and greenhouse gas emissions are some of the most challenging and pressing environmental problems of the twenty-first century (UNEP, 2019). The latest reports from the United Nations World Meteorological Organization (WMO, 2023, 2024) warn that the last nine years (2015-2023) have been the warmest on record, due to the growing concentrations of greenhouse gases (GHGs). Despite a temporary decrease in global emissions during the peak of the pandemic in 2020, greenhouse gas emissions have reached new highs in 2022, notwithstanding the energy crisis resulting from the war in Ukraine (WMO, 2022). In order to achieve the 2015 Paris target of limiting global warming to 1.5°C, nations need to reduce their global emissions immediately by nearly fifty percent by 2030 (IPCC, 2023). However, strong incentives for free-riding and the challenges in enforcing International Environmental Agreements (IEAs) lie at the heart of international failures to tackle climate change (Diamantoudi et al., 2018a).

In the absence of effective enforcement methods, current international environmental agreements rely on the good faith of signatories. For instance, the United States signed the Kyoto Protocol in 1998 but has never ratified it. Canada ratified the Kyoto Protocol in 2002 but later withdrew from it in 2011, citing the economic burden of compliance and the lack of commitments from major emitters like China and India. The 2019 United Nations Conference of the Parties (COP25) in Madrid, which aimed to finalize the Paris Agreement rulebook, failed to reach a consensus on several crucial issues. China, the world's largest carbon emitter, has shown no intention of halting the construction of coal plants domestically or shutting down existing ones (Standaert, 2021). Similarly, Canada has pledged to reduce emissions by investing in greener infrastructure but continues to provide subsidies to one of the country's largest sources of emissions, the oil and gas industry (Carter and Dordi, 2021). Moreover, many other major emitter countries, including India, Indonesia, Russia, and Iran, are still not on track to fulfill their commitments under the Paris Climate Agreement (CAT, 2021). Furthermore, as governments grapple with post-pandemic economic recovery and global inflationary pressures, the emissions reductions promised at the 2021 Glasgow Climate Pact (COP26) fell short of the necessary cuts to meet the targets set by the Paris Climate Agreement (COP21) (Evans et al., 2021). The focus of the 27th Conference of the Parties (COP27) held in Sharm el-Sheikh, Egypt, in 2022, was on addressing urgent climate action, strengthening international cooperation, and enhancing global commitments to effectively combat climate change. However, in such a chaotic world, with global emissions stubbornly high and yet another round of international environmental negotiations failing to make substantial progress, current pledges to reduce global emissions under the Paris Agreement remain vague promises rather than credible actions, and the fight against climate change is just being delayed.

The relationship between trade and the environment has often been viewed as a divergence between economic development and environmental degradation, with opportunities to align trade and environmental policies often overlooked. However, trade can play a vital role in reducing countries' incentives for free-riding and increasing their willingness to cooperate, while also providing support for stable climate coalitions (Diamantoudi et al. 2018c).

Bridging the divide between trade and the environment, preferential trade agreements today increasingly include environmental provisions. As indicated in Figure1, these norms have become a regular feature of almost 85% of preferential trade agreements signed between 1947 and 2018 (Morin et al. 2018). Moreover, they are gradually becoming more diverse and extensive, covering an increasingly wide range of environmental protection issues. Some directly address the reduction of greenhouse gas emissions, cooperation on Multilateral Environmental Agreements (MEAs), and the leveling of the playing field among trading partners. Some of these clauses are even more specific and restrictive than those found in multilateral environmental agreements (Morin and Jinnah, 2018). Assessing the environmental impact of these provisions, scholars have found that they increased green exports from developing countries (Brandi et al., 2020), and reduced the greenhouse gas emissions resulting from trade flows (Baghdadi et al. 2013, Zhou et al. 2017, Martínez-Zarzoso and Oueslati 2018, Sorgho and Tharakan 2022). These empirical studies suggest that the coordination of trade and environmental policies can be a valuable strategy in diffusing environmental policies across borders and strengthening international environmental cooperation beyond what is currently implemented.

Figure 1: Average Number of Environmental Provisions in Trade Agreements 1947 - 2018



Note. Data from https://www.chaire-epi.ulaval.ca/sites/chaire-epi.ulaval.ca/files/trend_2_public_version.xlsx

Within this context, this thesis explores the prospects of environmental cooperation among environmentally heterogeneous trading partners. In the context of international trade, governments face a tradeoff between enforcing higher environmental taxes to cooperatively reduce global emissions and facing higher tariffs on exports when acting noncooperatively. However, countries may not be equally vulnerable to global emissions exposure. The heterogeneity in environmental damages implies that environmental and trade policies can yield different welfare implications for different countries, creating diverse incentives for international environmental cooperation. Hence, in addition to free-riding incentives and enforcement challenges in international environmental agreements, this heterogeneity poses an additional obstacle to achieving international cooperation.

The first essay of this thesis, therefore, investigates the stability of both partial and global International Environmental Agreements (IEAs) among heterogeneous countries in a static three-country coalition formation game, considering the presence of exogenous import tariffs. Since trade and environmental policies are often not negotiated concurrently, the use of exogenous tariffs as a trade policy tool is examined in that context.

Building upon these insights, the second essay introduces an endogenous solution to the static three-country coalition formation game, incorporating endogenous import tariffs. In this essay, environmental cooperation within a coalition spans over trade and environmental policies, where environmental taxes and import tariffs are negotiated simultaneously.

These two essays contribute to and connect two branches of the theoretical literature: the one on Environmental Cooperation and Trade and the other on International Environmental Agreements.

Considering the literature on environmental cooperation and trade, scholars such as Conrad (1993), Barrett (1994), Kennedy (1994), and Tanguay (2001) have extensively examined strategic environmental policy within a symmetric trade framework. On the other hand, scholars studying strategic two-country trade models among heterogeneous countries have found that environmental cooperation among heterogeneous trading partners can lead to significant overall welfare gains. Duval and Hamilton (2002) conducted an analysis of environmental tax policies in a two-country trade union, examining differences in consumer market size, production costs, number of firms, and pollution diffusion. Cheikbossian (2010) specifically investigated the impact of heterogeneity in market size under free trade in a global market. Gautier (2017) addressed variations in abatement and production costs within the context of trade and Cournot oligopoly, focusing on environmental policy reforms. Baksi and Chaudhuri (2017) examined the heterogeneity in environmental damages in a two-country infinitely repeated game. Their used trigger strategies and border tax adjustments to evaluate the stability of environmental cooperation. Their findings indicated that environmental cooperation among heterogeneous countries resulted in significant overall welfare gains, which further increased with trade liberalization.

These two essays are comparable to the study carried out by Baksi and Chaudhuri (2017), which examined environmental damage heterogeneity in a strategic two-country repeated game. Nevertheless, in contrast to Baksi and Chaudhuri (2017), the present essays introduce a three-stage static coalition formation game involving three heterogeneous countries. The stability of environmental cooperation is assessed based on internal and external stability criteria (D'Aspremont et al., 1983), rather than exogenous trigger strategies and trade linkages.

These two essays also contribute to the literature on international environmental agreements among heterogeneous countries. Early studies by Hoel (1992) and Barrett (1997) were among the first to model heterogeneity in international environmental agreement games. Using internal and external stability criteria, they found that when countries were modeled as heterogeneous, the number of signatories remained small. Subsequent studies by Barrett (2001), Finus and Rundshagen (2003), Pavlova and de Zeeuw (2013), Hagen and Eisenack (2015), and Diamantoudi et al. (2018b) examined coalitional stability with heterogeneous countries, but not in the context of international trade, transfer payments, or trade linkages. It was observed that in pure IEAs, where a coalition only generates positive externalities for non-members, heterogeneity does not increase the size of stable coalitions and can reduce the likelihood of cooperation. However, when heterogeneity is associated with direct transfer payments, it can improve the prospects of cooperation and support the stability of larger coalitions (Biancardi and Villani 2010, Diamantoudi et al. 2018a, Bakalova and Eyckmans 2019, Finus and McGinty 2019). In this case, the coalition generates a positive externality through lower global emissions and a negative externality for non-signatories due to the forgone transfer. Non-members who do not sign the IEA essentially lose the transfer payment, which constitutes a negative externality generated by the coalition.

Moreover, heterogeneity, when associated with trade linkages, such as trade sanctions, can reduce free-riding incentives and increase the size of stable coalitions (Nordhaus 2015, Hagen and Schneider 2021). Similarly, scholars who have examined IEAs with R&D linkages (Biancardi and Villani 2018, Eichner and Kollenbach 2021) found that R&D linkages, similar to trade linkages, can improve the stability of environmental coalitions and increase the likelihood of cooperation in comparison to pure IEA models.

Few scholars, Cavagnac and Cheikbossian (2017), have examined the stability of international environmental agreements in the context of international trade with heterogeneous countries. Using Coalition-Proof Nash Equilibria (Bernheim et al., 1987) in a free trade setting, they show that market size heterogeneity supported the stability of a partial agreement rather than a global one, and the grand coalition would only form if the singleton structure were the sole alternative. These two essays are comparable to Cavagnac and Cheikbossian (2017). However, they differ in their approach to evaluating the stability of environmental coalitions, as they use internal and external stability criteria (D'Aspremont et al., 1983) instead of Coalition-Proof Nash Equilibria. Additionally, the focus is on environmental damage rather than market size heterogeneity, specifically in a segmented market with positive import tariffs, as opposed to a global market in a free trade setting.

The primary contribution of these two essays lies in demonstrating that using positive tariffs on imports within a segmented market setting, as opposed to a global market in a free trade setting, with punitive tariffs on outsiders, diminishes the free riding incentives of non-signatories and reinforces the stability of the global agreement, despite the heterogeneity among countries.

The first essay highlights that implementing trade penalties on countries choosing not to participate in a coalition can be an effective strategy for reducing global emissions and promoting a stable global environmental agreement. The main findings indicate that the global agreement consistently yields collective welfare gains, with environmental gains occurring only when exogenous tariffs are kept sufficiently low. The magnitude of punitive tariffs plays a critical role in determining coalitional stability. When punitive tariffs are sufficiently low at high degrees of heterogeneity, the grand coalition can give way to a stable partial coalition, where the two countries suffering the most from environmental damage form a pair. In the absence of such punitive tariffs or at sufficiently low levels, both the grand coalition and the partial coalition can become internally unstable, potentially resulting in a stable singleton structure at various degrees of heterogeneity.

Furthermore, the second essay illustrates that the coordination of environmental and trade policies, in the presence of endogenous import tariffs, proves to be a valuable strategy for reducing global emissions in sufficiently small markets, despite differences in environmental damages. With endogenous tariffs, the fully cooperative agreement emerges as the only stable coalition across various levels of heterogeneity and alternative market sizes.

Continuing the exploration of environmental cooperation and trade among heterogeneous countries, the third essay delves into the implementation of unilateral Carbon Border Adjustments (CBAs), exemplified by the European Union's Carbon Border Adjustment Mechanism (CBAM).

The urgent need for accelerated global climate action coincides with the imperative to address the current disparities in carbon pricing. Over the past decade, the carbon pricing schemes landscape has grown increasingly diverse, and the discrepancy in carbon costs has expanded significantly (ICAP, 2023), with European industries facing a disproportionately higher burden compared to other regions (Mathieu, 2021). Particularly, in the light of soaring energy prices in Europe, it becomes increasingly challenging for EU firms to remain competitive against foreign industries. To mitigate the risk of carbon leakage and level the playing field for EU and foreign firms, the EU CBAM, initiated in April 2023 under the EU Green Deal, aims to equalize the carbon price between EU domestic products and imports, playing a crucial role in the EU's emissions reduction efforts (EC, 2023).

The EU CBAM introduces a new concept of carbon pricing by applying it to imports for the first time. Foreign firms exporting to the EU will be required to pay the price difference between the carbon price of the country of production (or lack thereof) and the price of carbon allowances in the EU ETS. Designed to be compatible with WTO rules, foreign firms will not be charged more than the EU domestic carbon price. The CBAM, which has been gradually phased in starting October 2023, initially targets emission-intensive and trade-exposed (EITE) goods at a high risk of carbon leakage, including iron and steel, cement, fertilizer, aluminum, electricity generation, and hydrogen (EC, 2023). However, countries participating in the ETS or having a linked emissions trading system, like Switzerland, will be excluded from the CBAM. In the future, it is anticipated that the CBAM will be extended to encompass more carbon-intensive goods.

The EU Carbon Border Adjustment Mechanism (CBAM) imposes additional production costs on foreign firms exporting to the EU. The CBAM presents a choice for outsider countries to either pay the adjustment fee when exporting to the EU or raise the domestic carbon price and collect the revenues themselves (Tagliapietra and Veugelers, 2021). Developing countries that heavily rely on EU markets for exports may face challenges in shifting their exports away from the EU, potentially impacting their competitiveness. For instance, Zimbabwe is a major exporter of iron and steel to the EU, while Ukraine supplies the bloc with significant quantities of fertilizers (Maliszewska et al., 2023).

The EU CBAM can potentially discourage free riding behavior and create a “race to the top” in terms of environmental standards and regulations, thereby improving the global effectiveness of unilateral carbon emission pricing. Nordhaus (2015) has long been an advocate for a “climate club” concept, which employs punitive tariffs to penalize countries that fail to take sufficient action in reducing global emissions. He argued that imposing tariffs on imports from non-signatory countries to the climate club, the environmental coalition can be stabilized and expanded. While Nordhaus’ proposal for punitive tariffs differs in design and intention from the CBAM, which primarily tackles carbon leakage by considering the carbon content of imports, both instruments could potentially have significant welfare implications for EU trading partners (Magacho et al., 2023, Zhong and Pei, 2022).

Within this framework, the third essay examines the welfare implications of the CBAM and its potential to promote increased environmental cooperation among trading partners, with a focus on addressing environmental damage heterogeneity. Using a two-country strategic trade model, the analysis focuses on studying the impacts of myopic and farsighted carbon border adjustments (CBAs) on global welfare and emissions, comparing them with a basic trade model with bilateral endogenous tariffs on imports. In farsighted CBAs, the government’s welfare optimization problem and the resulting optimal emissions tax rate consider ex-ante the potential for carbon adjustments. Conversely, in the myopic CBA scenario, the government’s welfare optimization problem and the resulting optimal emissions tax rate initially do not account for carbon border adjustments, but these adjustments are incorporated subsequently.

This third essay contributes to the theoretical literature on environmental cooperation and trade, discussed in the preceding paragraphs, by providing evidence that international environmental cooperation among heterogeneous countries can lead to substantial collective welfare gains.

It also contributes to the literature on the strategic implications of carbon border adjustments. Examining the potential of carbon border adjustments to deter free riding behavior and reinforce international environmental agreements among homogeneous countries, scholars have obtained mixed results. Baksi and Chaudhuri (2020) discovered that the imposition of bilateral CBAs tends to destabilize an otherwise stable grand coalition and reduces the cost of unilaterally defecting from the grand coalition. Consequently, CBAs cannot always be used as a credible threat to foster a stable global climate agreement. On the contrary, Al Khourdajie and Finus (2020) found that CBAs, particularly under open membership, enhance the incentive for countries to participate in a climate agreement. This holds true whether coalition formation is modeled as a one-shot or sequential game.

Focusing on heterogeneous countries in two-country trade models with transboundary pollution, scholars found that CBAs can be a valuable tool to foster greater environmental cooperation. Eyland and Zaccour (2014) conducted numerical simulations and demonstrated that CBAs allow countries to set higher carbon taxes as opposed to the noncooperative equilibrium. They also showed that CBAs can serve as a credible threat to achieve an outcome that closely resembles the cooperative outcome. Similarly, Hecht and Peters (2018), examining Cournot and Bertrand competition in a two-country trade model with environmental damage heterogeneity, found that CBAs support the implementation of more stringent environmental policies. Anouliès (2015) shows that CBAs reduce free riding incentives and increase the likelihood of cooperation, even when countries exhibit heterogeneity in terms of environmental damage. Baksi and Chaudhuri (2017), in a North-South trade model with Cournot competition, found that unilateral CBAs imposed by the North can enhance the South's incentives to cooperate, particularly when heterogeneity is significant. Additionally, Elboghdadly and Finus (2020) modeling an escalating penalty game with various forms of CBAs, including import tariffs as well as export rebates with different rates, observed that CBAs can either fully internalize a global externality by enforcing complete cooperation or partially internalize it, depending on the CBA design.

This third essay builds upon the existing literature by thoroughly investigating various dimensions of Carbon Border Adjustments (CBAs). It examines their welfare implications, effectiveness in reducing global emissions, role in encouraging international environmental cooperation, and their divergence from the traditional tariff-based approach. Additionally, the study introduces a novel focus by examining the time sensitivity of CBAs, distinguishing between farsighted and myopic CBAs, and considering the potential for retaliation in myopic CBAs. Notably, some empirical studies (Böhringer et al., 2016; Fouré et al., 2016) underlined the risk of retaliation from non-EU countries as a response to the implementation of the CBAM.

Moreover, this essay complements the existing literature on carbon border adjustments by providing evidence that the effectiveness of CBAs ultimately depends on their time sensitivity. Notably, myopic CBAs fall short in delivering environmental gains when compared to alternative noncooperative climate measures, such as farsighted CBA and traditional tariff-based approaches. Only farsighted CBAs can prove to be an effective tool in reducing global emissions, under specific conditions. However, the essay demonstrates that myopic CBAs can encourage greater international environmental cooperation among trading partners, even in the presence of heterogeneity among countries.

The remainder of this thesis proceeds as follows: Essay 1 examines the impact of environmental damage heterogeneity on the stability of environmental coalitions in the presence of exogenous import tariffs. Building upon Essay 1, Essay 2 extends the exploration to investigate the effects of environmental damage heterogeneity on coalition stability, this time considering the presence of positive endogenous import tariffs. Finally, Essay 3 delves into the role of myopic and farsighted Carbon Border Adjustments (CBAs) in incentivizing international environmental cooperation among heterogeneous countries and their impact on global welfare and emissions.

ESSAY 1

ENVIRONMENTAL COOPERATION AND TRADE: THE IMPACT OF HETEROGENEITY IN ENVIRONMENTAL DAMAGES

1.1 Introduction

This essay examines environmental cooperation among heterogeneous trading partners to analyze the stability of both partial and global international environmental agreements.

The heterogeneity in environmental damages suggests that environmental and trade policies may lead to varying welfare outcomes among countries, thus creating diverse incentives for international environmental cooperation. Alongside free-riding incentives and the challenges in enforcing international environmental agreements, this heterogeneity presents an additional hurdle to achieving international cooperation.

Therefore, the main objectives of this essay are: i) To determine whether environmental cooperation among countries with different environmental damage parameters leads to environmental gains, overall welfare gains, or both. ii) To identify the cooperative scenarios that would emerge in a stable coalition among countries to exploit these gains. iii) To analyze the effect of heterogeneity in environmental damages on the stability of these environmental coalitions.

The model considers an open economy with three heterogeneous countries. Each country has a single firm that produces a homogeneous emission-intensive good while generating an equal number of transboundary emissions, such as carbon dioxide. Consumers in each country are affected by global emissions, and every unit produced generates exactly one unit of emissions. The firm's choice variable is production (emissions). While abatement is not explicitly modeled as a separate choice variable, the firm incurs an abatement cost in terms of forgone profit. Firms can reduce emissions by producing less output at the expense of reducing profits, and thus, face a tradeoff between emissions and profits. The three firms compete à la Cournot in a segmented market, where they serve linear market-specific demands rather than a shared global market demand.

International trade occurs in domestic markets. Therefore, each country can use import tariffs as a trade policy instrument to protect local production. The segmented market setting with positive exogenous tariffs rather than free trade is a novel approach in the theoretical literature, and it is particularly valuable when trade and environmental policies are not being negotiated concurrently. Each government imposes on the local firm a per-unit production (emissions) tax as an environmental policy tool. Collected tax and tariff revenues remain within their respective countries, with no transfer payments occurring.

The static coalition formation game is divided into three stages and is solved using backward induction. In stage one, the coalition formation game occurs, where each country selects its coalition membership. A coalition is considered stable if no country has an incentive to enter or exit the coalition (D'Aspremont et al., 1983). In the second stage, each country determines the emissions tax rate that maximizes the coalition's welfare. Finally, in the third stage, each firm independently chooses the production level that maximizes its own profits.

The analysis demonstrates that a global agreement, namely the grand coalition, remains stable at different levels of environmental damage heterogeneity, while still generating welfare gains. Numerical simulations also indicate that the grand coalition remains stable under various levels of exogenous tariffs and with different tariff structures. However, as heterogeneity increases, the stability of the grand coalition becomes more fragile and increasingly sensitive to the underlying exogenous tariff structure. A higher punitive tariff imposed on the outsider of the partial coalition reinforces the stability of the grand coalition. Conversely, at high degrees of heterogeneity, the grand coalition can give way to a partial coalition agreement when the punitive tariff magnitude is sufficiently low. In the absence of such punitive tariffs or at sufficiently low levels, the grand coalition and the partial coalition can become internally unstable, leading to a stable singleton structure at various degrees of heterogeneity.

Additionally, the main results suggest that the grand coalition generates environmental gains when exogenous import tariffs are kept sufficiently low. This finding aligns with Nordhaus (2015), emphasizing that trade penalties imposed on countries opting out of participation can reduce global emissions and promote a stable environmental agreement, even in the presence of heterogeneity among countries.

While Cavagnac and Cheikbossian (2017) observed that the grand coalition is less likely to emerge as a stable coalition structure in a free trade setting once a partial coalition is stable, this essay's primary contribution lies in demonstrating that implementing positive tariffs within a segmented market setting, rather than in a global market under free trade conditions, reduces the free-riding incentives of non-signatories and can enhance the stability of the global agreement

The remainder of this essay is organized as follows: Section 2 describes the model, Section 3 explores the heterogeneous case, Section 4 provides a summary of the results, and Section 5 concludes the essay.

1.2 The Model

The present model examines an open economy comprising three heterogeneous countries, denoted as $N = \{i, j, k\}$. In each country, a single firm seeks to maximize profits by producing a homogeneous emission-intensive good X. The total production of the firm located in country i is represented by the following expression, for i, j, k where $i \neq j, k$:

$$X_i = \left(x_{ii} + x_{ij} + x_{ik}\right), \tag{1.1}$$

Where x_{ii} is produced and sold in country i, and x_{ij} is produced in country i and exported to country j, $\forall\ i \neq j$. For the market structure to be maintained throughout the game and the model's solution to be interior, it is assumed that $X_i, x_{ii} \in \mathbb{R}_n^{++}$ and $x_{ij} \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$. The production process generates transboundary air pollution such as carbon dioxide. Every unit produced generates exactly one unit of emissions. The firm's choice variables are local production and exports, which also represent emissions. Hence, abatement[1] is neither an option nor a choice variable.

Total consumption in country i, for i, j, k where $i \neq j, k$, is expressed as follows:

$$Q_i = \left(x_{ii} + x_{ji} + x_{ki}\right), \tag{1.2}$$

where x_{ii} is locally produced and x_{ji} is imported from country j.

Firms compete à la Cournot in a segmented market. The linear demand in country i is given by:

$$Q_i = (\alpha - P_i), \tag{1.3}$$

where Q_i is the total consumption of the polluting good in country i, P_i is the price of the good in market i, and α is the maximal marginal utility derived from its consumption. For simplification, it is assumed that the marginal cost of production is equal to zero, and each firm can export to the other two foreign markets at no transaction costs.

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[1] Following Duval and Hamilton 2002, Cheikbossian 2010, Baksi and Chaudhuri 2017, and Cavagnac and Cheikbossian 2017 abatement has not been modeled as a separate choice variable to simplify the model.

Pollution generates environmental damage in each country; the social cost of pollution is linear in global emissions, such that:

$$D_i(X) = \beta_i(X_i + X_j + X_k), \tag{1.4}$$

where β_i is the marginal environmental damage in country i caused by aggregate production, that is, by global emissions. The linear environmental damage function makes the analysis more readable and the model more tractable. For the market to be active, it is assumed that the marginal environmental damage parameter cannot be higher than the maximal marginal utility of good X, given by α, and thus $\beta_i \in (0, \alpha)$, for i, j, k. The marginal environmental damage is constant horizontally but not across countries. Consumers in each country are affected by the global level of emissions. Differences in environmental damages stem from how the same level of emissions translates into costs, influenced by underlying factors such as income, health stock, defensive investment, or baseline exposure (Hsiang et al., 2019). Therefore, in this model, different environmental damages result from distinct impacts of the same level of global emissions. In other words, all three countries face the same global level of emissions but experience varying impacts.

The government in country i imposes an exogenous positive tariff $\tau_{i,j}$ per unit of imports from country j and $\tau_{i,k}$ per unit of imports from country k, where $i \neq j, k$. As a result, $\tau_{j,i}$ and $\tau_{k,i}$ are the effective marginal costs of the firm operating in country i on its exports to countries j and k, respectively.

In addition to import tariffs as a trade policy tool, each government uses a per-unit of production tax rate, t_i, that is imposed on the local firm as an environmental policy instrument. Since every unit produced precisely generates one unit of emissions, then a tax per unit of production t_i is equivalent to a tax per unit of emissions. Thus, the government in country i collects tariff revenues on imports from foreign markets, expressed by the following equation, for i, j, k where $i \neq j, k$:

$$TR_i = \left(\tau_{i,j} x_{ji} + \tau_{i,k} x_{ki}\right), \tag{1.5}$$

and emissions tax revenues defined as:

$$ER_i = t_i\left(x_{ii} + x_{ij} + x_{ik}\right) = t_i X_i. \tag{1.6}$$

It is assumed that there are no transfer payments between countries, and fiscal revenues collected from tariffs and emissions taxes remain in the country of origin.

Let $\mathcal{S}$ be a coalition where $\mathcal{S} \subset N = \{i, j, k\}$. $\mathcal{S}$ represents a group of countries cooperating on environmental issues. Coalition members will determine their emissions tax rate $t_{\mathcal{S}}$ jointly. Each coalition $\mathcal{S}$ is associated with two exogenous tariffs: $\tau_{\mathcal{S}}$ represents the common tariff rate that members of $\mathcal{S}$ would charge to each other, and $\tau_{\mathcal{S},k}$ where $k \notin \mathcal{S}$, represents the tariff rate that members of $\mathcal{S}$ would charge to each of its non-members. Therefore, it is explicitly assumed that coalition members will charge the same tariff rate to each other $\tau_{\mathcal{S}} = \tau_{i,j} = \tau_{j,i}$ if $i, j \in \mathcal{S}$, and the same tariff rate to non-members $\tau_{\mathcal{S},k} = \tau_{i,k} = \tau_{j,k}$ if $i, j \in \mathcal{S}$, and $k \notin \mathcal{S}$, even if coalition members are heterogeneous.

In a three-country model, there are three types of coalition structures: i) the grand coalition, ii) the singletons, and iii) a pair and a singleton. The static coalition formation game is composed of three stages and is solved by backward induction. Stage one is the coalition formation game; each country chooses its coalition membership $\mathcal{S}$ given exogenous tariffs. In the second stage, each country chooses $t_{\mathcal{S}}$, the emissions tax rate that maximizes the coalition's welfare $W_{\mathcal{S}} = \sum_{i \in \mathcal{S}} W_i$, given the coalition structure C and exogenous tariffs. In the third stage, each firm chooses noncooperatively its profit-maximizing production rate X_i, given the coalition structure C, exogenous tariffs, and the emissions tax rates.

1.2.1 Stage Three - The Firm's Optimization Problem

In stage three, each firm chooses noncooperatively its profit-maximizing output rate, taking as given the policies set by all three governments and the output decisions of the other foreign firms. Firms compete à la Cournot in domestic markets, and each firm has three choice variables: production for the local market, x_{ii}, and exports to the other two foreign markets, x_{ij} and x_{ik}. The total profit function for the firm located in country i consists of total revenues from the domestic market i and the foreign markets j and k, minus the emissions tax imposed on total production and the tariff costs incurred on exports. The firm's optimization problem[2] can be expressed as follows, for i, j, k where $i \neq j, k$:

$$\max_{x_{ij},\ j\in N} \pi_i \Rightarrow \max_{x_{ij},\ j\in N} \sum_{j\in N}\left(P_j(x_{ij})x_{ij} - t_i x_{ij}\right) - \sum_{j\in N/\{i\}} \tau_{ji}x_{ij}. \tag{1.7}$$

The first order conditions of the profit maximization problem (1.7) yield the following equilibrium quantities produced by the firm operating in country i, for i, j, k where $i \neq j, k$:

$$x_{ii}{}^{*} = \frac{1}{4}\left(\alpha - 3t_i + (t_j + t_k) + \tau_{i,j} + \tau_{i,k}\right) \tag{1.8}$$

$$x_{ij}{}^{*} = \frac{1}{4}\left(\alpha - 3t_i + (t_j + t_k) + \tau_{j,k} - 3\tau_{j,i}\right). \tag{1.9}$$

The Cournot equilibrium implies that domestic production and exports decrease in the local emissions tax rate, t_i, and increase in the tax rates imposed on foreign firms, t_j and t_k. Domestic production increases in the local tariff rates, $\tau_{i,j}$ and $\tau_{i,k}$, while exports are decreasing in foreign tariffs, $\tau_{j,i}$ and $\tau_{k,i}$. The third stage of the game is common to all coalition structures, and the welfare function of any country relies on the optimal output quantities obtained in this stage.

[2] The firm's profit maximization problem is detailed in Appendix A1.

1.2.2 Stage Two - The Government's Optimization Problem

In a three-country global economy, there are three types of coalition structures:

- A coalition structure C_{NC}, composed of three singletons, where each singleton contains one country, $C_{NC} = \{\{i\},\{j\},\{k\}\}$.
- A coalition structure C_G, composed of one coalition containing all three countries, the grand coalition, $C_G = \{\{i,j,k\}\}$.
- A coalition structure C_P, composed of two coalitions, a pair and a singleton. There are three such coalition structures. For example, $C_P^k = \{\{i,j\},\{k\}\}$ is composed of the pair formed by countries i and j, and country k which remains a singleton.

The emissions tax rate t_S is determined by maximizing the coalition's welfare, denoted by W_S, given the exogenous tariff rates, and the firms' optimal output quantities derived in stage three:

$$\max_{t_S} W_S \Rightarrow \max_{t_S} \textstyle\sum_{i \subset S} W_i\,(t_S) \text{ where } t_S = t_i{}^3, \forall i \in S \tag{1.10}$$

Recall, that firms regardless to which coalition their countries belong, they are competing à la Cournot, and still act independently of each other in the third stage of the oligopoly game.

The welfare function of country i, denoted by W_i, consists of the domestic consumer surplus CS_i, the local firm's profits π_i, the government's tariff revenues TR_i and emissions tax revenues ER_i, minus the environmental damage D_i caused by global emissions. Thus, the total welfare function of country i given any coalition structure C, is expressed as follows, for i, j, k:

$$W_i(C) = (CS_i + \pi_i + ER_i + TR_i - D_i). \tag{1.11}$$

[3] t_i and $t_{\{i\}}$ are used interchangeably in this essay.

More specifically, it can be detailed by the following expression, for i, j, k where $i \neq j, k$:

$$W_i(C) = \begin{bmatrix} \frac{1}{2}{Q_i}^2 - \beta_i\left(X_i + X_j + X_k\right) + \left(\tau_{i,j}x_{ji} + \tau_{i,k}x_{ki}\right) \\ +(\alpha - Q_i)x_{ii} + \left(\alpha - Q_j - \tau_{j,i}\right)x_{ij} + \left(\alpha - Q_k - \tau_{k,i}\right)x_{ik} \end{bmatrix}. \quad (1.12)$$

1.2.3 Stage One - Coalition Formation

The first stage of the game is the coalition formation stage. In this stage, each country selects its coalition membership, and the stability of each coalition structure is analyzed. A coalition structure is deemed stable if no country has an incentive to either enter or exit a coalition within the structure. This definition of stability is based on the original definition of cartel stability as per D'Aspremont et al. (1983).

Let C be the coalition structure to which a coalition S belongs; $W_{i\in S}^{C}$ denotes the welfare of country i, where i belongs to S. As such, $W_i^{C_{NC}}$, $W_i^{C_G}$, $W_i^{C_P^k}$, and $W_i^{C_P^i}$, represent, respectively, the welfare function of country i when i is a singleton, a member of the grand coalition, a pair member of a partial coalition formed by countries i and j, and an outsider to a partial coalition formed by countries j and k.

DEFINITION: A coalition $\mathcal{S} \subset N$, where $\mathcal{S} \in C$ is stable, if it is both internally and externally stable.

- $\mathcal{S}$ is internally stable $\Leftrightarrow \forall i \in \mathcal{S}, W_i^C \geq W_i^{C^f}$ where $C^f = C/\mathcal{S} \quad \cup \quad \{\mathcal{S}/\{i\}, \{i\}\}$ (1.13)
- $\mathcal{S}$ is externally stable $\Leftrightarrow \forall i \in \mathcal{S}, W_{\{i\}}^C \geq W_{i\subset \mathcal{S}}^{C^c}$ where $C^c = \{C/\{i\} \quad \cup \quad \{\mathcal{S} \cup \{i\}\}\}$ (1.14)

In particular, C^f is a finer coalition structure than C; that is, as country i leaves the coalition $\mathcal{S}$ to become a singleton, C^f contains the remaining members of $\mathcal{S}$ and a singleton $\{i\}$.

In contrast, C^c is a coarser coalition structure than C; since country i, initially behaving as a singleton $\{i\}$, now joins the other member(s) in the coalition $\mathcal{S}$.

Notably, the singleton coalition structure C_{NC} is internally stable by default as it is the finest coalition structure, and no country has the possibility to leave a coalition formed by itself. Similarly, the grand coalition C_G is externally stable by default as all countries are members of the coalition and there no outsiders to join the coalition. The partial coalition C_P is externally stable if no outsider has an incentive to join, and is internally stable if no member has an incentive to exit the coalition and become a singleton. In this framework, therefore, in the partial coalition structure, it is imperative to investigate whether both internal and external stabilities are satisfied. In the singleton structure, however, the focus is on checking for external stability, while in the case of the grand coalition, the emphasis is on checking for internal stability.

1.3 The Heterogeneous Case

The heterogeneous case assumes that countries have different environmental damage parameters, where $\beta_i > \beta_j > \beta_k > 0$. Members of a coalition $\mathcal{S}$ coordinate their environmental and trade policies with other members. They enforce a uniform emissions tax rate $t_{\mathcal{S}}$ and common positive exogenous tariffs $\tau_{\mathcal{S}}$ to be levied on each other, and $\tau_{\mathcal{S},k}$ to be imposed on non-members.

1.3.1 The Singleton Structure C_{NC}

Under the singleton structure C_{NC}, each government independently sets a noncooperative emissions tax t_i^{NC}, along with two exogenous import tariff rates $\tau_{i,j}$ and $\tau_{i,k}$ imposed on imports from other countries, for $i \neq j, k$. This results in three emissions tax rates, namely t_i^{NC}, t_j^{NC}, t_k^{NC}, along with six exogenous import tariff rates: $\tau_{i,j}$, $\tau_{i,k}$, $\tau_{j,i}$, $\tau_{j,k}$, $\tau_{k,i}$, and $\tau_{k,j}$.

The equilibrium quantities produced by the firm operating in country i, given by Equations (1.8) and (1.9), can, thus, be rewritten as follows, for i, j, k where $i \neq j, k$:

$$x_{ii}^*(C_{NC}) = \frac{1}{4}\left(\alpha - 3t_i^{NC} + \left(t_j^{NC} + t_k^{NC}\right) + \tau_{i,j} + \tau_{i,k}\right) \tag{1.15}$$

$$x_{ij}{}^{*}(C_{NC}) = \frac{1}{4}\left(\alpha - 3t_i{}^{NC} + \left(t_j{}^{NC} + t_k{}^{NC}\right) + \tau_{j,k} - 3\tau_{j,i}\right). \tag{1.16}$$

For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that $x_{ii}{}^{*}(C_{NC}) \in \mathbb{R}_n^{++}$ and $x_{ij}{}^{*}(C_{NC}) \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.

Accordingly, country i's welfare optimization problem[4] (1.10) can be written as follows:

$$\max_{t_i^{NC}} W_i{}^{C_{NC}} \Rightarrow \max_{t_i^{NC}} \begin{bmatrix} \frac{1}{2}Q_i{}^2(t_i^{NC}) - \beta_i\left(X_i(t_i^{NC}) + X_j(t_i^{NC}) + X_k(t_i^{NC})\right) \\ +\left(\tau_{i,j}x_{ji}^{*}(t_i^{NC}) + \tau_{i,k}x_{ki}^{*}(t_i^{NC})\right) + \left(\alpha - Q_i(t_i^{NC})\right)x_{ii}^{*}(t_i^{NC}) \\ +(\alpha - Q_j(t_i^{NC}) - \tau_{j,i})x_{ij}^{*}(t_i^{NC}) + (\alpha - Q_k(t_i^{NC}) - \tau_{k,i})x_{ik}^{*}(t_i^{NC}) \end{bmatrix}. \tag{1.17}$$

The first order condition of the welfare optimization problem (1.17) yields the following negative best response function, for i, j, k where $i \neq j, k$:

$$t_i{}^{NC}\left(t_j{}^{NC}, t_k{}^{NC}\right) = \frac{1}{17}\begin{pmatrix} 12\beta_i - 9\alpha - 5\left(t_j{}^{NC} + t_k{}^{NC}\right) \\ +3\left(\tau_{i,j} + \tau_{i,k}\right) + 6\left(\tau_{j,i} + \tau_{k,i}\right) - 2\left(\tau_{j,k} + \tau_{k,j}\right) \end{pmatrix}. \tag{1.18}$$

The singleton behaves noncooperatively; hence, it has a negative best response function.

Using (1.18) and the symmetry, the singleton's equilibrium tax rate is, for i, j, k where $i \neq j, k$:

$$t_i{}^{*NC}(C_{NC}) = \frac{1}{324}\begin{pmatrix} -108\alpha + 264\beta_i - 60\left(\beta_j + \beta_k\right) \\ +46\left(\tau_{i,j} + \tau_{i,k}\right) + 127\left(\tau_{j,i} + \tau_{k,i}\right) - 89\left(\tau_{j,k} + \tau_{k,j}\right) \end{pmatrix}. \tag{1.19}$$

Under this noncooperative equilibrium, country i's emissions tax rate is positively related to its environmental damage parameter β_i, and inversely related to the other countries' environmental damage parameters, β_j and β_k, implying solid free-riding incentives. Moreover, higher import tariffs enable higher environmental taxes by reducing competition from foreign imports.

A singleton's production, consumption, and welfare equations are detailed in Appendix B1.

[4] Country i's welfare optimization problem under the singleton structure is detailed in Appendix B1.

1.3.2 The Grand Coalition Structure C_G

The model assumes that any cooperative equilibrium under the grand coalition and the partial coalition structures, implies a uniform emissions tax adopted by all countries within a coalition S. Considering a tie-in scenario, members of a coalition S coordinate all their actions with other members. Thus, it is assumed that they impose a uniform emissions tax rate t_S, along with common positive import tariff rates τ_S to be levied on each other, and $\tau_{S,k}$ to be imposed on non-members.

Indeed, economists and academics have frequently advocated uniform emissions tax solutions as an efficient policy instrument to tackle global environmental problems (Hoel 1992, Finus and Rundshagen 1998, Nordhaus 2006, Weitzman 2014). Advocates of uniform solutions often argue that these solutions are straightforward, typically involving less negotiation time and thus fewer transaction costs than differentiated solutions. It is also argued that uniform emissions taxes appear equitable since every country faces the same tax rate and are generally viewed as "fair" by the public (Finus and Rundshagen 1998, McEvoy and McGinty 2018). Moreover, uniform emissions tax rates are easily verifiable in an agreement. The advantages of having uniform solutions in negotiations lie in having some sense of focal point, akin to Schelling (1960), around which bargaining partners find it relatively easy to reach agreement (Finus and Rundshagen 1998).

Under the grand coalition, countries collectively decide to tax the production of the polluting good at a uniform tax rate, $t_G(C_G)$, that maximizes the joint welfare of all three countries, such that,

$$t_i(C_G) = t_j(C_G) = t_k(C_G) = t_G(C_G).$$

Additionally, members of the grand coalition impose a common positive import tariff, such that:

$$\tau_{i,j}(C_G) = \tau_{i,k}(C_G) = \tau_{j,i}(C_G) = \tau_{j,k}(C_G) = \tau_{k,i}(C_G) = \tau_{k,j}(C_G) = \tau_G(C_G).$$

Hence, the equilibrium quantities produced by the firm operating in country i, given by Equations (1.8) and (1.9), can be reduced to the following expressions, for i, j, k where $i \neq j, k$:

$$x_{ii}{}^{*}(C_G) = \frac{1}{4}(\alpha - t_G + 2\tau_G) \tag{1.20}$$

$$x_{ij}{}^{*}(C_G) = x_{ik}{}^{*}(C_G) = \frac{1}{4}(\alpha - t_G - 2\tau_G). \tag{1.21}$$

It is crucial to note that the three firms, located in the countries that form the grand coalition, continue to compete à la Cournot in the third stage of the coalition formation game. Given the restrictions imposed on the model's parameters, all the above optima are indeed interior solutions, since it is assumed that $x_{ii}{}^{*}(C_G) \in \mathbb{R}_n^{++}$ and $x_{ij}{}^{*}(C_G) \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$, which guarantee positive production levels under the grand coalition.

In the grand coalition structure C_G, countries collectively choose a uniform emissions tax rate t_G that maximizes their joint welfare, where $W^{C_G} = \sum_i W_i^{C_G}$, and a common exogenous tariff rate τ_G. Given country i's welfare maximization problem (1.10), then the grand coalition's optimization problem[5] can be expressed as follows:

$$\max_{t_G} W^{C_G} \Rightarrow \max_{t_G} \sum_i \begin{bmatrix} \frac{1}{2} Q_i{}^2(t_G) - \beta_i \left(X_i(t_G) + X_j(t_G) + X_k(t_G)\right) \\ +\tau_G \left(x_{ji}^{*}(t_G) + x_{ki}^{*}(t_G)\right) + \left(\alpha - Q_i(t_G)\right)x_{ii}^{*}(t_G) \\ +(\alpha - Q_j(t_G) - \tau_G)x_{ij}^{*}(t_G) + (\alpha - Q_k(t_G) - \tau_G)x_{ik}^{*}(t_G) \end{bmatrix}. \tag{1.22}$$

The first order condition of the joint welfare optimization problem (1.22) yields the following equilibrium emissions tax rate:

$$t_G^{*}(C_G) = \frac{1}{3}\left(\left(4\sum_i \beta_i - \alpha\right) - 2\tau_G\right). \tag{1.23}$$

The fully cooperative agreement denotes that the equilibrium emissions tax is positively related to all three environmental damage parameters and negatively related to the exogenous tariff τ_G.

[5] Country i's welfare optimization problem under the grand coalition structure C_G is detailed in Appendix C1.

This inverse relationship between emissions taxes and tariffs is unique to a cooperative equilibrium, where changes in tariff rates are accounted for by changes in emissions taxes. Consequently, in a fully cooperative scenario, trade liberalization in the form of lower tariffs can lead to higher emissions taxes in all three countries. Furthermore, a member's production level $X_i(C_G)$ and global production $\sum_i X_i\,(C_G)$ remain independent of the exogenous tariff rate $\tau_G(C_G)$, as changes in tariffs are offset by changes in emissions taxes. Similarly, a member's individual welfare $W_i(C_G)$ and collective welfare $\sum_i W_i\,(C_G)$ are also unaffected by the exogenous tariff rate. Thus, the stability of the coalition structures remains unaltered by the assumed exogenous tariff value τ_G, as long as Equation (1.23) is satisfied. The production, consumption, and welfare equations of a member of the grand coalition, are detailed in Appendix C1.

Moreover, Equation (1.23) implies that members of the grand coalition can impose a positive emissions tax rate to reduce production levels and thus global emissions, when the market is sufficiently small, where $\alpha \leq (4\sum_i \beta_i - 2\tau_G)$. However, when the market is sufficiently large and driven by consumption and profits, that is when $\alpha > (4\sum_i \beta_i - 2\tau_G)$, they can enforce a subsidy to increase production since the polluting good can be underproduced due to the Cournot competition.

1.3.3 The Partial Coalition Structure C_P

Under the partial coalition structure C_P, two countries, i and j for example, form a coalition $\mathcal{S}$, and the third country, k in this case, remains a singleton. The pair cooperatively decides to tax the production of the polluting good X at a uniform tax rate, $t_{ij}\left(C_P^k\right)$, that maximizes their joint welfare, where ${W_{ij}}^{C_P^k} = {W_i}^{C_P^k} + {W_j}^{C_P^k}$. As such, for i, j, k where $i \neq j, k$:

$$t_i(C_P^k) = t_j(C_P^k) = t_{ij}(C_P^k).$$

The pair within a partial coalition structure also imposes common exogenous tariffs among themselves and levies the same tariff on imports from the outsider, that is, for i, j, k where $i \neq j, k$:

$$\tau_{i,j}(C_P^k) = \tau_{j,i}(C_P^k) = \tau_{ij}(C_P^k)$$

$$\tau_{i,k}\left(C_P^k\right) = \tau_{j,k}\left(C_P^k\right) = \tau_{ij,k}\left(C_P^k\right).$$

Let $\tau_{k,ij}\left(C_P^k\right)$ represents the tariff rate that a singleton will charge to the pair of countries in the same coalition structure. The singleton within the partial coalition structure treats the pair as one entity and charges the same tariff rate to each member of the pair, that is, for i, j, k where $i \neq j, k$:

$$\tau_{k,i}\left(C_P^k\right) = \tau_{k,j}\left(C_P^k\right) = \tau_{k,ij}\left(C_P^k\right).$$

The outsider to the pair, country k in this case, behaves noncooperatively as a singleton, maximizing its individual welfare function, given the pair's emissions tax $t_{ij}\left(C_P^k\right)$ and exogenous tariffs $\tau_{ij}\left(C_P^k\right)$ and $\tau_{ij,k}\left(C_P^k\right)$. It is assumed, however, that the outsider can be denied the preferential market access enjoyed by pair members, and hence, for i, j, k where $i \neq j, k$:

$$\tau_{ij,k}\left(C_p^k\right) \geq \tau_{ij}\left(C_p^k\right).$$

The use of preferential tariffs as a carrot-and-stick mechanism to promote environmental policy and other non-trade policy objectives, including human rights, labor standards, the production of narcotic drugs, and security issues, has been a common practice in the European Union (EU). For instance, in 2010, when Sri Lanka violated several UN human rights conventions, the European Union revoked its trading partner's preferential market access with lower tariffs. Similarly, the EU withheld preferential access to the European market from Venezuela in 2010 when it failed to ratify the UN convention against corruption (Borchert et al., 2021). Consistent with these practices, it is assumed in this essay that the pair would penalize the outsider for his free-riding behavior by denying preferential access with lower tariffs to their markets.

Under the partial coalition structure C_P, there are three possible arrangements, namely, $\{\{i,j\},\{k\}\}$, $\{\{i,k\},\{j\}\}$, and $\{\{j,k\},\{i\}\}$. Therefore, there are three emissions tax rates among pair members: $t_{ij}(C_P^k)$, $t_{ik}(C_P^j)$, and $t_{jk}(C_P^i)$, along with the corresponding outsider's emissions tax rate $t_k^P(C_P^k)$, $t_j^P(C_P^j)$, and $t_i^P(C_P^i)$. In terms of exogenous tariffs, there are six pair members rates, $\tau_{ij}(C_P^k)$, $\tau_{ij,k}(C_P^k)$, $\tau_{ik}(C_P^j)$, $\tau_{ik,j}(C_P^j)$, $\tau_{jk}(C_P^i)$, and $\tau_{jk,i}(C_P^i)$, and three tariffs imposed by the outsider on pair members, $\tau_{k,ij}(C_P^k)$, $\tau_{j,ik}(C_P^j)$, and $\tau_{i,jk}(C_P^i)$.

1.3.3.1 The Partial Coalition's Pair

Given the outsider's emissions tax rate, $t_k^P(C_P^k)$, and exogenous tariff, $\tau_{k,ij}(C_P^k)$, the equilibrium quantities produced by the firm operating in any country within a pair, given by Equations (1.8) and (1.9), can thus be reduced as follows, for i,j,k where $i \neq j,k$:

$$x_{ii}^*(C_P^k) = \tfrac{1}{4}\left(\alpha - 2t_{ij} + t_k^P + \tau_{ij} + \tau_{ij,k}\right) \tag{1.24}$$

$$x_{ij}^*(C_P^k) = \tfrac{1}{4}\left(\alpha - 2t_{ij} + t_k^P - 3\tau_{ij} + \tau_{ij,k}\right) \tag{1.25}$$

$$x_{ik}^*(C_P^k) = \tfrac{1}{4}\left(\alpha - 2t_{ij} + t_k^P - 2\tau_{k,ij}\right). \tag{1.26}$$

It is important to recognize that the two firms located in the countries forming the pair still act independently of each other in the third stage of the coalition formation game. Given the imposed restrictions on the parameters of the model, local production $x_{ii}^*(C_P^k) \in \mathbb{R}_n^{++}$ and exports $x_{ij}^*(C_P^k)$, $x_{ik}^*(C_P^k) \in \mathbb{R}_n^{+}$, for i,j,k where $i \neq j,k$.

The pair collectively decides to tax the production of the polluting good at a rate that maximizes their joint welfare, where $W_{ij}^{C_P^k} = W_i^{C_P^k} + W_j^{C_P^k}$.

The pair's joint welfare optimization problem[6] (1.10) can be written as follows:

$$\max_{t_{ij}} W_{ij}{}^{C_P^k} \Rightarrow \max_{t_{ij}} \begin{bmatrix} \frac{1}{2}\left(Q_i{}^2(t_{ij}) + Q_j{}^2(t_{ij})\right) - (\beta_i + \beta_j)\left(X_i(t_{ij}) + X_j(t_{ij}) + X_k(t_{ij})\right) \\ \left(\alpha - Q_i(t_{ij})\right)\left(x_{ii}^*(t_{ij}) + x_{ji}^*(t_{ij})\right) + \left(\alpha - Q_j(t_{ij})\right)\left(x_{ij}^*(t_{ij}) + x_{jj}^*(t_{ij})\right) \\ +(\alpha - Q_k(t_{ij}) - \tau_{k,ij})\left(x_{ik}^*(t_{ij}) + x_{jk}^*(t_{ij})\right) + \tau_{ij,k}\left(x_{ki}^*(t_{ij}) + x_{kj}^*(t_{ij})\right) \end{bmatrix} \quad (1.27)$$

The first order condition of the welfare optimization problem (1.27) yields the following upward sloping best response function:

$$t_{ij}(t_k^P) = \frac{1}{10}\left(-3\alpha + 6(\beta_i + \beta_j) + t_k^P + \left(5\tau_{ij,k} - 3\tau_{ij}\right)\right). \quad (1.28)$$

A pair member exhibits a positive upward sloping best response function implying a cooperative response towards the outsider, while the latter is behaving noncooperatively as a singleton. A higher emissions tax rate levied on the firm operating in the noncooperative country, country k in this case, increases its costs and reduces its competitiveness. Hence, it prompts pair members to increase the emissions taxes levied in their own countries, leading to more stringent environmental regulations despite the singleton's noncooperative behavior.

The pair members equilibrium tax rate is expressed as follows, for i, j, k where $i \neq j, k$:

$$t_{ij}^*(C_P^k) = \frac{1}{180}\left(102(\beta_i + \beta_j) + 12\beta_k - 60\alpha - 55\tau_{ij} + \left(97\tau_{ij,k} + 6\tau_{k,ij}\right)\right). \quad (1.29)$$

The positive best response function indicates that the pair's equilibrium emissions tax is positively related to its own damage parameters, as well as to the outsider's parameter. Like members of the grand coalition, countries within the pair impose a positive emissions tax when the market size, captured by α, is sufficiently small, $\forall \alpha \leq \frac{1}{60}\left(102(\beta_i + \beta_j) + 12\beta_k + 97\tau_{ij,k} + 6\tau_{k,ij} - 55\tau_{ij}\right)$, and they can opt for a subsidy when the market is sufficiently larger, due to the Cournot dynamics.

[6] Country i's optimization problem as a pair member in the partial coalition structure is detailed in Appendix D1.

Changes in import tariffs are twofold. Firstly, import tariffs among pair members, $\tau_{ij}\left(C_P^k\right)$, are indirectly related to their emissions tax. Similar to the grand coalition, this inverse relationship between emissions taxes and tariffs is due to the cooperation among countries within the pair. It follows that aggregate production $\sum_i X_i\left(C_P^k\right)$ under the partial coalition structure is independent of the exogenous tariff rate $\tau_{ij}\left(C_P^k\right)$, as changes in tariffs are offset by changes in emissions tax rates. Secondly, the emissions tax rate is positively related to the tariff imposed by the pair on the outsider, $\tau_{ij,k}(C_P^k)$, and that imposed by the outsider on imports from the pair, $\tau_{k,ij}(C_P^k)$. In this partially cooperative scenario, lower tariffs among the pair and the outsider will decrease the pair's emissions tax, potentially leading to laxer environmental regulations.

A pair member's production, consumption, and welfare equations are detailed in Appendix D1.

1.3.3.2 The Partial Coalition's Outsider

Given pair members' emissions tax rate $t_{ij}\left(C_P^k\right)$ and tariffs $\tau_{ij}\left(C_P^k\right)$ and $\tau_{ij,k}\left(C_P^k\right)$, the equilibrium quantities produced by the firm in country k (the outsider to the pair), expressed in Equations (1.8) and (1.9), can be reduced as follows, for i, j, k where $i \neq j, k$:

$$x_{kk}{}^*\left(C_P^k\right) = \frac{1}{4}\left(\alpha - 3t_k^P + 2t_{ij} + 2\tau_{k,ij}\right) \tag{1.30}$$

$$x_{ki}{}^*\left(C_P^k\right) = x_{kj}{}^*\left(C_P^k\right) = \frac{1}{4}\Big(\alpha - 3t_k^P + 2t_{ij} - \left(3\tau_{ij,k} - \tau_{ij}\right)\Big). \tag{1.31}$$

The constraints imposed on the parameters ensure that $x_{kk}{}^*\left(C_P^k\right) \in \mathbb{R}_n^{++}$ and $x_{ki}{}^*\left(C_P^k\right) \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.

The outsider to a pair behaves noncooperatively and its optimization problem[7] (1.10) is as follows:

$$\max_{t_k^P} W_k^{C_P^k} \Rightarrow \max_{t_k^P}\begin{bmatrix} \frac{1}{2}Q_k{}^2(t_k^P) - \beta_k\left(X_i(t_k^P) + X_j(t_k^P) + X_k(t_k^P)\right) \\ +\tau_{k,ij}\left((x_{ik}^*(t_k^P) + x_{jk}^*(t_k^P)\right) + \left(\alpha - Q_k(t_k^P)\right)x_{kk}^*(t_k^P) \\ +\left(\alpha - Q_i(t_k^P) - \tau_{ij,k}\right)x_{ki}^*(t_k^P) + \left(\alpha - Q_j(t_k^P) - \tau_{ij,k}\right)x_{kj}^*(t_k^P) \end{bmatrix}. \tag{1.32}$$

[7] Country k's optimization problem as an outsider in the partial coalition structure is detailed in Appendix D1.

The first order condition of the welfare maximization problem (1.32) yields the following downward sloping best response function:

$$t_k^P(t_{ij}) = \frac{1}{17}\left(12\beta_k - 9\alpha - 10t_{ij} - 4\tau_{ij} + (12\tau_{ij,k} + 6\tau_{k,ij})\right). \tag{1.33}$$

Unlike the pair, the outsider has a downward sloping best response function.

The outsider's equilibrium emissions tax rate, for i, j, k where $i \neq j, k$, is as follows:

$$t_k^{*P}(C_P^k) = \frac{1}{18}\left(12\beta_k - 6(\beta_i + \beta_j) - 6\alpha + (6\tau_{k,ij} + 7\tau_{ij,k}) - \tau_{ij}\right). \tag{1.34}$$

The outsider's equilibrium tax rate is positively related to its own environmental damage parameter and negatively related to those of the pair, as it free rides on the environmental benefits provided by them. With exogenous positive tariffs in place, numerical simulations indicate that the outsider subsidizes the production of the polluting good.

Furthermore, higher tariffs between the outsider and the pair, allow for higher environmental taxes in the outsider country. Conversely, a higher tariff rate among countries within the pair, $\tau_{ij}(C_P^k)$, which reduces the trade between them, lowers the outsider's environmental tax rate.

The outsider's production, consumption, and welfare equations are detailed in Appendix D1.

1.4 Results

Having examined all possible equilibria, the aim is to identify which cooperative scenarios will emerge in a stable environmental coalition and to capture the effect of environmental damage heterogeneity on the stability of these coalitions. Due to the complexities of the equations, the analysis had to rely on numerical simulations, which are subject to certain parameters restrictions. The analytical and simulation results are summarized in the following two subsections.

1.4.1 Analytical Results

Proposition 1.4.1.1: *Compared to the singleton and the partial coalition structures, the grand coalition can yield environmental benefits in terms of lower global emissions when exogenous tariff rates are sufficiently low.*

The complete proof of Proposition 1.4.1.1 is delineated to Appendix G1.

Let $X(C_{NC})$, $X(C_G)$, $X(C_P^k)$, represent global production under the singletons C_{NC}, the grand coalition C_G, and the partial coalition C_P^k, respectively. These production levels are, respectively:

$$X(C_{NC}) = \sum_i X_i(C_{NC}) = \frac{1}{9}\left(27\alpha - 3\sum_i \beta_i - 4\sum_i \sum_j \tau_{i,j}\right) \tag{1.35}$$

$$X(C_G) = \sum_i X_i\,(C_G) = 3(\alpha - \sum_i \beta_i) \tag{1.36}$$

$$X(C_P^k) = \sum_i X_i\,(C_P^k) = \frac{1}{5}\left(15\alpha - 3\sum_i \beta_i - 4\left(\tau_{k,ij} + 2\tau_{ij,k}\right)\right). \tag{1.37}$$

Using (1.35) and (1.36), the collective environmental gains provided by the grand coalition in comparison to the singleton structure are as follows:

$$X(C_{NC}) - X(C_G) = \frac{4}{9}\left(6\sum_i \beta_i - \sum_i \sum_j \tau_{i,j}\right). \tag{1.38}$$

Equation (1.38) clearly indicates that the grand coalition provides environmental gains, when $\sum_i \sum_j \tau_{i,j} < 6\sum_i \beta_i$, for i, j, k where $i \neq j, k$. This holds true at various degrees of environmental damage heterogeneity, and these gains improve as global damage, $\sum_i \beta_i$, becomes more significant.

Using (1.36) and (1.37), the collective environmental gains provided by the grand coalition in comparison to the partial coalition C_P^k, and by symmetry for C_P^j and C_P^i, are as follows:

$$X(C_P^k) - X(C_G) = \frac{4}{5}\left(3\sum_i \beta_i - \left(2\tau_{ij,k} + \tau_{k,ij}\right)\right). \tag{1.39}$$

Equation (1.39) demonstrates that the grand coalition results in lower global production in comparison to the partial coalition C_P^k, when $\left(2\tau_{ij,k} + \tau_{k,ij}\right) < 3\sum_i \beta_i$, for i, j, k where $i \neq j, k$.

Notably, these environmental benefits in terms of lower emissions are directly tied to global environmental damage, as captured here by $\sum_i \beta_i$. Tariffs act as the effective marginal costs on exports, reducing global production under the singleton and the partial coalition structures, as shown by Equations (1.35) and (1.37). Lower import tariffs will lead to more output under these coalitions, and therefore, more significant environmental gains under the grand coalition compared to the other structures. This finding aligns with Baksi and Chaudhury (2017), who demonstrated that trade liberalization generates more significant environmental gains from cooperation.

Proposition 1.4.1.2: *In a free trade setting, the grand coalition is stable only in the homogeneous benchmark case and some scenarios with sufficiently low degrees of heterogeneity.*

The complete proof of Proposition 1.4.1.2 is delineated to Appendix H1.

Let $W_i(C_G) - W_i\left(C_p^i\right)$ be country i's individual welfare gains as a member of the grand coalition in comparison to behaving as an outsider to a pair within the partial coalition structure. Given the stability conditions (1.13) and (1.14), the grand coalition is externally stable by default, and internally stable if $W_i(C_G) - W_i\left(C_p^i\right) \geq 0$, for i, j, k where $i \neq j, k$.

In a free trade setting, these individual welfare gains are as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i\left(C_p^i\right) = \frac{3}{25}\left[\sum_i \beta_i \left(18\beta_i - 7\left(\beta_j + \beta_k\right)\right)\right]. \tag{1.40}$$

Given the heterogeneity assumption, where $\beta_i > \beta_j > \beta_k > 0$, it is evident from Equation (1.40) that members of the grand coalition do not benefit equally from the fully cooperative agreement. Country i consistently favors the grand coalition, whereas countries j and k, would only favor the fully cooperative agreement, when the degree of heterogeneity is sufficiently low[8]. With free trade, the stability of the grand coalition requires that $\beta_i \geq \frac{7}{18}\left(\beta_j + \beta_k\right)$ where $\beta_i > \beta_j > \beta_k > 0$, for i, j, k where $i \neq j, k$.

This finding aligns with Cavagnac and Cheikbossian (2017), who found that a global coalition within a free trade framework is less likely to form as a stable equilibrium when there is significant asymmetry in country sizes.

In the homogeneous case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, Equation (1.40) is reduced to, for i, j, k:

$$\widehat{W}_i(C_G) - \widehat{W}_i\left(C_p^i\right) = \left(\frac{6}{5}\hat{\beta}\right)^2. \tag{1.41}$$

Equation (1.41) clearly indicates that the grand coalition is unambiguously stable at any value of the marginal environmental damage $\hat{\beta}$, since $\widehat{W}_i(C_G) - \widehat{W}_i > 0$, $\forall \hat{\beta} > 0$. Also, these individual welfare gains can improve exponentially as the damage parameter $\hat{\beta}$ takes a higher value.

Proposition 1.4.1.3: *In a free trade setting, the singleton structure is stable only in the homogeneous benchmark case and some scenarios with sufficiently low degrees of heterogeneity.*

The complete proof of Proposition 1.4.1.3 is delineated to Appendix I1.

Let $W_i(C_{NC}) - W_i\left(C_p^j\right)$ be country i's individual welfare gains when behaving as a singleton in comparison to forming a pair with country k within the partial coalition C_p^j. Given the stability conditions (1.13) and (1.14), the singleton k is internally stable by default, and externally stable, if $W_i(C_{NC}) - W_i\left(C_p^j\right) \geq 0$ and $W_j(C_{NC}) - W_j\left(C_p^i\right) \geq 0$, and by symmetry for singletons i and j.

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[8] For instance, $\left(\beta_i, \beta_j, \beta_k\right) = (0.50, 0.34, 0.33)$ and $\left(\beta_i, \beta_j, \beta_k\right) = (0.39, 0.33, 0.28)$, both satisfy Equation (1.40). These sets correspond to a level of heterogeneity, with values of 21% and 16.4%, respectively, as measured by $(\beta_i - \beta_k)/(\beta_i + \beta_k)$.

In a free trade setting, these individual welfare gains, for i, j, k where $i \neq j, k$, are expressed as:

$$W_i(C_{NC}) - W_i\left(C_P^j\right) = \frac{1}{2\times3^4\times5}\sum_i \beta_i \left[\left(247\beta_k - 239\beta_i\right) + 4\beta_j\right]. \tag{1.42}$$

In the presence of heterogeneity, where $\beta_i > \beta_j > \beta_k > 0$, the stability of the singleton structure requires that $239\beta_i \leq \left(247\beta_k + 4\beta_j\right)$, for i, j, k where $i \neq j, k$. This condition represents a range of parameters[9] that corresponds to very low degrees of environmental damage heterogeneity.

Alternatively, in the homogeneous benchmark case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, Equation (1.42), can be reduced as follows, for i, j, k:

$$\widehat{W}_i(C_{NC}) - \widehat{W}_i\left(C_P^j\right) = \frac{2}{3^2\times5}\hat{\beta}^2. \tag{1.43}$$

Equation (1.43) indicates that in a free trade setting, the singleton structure is unambiguously stable in the homogeneous case at any value of marginal environmental damage $\hat{\beta}$, where $\hat{\beta} > 0$.

Proposition 1.4.1.4: *In a free trade setting, there isn't a range of parameters where the partial coalition structure is stable.*

The complete proof of Proposition 1.4.1.4 is delineated to Appendix J1.

Let $W_i\left(C_p^i\right) - W_i(C_G)$ be country i's welfare gains as an outsider to a pair in the partial coalition C_p^i in comparison to being a member of the grand coalition. Given the stability condition (1.14), the partial coalition C_p^i is externally stable, if $W_i\left(C_p^i\right) - W_i(C_G) \geq 0$, and by symmetry for C_p^j and C_p^k. With free trade, these welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i\left(C_p^i\right) - W_i(C_G) = \frac{3}{25}\sum_i \beta_i \left(7\left(\beta_j + \beta_k\right) - 18\beta_i\right). \tag{1.44}$$

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[9] For instance, $\left(\beta_i, \beta_j, \beta_k\right) = (0.50, 0.49, 0.48)$ and $\left(\beta_i, \beta_j, \beta_k\right) = (0.342, 0.33, 0.328)$, both satisfy Equation (1.42). Both sets of values correspond to a level of heterogeneity, as measured by $(\beta_i - \beta_k)/(\beta_i + \beta_k)$, equivalent to 2%.

In the presence of heterogeneity, where $\beta_i > \beta_j > \beta_k > 0$, Equation (1.44) indicates that the partial coalition C_p^i is externally unstable, since $W_i(C_p^i) - W_i(C_G) < 0, \forall\, \beta_i > \beta_j > \beta_k > 0$. For the partial coalitions C_p^j and C_p^k, their external stability requires, respectively, $\beta_j \leq \frac{7}{18}(\beta_i + \beta_k)$ and $\beta_k \leq \frac{7}{18}(\beta_i + \beta_j)$, where $\beta_i > \beta_j > \beta_k > 0$.

Let $W_i(C_p^k) - W_i(C_{NC})$ be country i's welfare gains when forming a pair with country j, in comparison to behaving as a singleton. Given the stability condition (1.13), the partial coalition C_p^k is internally stable, if $W_i(C_p^k) - W_i(C_{NC}) \geq 0$ and $W_j(C_p^k) - W_j(C_{NC}) \geq 0$. With free trade, these individual welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_p^k) - W_i(C_{NC}) = \frac{1}{2\times3^4\times5}\sum_i \beta_i \left((239\beta_i - 247\beta_j) - 4\beta_k\right) \tag{1.45}$$

When $\beta_i > \beta_j > \beta_k > 0$, Equation (1.45) demonstrates that all partial coalition arrangements, C_p^i, C_p^j and C_p^k, are internally unstable. Country k, is consistently better off as a singleton in C_p^i, since $W_k(C_p^i) - W_k(C_{NC}) < 0, \forall 0 < \beta_k < \beta_j < \beta_i$. It also favors the singleton structure to C_p^j, since $W_k(C_p^j) - W_k(C_{NC}) < 0, \forall 0 < \beta_k < \beta_j < \beta_i$. For C_p^k, country j will deviate from the pair, since $W_j(C_p^k) - W_j(C_{NC}) < 0, \forall 0 < \beta_k < \beta_j < \beta_i$.

Hence, in the presence of heterogeneity, the partial coalition is internally and externally unstable.

Additionally, in the homogeneous case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, the partial coalition remains internally and externally unstable, as Equations (1.44) and (1.45) are negative, $\forall \hat{\beta} > 0$.

Proposition 1.4.1.5: *In a free trade setting, a member of the grand coalition can be individually better off than when it behaves noncooperatively as a singleton.*

The complete proof of Proposition 1.4.1.5 is delineated to Appendix K1.1.

Let $W_i(C_G) - W_i(C_{NC})$ be country i's individual welfare gains as a member of the grand coalition in comparison to a singleton. With free trade, these welfare gains are, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i(C_{NC}) = \frac{1}{3^4} \sum_i \beta_i \left((97\beta_i - 49\beta_j) + (97\beta_i - 49\beta_k) \right) \qquad (1.46)$$

Equation (1.46) demonstrates that country i, having the highest environmental damage parameter, consistently benefits from the fully cooperative agreement, with its welfare gains improving when the degree of heterogeneity rises. Though, given the heterogeneity assumption, $\beta_i > \beta_j > \beta_k > 0$, members of the grand coalition do not benefit equally from the fully cooperative agreement. Country j would only be better off under the grand coalition, when $194\beta_j > 49(\beta_i + \beta_k)$, and country k, when $194\beta_k > 49\left(\beta_i + \beta_j\right)$, $\forall\, \beta_i > \beta_j > \beta_k > 0$.

In the homogeneous case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, Equation (1.46) is reduced to, for i, j, k:

$$\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) = \frac{2^5}{3^2} \left(\hat{\beta}\right)^2. \qquad (1.47)$$

Equation (1.47) indicates that any country is always individually better off within the grand coalition in comparison to behaving as a singleton, since $\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) > 0$, $\forall \hat{\beta} > 0$, and these welfare gains can significantly improve as the damage parameter $\hat{\beta}$ takes a higher value.

Proposition 1.4.1.6: *In a free trade setting, a member of the grand coalition is not always individually better off than when forming a pair in the partial coalition structure.*

The complete proof of Proposition 1.4.1.6 is delineated to Appendix K1.2.

Let $W_i(C_G) - W_i\left(C_p^k\right)$ be country i's individual welfare gains as a member of the grand coalition in comparison to forming a pair with country j in the partial coalition C_p^k. In a free trade setting, these individual welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i\left(C_p^k\right) = \frac{3}{10} \sum_i \beta_i \left((7\beta_i - \beta_j) - 2\beta_k \right). \qquad (1.48)$$

Since $\beta_i > \beta_j > \beta_k > 0$, Equation (1.48) indicates that these welfare gains are unambiguously positive, when $\beta_i \geq \frac{1}{7}(\beta_j + 2\beta_k)$, for i, j, k where $i \neq j, k$. It is also evident that country i, with the highest environmental damage parameter β_i, consistently favors the grand coalition, since $W_i(C_G) - W_i(C_p^k) > 0$, $\forall \beta_i > \beta_j > \beta_k > 0.$ However, countries j and k may, depending on the degree of heterogeneity, favor the partial cooperative agreement to the fully cooperative one.

Alternatively, when $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, Equation (1.48) can be reduced as follows, for i, j, k:

$$\widehat{W}_i(C_G) - \widehat{W}_i(C_p^k) = \frac{18}{5}\hat{\beta}^2 \tag{1.49}$$

It is evident from Equation (1.49) that any country is always individually better off within the grand coalition compared to forming a pair within the partial coalition structure, since, for i, j, k, $\widehat{W}_i(C_G) - \widehat{W}_i(C_p^k) > 0$, $\forall \hat{\beta} > 0$. Moreover, these welfare gains from the grand coalition can increase exponentially as the marginal environmental damage parameter $\hat{\beta}$ takes a higher value.

Proposition 1.4.1.7: *A larger value of the parameter α reinforces the stability of the grand coalition when punitive tariffs are sufficiently high.*

Let $W_i(C_G) - W_i(C_p^i)$ be country i's individual welfare gains as a member of the grand coalition in comparison to being an outsider in the partial coalition C_p^i. Using (1.13) and (1.14), the grand coalition is externally stable by default, and its internal stability requires $W_i(C_G) - W_i(C_p^i) \geq 0$, for i, j, k where $i \neq j, k$. These welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i(C_p^i) = \frac{1}{450}\begin{bmatrix} 54\sum_i \beta_i\left(18\beta_i - 7(\beta_j + \beta_k)\right) - 25\tau_{jk}(3\alpha + \tau_{jk} + \tau_{i,jk} - 6\tau_{jk,i}) \\ +6\tau_{i,jk}(-25\alpha - 58\beta_i + 17(\beta_j + \beta_k) + 43\tau_{i,jk}) \\ +\tau_{jk,i}(225\alpha + 204(\beta_j + \beta_k) - 696\beta_i - 293\tau_{jk,i} + 7\tau_{i,jk}) \end{bmatrix} \tag{1.50}$$

The impact of the value of α on the grand coalition's internal stability condition is given by:

$$\frac{\partial[W_i(C_G)-W_i(C_p^i)]}{\partial\alpha} = \frac{1}{6}\left[3\tau_{jk,i} - \left(\tau_{jk} + 2\tau_{i,jk}\right)\right]. \tag{1.51}$$

The grand coalition's stability can be reinforced by a larger α value, when punitive tariffs are such that $\tau_{jk,i} > \frac{1}{3}\left(\tau_{jk} + 2\tau_{i,kj}\right)$, which guarantee that $\frac{\partial\left(W_i(C_G)-W_i(C_p^i)\right)}{\partial\alpha} > 0$, for i, j, k where $i \neq j, k$.

1.4.2 Simulation Results

In the numerical simulations, the model's parameters are constrained to ensure several conditions. First, the restrictions ensure an active market by setting any marginal environmental damage parameter to be less than the maximal marginal utility of good X, denoted by the parameter α, such that $\alpha > \beta_i > \beta_j > \beta_k > 0$. Second, the restrictions maintain the market structure throughout the game and ensure a positive interior solution by restricting local production in any country to be strictly positive and requiring exports to be positive. Third, the constrained parameters set an upper bound on non-negative import tariffs to guarantee positive trade flows among countries. The parameters chosen in the numerical simulations adhere precisely to these restrictions[10].

Given the stability conditions defined in Equations (1.13) and (1.14), the numerical simulations demonstrate that the grand coalition remains stable across various degrees of environmental damage heterogeneity and levels and structures of exogenous import tariffs. However, the stability of the grand coalition becomes more fragile and increasingly sensitive to exogenous tariffs as the degree of heterogeneity increases. At high degrees of heterogeneity, when punitive tariffs are sufficiently low, the grand coalition can give way to the partial coalition arrangement C_p^k. While, at sufficiently low levels or in the absence of such punitive tariffs, the singleton structure can become stable at various degrees of heterogeneity.

[10] The most restrictive conditions on the model's parameters are summarized in Appendix E1.

Remark 1.4.2.1: *There exists a range of parameters where the grand coalition is stable in the homogeneous benchmark case and at different levels of environmental damage heterogeneity.*

The numerical simulation of the model reveals that the grand coalition is stable across varying degrees of environmental damage heterogeneity. It also confirms that the grand coalition remains stable at various levels of exogenous tariffs and different tariff structures. Nevertheless, at high levels of heterogeneity, the stability of the grand coalition becomes more fragile and increasingly sensitive to the underlying exogenous tariff structure. A higher punitive tariff on the outsider in a partial coalition consistently reinforce the stability of the grand coalition and extends the range of parameters where it is stable.

Let $(\beta_i - \beta_k)/(\beta_i + \beta_k)$ be a measure of heterogeneity, where β_i denotes the marginal environmental damage incurred by the country that suffers the most, and β_k denotes the marginal environmental damage incurred by the country experiencing the least damage. The numerical simulations indicate that the grand coalition is stable over a wide range[11] of heterogeneity, where $0 \leq (\beta_i - \beta_k)/(\beta_i + \beta_k) \leq 1$.

Let $W_i(C_G) - W_i(C_p^i)$ be the individual welfare gains achieved by country i for being a member of the grand coalition in comparison to being an outsider to a pair within the partial coalition C_p^i. Given the stability conditions (1.13) and (1.14), the grand coalition is externally stable by default, and internally stable $\Leftrightarrow W_i(C_G) - W_i(C_p^i) \geq 0$, for i, j, k where $i \neq j, k$.

These individual welfare gains are given by the following expression, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i(C_p^i) = \frac{1}{450}\left[54 \textstyle\sum_i \beta_i \left(18\beta_i - 7(\beta_j + \beta_k)\right) - \Omega_i(C_p^i)\right], \tag{1.52}$$

[11] The upper bound of this range is very sensitive to the assumed parameters values in the simulations, in particular, the α value and the underlying exogenous tariff structure. This upper bound is based on the following assumptions: $\sum_i \beta_i = 1$, $\alpha = 3.5 \sum_i \beta_i$, and the following exogenous tariff structure, for i, j, k where $i \neq j, k$: $\tau_G(C_G) = 0$, $\tau_{i,j}(C_{NC}) = \frac{1}{15}(3\beta_i - 2\beta_j + \beta_k + \alpha)$, $\tau_{ij}(C_p^k) = \frac{1}{10} Avg(\tau_{i,j}, \tau_{j,i})$, $\tau_{ij,k}(C_p^k) = \frac{15}{10} Avg(\tau_{i,k}, \tau_{j,k})$, $\tau_{k,ij}(C_p^k) = Avg(\tau_{k,i}, \tau_{k,j})$.

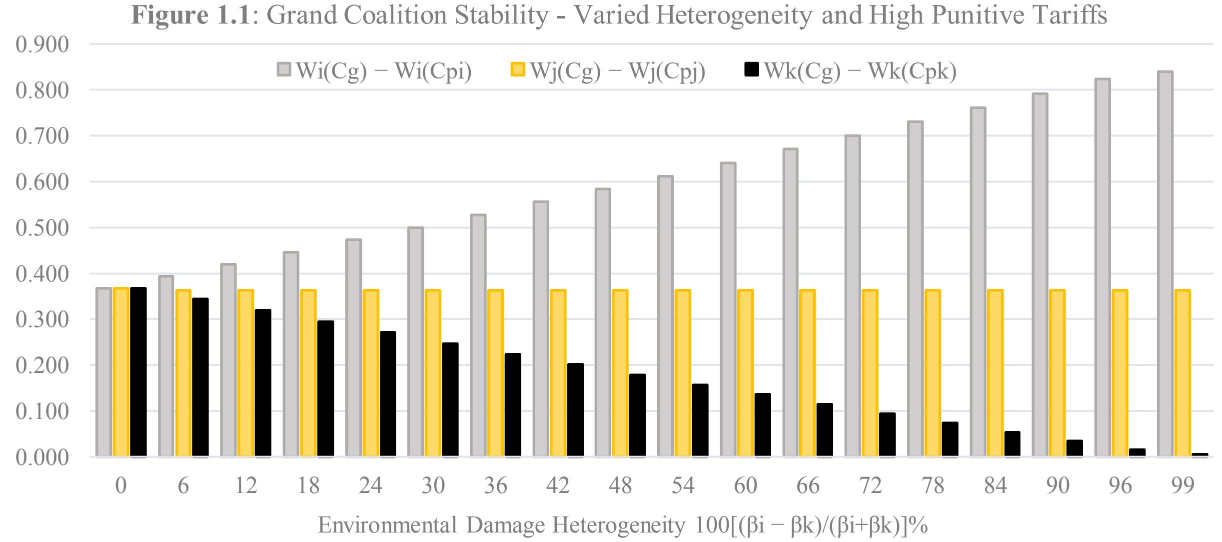
where $\Omega_i(C_p^i)$ captures the exogenous tariff structure of the partial coalition C_p^i, and is given by:

$$\Omega_i(C_P^i) = \begin{bmatrix} 25\tau_{jk}(3\alpha + \tau_{jk} + \tau_{i,jk}) + 6\tau_{i,jk}(25\alpha + 58\beta_i - 17(\beta_j + \beta_k) - 43\tau_{i,jk}) \\ +\tau_{jk,i}(-225\alpha - 204(\beta_j + \beta_k) + 696\beta_i - 150\tau_{jk} + 293\tau_{jk,i} - 7\tau_{i,jk}) \end{bmatrix}. \quad (1.53)$$

Given the heterogeneity assumption, where $\beta_i > \beta_j > \beta_k > 0$, members of the grand coalition do not benefit equally from the fully cooperative agreement. Assuming $\alpha = 3.5 \sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 1.1 depicts the individual welfare gains derived by countries i, j, k from joining the grand coalition at varying levels of environmental damage heterogeneity. In this scenario, β_i takes a higher value, β_j has the same value, and β_k takes a lower value, drifting further away from β_i and β_j, leading to an increasing degree of heterogeneity, while maintaining $\sum_i \beta_i = 1$.

Figure 1.1 shows that country i enjoys greater welfare gains, while country k derives smaller welfare gains as the degree of heterogeneity increases. The lower production resulting from the grand coalition significantly reduces country i's environmental damage, consequently boosting its net consumer surplus as β_i takes a higher value. These improvements, coupled with higher pre-tax profits, outweigh the reduction in tariff revenues brought about by the grand coalition and lead to increasing welfare gains for country i.

Figure 1.1: Grand Coalition Stability - Varied Heterogeneity and High Punitive Tariffs

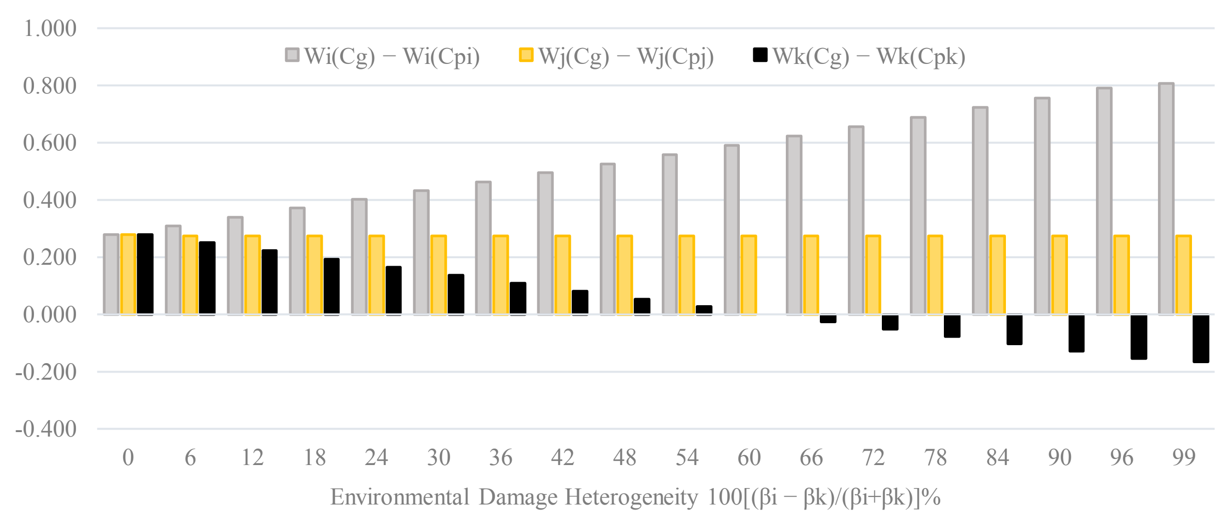


By contrast, country k has weaker incentives to join the grand coalition. As β_k takes a lower value, the welfare gains from reduced production and subsequent lower environmental damage diminish, resulting in a decreased net consumer surplus and less significant improvements in its welfare.

The magnitude of the punitive tariff on the outsider in the partial coalition structure plays a critical role in determining coalitional stability. The numerical simulations demonstrate that when such punitive tariffs are relatively low, the grand coalition can become unstable at high degrees of heterogeneity, and instead the partial coalition arrangement C_p^k becomes stable, where countries i and j coordinate their environmental and trade policies, and country k behaves as a singleton.

Figure 1.2 depicts Equation (1.52) for countries i, j and k under the same conditions as Figure 1.1, except the values of the punitive tariffs[12] imposed on outsiders are lower. It is evident from Figure 1.2 that the grand coalition is stable at various degrees of heterogeneity up to 60%, while at higher levels, country k no longer favors the fully cooperative scenario.

Figure 1.2: Grand Coalition Stability - Varied Heterogeneity and Low Punitive Tariffs



[12] Figure 1.2 assumes $\sum_i \beta_i = 1$, $\alpha = 3.5 \sum_i \beta_i$, and the exogenous tariff structure, for i, j, k and $i \neq j$: $\tau_G(C_G) = 0$, $\tau_{i,j}(C_{NC}) = \frac{1}{15}(3\beta_i - 2\beta_j + \beta_k + \alpha)$, $\tau_{ij}(C_p^k) = \frac{1}{10} Avg(\tau_{i,j}, \tau_{j,i})$, $\tau_{ij,k}(C_p^k) = \frac{12}{10} Avg(\tau_{i,k}, \tau_{j,k})$, $\tau_{k,ij}(C_p^k) = Avg(\tau_{k,i}, \tau_{k,j})$.

For country k, the lower punitive tariff reduces the cost of deviation from the grand coalition. As an outsider, country k benefits from increased production and consumption, leading to a higher net consumer surplus. This improvement, along with additional tariff revenues, outweighs the losses in pre-tax profits, resulting in welfare gains. For both countries i and j, their welfare improvements as a pair are mainly driven by higher pre-tax profits compared to behaving noncooperatively as singletons.

For the assumed tariff structure and set of parameters, these results remain consistent for any punitive tariff $\tau_{ij,k}(C_p^k)$, where $\tau_{ij,k}(C_p^k) \geq \frac{8}{10}\left(\frac{\tau_{i,k}+\tau_{j,k}}{2}\right)$. Moreover, when punitive tariffs are sufficiently high, the grand coalition's stability can be reinforced by a larger α value as indicated by Proposition 1.4.1.7. These results are robust to changes in exogenous tariff levels and structures, changes in α values, where $\alpha \geq \frac{1}{60}\left[66\left(\beta_i + \beta_j\right) - 24\beta_k - 25\tau_{ij} + \left(31\tau_{ij,k} + 78\tau_{k,ij}\right)\right]$, and when relaxing the $\sum_i \beta_i = 1$ assumption[13].

Remark 1.4.2.2 *There exists a range of parameters where the partial coalition C_p^k is stable at sufficiently high levels of environmental damage heterogeneity.*

The numerical simulations of the model reveal that the partial coalition C_p^k can be stable at sufficiently high degrees of environmental damage heterogeneity. Given the stability conditions (1.13) and (1.14), the partial coalition C_p^k is externally stable $\Leftrightarrow W_k(C_p^k) - W_k(C_G) \geq 0$, and internally stable $\Leftrightarrow W_i(C_p^k) - W_i(C_{NC}) \geq 0$, for i, j where $i \neq j$.

[13] When $\sum_i \beta_i$ is increasing compared to when $\sum_i \beta_i = 1$, keeping α constant to explore the effect of heterogeneity restricts the range of parameters that satisfy all the constraints imposed on the model's parameters, as outlined in Appendix E1. Nevertheless, the grand coalition remains stable over some range of heterogeneity. The simulation results for the case where $\sum_i \beta_i$ increases are presented in Appendix L1.

Using (1.52), country k's individual welfare gains from behaving as an outsider to the pair formed by i and j, in comparison to joining the grand coalition, are given by the following expression:

$$W_k(C_p^k) - W_k(C_G) = \frac{1}{2\times3^2\times5^2}\left[\Omega_k(C_p^k) - 54\sum_i \beta_i\left(18\beta_k - 7(\beta_i + \beta_j)\right)\right], \tag{1.54}$$

where $\Omega_k(C_p^k)$ captures the exogenous tariff structure of the partial coalition C_p^k and is outlined in Equation (1.53).

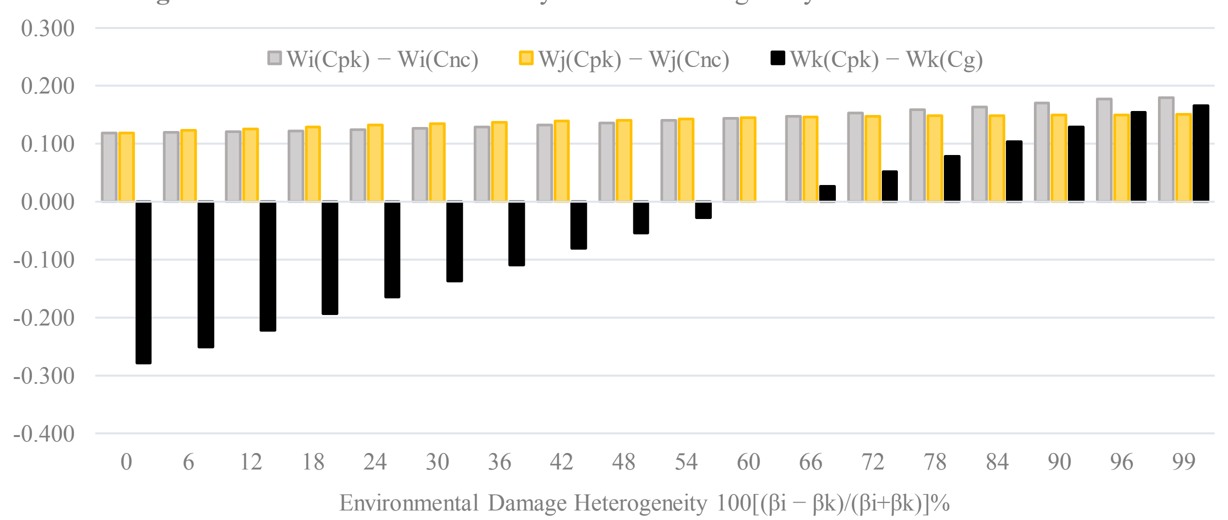
For a member within the pair, the welfare gains from the partial coalition in comparison to behaving as a singleton, are expressed as follows, for i, j where $i \neq j$:

$$W_i(C_p^k) - W_i(C_{NC}) = \frac{1}{2^5\times3^6\times5}\left[144\sum_i \beta_i\left(239\beta_i - 247\beta_j - 4\beta_k\right) + \left(81\Omega_i(C_p^k) - 5\Omega_i(C_{NC})\right)\right], \tag{1.55}$$

where $\Omega_i(C_p^k)$ and $\Omega_i(C_{NC})$ capture the underlying exogenous tariff structure of the partial coalition's pair and the singleton, respectively, and are detailed in Appendix F1.

Figure 1.3 depicts Equations (1.54) for country k and (1.55) for countries i and j, under the same conditions as Figure 1.2, that is, $\alpha = 3.5\sum_i \beta_i$, $\sum_i \beta_i = 1$, and the same exogenous tariff structure.

Figure 1.3: Partial Coalition Stability - Varied Heterogeneity and Low Punitive Tariffs



It is evident from Figure 1.3, that the partial coalition C_p^k is stable at degrees of heterogeneity above 60%. As an outsider to the pair, country k benefits from increased production and consumption, which lead to a higher net consumer surplus and greater tariff revenues. These improvements surpass the losses in pre-tax profits, resulting in welfare gains as β_k takes a lower value. Due to their cooperation, countries i and j experience welfare improvements as a pair, mainly driven by higher pre-tax profits compared to behaving non-cooperatively as singletons.

While there exists a range of parameters where the partial coalition C_p^k is stable at sufficiently high levels of heterogeneity, this range depends heavily on the assumed value of the parameters and the underlying exogenous tariff structure, in particular the magnitude of the punitive tariff enforced on the partial coalition's outsider. For the assumed tariff structure and parameters, these results remain consistent for any punitive tariff $\tau_{ij,k}(C_p^k)$, where $\frac{9}{10}\left(\frac{\tau_{i,k}+\tau_{j,k}}{2}\right) \leq \tau_{ij,k}(C_p^k) < \frac{15}{10}\left(\frac{\tau_{i,k}+\tau_{j,k}}{2}\right)$.

Additionally, the numerical simulations indicate that the external stability of the partial coalition C_p^k is reinforced when the punitive tariff on the outsider decreases, reducing its cost of deviation, and when the tariff imposed by the outsider on the pair increases, improving its tariff revenues. These results remain consistent when modifying exogenous tariff levels and structures, when varying α values, where $\alpha \geq \frac{1}{60}\left[66\left(\beta_i+\beta_j\right)-24\beta_k-25\tau_{ij}+\left(31\tau_{ij,k}+78\tau_{k,ij}\right)\right]$, and when relaxing the assumption[14] of $\sum_i \beta_i = 1$.

It should be noted that C_p^k is the only partial coalition arrangement that is stable under specific conditions, while C_p^j and C_p^i are externally unstable. The numerical simulations did not reveal any range of parameters where C_p^j and C_p^i are stable.

[14] The simulation results for the case where $\sum_i \beta_i$ increases are presented in Appendix L1.

Remark 1.4.2.3 *In the absence of punitive tariffs or at sufficiently low levels, there exists a range of parameters where the singleton structure is stable in both the homogeneous benchmark case and at various levels of environmental damage heterogeneity.*

Given the stability conditions (1.13) and (1.14), the singleton structure is internally stable by default, and externally stable $\Leftrightarrow W_i(C_{NC}) - W_i(C_p^k) \geq 0$ and $W_k(C_{NC}) - W_k(C_p^i) \geq 0$, for i, j, k, where $i \neq j, k$.

For the singleton i, and by symmetry for the singletons j and k, the welfare gains from behaving noncooperatively in comparison to forming a pair, are as follows, for i, j, k, where $i \neq j, k$:

$$W_i(C_{NC}) - W_i(C_p^k) = \frac{1}{2^5 \times 3^6 \times 5}\left[\left(5\Omega_i(C_{NC}) - 81\Omega_i(C_p^k)\right) - 144\sum_i \beta_i\left((239\beta_i - 247\beta_j) - 4\beta_k\right)\right], \quad (1.56)$$

where $\Omega_i(C_{NC})$ and $\Omega_i(C_p^k)$ capture the underlying exogenous tariff structure of the singleton and the partial coalition's pair, respectively, and are detailed in Appendix F1.

Figure 1.4[15], with its three panels (a), (b), and (c), depicts the stability conditions of singletons i, j, and k, respectively, while $\alpha = 3.5\sum_i \beta_i$, $\sum_i \beta_i = 1$, and $\tau_{ij,k}(C_p^k) = \tau_{ij}(C_p^k)$, for i, j, k, where $i \neq j, k$. In the absence of punitive tariffs, Figure 1.4 demonstrates that the singleton structure is stable in the homogeneous benchmark case and at different degrees of heterogeneity.

At high levels of heterogeneity, in the absence of or with sufficiently low punitive tariffs on country k, the partial coalition C_p^k becomes internally unstable, leading to a stable singleton structure. Countries i and j are net importers under C_p^k, since $Q_i(C_p^k) - X_i(C_p^k) > 0$, for i, j where $i \neq j$. Lower tariff revenues, coupled with lower production and pre-tax profits within the pair,

[15] Figure 1.4 assumes $\sum_i \beta_i = 1$, $\alpha = 3.5\sum_i \beta_i$, and the following exogenous tariff structure, for i, j, k where $i \neq j, k$: $\tau_{i,j}(C_{NC}) = \frac{1}{15}(3\beta_i - 2\beta_j + \beta_k + \alpha)$, $\tau_{ij}(C_p^k) = \tau_{ij,k}(C_p^k) = \frac{1}{10}Avg(\tau_{i,j}, \tau_{j,i})$, $\tau_{k,ij}(C_p^k) = Avg(\tau_{k,i}, \tau_{k,j})$.

destabilize the partial cooperative agreement C_p^k. While, at low levels of heterogeneity, sufficiently low punitive tariffs can destabilize the grand coalition, leading to a stable singleton structure.

Figure 1.4a: Stability of Singleton *i* - Varied Heterogeneity

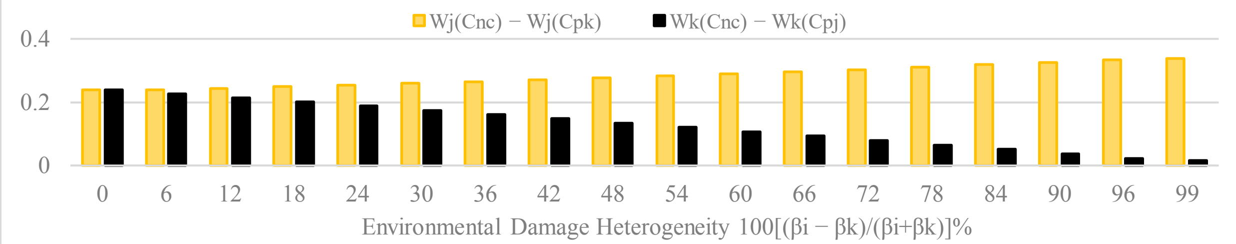


Figure 1.4b: Stability of Singleton *j* - Varied Heterogeneity

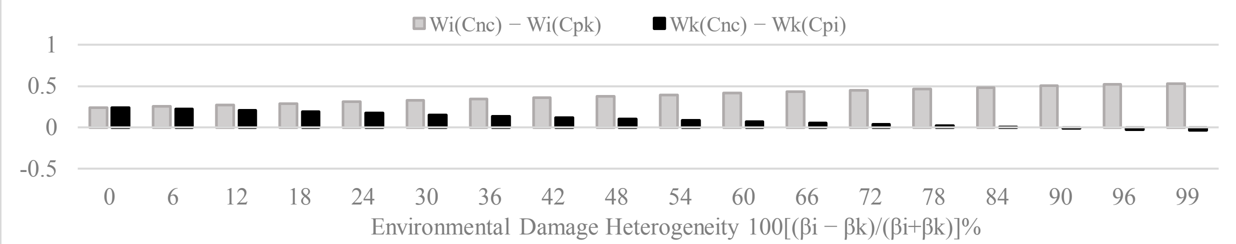
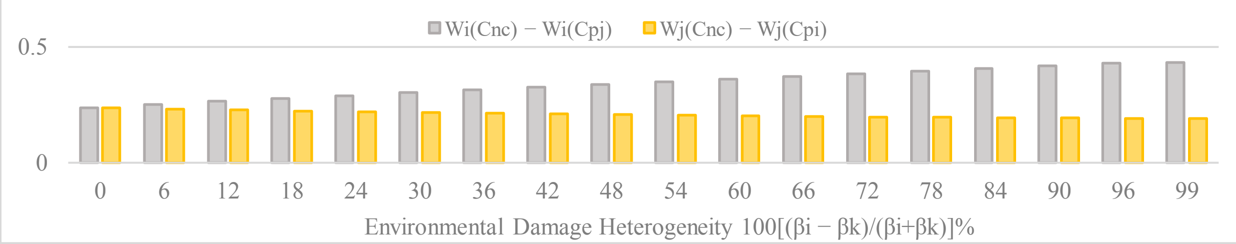


Figure 1.4c: Stability of Singleton *k* - Varied Heterogeneity



As singletons, all three countries benefit from larger production leading to improved pre-tax profits, which coupled with increased tariff revenues, surpass losses in net consumer surplus. This leads to significant welfare gains and a stable singleton structure at various levels heterogeneity. However, when punitive tariffs on outsiders are gradually increased, the range over which the singleton structure is stable contracts. For the assumed exogenous tariff structure and parameters, the singleton structure remains stable, where $\tau_{ij}\left(C_p^k\right) \leq \tau_{ij,k}\left(C_p^k\right) < \frac{8}{10}\left(\frac{\tau_{i,k}+\tau_{j,k}}{2}\right)$ for i, j, k, where $i \neq j, k$. These findings remain consistent when modifying exogenous tariffs, varying α values, where $\alpha \geq \frac{1}{60}\left[66\left(\beta_i+\beta_j\right)-24\beta_k-25\tau_{ij}+\left(31\tau_{ij,k}+78\tau_{k,ij}\right)\right]$, and in the case where $\sum_i \beta_i$ increases[16].

Remark 1.4.2.4: *Members of the grand coalition can be better off individually and collectively in comparison to the singleton structure, across various heterogeneity levels.*

Let $W_i(C_G)-W_i(C_{NC})$ be country i 's individual welfare gains as a member of the grand coalition in comparison to behaving as a singleton. These welfare gains are, for i,j,k where $i \neq j,k$:

$$W_i(C_G)-W_i(C_{NC})=\frac{1}{2}\frac{1}{108^2}\left[288\sum_i \beta_i\left(194\beta_i-49(\beta_j+\beta_k)\right)-\Omega_i(C_{NC})\right], \qquad (1.57)$$

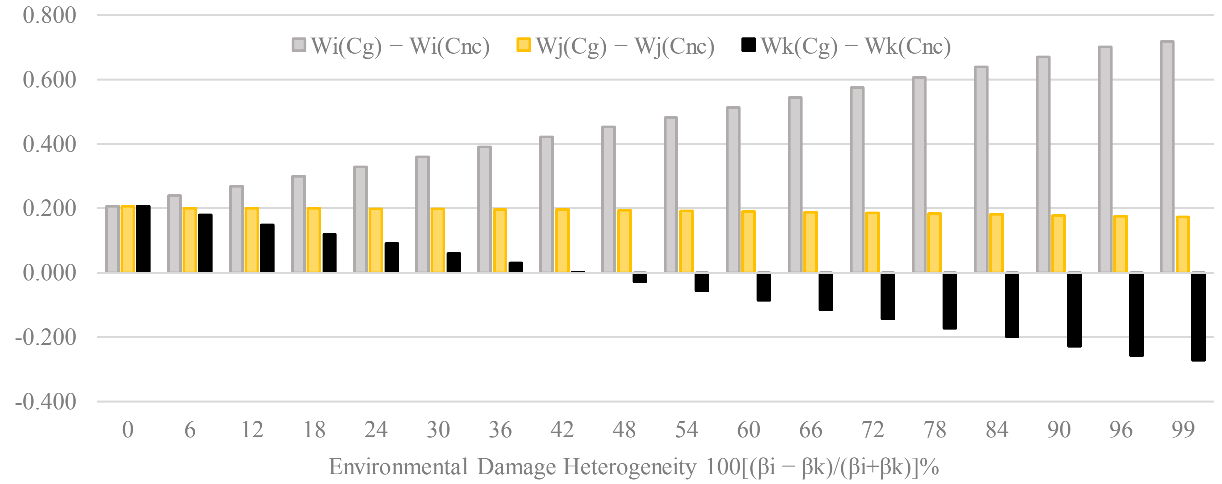
where $\Omega_i(C_{NC})$[17] captures the singleton's underlying exogenous tariff structure.

Assuming $\alpha = 3.5\sum_i \beta_i$ and $\sum_i \beta_i = 1$, the model's numerical simulations demonstrate that these individual welfare gains can be positive across various levels of heterogeneity. It is evident from Figure 1.5[18], that country i achieves the most significant welfare gains, while country k, with the lowest damage parameter, experiences the least substantial welfare gains. In this scenario, the grand coalition imposes a positive emissions tax rate, where $t_G^*(C_G)=\frac{1}{3}(4\sum_i \beta_i-\alpha)>0$, resulting in lower global production and, hence, lower global emissions.

The reduction in production levels within the grand coalition notably elevates prices across all markets. When combined with lower tariffs, the firm operating in country i observes an increase in pre-tax profits. These gains exceed any reductions in tariff revenues and net consumer surplus, ultimately contributing to an improvement in country i's overall welfare.

[16] The simulation results for the case where $\sum_i \beta_i$ increases are presented in Appendix L1.
[17] $\Omega_i(C_{NC})$ is expressed in detail in Appendix F1.
[18] In Figure 1.5, $\alpha = 3.5\sum_i \beta_i, \sum_i \beta_i = 1, \tau_G(C_G) = 0,\ \tau_{i,j}(C_{NC}) = \frac{1}{15}(3\beta_i - 2\beta_j + \beta_k + \alpha), \tau_{ij}(C_p^k) = \frac{1}{10}Avg(\tau_{i,j},\tau_{j,i})$, $\tau_{ij,k}(C_p^k) = \frac{15}{10}Avg(\tau_{i,k},\tau_{j,k}), \tau_{k,ij}(C_p^k) = Avg(\tau_{k,i},\tau_{k,j})$, for i,j,k where $i \neq j,k$.

Figure 1.5: Individual Welfare Gains: Comparing the Grand Coalition to the Singleton Structure - Varied Heterogeneity



By contrast, countries j and k do not experience the same benefits over the same range of heterogeneity. Country k, for instance, experiences modest welfare gains at sufficiently low degrees of heterogeneity, and welfare losses when the degree of heterogeneity surpasses 42%. In such cases, the losses primarily stem from reductions in net consumer surplus and government tariff revenues induced by the grand coalition, outweighing the increase in pre-tax profits. As heterogeneity increases, the reductions in net consumer surplus become more significant, as β_k takes a lower value.

In this scenario, country i emerges as the primary beneficiary of the grand coalition due to its highest environmental damage parameter. These results are consistent when varying the values of the parameter α, where $\alpha \geq \frac{1}{60}\left(66\left(\beta_i+\beta_j\right)-24\beta_k-25\tau_{ij}+\left(31\tau_{ij,k}+78\tau_{k,ij}\right)\right)$, and when modifying exogenous tariff levels and structures. They also remain valid in the case where $\sum_i \beta_i$ increases[19] in comparison to where $\sum_i \beta_i$ is held constant and normalized to 1.

[19] The simulation results for the case where $\sum_i \beta_i$ increases are presented in Appendix L1.

In comparison, while examining the homogeneous benchmark case, where $\beta_i = \beta_j = \beta_k = \hat{\beta}$, equation (1.57) can be reduced as follows, for i, j, k where $i \neq j, k$:

$$\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) = \frac{\sqrt{2}}{81}\left(3\hat{\beta} - \hat{\tau}\right)^2 \tag{1.58}$$

These individual welfare gains are unequivocally positive for any member of the grand coalition, increasing when the damage parameter $\hat{\beta}$ takes a higher value and as exogenous tariffs decrease.

The collective welfare gains from the grand coalition compared to the singletons are expressed as:

$$W(C_G) - W(C_{NC}) = \frac{1}{2^5 \times 3^5}\begin{bmatrix} 96\sum_i \beta_i \left(\sum_i \beta_i - 32\sum_i \sum_j \tau_{i,j}\right) \\ +\left(\tau_{i,j} + \tau_{i,k}\right)\left(418\left(\tau_{i,j} + \tau_{i,k}\right) + 175\left(\tau_{j,i} + \tau_{j,k} + \tau_{k,i} + \tau_{k,j}\right)\right) \\ +\left(\tau_{j,i} + \tau_{j,k}\right)\left(418\left(\tau_{j,i} + \tau_{j,k}\right) + 175\left(\tau_{i,j} + \tau_{i,k} + \tau_{k,i} + \tau_{k,j}\right)\right) \\ +\left(\tau_{k,i} + \tau_{k,j}\right)\left(418\left(\tau_{k,i} + \tau_{k,j}\right) + 175\left(\tau_{i,j} + \tau_{i,k} + \tau_{j,i} + \tau_{j,k}\right)\right) \end{bmatrix}. \tag{1.59}$$

The numerical simulations confirm that these welfare gains are strictly positive across alternative exogenous tariff structures.

Remark 1.4.2.5: *A member of the grand coalition is not always individually better off than when forming a pair in the partial coalition structure.*

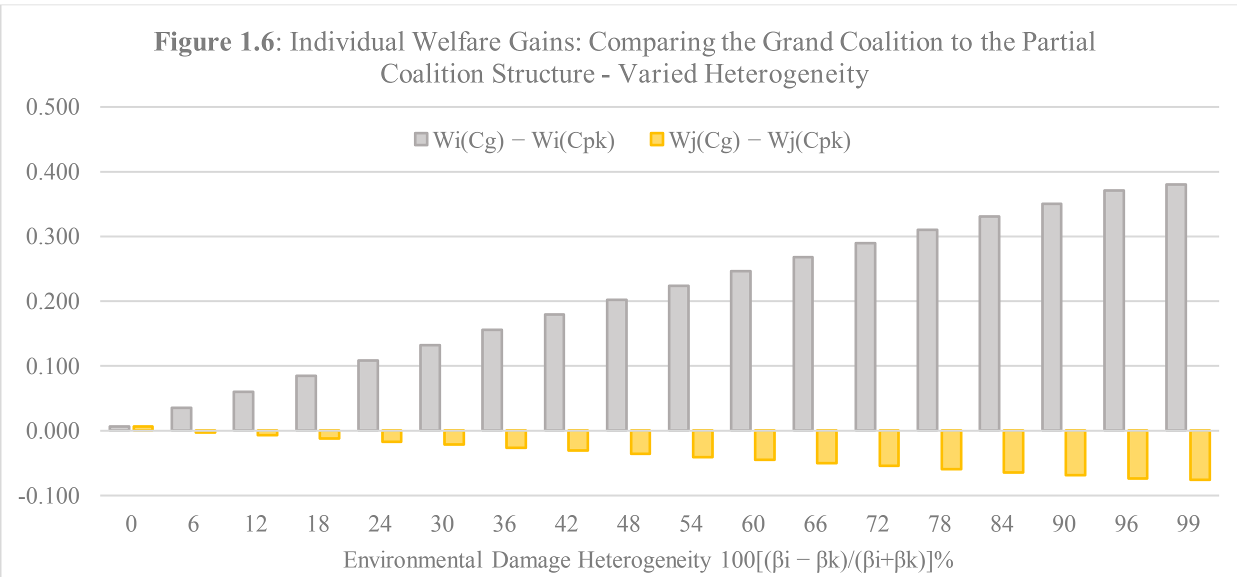
Let $W_i(C_G) - W_i(C_p^k)$ be country i's welfare gains as a member of the grand coalition in comparison to forming a pair with country j in the partial coalition C_p^k. These individual welfare gains are given by the following expression, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i\left(C_p^k\right) = \frac{1}{1440}\left[432\sum_i \beta_i\left(\left(7\beta_i - \beta_j\right) - 2\beta_k\right) - \Omega_i\left(C_p^k\right)\right], \tag{1.60}$$

where $\Omega_i\left(C_p^k\right)$[20] captures the exogenous tariff structure underlying the partial coalition structure.

[20] $\Omega_i\left(C_p^k\right)$ is expressed in detail in Appendix F1.

Assuming $\alpha = 3.5\sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 1.6[21] depicts Equation (1.60) for countries i and j. It indicates that country i, with the highest environmental damage parameter, consistently achieves higher welfare gains than country j, and these gains are positive over a wide range of heterogeneity. The numerical simulations consistently indicate a positive value for the term $\Omega_i(C_p^k)$. This suggests that countries would see overall welfare improvements by joining the grand coalition with trade liberalization.



In this scenario, $t_G^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha) > 0$, and the grand coalition generates environmental gains compared to the partial coalition C_p^k. Country *i* experiences higher pre-tax profits, along with improvements in net consumer surplus with higher values of β_i, leading to increasing welfare gains. In contrast, country *j* experiences increasing welfare losses over the same range of heterogeneity, except in the homogeneous case. Initially, country *j* benefits from higher profits as the grand coalition reduces production. However, as β_i takes a higher value and β_j stays the same,

[21] Figure 1.6 assumes the following exogenous tariff structure, for i, j, k where $i \neq j, k$: $\tau_G(C_G) = 0$ $\tau_{i,j}(C_{NC}) = \frac{1}{15}(3\beta_i - 2\beta_j + \beta_k + \alpha)$, $\tau_{ij} = \frac{1}{10}Avg(\tau_{i,j}, \tau_{j,i})$, $\tau_{ij,k} = \frac{15}{10}Avg(\tau_{i,k}, \tau_{j,k})$, $\tau_{k,ij} = Avg(\tau_{k,i}, \tau_{k,j})$.

the welfare gains from reduced production and subsequent higher profits fall short of the losses in net consumer surplus and tariff revenues caused by the grand coalition, resulting in welfare losses. Having the highest marginal environmental damage parameter, country i stands out as the main beneficiary of the grand coalition.

These results are robust to changes in exogenous import tariffs, changes in the values of α, where $\alpha \geq \frac{1}{60}\left(66\left(\beta_i + \beta_j\right) - 24\beta_k - 25\tau_{ij} + \left(31\tau_{ij,k} + 78\tau_{k,ij}\right)\right)$, and when assuming that all three marginal environmental damage parameters take higher values[22] with rising heterogeneity.

Let $W(C_G) - W\left(C_p^k\right)$ be the collective welfare gains experienced by members the grand coalition in comparison to the partial coalition structure C_p^k; these gains are expressed as follows:

$$W(C_G) - W\left(C_p^k\right) = \frac{1}{1200}\begin{bmatrix} 1152\left(\sum_i \beta_i\right)^2 - 4\tau_{k,ij}\left(192\sum_i \beta_i - 103\tau_{ij,k} - 57\tau_{k,ij}\right) \\ -25\tau_{ij}\left(4\tau_{k,ij} - 2\tau_{ij,k} - \tau_{ij}\right) - 3\tau_{ij,k}\left(512\sum_i \beta_i - 179\tau_{ij,k}\right) \end{bmatrix}. \quad (1.61)$$

While the individual impacts of these exogenous tariffs are not straightforward on collective gains, the numerical simulations reveal that these gains are diminished by bilateral tariffs, emphasizing the importance of trade liberalization for members of the grand coalition to benefit fully from cooperation.

1.5 Conclusion

The current essay, which incorporates exogenous import tariffs, demonstrates the stability of a fully cooperative equilibrium even when environmental and trade policies are not negotiated concurrently. Numerical simulations confirm that the grand coalition can be stable across different levels of exogenous import tariffs and various tariff structures. Considering the model's parameter

[22] The simulation results when assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix L1.

restrictions, which maintain the market structure throughout the game and ensure a positive interior solution with positive trade flows, it is always possible to find a combination of positive tariffs that leads to a stable grand coalition over a broad range of heterogeneity, even when tariffs are exogenous and suboptimal.

The main contribution of this essay to the literature lies in demonstrating that the use of positive tariffs on imports within a segmented market setting, rather than in a global market with free trade conditions, reduces the free-riding incentives of non-signatories and enhances the stability of the global agreement. It underscores that the magnitude of punitive tariffs on outsiders in the partial coalition structure plays a critical role in determining coalitional stability. At high degrees of heterogeneity, the stability of the grand coalition becomes more fragile and increasingly sensitive to exogenous tariffs. At high levels of heterogeneity when punitive tariffs are sufficiently low, the grand coalition can give way to the partial coalition arrangement C_p^k. Conversely, at sufficiently lower levels or in the absence of such punitive tariffs, the singleton structure can become stable at various degrees of heterogeneity.

In the absence of effective enforcement methods, current international environmental agreements pose a real challenge, and their effectiveness hinges on countries' willingness to adhere to their commitments. However, the current essay demonstrates that using preferential market access as a reward for coalition members and imposing higher tariffs as a penalty on non-signatories can effectively promote international environmental cooperation among heterogeneous trading partners. This approach offers a novel perspective on the trade and environment relationship, typically perceived as one of divergence rather than synergy. It highlights environmental benefits and overall welfare improvements when trade and environmental policies are pursued in tandem.

However, the simplified framework of the current model introduces certain limitations. Specifically, to examine the impact of environmental damage heterogeneity, the model assumes that all three countries have the same market size, incur identical marginal production costs, and that each firm can export to the other two foreign markets without any shipping costs. Furthermore, it assumes that environmental damage is a linear function of aggregate production to make the model more tractable. These simplifications lay the groundwork for future research inquiries to explore potential outcomes if any of these assumptions were relaxed.

In summary, countries do not equally experience the consequences of environmental damage, and they vary in their institutional and individual capacity to adapt to climate change swiftly. However, given the recent alarming levels of the climate crisis, it becomes imperative to enhance our environmental policies beyond what is currently implemented. This essay highlights that coordinating environmental and trade policies can prove to be a valuable strategy in fostering a stronger international commitment, even amidst the heterogeneity among countries. This coordination can result in environmental gains, notably in terms of reducing global emissions, particularly when tariffs are maintained at sufficiently low levels.

1.6 Appendices

1.6.1 Appendix A1: The Firm's Optimization Problem

In stage three, firms compete à la Cournot in domestic markets. Each firm independently chooses its profit-maximizing output rate, considering the policies set by all governments and the output decisions of foreign firms. The firm's optimization problem (1.7) is detailed as follows:

$$\max_{x_{ii},x_{ij},x_{ik}} \pi_i \Rightarrow \max_{x_{ii},x_{ij},x_{ik}} \begin{bmatrix} (\alpha - (x_{ii} + x_{ji} + x_{ki}) - t_i)x_{ii} \\ +(\alpha - (x_{jj} + x_{ij} + x_{kj}) - t_i - \tau_{j,i})x_{ij} \\ +(\alpha - (x_{kk} + x_{ik} + x_{jk}) - t_i - \tau_{k,i})x_{ik} \end{bmatrix}. \tag{A1.1}$$

The first order conditions with respect to local production and exports, are, respectively:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow (\alpha - 2x_{ii} - x_{ji} - x_{ki} - t_i) = 0 \tag{A1.2}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow (\alpha - 2x_{ij} - x_{jj} - x_{kj} - t_i - \tau_{j,i}) = 0 \tag{A1.3}$$

$$\frac{\partial \pi_i}{\partial x_{ik}} = 0 \Rightarrow (\alpha - 2x_{ik} - x_{kk} - x_{jk} - t_i - \tau_{k,i}) = 0. \tag{A1.4}$$

The second order conditions (SOCs) are satisfied, as per the following conditions:

$$\frac{\partial^2 \pi_i}{\partial x_{ii}{}^2} < 0, \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} < 0, \text{ and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}} \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} - \left(\frac{\partial^2 \pi_i}{\partial x_{ii} \partial x_{ij}}\right) > 0.$$

By symmetry, using (A1.3) and (A1.4), the FOCs with respect to x_{ji} and x_{ki}, are respectively:

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow (\alpha - 2x_{ji} - x_{ii} - x_{ki} - t_j - \tau_{i,j}) = 0 \tag{A1.5}$$

$$\frac{\partial \pi_k}{\partial x_{ki}} = 0 \Rightarrow (\alpha - 2x_{ki} - x_{ii} - x_{ji} - t_k - \tau_{i,k}) = 0. \tag{A1.6}$$

Using (A1.2), (A1.5), and (A1.6), the equilibrium quantities (1.8) and (1.9) produced by the firm operating in country i, for i, j, k where $i \neq j, k$, are expressed as follows:

$$x_{ii}{}^* = \frac{1}{4}(\alpha - 3t_i + (t_j + t_k) + \tau_{i,j} + \tau_{i,k}) \tag{A1.7}$$

$$x_{ij}{}^* = \frac{1}{4}(\alpha - 3t_i + (t_j + t_k) + \tau_{j,k} - 3\tau_{j,i}). \tag{A1.8}$$

1.6.2 Appendix B1: The Government's Optimization Problem - The Singletons

Let $W_i^{C_{NC}}$ be the welfare equation of country i under the singleton structure C_{NC}, then country i's welfare maximization problem (1.17) can be detailed as follows, for i, j, k where $i \neq j, k$:

$$\max_{t_i^{NC}} W_i^{C_{NC}} \Rightarrow \max_{t_i^{NC}} \begin{bmatrix} 3\alpha(5\alpha - 24\beta_i) \\ +t_i^{NC}\left(-18\alpha + 24\beta_i - 17t_i^{NC} - 10\left(t_j^{NC} + t_k^{NC}\right)\right) \\ +\left(t_j^{NC} + t_k^{NC}\right)\left(6\alpha + 24\beta_i + 7\left(t_j^{NC} + t_k^{NC}\right)\right) \\ +\tau_{i,j}\left(8\beta_i + 6\alpha + 6t_i^{NC} - 18t_j^{NC} + 14t_k^{NC} + \left(11\tau_{i,k} - 21\tau_{i,j}\right)\right) \\ +\tau_{i,k}\left(8\beta_i + 6\alpha + 6t_i^{NC} + 14t_j^{NC} - 18t_k^{NC} + \left(11\tau_{i,j} - 21\tau_{i,k}\right)\right) \\ +\tau_{j,i}\left(8\beta_i - 12\alpha + 12t_i^{NC} - 12\left(t_j^{NC} + t_k^{NC}\right) + 6\left(3\tau_{j,i} - \tau_{j,k}\right)\right) \\ +\tau_{j,k}\left(8\beta_i + 4\alpha - 4t_i^{NC} + 4\left(t_j^{NC} + t_k^{NC}\right) + 2\left(\tau_{j,k} - 3\tau_{j,i}\right)\right) \\ +\tau_{k,i}\left(8\beta_i - 12\alpha + 12t_i^{NC} - 12\left(t_j^{NC} + t_k^{NC}\right) + 6\left(3\tau_{k,i} - \tau_{k,j}\right)\right) \\ +\tau_{k,j}\left(8\beta_i + 4\alpha - 4t_i^{NC} + 4\left(t_j^{NC} + t_k^{NC}\right) + 2\left(\tau_{k,j} - 3\tau_{k,i}\right)\right) \end{bmatrix} \quad \text{(B1.1)}$$

The first order condition with respect to the emissions tax rate, t_i^{NC}, is expressed as follows:

$$\frac{\delta W_i^{C_{NC}}}{\delta t_i^{NC}} = 0 \Rightarrow 17t_i^{NC} = \begin{pmatrix} 12\beta_i - 9\alpha - 5\left(t_j^{NC} + t_k^{NC}\right) \\ +3\left(\tau_{i,j} + \tau_{i,k}\right) + 6\left(\tau_{j,i} + \tau_{k,i}\right) - 2\left(\tau_{j,k} + \tau_{k,j}\right) \end{pmatrix}. \quad \text{(B1.2)}$$

By symmetry, using (B1.2), the FOCs with respect to t_j^{NC} and t_k^{NC}, are, respectively, as follows:

$$\frac{\delta W_j^{C_{NC}}}{\delta t_j^{NC}} = 0 \Rightarrow 17t_j^{NC} = \begin{pmatrix} 12\beta_j - 9\alpha - 5(t_i^{NC} + t_k^{NC}) \\ +3\left(\tau_{j,i} + \tau_{j,k}\right) + 6\left(\tau_{i,j} + \tau_{k,j}\right) - 2\left(\tau_{i,k} + \tau_{k,i}\right) \end{pmatrix} \quad \text{(B1.3)}$$

$$\frac{\delta W_k^{C_{NC}}}{\delta t_k^{NC}} = 0 \Rightarrow 17t_k^{NC} = \begin{pmatrix} 12\beta_k - 9\alpha - 5\left(t_i^{NC} + t_j^{NC}\right) \\ +3\left(\tau_{k,i} + \tau_{k,j}\right) + 6\left(\tau_{i,k} + \tau_{j,k}\right) - 2\left(\tau_{i,j} + \tau_{j,i}\right) \end{pmatrix}. \quad \text{(B1.4)}$$

Using (B1.2), (B1.3), and (B1.4), the singleton's equilibrium tax, for i, j, k where $i \neq j, k$, is:

$$t_i^{*NC}(C_{NC}) = \frac{1}{324}\begin{pmatrix} 264\beta_i - 108\alpha - 60\left(\beta_j + \beta_k\right) \\ +46\left(\tau_{i,j} + \tau_{i,k}\right) + 127\left(\tau_{j,i} + \tau_{k,i}\right) - 89\left(\tau_{j,k} + \tau_{k,j}\right) \end{pmatrix}. \quad \text{(B1.5)}$$

Given (A1.7), (A1.8), and (B1.5), country i's local production $x_{ii}(C_{NC})$ and exports $x_{ij}(C_{NC})$ are expressed as follows, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_{NC}) = \frac{1}{162}\begin{pmatrix} 54\alpha - 114\beta_i + 48\left(\beta_j + \beta_k\right) \\ +28(\tau_{i,j} + \tau_{i,k}) + 55(\tau_{j,k} + \tau_{k,j}) - 53(\tau_{j,i} + \tau_{k,i}) \end{pmatrix} \tag{B1.6}$$

$$x_{ij}(C_{NC}) = \frac{1}{324}\begin{pmatrix} 108\alpha - 228\beta_i + 96\left(\beta_j + \beta_k\right) \\ -25(\tau_{i,j} + \tau_{i,k}) - 349\tau_{j,i} + 191\tau_{j,k} + 110\tau_{k,j} - 106\tau_{k,i} \end{pmatrix}. \tag{B1.7}$$

The total quantities produced and consumed in country i are, respectively, for i, j, k where $i \neq j, k$:

$$X_i(C_{NC}) = \frac{1}{108}\begin{pmatrix} 108\alpha - 228\beta_i + 96\left(\beta_j + \beta_k\right) \\ +2(\tau_{i,j} + \tau_{i,k}) - 187(\tau_{j,i} + \tau_{k,i}) + 137(\tau_{j,k} + \tau_{k,j}) \end{pmatrix} \tag{B1.8}$$

$$Q_i(C_{NC}) = \frac{1}{108}\left(108\alpha - 12\textstyle\sum_i \beta_i - 34(\tau_{i,j} + \tau_{i,k}) - 7(\tau_{j,i} + \tau_{j,k} + \tau_{k,i} + \tau_{k,j})\right). \tag{B1.9}$$

The world market clears as global production equals global consumption, given by this expression:

$$\textstyle\sum_i X_i(C_{NC}) = \sum_i Q_i\,(C_{NC}) = \frac{1}{9}\left(27\alpha - 3\sum_i \beta_i - 4\sum_i \sum_j \tau_{i,j}\right). \tag{B1.10}$$

Given the assumption that every unit of production generates exactly one unit of global emissions, then Equation (B1.10) represents global emissions as well.

Country i's welfare, $W_i(C_{NC})$, for i, j, k where $i \neq j, k$, is given by the following expression:

$$W_i(C_{NC}) = \frac{1}{2}\frac{1}{108^2}\begin{bmatrix} 144\left[81\alpha^2 - 486\alpha\beta_i + 17\left(\sum_i \beta_i\right)^2\right] \\ +2\tau_{i,j}\begin{bmatrix} 1944\alpha + 5424\beta_i - 6240\beta_j + 5424\beta_k \\ -11468\tau_{i,j} + 7972\tau_{i,k} - 3163\tau_{j,i} + 1049\tau_{j,k} + 1697\tau_{k,i} - 1867\tau_{k,j} \end{bmatrix} \\ +2\tau_{i,k}\begin{bmatrix} 1944\alpha + 5424\beta_i + 5424\beta_j - 6240\beta_k \\ +7972\tau_{i,j} - 11468\tau_{i,k} + 1697\tau_{j,i} - 1867\tau_{j,k} - 3163\tau_{k,i} + 1049\tau_{k,j} \end{bmatrix} \\ +\tau_{j,i}\begin{bmatrix} -5832\alpha + 15168\beta_i - 8160\left(\beta_j + \beta_k\right) \\ +1854(\tau_{i,j} + \tau_{i,k}) + 16277\tau_{j,i} - 8347\tau_{j,k} + 3155\tau_{k,i} - 3973\tau_{k,j} \end{bmatrix} \\ +\tau_{j,k}\begin{bmatrix} 1944\alpha + 6528\sum_i \beta_i \\ +54(\tau_{i,j} + \tau_{i,k}) - 8851\tau_{j,i} + 5405\tau_{j,k} - 4477\tau_{k,i} + 3947\tau_{k,j} \end{bmatrix} \\ +\tau_{k,i}\begin{bmatrix} -5832\alpha + 15168\beta_i - 8160\left(\beta_j + \beta_k\right) \\ +1854(\tau_{i,j} + \tau_{i,k}) + 3155\tau_{j,i} - 3973\tau_{j,k} + 16277\tau_{k,i} - 8347\tau_{k,j} \end{bmatrix} \\ +\tau_{k,j}\begin{bmatrix} 1944\alpha + 6528\sum_i \beta_i \\ +54(\tau_{i,j} + \tau_{i,k}) - 4477\tau_{j,i} + 3947\tau_{j,k} - 8851\tau_{k,i} + 5405\tau_{k,j} \end{bmatrix} \end{bmatrix}. \tag{B1.11}$$

1.6.3 Appendix C1: The Government's Optimization Problem - The Grand Coalition

Let W^G be the collective welfare of all three members within the grand coalition C_G, then their joint welfare optimization problem (1.22) can be detailed as follows:

$$\max_{t_G} W^G \Rightarrow \max_{t_G} \begin{bmatrix} (15\alpha^2 - 24\alpha \sum_i \beta_i) + t_G(-6\alpha + 24\sum_i \beta_i - 9t_G) \\ +\tau_G(16\sum_i \beta_i - 4\alpha - 12t_G - 4\tau_G) \end{bmatrix} \tag{C1.1}$$

The first order condition with respect to the tax rate, t_G, is given by the following equation:

$$\frac{\delta W^G}{\delta t_G} = 0 \Rightarrow (4\sum_i \beta_i - \alpha - 3t_G - 2\tau_G) = 0. \tag{C1.2}$$

The first order condition yields the following equilibrium tax rate, for i, j, k where $i \neq j, k$:

$$t_G^*(C_G) = \frac{1}{3}\big((4\sum_i \beta_i - \alpha) - 2\tau_G\big). \tag{C1.3}$$

Using (A1.7), (A1.8), and (C1.3), country i's local production and exports are, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_G) = \frac{1}{3}(\alpha - \sum_i \beta_i + 2\tau_G) \tag{C1.4}$$

$$x_{ij}(C_G) = x_{ik}(C_G) = \frac{1}{3}(\alpha - \sum_i \beta_i - \tau_G). \tag{C1.5}$$

The total quantities produced and consumed are equal in any market, for i, j, k where $i \neq j, k$:

$$X_i(C_G) = Q_i(C_G) = (\alpha - \sum_i \beta_i). \tag{C1.6}$$

The global market clears as global production equals global consumption, as expressed here:

$$\sum_i X_i\,(C_G) = \sum_i Q_i\,(C_G) = 3(\alpha - \sum_i \beta_i). \tag{C1.7}$$

Given the assumption that every unit of production generates exactly one unit of global emissions, then Equation (C1.7) represents global emissions as well.

Country i's welfare, as a member of the grand coalition, $W_i(C_G)$, for i, j, k where $i \neq j, k$, is:

$$W_i(C_G) = \frac{1}{2}(\alpha - \sum_i \beta_i)\Big(\alpha - 5\beta_i + \big(\beta_j + \beta_k\big)\Big). \tag{C1.8}$$

The grand coalition's collective welfare, $W(C_G) = \sum_i W_i(C_G)$, is expressed as follows:

$$W(C_G) = \frac{3}{2}(\alpha - \sum_i \beta_i)^2. \tag{C1.9}$$

Note that $X_i(C_G)$, $W_i(C_G)$, $\sum_i X_i\,(C_G)$, and $W(C_G)$, are independent of the exogenous tariff $\tau_G(C_G)$, since changes in tariffs are offset by changes in emissions taxes, as shown in equation (C1.3).

1.6.4 Appendix D1: The Government's Optimization Problem - The Partial Coalition

Let ${W_{ij}}^{C_P^k} = {W_i}^{C_P^k} + {W_j}^{C_P^k}$ be the joint welfare equation of the pair within the partial coalition C_P^k. Their joint welfare optimization problem (1.27) is expressed as follows, for i, j, k where $i \neq j, k$:

$$\max_{t_{ij}} {W_{ij}}^{C_P^k} \Rightarrow \max_{t_{ij}} \begin{bmatrix} (15\alpha^2 - 36\alpha\beta_i - 36\alpha\beta_j) + t_{ij}\left(-12\alpha + 24(\beta_i + \beta_j) - 20t_{ij} + 2t_k^P\right) \\ +t_k^P\left(6\alpha + 12(\beta_i + \beta_j) + 2t_{ji} + 7t_k^P\right) \\ +\tau_{ij}\left(8(\beta_i + \beta_j) - 6\alpha - 12t_{ij} + 2t_k^P - 3\tau_{ij} + 5\tau_{ij,k}\right) \\ +\tau_{ij,k}\left(8(\beta_i + \beta_j) + 10\alpha + 20t_{ij} - 14t_k^P - 19\tau_{ij,k} + 5\tau_{ij}\right) \\ +8\tau_{k,ij}\left((\beta_i + \beta_j) - \alpha - t_k^P + \tau_{k,ij}\right) \end{bmatrix}. \quad \text{(D1.1)}$$

The first order condition with respect to the tax rate $t_{ij}(C_P^k)$, is given by the following equation:

$$\frac{\delta {W_{ij}}^{C_P^k}}{\delta t_{ij}} = 0 \Rightarrow \left(-3\alpha + 6(\beta_i + \beta_j) - 10t_{ij} + t_k^P - 3\,\tau_{ij} + 5\tau_{ij,k}\right) = 0. \quad \text{(D1.2)}$$

Given the pair's tax rate, $t_{ij}(C_P^k)$, and import tariffs, $\tau_{ij}(C_P^k)$ and $\tau_{ij,k}(C_P^k)$, the outsider to the pair behaves as a singleton, and its welfare maximization problem (1.32) is detailed as follows:

$$\max_{t_k^P} {W_k}^{C_P^k} \Rightarrow \max_{t_k^P} \begin{bmatrix} (15\alpha^2 - 72\alpha\beta_k) + t_k^P\left(-18\alpha + 24\beta_k - 10t_{ij} - 17t_k^P\right) \\ +t_{ij}\left(12\alpha + 48\beta_k - 10t_k^P + 28t_{ij}\right) \\ +\tau_{k,ij}\left(16\beta_k + 12\alpha + 12t_k^P - 8t_{ij} - 20\tau_{k,ij}\right) \\ +\tau_{ij,k}\left(16\beta_k - 24\alpha + 24t_k^P - 48t_{ij} + 36\tau_{ij,k} - 12\tau_{ij}\right) \\ +\tau_{ij}\left(16\beta_k + 8\alpha - 8t_k^P + 16t_{ij} + 4\tau_{ij} - 12\tau_{ij,k}\right) \end{bmatrix}. \quad \text{(D1.3)}$$

The first order condition of the welfare optimization problem with respect to $t_k^P(C_P^k)$, is:

$$\frac{\delta {W_k}^{C_P^k}}{\delta t_k^P} = 0 \Rightarrow \left(-18\alpha + 24\beta_k - 20t_{ij} - 34t_k^P + 12\tau_{k,ij} + 24\tau_{ij,k} - 8\tau_{ij}\right) = 0. \quad \text{(D1.4)}$$

Using (D1.2) and (D1.4), the pair's equilibrium tax rate, for i, j, k where $i \neq j, k$, is as follows:

$$t_{ij}^*(C_P^k) = \tfrac{1}{180}\left(102(\beta_i + \beta_j) + 12\beta_k - 60\alpha + (6\tau_{k,ij} + 97\tau_{ij,k}) - 55\tau_{ij}\right). \quad \text{(D1.5)}$$

Using (D1.2) and (D1.4), the outsider's equilibrium tax rate, for i, j, k where $i \neq j, k$, is as follows:

$$t_k^{*P}(C_P^k) = \tfrac{1}{18}\left(12\beta_k - 6(\beta_i + \beta_j) - 6\alpha + (6\tau_{k,ij} + 7\tau_{ij,k}) - \tau_{ij}\right). \quad \text{(D1.6)}$$

Using (A1.7), (A1.8), (D1.5) and (D1.6), a pair member domestic production is expressed as follows, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_P^k) = x_{jj}(C_P^k) = \frac{1}{90}\left(30\alpha - 33(\beta_i + \beta_j) + 12\beta_k + 35\tau_{ij} + 7\tau_{ij,k} + 6\tau_{k,ij}\right). \quad \text{(D1.7)}$$

Exports among them are given by the following expression, for i, j, k where $i \neq j, k$:

$$x_{ij}(C_P^k) = x_{ji}(C_P^k) = \frac{1}{90}\left(30\alpha - 33(\beta_i + \beta_j) + 12\beta_k + 7\tau_{ij,k} - 55\tau_{ij} + 6\tau_{k,ij}\right). \quad \text{(D1.8)}$$

While exports from any of the countries within the pair to the outsider are, for i, j, k where $i \neq j, k$:

$$x_{ik}(C_P^k) = x_{jk}(C_P^k) = \frac{1}{180}\left(60\alpha - 66(\beta_i + \beta_j) + 24\beta_k - 31\tau_{ij,k} + 25\tau_{ij} - 78\tau_{k,ij}\right). \quad \text{(D1.9)}$$

The total production and consumption of a pair member are, respectively, for i, j, k where $i \neq j, k$:

$$X_i(C_P^k) = X_j(C_P^k) = \frac{1}{60}\left(60\alpha - 66(\beta_i + \beta_j) + 24\beta_k - \left(5\tau_{ij} + \tau_{ij,k} + 18\tau_{k,ij}\right)\right) \quad \text{(D1.10)}$$

$$Q_i(C_P^k) = Q_j(C_P^k) = \frac{1}{60}\left(60\alpha - 12\textstyle\sum_i \beta_i - \left(5\tau_{ij} + 37\tau_{ij,k} + 6\tau_{k,ij}\right)\right). \quad \text{(D1.11)}$$

The difference between total consumption and production, for i, j, k where $i \neq j, k$, is given by:

$$Q_i(C_p^k) - X_i(C_p^k) = \frac{1}{60}\left(54(\beta_i + \beta_j) - 36\beta_k + 12\left(\tau_{k,ij} - 3\tau_{ij,k}\right)\right) \quad \text{(D1.12)}$$

The joint production of the pair within the partial coalition C_P^k is:

$$X_i(C_P^k) + X_j(C_P^k) = \frac{1}{30}\left(60\alpha - 66(\beta_i + \beta_j) + 24\beta_k - \left(5\tau_{ij} + \tau_{ij,k} + 18\tau_{k,ij}\right)\right). \quad \text{(D1.13)}$$

The individual welfare of country i within the pair, is given by, for i, j, k where $i \neq j, k$:

$$W_i(C_P^k) = \frac{1}{1440}\begin{bmatrix} 720\alpha(\alpha - 6\beta_i) + 144\sum_i \beta_i\left(4\beta_i - 2\beta_j + \beta_k\right) \\ +5\tau_{ij}\left(-24\alpha - 11\tau_{ij} + 42\tau_{ij,k} + 4\tau_{k,ij}\right) \\ +\tau_{ij,k}\left(360\alpha + 96(25\beta_i + \beta_j) - 192\beta_k - 791\tau_{ij,k} - 236\tau_{k,ij}\right) \\ +12\tau_{k,ij}\left(-20\alpha + 4(25\beta_i + \beta_j) - 8\beta_k + 23\tau_{k,ij}\right) \end{bmatrix}. \quad \text{(D1.14)}$$

The joint welfare of the pair is expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_P^k) + W_j(C_P^k) = \frac{1}{720}\begin{bmatrix} 720\alpha^2 - 2160\alpha(\beta_i + \beta_j) + 144(\sum_i \beta_i)^2 \\ -5\tau_{ij}\left(24\alpha + 11\tau_{ij} - \left(42\tau_{ij,k} + 4\tau_{k,ij}\right)\right) \\ +\tau_{ij,k}(360\alpha + 1248(\beta_i + \beta_j) - 192\beta_k - 791\tau_{ij,k} - 236\tau_{k,ij}) \\ +12\tau_{k,ij}(-20\alpha + 52(\beta_i + \beta_j) - 8\beta_k + 23\tau_{k,ij}) \end{bmatrix} \quad \text{(D1.15)}$$

The outsider's local production and exports, are, respectively, for i, j, k where $i \neq j, k$:

$$x_{kk}(C_P^k) = \frac{1}{45}\left(15\alpha + 24(\beta_i + \beta_j) - 21\beta_k + 12\tau_{k,ij} - \tau_{ij,k} - 5\tau_{ij}\right) \quad \text{(D1.16)}$$

$$x_{ki}(C_P^k) = x_{kj}(C_P^k) = \frac{1}{180}\left(60\alpha + 96(\beta_i + \beta_j) - 84\beta_k - 42\tau_{k,ij} - 139\tau_{ij,k} + 25\tau_{ij}\right). \quad \text{(D1.17)}$$

The outsider's total quantities produced and consumed are, respectively, for i, j, k where $i \neq j, k$:

$$X_k(C_P^k) = \frac{1}{30}\left(30\alpha + 48(\beta_i + \beta_j) - 42\beta_k - 6\tau_{k,ij} - 47\tau_{ij,k} + 5\tau_{ij}\right) \quad \text{(D1.18)}$$

$$Q_k(C_P^k) = \frac{1}{30}\left(30\alpha - 6(\beta_i + \beta_j + \beta_k) - 18\tau_{k,ij} - 11\tau_{ij,k} + 5\tau_{ij}\right). \quad \text{(D1.19)}$$

The world market clears, as global production equals global consumption, as indicated here:

$$\sum_i X_i\left(C_P^k\right) = \sum_i Q_i\left(C_P^k\right) = \frac{1}{5}\left(15\alpha - 3\sum_i \beta_i - 4\left(\tau_{k,ij} + 2\tau_{ij,k}\right)\right). \quad \text{(D1.20)}$$

Given the assumption that every unit of production generates exactly one unit of global emissions, then Equation (D1.20) represents global emissions as well.

The outsider's welfare is given by the following expression, for i, j, k where $i \neq j, k$:

$$W_k(C_P^k) = \frac{1}{450}\begin{bmatrix} 225\alpha(\alpha - 6\beta_k) + 153(\sum_i \beta_i)^2 + 25\tau_{ij}(3\alpha + \tau_{ij} - 6\tau_{ij,k} + \tau_{k,ij}) \\ +\tau_{ij,k}(-225\alpha - 204(\beta_i + \beta_j) + 696\beta_k + 293\tau_{ij,k} - 7\tau_{k,ij}) \\ +6\tau_{k,ij}(25\alpha - 17(\beta_i + \beta_j) + 58\beta_k - 43\tau_{k,ij}) \end{bmatrix}. \quad \text{(D1.21)}$$

The collective welfare under the partial coalition C_P^k is as follows, for i, j, k where $i \neq j, k$:

$$W(C_P^k) = \frac{1}{1200}\begin{bmatrix} 1800\alpha(\alpha - 2\sum_i \beta_i) + 648(\sum_i \beta_i)^2 \\ -25\tau_{ij}(\tau_{ij} + 2\tau_{ij,k} - 4\tau_{k,ij}) + 12\tau_{k,ij}(64\sum_i \beta_i - 19\tau_{k,ij}) \\ +\tau_{ij,k}(1536\sum_i \beta_i - 537\tau_{ij,k} - 412\tau_{k,ij}) \end{bmatrix}. \quad \text{(D1.22).}$$

1.6.5 Appendix E1: Restrictions on the Model's Parameters

Due to the complexities of the equations, the analysis had to rely on numerical simulations, which are subject to certain parameters restrictions.

First, for the market to be active, it is assumed that any marginal environmental damage parameter β_i cannot be higher than the maximal marginal utility of good X, given by α, and thus $\beta_i \in (0, \alpha)$, for i, j, k where $i \neq j, k$.

Second, for the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that, for i, j, k where $i \neq j, k$: $X_i, x_{ii} \in \mathbb{R}_n^{++}$ and $x_{ij} \in \mathbb{R}_n^{+}$.

Third, the constrained parameters set an upper bound on non-negative import tariffs to warrant positive trade flows among countries.

The most restrictive conditions on local production and exports are summarized here:

- From the Singleton Structure:

$$x_{ij}(C_{NC}) \geq 0 \Rightarrow$$

$$\alpha \geq \frac{1}{108}\left(228\beta_i - 96\left(\beta_j + \beta_k\right) + 25\left(\tau_{i,j} + \tau_{i,k}\right) + \left(349\tau_{j,i} + 106\tau_{k,i}\right) - \left(191\tau_{j,k} + 110\tau_{k,j}\right)\right) \quad \text{(E1.1)}$$

$$x_{ik}(C_{NC}) \geq 0 \Rightarrow$$

$$\alpha \geq \frac{1}{108}\left(228\beta_i - 96\left(\beta_j + \beta_k\right) + 25\left(\tau_{i,j} + \tau_{i,k}\right) + \left(349\tau_{k,i} + 106\tau_{j,i}\right) - \left(191\tau_{k,j} + 110\tau_{j,k}\right)\right) \quad \text{(E1.2)}$$

- From the Grand Coalition Structure:

$$x_{ij}(C_G) \geq 0 \Rightarrow 0 \leq \tau_G \leq (\alpha - \textstyle\sum_i \beta_i). \quad \text{(E1.3)}$$

$$X_i(C_G) > 0 \Rightarrow 0 < \textstyle\sum_i \beta_i < \alpha \quad \text{(E1.4)}$$

- From the Partial Coalition Structure:

$$x_{ik}\left(C_P^k\right) = x_{jk}\left(C_P^k\right) \geq 0 \Rightarrow$$

$$\alpha \geq \frac{1}{60}\left(66\left(\beta_i + \beta_j\right) - 24\beta_k - 25\tau_{ij} + \left(31\tau_{ij,k} + 78\tau_{k,ij}\right)\right). \quad \text{(E1.5)}$$

$$x_{ik}\left(C_P^i\right) = x_{ij}\left(C_P^i\right) \geq 0 \Rightarrow$$

$$\alpha \geq \frac{1}{60}\left(84\beta_i - 96\left(\beta_j + \beta_k\right) - 25\tau_{jk} + \left(139\tau_{jk,i} + 42\tau_{i,jk}\right)\right). \quad \text{(E1.6)}$$

1.6.6 Appendix F1: Exogenous Tariff Structures in Remarks 1.4.2.2, 1.4.2.3, 1.4.2.4, and 1.4.2.5.

Using (B1.11) and (C1.8), country i's welfare gains from the grand coalition in comparison to being a singleton, for i, j, k where $i \neq j, k$, are expressed as follows:

$$W_i(C_G) - W_i(C_{NC}) = \frac{1}{2}\frac{1}{108^2}\left(288\sum_i \beta_i \left(194\beta_i - 49\left(\beta_j + \beta_k\right)\right) - \Omega_i(C_{NC})\right), \qquad \text{(F1.1)}$$

where $\Omega_i(C_{NC})$ captures the singleton's underlying exogenous tariff structure, and is given by:

$$\Omega_i(C_{NC}) = \begin{bmatrix} +2\tau_{i,j}\begin{bmatrix} 1944\alpha + 5424\beta_i - 6240\beta_j + 5424\beta_k \\ -11468\tau_{i,j} + 7972\tau_{i,k} - 3163\tau_{j,i} + 1049\tau_{j,k} + 1697\tau_{k,i} - 1867\tau_{k,j} \end{bmatrix} \\ +2\tau_{i,k}\begin{bmatrix} 1944\alpha + 5424\beta_i + 5424\beta_j - 6240\beta_k \\ +7972\tau_{i,j} - 11468\tau_{i,k} + 1697\tau_{j,i} - 1867\tau_{j,k} - 3163\tau_{k,i} + 1049\tau_{k,j} \end{bmatrix} \\ +\tau_{j,i}\begin{bmatrix} -5832\alpha + 15168\beta_i - 8160\left(\beta_j + \beta_k\right) \\ +1854\left(\tau_{i,j} + \tau_{i,k}\right) + 16277\tau_{j,i} - 8347\tau_{j,k} + 3155\tau_{k,i} - 3973\tau_{k,j} \end{bmatrix} \\ +\tau_{j,k}\begin{bmatrix} 1944\alpha + 6528\sum_i \beta_i \\ +54\left(\tau_{i,j} + \tau_{i,k}\right) - 8851\tau_{j,i} + 5405\tau_{j,k} - 4477\tau_{k,i} + 3947\tau_{k,j} \end{bmatrix} \\ +\tau_{k,i}\begin{bmatrix} -5832\alpha + 15168\beta_i - 8160\left(\beta_j + \beta_k\right) \\ +1854(\tau_{i,j} + \tau_{i,k}) + 3155\tau_{j,i} - 3973\tau_{j,k} + 16277\tau_{k,i} - 8347\tau_{k,j} \end{bmatrix} \\ +\tau_{k,j}\begin{bmatrix} 1944\alpha + 6528\sum_i \beta_i \\ +54(\tau_{i,j} + \tau_{i,k}) - 4477\tau_{j,i} + 3947\tau_{j,k} - 8851\tau_{k,i} + 5405\tau_{k,j} \end{bmatrix} \end{bmatrix}. \qquad \text{(F1.2)}$$

Using (C1.8) and (D1.14), country i's welfare gains from the grand coalition in comparison to forming a pair with country j within the partial coalition C_p^k, for i, j, k where $i \neq j, k$, are given by:

$$W_i(C_G) - W_i\left(C_p^k\right) = \frac{1}{1440}\left(432\sum_i \beta_i \left(7\beta_i - \left(\beta_j + 2\beta_k\right)\right) - \Omega_i\left(C_p^k\right)\right), \qquad \text{(F1.3)}$$

where $\Omega_i\left(C_p^k\right)$ captures the exogenous tariff structure underlying the partial coalition C_p^k and is expressed as follows, for i, j, k where $i \neq j, k$:

$$\Omega_i\left(C_p^k\right) = \begin{bmatrix} +5\tau_{ij}\left(-24\alpha - 11\tau_{ij} + 42\tau_{ij,k} + 4\tau_{k,ij}\right) \\ +\tau_{ij,k}\left(360\alpha + 2400\beta_i + 96\beta_j - 192\beta_k - \left(791\tau_{ij,k} + 236\tau_{k,ij}\right)\right) \\ +12\tau_{k,ij}\left(-20\alpha + 100\beta_i + 4\beta_j - 8\beta_k + 23\tau_{k,ij}\right) \end{bmatrix}. \qquad \text{(F1.4)}$$

1.6.7 Appendix G1: Proof of Proposition 1.4.1.1

Using (B1.10), global production in the singleton structure, $X(C_{NC}) = \sum_i X_i(C_{NC})$, is as follows:

$$X(C_{NC}) = \tfrac{1}{9}\left(27\alpha - 3\sum_i \beta_i - 4\sum_i \sum_j \tau_{i,j}\right). \tag{G1.1}$$

Using (C1.7), the grand coalition's aggregate production, $X(C_G) = \sum_i X_i\,(C_G)$, is as follows:

$$X(C_G) = 3(\alpha - \textstyle\sum_i \beta_i). \tag{G1.2}$$

Using (G1.1) and (G1.2), the collective environmental gains provided by the grand coalition in comparison to the singletons, is as follows, for i, j, k where $i \neq j, k$.

$$X(C_{NC}) - X(C_G) = \tfrac{4}{9}\left(6\sum_i \beta_i - \sum_i \sum_j \tau_{i,j}\right). \tag{G1.3}$$

$$X(C_{NC}) - X(C_G) > 0 \Rightarrow \forall 6\sum_i \beta_i > \sum_i \sum_j \tau_{i,j}.$$

Using (D1.20), global production in the partial coalition C_P^k, $X(C_P^k) = \sum_i X_i\,(C_P^k)$, is given by:

$$X(C_P^k) = \tfrac{1}{5}\left(15\alpha - 3\sum_i \beta_i - 4\left(\tau_{k,ij} + 2\tau_{ij,k}\right)\right). \tag{G1.4}$$

Using (G1.2) and (G1.4), the collective environmental gains provided by the grand coalition in comparison to the partial coalition C_P^k, and by symmetry for C_P^j and C_P^i, are as follows:

$$X(C_P^k) - X(C_G) = \tfrac{4}{5}\left(3\sum_i \beta_i - \left(2\tau_{ij,k} + \tau_{k,ij}\right)\right). \tag{G1.5}$$

$$X(C_P^k) - X(C_G) > 0 \Rightarrow \forall\left(2\tau_{ij,k} + \tau_{k,ij}\right) < 3\sum_i \beta_i \quad \bullet \text{ Q.E.D.}$$

1.6.8 Appendix H1: Proof of Proposition 1.4.1.2

Using (C1.8), country i's welfare as a member of the grand coalition, $W_i(C_G)$, and by symmetry for countries j and k, can be expressed as follows:

$$W_i(C_G) = \tfrac{1}{2}\left[\alpha(\alpha - 6\beta_i) + \textstyle\sum_i \beta_i \left(5\beta_i - \left(\beta_j + \beta_k\right)\right)\right]. \tag{H1.1}$$

Using (D1.21), country i's welfare as an outsider to a pair in the partial coalition structure, $W_i\left(C_P^i\right)$, and by symmetry for countries j and k, can be reduced as follows in a free trade setting:

$$W_i\left(C_P^i\right) = \tfrac{1}{450}\left[225\alpha(\alpha - 6\beta_i) + 153\left(\textstyle\sum_i \beta_i\right)^2\right]. \tag{H1.2}$$

Using (H1.1) and (H1.2), country i's individual welfare gains in a free trade setting, as a member of the grand coalition in comparison to being an outsider to a pair within the partial coalition C_P^i, and by symmetry for countries j and k, are expressed as follows:

$$W_i(C_G) - W_i\left(C_p^i\right) = \tfrac{3}{25}\left[\textstyle\sum_i \beta_i \left(18\beta_i - 7\left(\beta_j + \beta_k\right)\right)\right]. \tag{H1.3}$$

Given (1.13) and (1.14), the grand coalition is externally stable by default, and internally stable $\Leftrightarrow W_i(C_G) - W_i\left(C_p^i\right) \geq 0$, for i, j, k where $i \neq j, k$.

Since by assumption, $\beta_i > \beta_j > \beta_k > 0$, then: $W_i(C_G) - W_i\left(C_p^i\right) > 0$, when $\beta_i > \beta_j > \beta_k > 0$.

$W_j(C_G) - W_j\left(C_p^j\right) \geq 0$, when $\beta_j \geq \frac{7}{18}(\beta_i + \beta_k)$ and $\beta_i > \beta_j > \beta_k > 0$.

$W_k(C_G) - W_k\left(C_p^k\right) \geq 0$, when $\beta_k \geq \frac{7}{18}\left(\beta_i + \beta_j\right)$ and $\beta_i > \beta_j > \beta_k > 0$.

In the homogeneous case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, equation (H1.3) is reduced to:

$$\widehat{W}_i(C_G) - \widehat{W}_i\left(C_p^i\right) = \left(\tfrac{6}{5}\hat{\beta}\right)^2. \tag{H1.4}$$

Equation (H1.4) demonstrates that $\widehat{W}_i(C_G) - \widehat{W}_i\left(C_p^i\right) > 0, \forall \hat{\beta} > 0$. • Q.E.D.

1.6.9 Appendix I1: Proof of Proposition 1.4.1.3

Using (B1.11), country i's individual welfare as a singleton, $W_i(C_{NC})$, and by symmetry for countries j and k, can be reduced as follows in a free trade setting:

$$W_i(C_{NC}) = \frac{1}{162}\left[\left(81\alpha\left(\alpha - 6\beta_i\right) + 17\left(\sum_i \beta_i\right)^2\right)\right]. \tag{I1.1}$$

Using (D1.14), country i's individual welfare as a pair member under the partial coalition C_P^k, $W_i\left(C_P^k\right)$, and by symmetry for countries j and k, can be reduced as follows in a free trade setting:

$$W_i\left(C_P^k\right) = \frac{1}{10}\left[5\alpha(\alpha - 6\beta_i) + \sum_i \beta_i \left(4\beta_i - 2\beta_j + \beta_k\right)\right]. \tag{I1.2}$$

Using (I1.1) and (I1.2), country i's individual welfare gains as a singleton in comparison to forming a pair with country j, and by symmetry for countries j and k, are given by the following expression in a free trade setting:

$$W_i(C_{NC}) - W_i\left(C_p^k\right) = \frac{1}{2\times3^4\times5}\sum_i \beta_i \left[\left(247\beta_j - 239\beta_i\right) + 4\beta_k\right]. \tag{I1.3}$$

Given (1.13) and (1.14), the singleton structure is internally stable by default, and externally stable $\Leftrightarrow W_i(C_{NC}) - W_i\left(C_p^k\right) \geq 0$ and $W_k(C_{NC}) - W_k\left(C_p^i\right) \geq 0$, for i, j, k where $i \neq j, k$.

Since $\beta_i > \beta_j > \beta_k > 0$ by assumption, then for i, j, k and $i \neq j, k$:

$W_i(C_{NC}) - W_i\left(C_p^k\right) \geq 0$, when $239\beta_i \leq \left(247\beta_j + 4\beta_k\right)$, and

$W_k(C_{NC}) - W_k\left(C_p^i\right) \geq 0$, when $239\beta_k \leq \left(247\beta_j + 4\beta_i\right)$.

In the homogeneous case, where $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, equation (I1.3) is reduced to:

$$\widehat{W}_i(C_{NC}) - \widehat{W}_i\left(C_P^k\right) = \frac{2}{3^2\times5}\hat{\beta}^2. \tag{I1.4}$$

Equation (I1.4) indicates that, $\widehat{W}_i(C_{NC}) - \widehat{W}_i\left(C_P^k\right) > 0, \forall\hat{\beta} > 0$. • Q.E.D.

1.6.10 Appendix J1: Proof of Proposition 1.4.1.4

Using (H1.1) and (H1.2), country i's welfare gains as an outsider in the partial coalition C_p^i, compared to the grand coalition in a free trade setting, are, for i, j, k where $i \neq j, k$:

$$W_i(C_p^i) - W_i(C_G) = \frac{3}{25}\sum_i \beta_i \left(7(\beta_j + \beta_k) - 18\beta_i\right). \tag{J1.1}$$

Given (1.14), C_p^i is externally stable $\Leftrightarrow W_i(C_p^i) - W_i(C_G) \geq 0$, and by symmetry for C_p^j and C_p^k.

$W_i(C_p^i) - W_i(C_G) < 0, \forall\, 0 < \beta_k < \beta_j < \beta_i \Rightarrow C_p^i$ is externally unstable.

The external stability of the partial coalition C_p^j requires, $\beta_j \leq \frac{7}{18}(\beta_i + \beta_k), \forall 0 < \beta_k < \beta_j < \beta_i$.

The external stability of the partial coalition C_p^k requires, $\beta_k \leq \frac{7}{18}(\beta_i + \beta_j), \forall 0 < \beta_k < \beta_j < \beta_i$.

Using (I1.3), country i's welfare gains when forming a pair with country j, in comparison to behaving as a singleton, in a free trade setting, are, for i, j, k where $i \neq j, k$:

$$W_i(C_p^k) - W_i(C_{NC}) = \frac{1}{2\times 3^4 \times 5}\sum_i \beta_i \left((239\beta_i - 247\beta_j) - 4\beta_k\right) \tag{J1.2}$$

Given (1.13), C_p^k is internally stable $\Leftrightarrow W_i(C_p^k) - W_i(C_{NC}) \geq 0$ and $W_j(C_p^k) - W_j(C_{NC}) \geq 0$.

The partial coalition C_p^k is internally unstable, as $W_j(C_p^k) - W_j(C_{NC}) < 0, \forall\, 0 < \beta_k < \beta_j < \beta_i$.

The partial coalition C_p^j is internally unstable, as $W_k(C_p^j) - W_k(C_{NC}) < 0, \forall\, 0 < \beta_k < \beta_j < \beta_i$.

The partial coalition C_p^i is internally unstable, as $W_k(C_p^i) - W_k(C_{NC}) < 0, \forall\, 0 < \beta_k < \beta_j < \beta_i$.

It follows that C_p^i, C_p^j, and C_p^k are all unstable, $\forall\, 0 < \beta_k < \beta_j < \beta_i$.

When $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, (J1.1) and (J1.2) are reduced, respectively, as follows:

$$\widehat{W}_i(C_p^i) - \widehat{W}_i(C_G) = -\left(\frac{6}{5}\hat{\beta}\right)^2 \tag{J1.3}$$

$$\widehat{W}_i(C_p^k) - \widehat{W}_i(C_{NC}) = -\frac{2}{45}\left(\hat{\beta}\right)^2 \tag{J1.4}$$

The partial coalition remains internally and externally unstable, $\forall \hat{\beta} > 0$. • Q.E.D.

1.6.11 Appendix K1: Proves of Propositions 1.4.1.5 and 1.4.1.6

1.6.11.1 Proof of Proposition 1.4.1.5

Using (H1.1) and (I1.1), country i's welfare gains from the grand coalition compared to being a singleton in a free trade setting, and by symmetry for countries j and k, are:

$$W_i(C_G) - W_i(C_{NC}) = \frac{1}{3^4}\left[288\sum_i \beta_i\left((97\beta_i - 49\beta_j) + (97\beta_i - 49\beta_k)\right)\right]. \quad \text{(K1.1.1)}$$

$W_i(C_G) - W_i(C_{NC}) > 0, \forall\ \beta_i > \beta_j > \beta_k > 0.$

$W_j(C_G) - W_j(C_{NC}) \geq 0$, when $194\beta_j \geq 49(\beta_i + \beta_k)$ and $\beta_i > \beta_j > \beta_k > 0$.

$W_k(C_G) - W_k(C_{NC}) \geq 0$, when $194\beta_k \geq 49\left(\beta_i + \beta_j\right)$ and $\beta_i > \beta_j > \beta_k > 0$.

When $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, equation (K1.1.1) can be reduced as follows:

$$\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) = \frac{32}{9}\left(\hat{\beta}\right)^2. \quad \text{(K1.1.2)}$$

Equation (K1.1.2) indicates that $\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) > 0, \forall\hat{\beta} > 0.$ • Q.E.D.

1.6.11.2 Proof of Proposition 1.4.1.6

Using (H1.1) and (I1.2), country i's welfare gains from the grand coalition compared to forming a pair with country j in the partial coalition C_p^k in a free trade setting, are, for i, j, k where $i \neq j, k$:

$$W_i(C_G) - W_i\left(C_p^k\right) = \frac{3}{10}\sum_i \beta_i\left(7\beta_i - (\beta_j + 2\beta_k)\right). \quad \text{(K1.2.1)}$$

As $\beta_i > \beta_j > \beta_k > 0$, $W_i(C_G) - W_i\left(C_p^k\right) \geq 0$, when $\beta_i \geq \frac{1}{7}(\beta_j + 2\beta_k)$, for i, j, k where $i \neq j, k$.

When $\beta_i = \beta_j = \beta_k = \hat{\beta} > 0$, equation (K1.2.1) can be reduced a s follows:

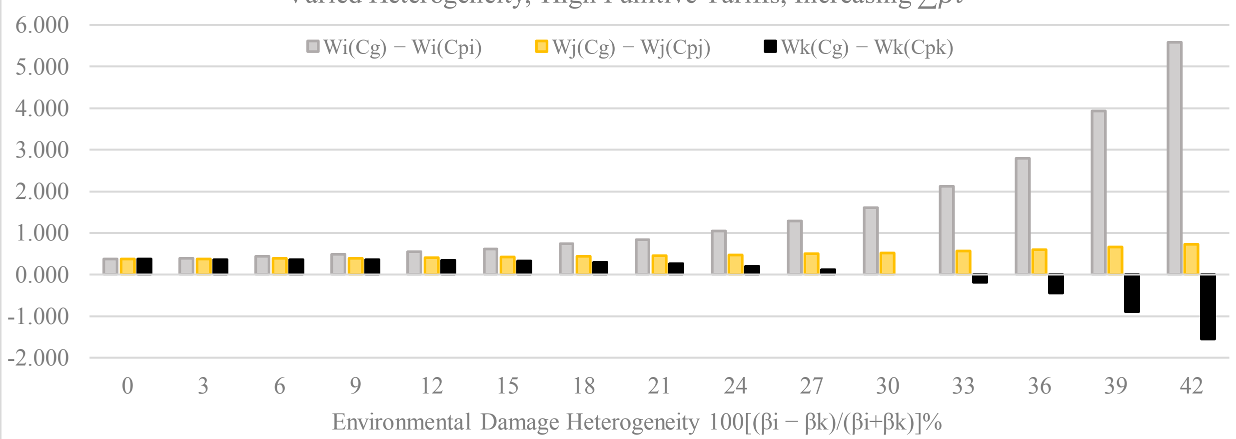
$$\widehat{W}_i(C_G) - \widehat{W}_i\left(C_p^k\right) = \frac{18}{5}\hat{\beta}^2. \quad \text{(K1.2.2)}$$

Equation (K1.2.2) indicates that, $\widehat{W}_i(C_G) - \widehat{W}_i(C_{NC}) > 0, \forall\hat{\beta} > 0.$ • Q.E.D.

1.6.12 Appendix L1: Coalitional Stability and Welfare Simulations - Increasing $\sum_i \beta_i$.

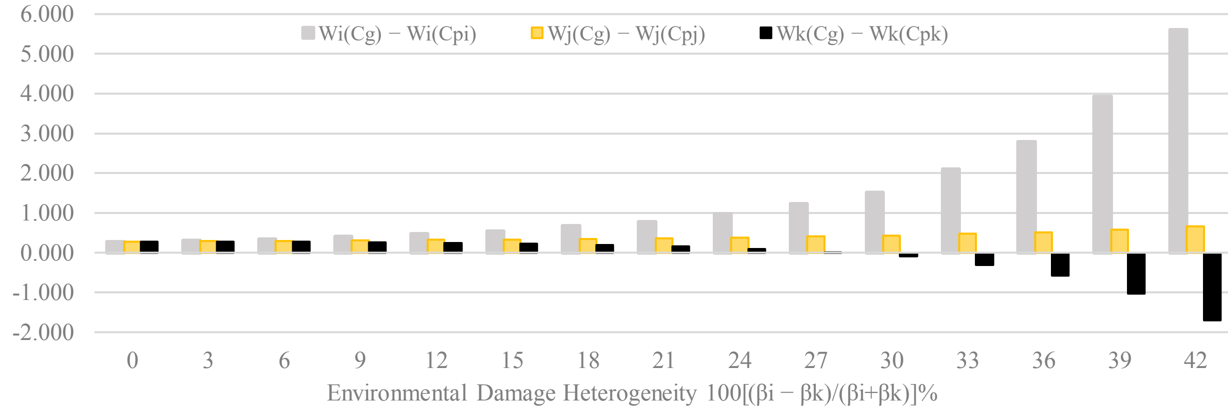
The analysis here and the subsequent figures depict the simulation results under an increasing $\sum_i \beta_i$ scenario compared to the case where $\sum_i \beta_i = 1$. As β_i, β_j, and β_k take higher values, while maintaining the heterogeneity assumption, where $\beta_i > \beta_j > \beta_k > 0$, $\sum_i \beta_i$ increases. In this scenario, keeping α constant to explore the effect of heterogeneity restricts the range of parameters that satisfy all the conditions imposed on the model's parameters, as outlined in Appendix E1. Hence, for any particular α value, the comparison is only possible within a limited range of heterogeneity. Nevertheless, the numerical simulation results remain consistent when assuming that $\sum_i \beta_i$ increases, in contrast to when $\sum_i \beta_i$ is held constant and normalized to 1.

Figure 1.7: Grand Coalition Stability - Varied Heterogeneity, High Punitive Tariffs, Increasing $\sum \beta i$



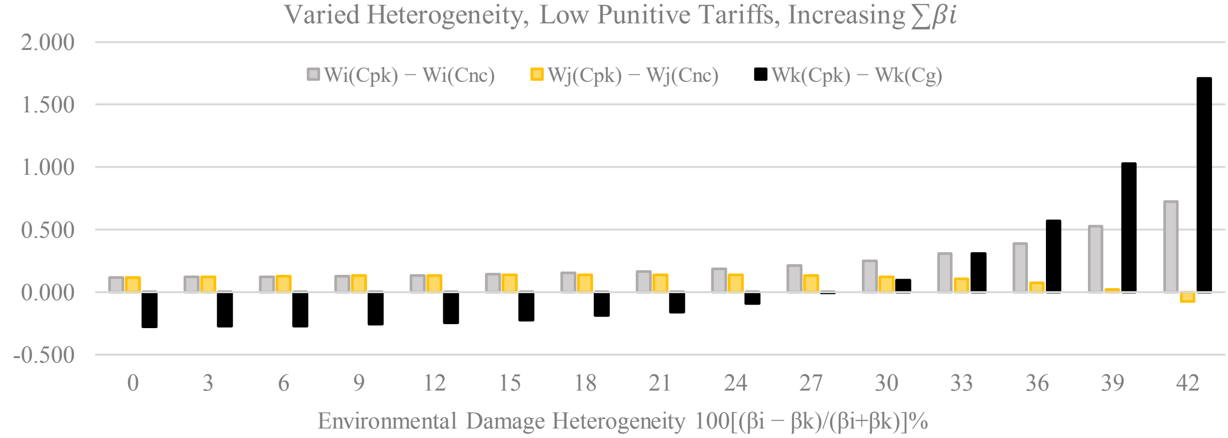
Assuming $\alpha = 3.5$ and the same exogenous tariff structure as in Figure 1.1, Figure 1.7 depicts Equation (1.52) for countries i, j, and k as $\sum_i \beta_i$ increases. Figure 1.7 indicates that the grand coalition remains stable over certain degrees of heterogeneity. Similar to Figure 1.1, as heterogeneity increases, country k has weaker incentives to join the grand coalition and may deviate from the agreement. In this case, the fully cooperative agreement becomes unstable after 30% heterogeneity. As demonstrated in Proposition 1.4.1.7, a higher α value can reinforce the stability of the grand coalition and extend the range over which the grand coalition remains stable.

Figure 1.8: Grand Coalition Stability -
Varied Heterogeneity, Low Punitive Tariffs, Increasing $\sum\beta i$



Assuming $\alpha = 3.5$ and the same exogenous tariffs as in Figure 1.2, Figure 1.8 depicts Equation (1.52) for countries i, j and k with low punitive tariffs. Similar to Figure 1.2, Figure 1.8 indicates that lower punitive tariffs reduce the range over which the grand coalition is stable. Here, the grand coalition is only stable up to 27% heterogeneity, compared to 30% in Figure 1.7. As heterogeneity increases, country k no longer favors the grand coalition, causing it to become unstable.

Figure 1.9: Partial Coalition Stability -
Varied Heterogeneity, Low Punitive Tariffs, Increasing $\sum\beta i$



Assuming $\alpha = 3.5$ and the same exogenous tariff structure as in Figure 1.3, Figure 1.9 depicts Equations (1.54) for country k and (1.55) for countries i and j with low punitive tariffs. Similar to Figure 1.3, Figure 1.9 shows that the grand coalition, which is externally unstable at sufficiently high degrees of heterogeneity, gives way to a stable partial coalition C_p^k above 27% heterogeneity.

In the absence of punitive tariffs or at sufficiently low levels, the singleton structure becomes stable, as $\sum_i \beta_i$ increases. Assuming $\alpha = 3.5$ and the same exogenous tariff structure as in Figure 1.4, Figure 1.10, with its three panels (a), (b), and (c), depicts the stability conditions of singletons i, j, and k, respectively, when $\tau_{ij,k}(C_p^k) = \tau_{ij}(C_p^k)$, for i, j, k, where $i \neq j, k$. Similar to Figure 1.4, in the absence of punitive tariffs, Figure 1.10 demonstrates that the singleton structure is stable in both the homogeneous benchmark case and at various degrees of heterogeneity.

Figure 1.10a: Stability of Singleton i - Varied Heterogeneity, Increasing $\sum \beta i$

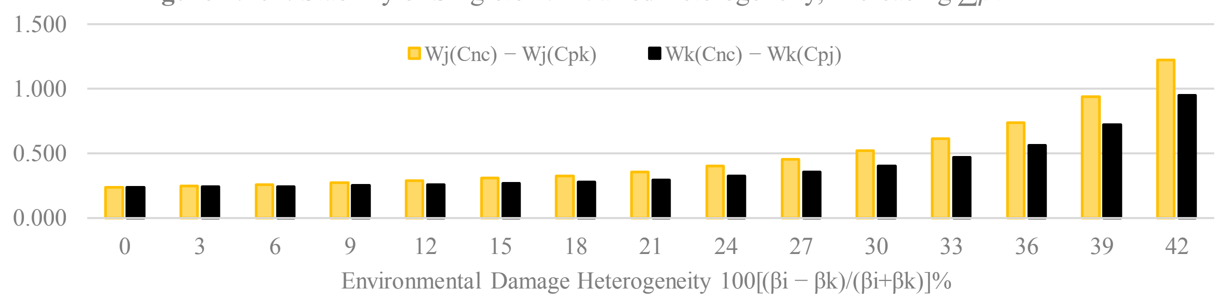


Figure 1.10b: Stability of Singleton j - Varied Heterogeneity, Increasing $\sum \beta i$

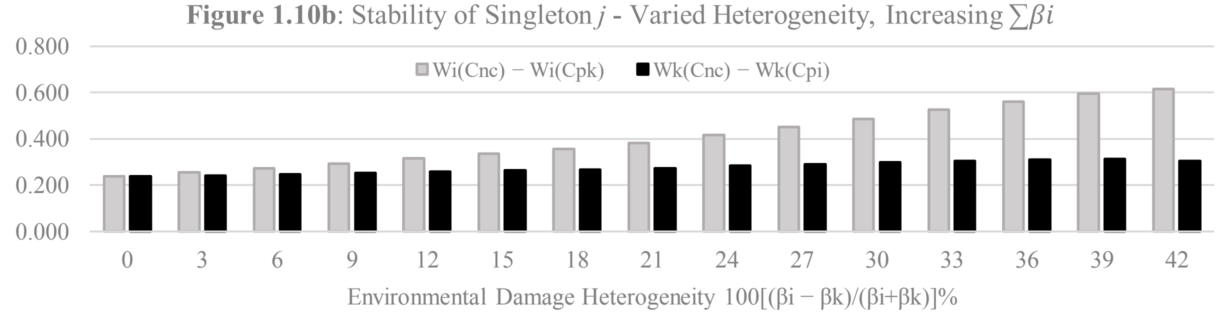
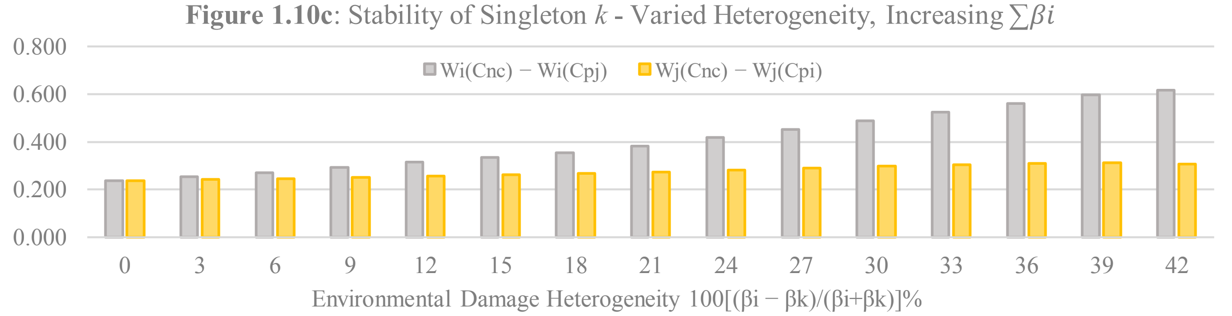
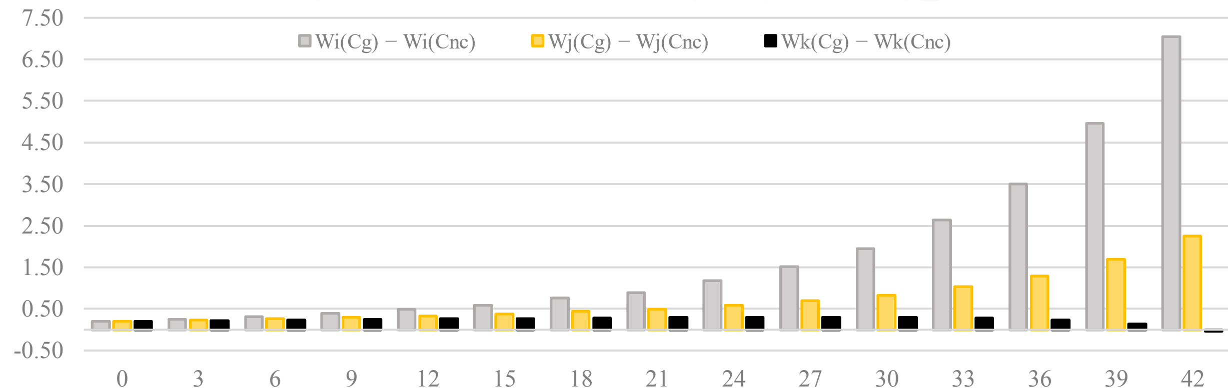


Figure 1.10c: Stability of Singleton k - Varied Heterogeneity, Increasing $\sum \beta i$



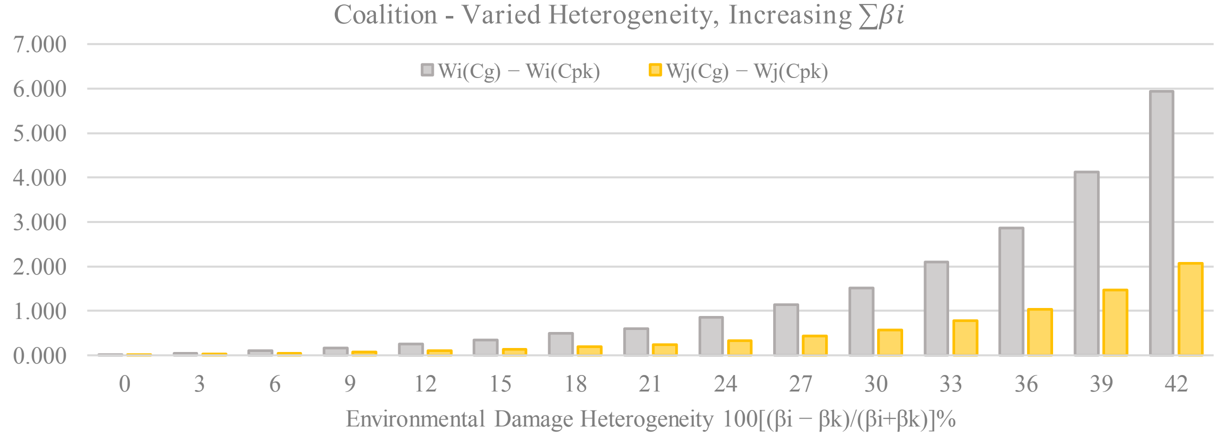
Assuming $\alpha = 3.5$ and the same exogenous tariffs as in Figure 1.5, Figure 1.11 depicts the welfare gains of countries i, j, and k as members of the grand coalition compared to behaving as singletons, when the grand coalition is stable and $t_G^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha) > 0$. Similar to Figure 1.5, Figure 1.11 demonstrates that these individual welfare gains can be positive for all members over a range of heterogeneity, with country i continuing to be the primary beneficiary of the grand coalition.

Figure 1.11: Individual Welfare Gains: Comparing the Grand Coalition to the Singleton Structure - Varied Heterogeneity, Increasing $\sum\beta i$



Finally, assuming $\alpha = 3.5$ and the same exogenous tariff structure as Figure 1.6, Figure 1.12 depicts Equation (1.61) for countries i and j, as pair members in the partial coalition C_p^k. Similar to Figure 1.6, it is evident from Figure 1.12 that both countries can be better off in the grand coalition compared to the partial agreement C_p^k. Country i, having the highest marginal environmental damage parameter, consistently achieves higher welfare gains than country j, while these gains remain positive across various levels of heterogeneity for both countries.

Figure 1.12: Individual Welfare Gains: Comparing the Grand Coalition to the Partial Coalition - Varied Heterogeneity, Increasing $\sum\beta i$



ESSAY 2

ENVIRONMENTAL COOPERATION AND TRADE: THE IMPACT OF HETEROGENEITY IN ENVIRONMENTAL DAMAGES – AN ENDOGENOUS SOLUTION

2.1 Introduction

The present essay extends the previous analysis in the first chapter by incorporating endogenous import tariffs into the static three-country coalition formation game. It examines the stability of both partial and global International Environmental Agreements (IEAs) among heterogeneous trading partners, when environmental taxes and import tariffs are negotiated simultaneously.

The main objectives of this essay, therefore, are: i) To determine whether environmental cooperation among countries with different environmental damage parameters leads to environmental gains, overall welfare gains, or both. ii) To identify the cooperative scenarios that would emerge in a stable coalition to exploit these gains. iii) To analyze the effect of heterogeneity in environmental damages on the stability of these environmental coalitions.

The current essay examines an open economy with three heterogeneous countries, each characterized by a different environmental damage parameter. In each country, there is a single firm producing an emission-intensive good, generating transboundary emissions, such as carbon dioxide. Consumers in each country are affected by global emissions, and each unit of production generates precisely one unit of global emissions. The firm's choice variable is the production level, which also represent emissions. Although abatement is not explicitly modeled as a separate choice variable, the firm incurs an abatement cost in terms of forgone profit. The firms compete à la

Cournot in a segmented market, where each firm serves linear market-specific demands rather than a shared global market demand.

International trade occurs in domestic markets, allowing each country to use import tariffs as a trade policy instrument to protect local production. The use of a segmented market setting with endogenous import tariffs, in comparison to free trade conditions, represents a novel approach in the theoretical literature. This approach proves especially valuable when coordination involves environmental and trade policies concurrently. Furthermore, each government uses a per-unit-of-production (emissions) tax rate as an environmental policy tool. It is assumed that transfer payments do not occur between countries, and fiscal revenues remain within the state of origin.

The static coalition formation game consists of three stages. In the first stage, the coalition formation game takes place, with each country selecting its coalition membership. A coalition is considered stable if no country has an incentive to enter or exit the coalition (D'Aspremont et al., 1983). In the second stage, each country determines the emissions tax and endogenous tariff rates that maximize the coalition's welfare. Finally, in the third stage, each firm independently chooses the production rate that maximizes its own profit. The solution to the coalition formation game is determined through backward induction, starting from the third stage and progressing backward to the first stage.

The numerical simulations reveal that the grand coalition remains stable across various levels of environmental damage heterogeneity. When the market size is sufficiently small, the grand coalition results in both environmental and overall welfare gains. However, as the market size grows sufficiently larger, the grand coalition only yields overall welfare gains. While it cannot be proven analytically, a range of parameters where the grand coalition is not stable has not been identified.

The main policy implications suggest that implementing trade penalties on countries opting out of participation is a valuable strategy to foster a stable global agreement, even in the presence of heterogeneity in environmental damages. Furthermore, the coordination of environmental and trade policies proves effective in reducing global emissions in sufficiently small markets.

The primary contribution of this essay to the literature lies in demonstrating that using positive tariffs on imports within a segmented market instead of a global market in a free trade setting, reduces non-signatories' free riding incentives and reinforces the stability of the global agreement. The results confirm Nordhaus (2015) concept of the "Climate Club" which suggests that imposing trade penalties on non-members can promote greater cooperation in addressing climate change.

The rest of the essay is structured as follows: Section 2 describes the model, Section 3 explores the heterogeneous endogenous case, Section 4 provides a summary of the results, and Section 5 concludes the essay.

2.2 The Model

The static coalition formation game unfolds in three stages: first, coalition formation; then, government welfare optimization; and finally, firm profit maximization. The model considers an open economy with three heterogeneous countries, $N = \{i, j, k\}$. Each country has one profit-maximizing firm, producing a homogeneous emission-intensive good X. The total production of the firm located in country i is given by,

$$X_i = \left(x_{ii} + x_{ij} + x_{ik}\right), \tag{2.1}$$

where x_{ii} is produced and sold in country i, and x_{ij} is produced in country i and exported to country j, $\forall\ i \neq j$. For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that $X_i, x_{ii} \in \mathbb{R}_n^{++}$ and $x_{ij} \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.

The production process generates transboundary air pollution such as carbon dioxide. Every unit produced generates exactly one unit of global emissions. The firm's choice variables are local production and exports, which also represent emissions. Firms can reduce emissions by producing less output, at the expense of reducing profits, and thus face a tradeoff between emissions and profits. Hence, abatement is neither an option nor a choice variable.

Total consumption in country i is given by:

$$Q_i = \left(x_{ii} + x_{ji} + x_{ki}\right), \tag{2.2}$$

where x_{ii} is locally produced and x_{ji} is imported from country j, for $i \neq j$.

Firms compete à la Cournot in a segmented market where each firm faces linear market-specific demands. The market demand in country i is given by:

$$Q_i = (\alpha - P_i), \tag{2.3}$$

where Q_i is the total consumption of the polluting good in country i, P_i is the price of the good in market i, and α is the maximal marginal utility derived from its consumption. For simplification, it is assumed that the marginal cost of production is equal to zero, and each firm can export to the other two foreign markets at no transaction costs.

Pollution generates environmental damage in each country; the social cost of pollution is linear in global emissions:

$$D_i(X) = \beta_i\left(X_i + X_j + X_k\right), \tag{2.4}$$

where β_i is the marginal environmental damage in country i caused by aggregate production, that is, by global emissions. The linear environmental damage function makes the analysis more readable and the model more tractable. For the market to be active, it is assumed that a marginal environmental damage parameter cannot be higher than the maximal marginal utility of good X represented by α, and thus $\beta_i \in (0, \alpha)$, for i, j, k. Consumers in each country are affected by the global level of emissions. As such, variance in environmental damages does not manifest through different emissions exposure levels, but how the same number of emissions translates into costs, given the underlying determinants of heterogeneity, such as income, health stock, defensive investment, or baseline exposure (Hsiang et al., 2019). In this model, therefore, different environmental damages result from varying impacts of the same level of global emissions.

The government in country i imposes a positive endogenous tariff $\tau_{i,j}$ per unit of imports from country j and $\tau_{i,k}$ per unit of imports from country k, where $i \neq j, k$. As a result, $\tau_{j,i}$ and $\tau_{k,i}$ are the effective marginal costs of the firm operating in country i on its exports to countries j and k, respectively. The main distinction between this essay and the previous one is that import tariffs are endogenous, that is optimal, rather than exogenous.

In addition to import tariffs as a trade policy tool, each government uses a per-unit of production tax rate t_i that is imposed on the local firm as an environmental policy instrument. Since every unit produced precisely generates one unit of emissions, then a tax per unit of production is equivalent to a tax per unit of emissions. Thus, the government in country i collects tariff revenues on imports from foreign markets given by,

$$TR_i = \left(\tau_{i,j} x_{ji} + \tau_{i,k} x_{ki}\right), \tag{2.5}$$

and emissions tax revenues expressed as,

$$ER_i = t_i\left(x_{ii} + x_{ij} + x_{ik}\right) = t_i X_i. \tag{2.6}$$

It is assumed that there are no transfer payments between countries since transfers can alter the incentives behind environmental cooperation.

Let $\mathcal{S}$ be a coalition where $\mathcal{S} \subset N = \{i, j, k\}$. A coalition $\mathcal{S}$ represents a group of countries cooperating on environmental and trade policies concurrently. Coalition members will determine their emissions tax $t_{\mathcal{S}}$ jointly. Each coalition $\mathcal{S}$ is also associated with two endogenous import tariffs: $\tau_{\mathcal{S}}$ represents the common tariff that members of $\mathcal{S}$ would charge to each other, and $\tau_{\mathcal{S},k}$ where $k \notin \mathcal{S}$, represents the tariff that members of $\mathcal{S}$ would charge to each of its non-members. Therefore, it is explicitly assumed that coalition members will charge the same tariff to each other, $\tau_{\mathcal{S}} = \tau_{i,j} = \tau_{j,i}$, if $i, j \in \mathcal{S}$ and the same tariff to non-members, $\tau_{\mathcal{S},k} = \tau_{i,k} = \tau_{j,k}$, if $i, j \in \mathcal{S}$ and $k \notin \mathcal{S}$, even if coalition members have different marginal environmental damage parameters.

In a three-country model, there are three types of coalition structures: i) the grand coalition, ii) the singletons, and iii) a pair and a singleton. The static coalition formation game is composed of three stages. Stage one is the coalition formation game; each country chooses its coalition membership $\mathcal{S}$. A coalition is deemed stable when no country has an incentive to join or leave the coalition (D'Aspremont et al., 1983). In the second stage, each country chooses the emissions tax $t_{\mathcal{S}}$ and the import tariffs $\tau_{\mathcal{S}}$ and $\tau_{\mathcal{S},k}$ that maximize the coalition's welfare $W_{\mathcal{S}} = \sum_{i \in \mathcal{S}} W_i$, given the coalition structure C. In the third stage, each firm chooses independently its profit-maximizing production level X_i, given the coalition structure C, emissions taxes, and import tariffs. The coalition formation game is solved by backward induction, starting from the third stage, and moving backward to the first stage.

2.2.1 Stage Three - The Firm's Optimization Problem

In stage three, each firm chooses noncooperatively its profit-maximizing output, taking as given the policies set by all governments and the output decisions of the other two foreign firms. Firms compete à la Cournot in domestic markets, and each firm has three choice variables: production for the local market x_{ii}, and exports to the other foreign markets x_{ij} and x_{ik}. The profit function of the firm located in country i consists of total revenues from the domestic market i and foreign markets j and k, minus the emissions tax imposed on its total production and the tariff costs incurred on its exports. The firm's optimization problem[23] is expressed as follows, for i, j, k:

$$\max_{x_{ij\ j\in N}} \pi_i = \max_{x_{ij\ j\in N}} \sum_{j\in N}\left(P_j(x_{ij})x_{ij} - t_i x_{ij}\right) - \sum_{j\in N/\{i\}} \tau_{ji} x_{ij} \tag{2.7}$$

The first order conditions yield the following equilibrium quantities, for i, j, k where $i \neq j, k$:

$$x_{ii}{}^{*} = \frac{1}{4}\left(\alpha - 3t_i + \left(t_j + t_k\right) + \tau_{i,j} + \tau_{i,k}\right) \tag{2.8}$$

$$x_{ij}{}^{*} = \frac{1}{4}\left(\alpha - 3t_i + \left(t_j + t_k\right) + \tau_{j,k} - 3\tau_{j,i}\right). \tag{2.9}$$

The Cournot equilibrium implies that domestic production and exports are decreasing in the local emissions tax t_i, and increasing in the taxes imposed on foreign firms t_j and t_k. Domestic production increases in local tariffs $\tau_{i,j}$ and $\tau_{i,k}$, while exports are decreasing in foreign tariffs $\tau_{j,i}$ and $\tau_{k,i}$. The third stage of the game is common to all coalition structures. A country's welfare function is based on the optimal output quantities obtained in this stage.

2.2.2 Stage Two - The Government's Optimization Problem

In a three-country global economy, there are three types of coalition structures:

- A coalition structure C_{NC}, composed of three singletons, containing one country each, where $C_{NC} = \{\{i\},\{j\},\{k\}\}$.
- A coalition structure C_G, composed of one coalition containing all three countries, the grand coalition, where $C_G = \{\{i, j, k\}\}$.
- A coalition structure C_P, composed of two coalitions, a pair and a singleton. There are three such coalition structures. For example, $C_P^k = \{\{i, j\},\{k\}\}$ is composed of the pair formed by countries i and j, and of country k which behaves as a singleton.

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[23] The firm's profit maximization problem is detailed in Appendix A2.

The emissions tax rate $t_{\mathcal{S}}$ and the tariff rates $\tau_{\mathcal{S}}$ and $\tau_{\mathcal{S},k}$, are determined by maximizing the coalition's welfare $W_{\mathcal{S}}$, given the firms' optimal output quantities derived in stage three, $\forall i \in \mathcal{S}$:

$$\max_{t_{\mathcal{S}},\tau_{\mathcal{S}},\tau_{\mathcal{S},k}} W_{\mathcal{S}} \Rightarrow \max_{t_{\mathcal{S}},\tau_{\mathcal{S}},\tau_{\mathcal{S},k}} \sum_{i\subset\mathcal{S}} W_i\left(t_{\mathcal{S}},\tau_{\mathcal{S}},\tau_{\mathcal{S},k}\right), \text{ where } t_{\mathcal{S}} = t_i{}^{24} \tag{2.10}$$

The current model assumes that any cooperative equilibrium under the grand coalition and the partial coalition structure, would imply a uniform emissions tax rate $t_{\mathcal{S}}$, adopted by all countries within the coalition $\mathcal{S}$, and common import tariffs $\tau_{\mathcal{S}}$ and $\tau_{\mathcal{S},k}$. Indeed, scholars have frequently advocated uniform emissions tax solutions as an efficient policy instrument to address global environmental problems (Hoel 1992, Finus and Rundshagen 1998, Nordhaus 2006, Weitzman 2014). Proponents of uniform solutions argue that they are straightforward, typically involving less negotiation time, and therefore, fewer transaction costs than differentiated solutions. It is also argued that uniform emissions taxes appear equitable, as every country faces the same tax rate, and are generally perceived as "fair" by the public (Finus and Rundshagen 1998, McEvoy and McGinty 2018). Moreover, uniform emissions tax rates are easily verifiable in an agreement. Recall, that firms regardless to which coalition $\mathcal{S}$ their countries belong, they are competing à la Cournot, and still act independently of each other in the third stage of the oligopoly game.

The welfare function of country i, denoted by W_i, consists of the domestic consumer surplus CS_i, the local firm's profits π_i, the government's tariff revenues TR_i and emissions tax revenues ER_i, minus the environmental damages D_i caused by global emissions. Thus, country i's individual welfare function can be written as, for i, j, k and $i \neq j, k$:

$$W_i(C) = (CS_i - D_i + \pi_i + ER_i + TR_i), \tag{2.11}$$

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[24] t_i and $t_{\{i\}}$ will be used interchangeably in this essay.

and more specifically, it can be detailed by the following expression:

$$W_i(C) = \begin{bmatrix} \frac{1}{2}(Q_i)^2 - \beta_i(X_i + X_j + X_k) + (\tau_{i,j}x_{ji} + \tau_{i,k}x_{ki}) \\ +(\alpha - Q_i)x_{ii} + (\alpha - Q_j - \tau_{j,i})x_{ij} + (\alpha - Q_k - \tau_{k,i})x_{ik} \end{bmatrix}. \tag{2.12}$$

2.2.3 Stage One - Coalition Formation

In the first stage, the coalition formation game occurs, during which each country selects its coalition membership. The stability of each coalition structure is analyzed based on internal and external stability criteria, as developed by D'Aspremont et al. (1983), where a coalition is deemed stable if no country has an incentive to enter or exit the coalition within the structure.

Let C be the coalition structure to which a coalition $\mathcal{S}$ belongs; $W_{i\in\mathcal{S}}^{C}$ denotes the welfare of country i, where i belongs to $\mathcal{S}$. As such, $W_i^{C_{NC}}$, $W_i^{C_G}$, $W_i^{C_P^k}$, and $W_i^{C_P^i}$, represent, respectively, the welfare function of country i when i is a singleton, a member of the grand coalition, a pair member of a partial coalition formed by countries i and j, and an outsider to a pair formed by countries j and k.

Definition: A coalition $\mathcal{S} \subset N$, where $\mathcal{S} \in C$, is stable if it is both internally and externally stable.

- $\mathcal{S}$ is internally stable $\Leftrightarrow \forall i \in \mathcal{S}, W_i^C \geq W_i^{C^f}$ where $C^f = C/\mathcal{S} \quad \cup \quad \{\mathcal{S}/\{i\}, \{i\}\}$. (2.13)
- $\mathcal{S}$ is externally stable $\Leftrightarrow \forall i \in \mathcal{S}, W_{\{i\}}^C \geq W_{i\subset\mathcal{S}}^{C^c}$ where $C^c = \{C/\{i\} \quad \cup \quad \{\mathcal{S} \cup \{i\}\}\}$. (2.14)

In particular, C^f is a finer coalition structure than C; that is, as country i leaves the coalition $\mathcal{S}$ to become a singleton, C^f contains the remaining members of $\mathcal{S}$ and a singleton $\{i\}$.

In contrast, C^c is a coarser coalition structure than C; since country i, initially behaving as a singleton $\{i\}$, now joins the other member(s) in the coalition $\mathcal{S}$.

The singleton coalition structure, C_{NC}, is internally stable by default as it represents the finest coalition structure, where no country can depart from a coalition formed by itself. The grand coalition, C_G, is externally stable by default, since all countries are members, leaving no outsiders with the opportunity to join. The partial coalition, C_P, achieves external stability when no outsider has an incentive to join and internal stability when no member has an incentive to leave the coalition and form a singleton.

Within this framework, it is crucial to investigate whether both internal and external stability conditions are met in the partial coalition structure. In contrast, in the singleton structure, the focus lies solely on confirming external stability. Whereas, for the grand coalition, the emphasis is only on verifying internal stability.

2.3 The Heterogeneous Endogenous Case

The heterogeneous case assumes that countries have different environmental damage parameters, where $\beta_i > \beta_j > \beta_k > 0$. In a tie-in scenario, members of a coalition $\mathcal{S}$ coordinate their environmental and trade policies with other members. They enforce a uniform emissions tax $t_{\mathcal{S}}$ and common positive tariffs $\tau_{\mathcal{S}}$ to be levied on each other, and $\tau_{\mathcal{S},k}$ to be imposed on non-members.

2.3.1 The Singleton Structure C_{NC} - Noncooperative Equilibrium

In the singleton structure C_{NC}, the government in country i independently sets a noncooperative emissions tax rate ${t_i}^{NC}$, as well as two tariff rates imposed on imports from other countries. The analysis examines two different endogenous tariff scenarios within the singleton structure: optimal unrestricted tariffs, which are not restricted by WTO regulations, and WTO-restricted tariffs, which are constrained by the WTO Most-Favored-Nation (MFN) principle that prohibits discriminatory treatment between trading partners.

2.3.1.1 Optimal Unrestricted Tariffs

Let $\tau_{i,j}$ and $\tau_{i,k}$ be the tariff rates imposed by country i on imports from countries j and k, respectively, for i, j, k where $i \neq j, k$. There are, therefore, three emissions taxes, $t_i{}^{NC}$, $t_j{}^{NC}$, $t_k{}^{NC}$, and six endogenous tariff rates, $\tau_{i,j}$, $\tau_{i,k}$, $\tau_{j,i}$, $\tau_{j,k}$, $\tau_{k,i}$, and $\tau_{k,j}$.

The equilibrium quantities produced by the firm operating in country i, given by Equations (2.8) and (2.9), can thus be reduced to the following expressions, for i, j, k where $i \neq j, k$:

$$x_{ii}{}^*(C_{NC}) = \tfrac{1}{4}\left(\alpha - 3t_i^{NC} + \left(t_j{}^{NC} + t_k{}^{NC}\right) + \tau_{i,j} + \tau_{i,k}\right) \tag{2.15}$$

$$x_{ij}{}^*(C_{NC}) = \tfrac{1}{4}\left(\alpha - 3t_i^{NC} + \left(t_j{}^{NC} + t_k{}^{NC}\right) + \tau_{j,k} - 3\tau_{j,i}\right). \tag{2.16}$$

For the market structure to be maintained throughout the game, and to guarantee a positive interior solution, it is assumed that $x_{ii}{}^*(C_{NC}) \in \mathbb{R}_n^{++}$ and $x_{ij}{}^*(C_{NC}) \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.

Accordingly, country i's welfare optimization problem[25] (2.10) as a singleton can be written as,

$$\max_{t_i^{NC}, \tau_{i,j}, \tau_{i,k}} W_i^{C_{NC}} \Rightarrow \max_{t_i^{NC}, \tau_{i,j}, \tau_{i,k}} \begin{bmatrix} \tfrac{1}{2} Q_i{}^2(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) - \beta_i \left(X_i(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) + X_j(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) + X_k(t_i^{NC}, \tau_{i,j}, \tau_{i,k})\right) \\ + \left(\alpha - Q_i(t_i^{NC}, \tau_{i,j}, \tau_{i,k})\right) x_{ii}^*(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) + (\alpha - Q_j(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) - \tau_{j,i}) x_{ij}^*(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) \\ + (\alpha - Q_k(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) - \tau_{k,i}) x_{ik}^*(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) + \tau_{i,j} x_{ji}^*(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) + \tau_{i,k} x_{ki}^*(t_i^{NC}, \tau_{i,j}, \tau_{i,k}) \end{bmatrix} \tag{2.17}$$

The first order condition of the welfare maximization problem (2.17) with respect to the emissions tax t_i^{NC} yields the following negative best response function, for i, j, k where $i \neq j, k$:

$$t_i{}^{NC}\left(t_j{}^{NC}, t_k{}^{NC}, \tau\right) = \tfrac{1}{17} \begin{bmatrix} 12\beta_i - 9\alpha - 5\left(t_j{}^{NC} + t_k{}^{NC}\right) \\ +3\left(\tau_{i,j} + \tau_{i,k}\right) + 6\left(\tau_{j,i} + \tau_{k,i}\right) - 2\left(\tau_{j,k} + \tau_{k,j}\right) \end{bmatrix}. \tag{2.18}$$

The singleton, which behaves noncooperatively, has a negative best response function, implying free riding behavior as demonstrated by Equation (2.18).

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[25] Country i's optimization problem as a singleton with optimal unrestricted tariffs is detailed in Appendix B2.1.

The equilibrium emissions tax and import tariff rates are, respectively, for i, j, k where $i \neq j, k$:

$$t_i^{*NC}(C_{NC}) = \frac{1}{688}\left(-129\alpha + 499\beta_i - 13(\beta_j + \beta_k)\right) \tag{2.19}$$

$$\tau_{i,j}^{*}(C_{NC}) = \frac{1}{1376}\left(387\alpha + 19(45\beta_i - 19\beta_j) + 151\beta_k\right). \tag{2.20}$$

In this noncooperative equilibrium, each country's emissions tax rate is positively related to its own environmental damage parameter and inversely related to the parameters of the other two countries, implying solid free-riding incentives. Moreover, as indicated by Equation (2.19), the singleton's emissions tax rate is positive at sufficiently small values of the parameter α, that is, when $\alpha \leq \frac{1}{129}\left(499\beta_i - 13(\beta_j + \beta_k)\right)$, and becomes negative otherwise. Essentially, when a low value of α is coincides with high damage, as captured by β_i, then a singleton's welfare is mainly driven by damage. In this case, the singleton internalizes the negative externality associated with the production of the polluting good X by implementing a positive emissions tax, which reduces its production. Alternatively, when a high value of α concurs with a low damage parameter, then a singleton's welfare is basically driven by consumption and profits. Thus, a singleton can enforce a subsidy to increase production of the polluting good, and subsequently increasing welfare.

Additionally, Equation (2.19) demonstrates that country i, having the highest environmental damage parameter, sets the highest emissions tax rate as demonstrated by the following equation:

$$t_i^{*NC} - t_j^{*NC} = \frac{2^5}{43}(\beta_i - \beta_j) > 0 \qquad \forall \beta_i > \beta_j > 0. \tag{2.21}$$

Country i's local production $x_{ii}(C_{NC})$ and exports $x_{ij}(C_{NC})$ are, respectively, $\forall i, j, k$ and $i \neq j, k$:

$$x_{ii}(C_{NC}) = \frac{1}{688}\left(301\alpha - 167\beta_i + 105(\beta_j + \beta_k)\right) \tag{2.22}$$

$$x_{ij}(C_{NC}) = \frac{1}{1376}\left(215\alpha - (453\beta_i + 165\beta_j) + 59\beta_k\right). \tag{2.23}$$

Moreover, country i is a net importer when behaving as a singleton, as $Q_i(C_{NC}) - X_i(C_{NC}) > 0$, $\forall \beta_i > \beta_j > \beta_k > 0$, as demonstrated by the following equation, for i, j, k where $i \neq j, k$:

$$Q_i(C_{NC}) - X_i(C_{NC}) = \frac{9}{43}\Big(\big(\beta_i - \beta_j\big) + \big(\beta_i - \beta_k\big)\Big). \tag{2.24}$$

While country j can either be a net exporter or a net importer depending on the degree of heterogeneity. Country k, on the other hand, is consistently a net exporter when acting as a singleton, given that $X_k(C_{NC}) - Q_k(C_{NC}) > 0$, $\forall \beta_i > \beta_j > \beta_k > 0$.

2.3.1.2 WTO-Restricted Tariffs

Under the WTO-restricted tariff scenario, countries are obligated to adhere to the WTO Most-Favored-Nation (MFN) principle, which ensures that they do not show preferential treatment or discriminate against their trading partners, thereby promoting fairness and non-discrimination in international trade. Hence, in this case, each government sets independently a noncooperative emissions tax $\tilde{t}_i^{NC}$, and charges the same tariff on imports from the other foreign markets, that is $\tau_{i,j} = \tau_{i,k} = \tilde{\tau}_i$, for i, j, k where $i \neq j, k$. Thus, there are three emissions tax rates $\tilde{t}_i^{NC}$, $\tilde{t}_j^{NC}$, $\tilde{t}_k^{NC}$and three endogenous import tariff rates, specifically, $\tilde{\tau}_i$, $\tilde{\tau}_j$, and $\tilde{\tau}_k$.

The equilibrium quantities produced by the firm operating in country i, given by Equations (2.8) and (2.9), can thus be rewritten as follows, for i, j, k where $i \neq j, k$:

$$\tilde{x}_{ii}^{\;*}(C_{NC}) = \frac{1}{4}\left(\alpha - 3\tilde{t}_i^{\;NC} + \left(\tilde{t}_j^{\;NC} + \tilde{t}_k^{\;NC}\right) + 2\tilde{\tau}_i\right) \tag{2.25}$$

$$\tilde{x}_{ij}^{\;*}(C_{NC}) = \frac{1}{4}\left(\alpha - 3\tilde{t}_i^{\;NC} + \left(\tilde{t}_j^{\;NC} + \tilde{t}_k^{\;NC}\right) - 2\tilde{\tau}_j\right). \tag{2.26}$$

For the market structure to be maintained throughout the game, and to guarantee a positive interior solution, it is assumed that $\tilde{x}_{ii}^{\;*}(C_{NC}) \in \mathbb{R}_n^{++}$ and $\tilde{x}_{ij}^{\;*}(C_{NC}) \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.

Accordingly, country i's welfare optimization problem[26] (2.10) as a singleton can be written as,

$$\max_{\tilde{t}_i^{NC},\tilde{\tau}_i} \widetilde{W}_i^{C_{NC}} \Rightarrow \max_{\tilde{t}_i^{NC},\tilde{\tau}_i} \begin{bmatrix} \frac{1}{2}\left(\tilde{Q}_i(\tilde{t}_i^{NC},\tilde{\tau}_i)\right)^2 - \beta_i\left(\tilde{X}_i(\tilde{t}_i^{NC},\tilde{\tau}_i) + \tilde{X}_j(\tilde{t}_i^{NC},\tilde{\tau}_i) + \tilde{X}_k(\tilde{t}_i^{NC},\tilde{\tau}_i)\right) \\ +\left(\alpha - \tilde{Q}_i(\tilde{t}_i^{NC},\tilde{\tau}_i)\right)\tilde{x}_{ii}^*(\tilde{t}_i^{NC},\tilde{\tau}_i) + \left(\alpha - \tilde{Q}_j(\tilde{t}_i^{NC},\tilde{\tau}_i) - \tilde{\tau}_j\right)\tilde{x}_{ij}^*(\tilde{t}_i^{NC},\tilde{\tau}_i) \\ +\left(\alpha - \tilde{Q}_k(\tilde{t}_i^{NC},\tilde{\tau}_i) - \tilde{\tau}_k\right)\tilde{x}_{ik}^*(\tilde{t}_i^{NC},\tilde{\tau}_i) + \tilde{\tau}_i\left(\tilde{x}_{ji}^*(\tilde{t}_i^{NC},\tilde{\tau}_i) + \tilde{x}_{ki}^*(\tilde{t}_i^{NC},\tilde{\tau}_i)\right) \end{bmatrix}. \quad (2.27)$$

The first order condition of the welfare maximization problem (2.27) with respect to the emissions tax rate $\tilde{t}_i^{NC}$ yields the following negative best response function, for i, j, k where $i \neq j, k$:

$$\tilde{t}_i^{NC}(\tilde{t}_j^{NC},\tilde{t}_k^{NC},\tilde{\tau}) = \frac{1}{17}\left(-9\alpha + 12\beta_i - 5(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}) + 6\tilde{\tau}_i + 4(\tilde{\tau}_j + \tilde{\tau}_k)\right). \quad (2.28)$$

The singleton behaves noncooperatively, which results in a negative best response function as demonstrated by Equation (2.28), suggesting solid incentives for free-riding behavior.

The singleton's equilibrium emissions tax and tariff are, respectively, for i, j, k where $i \neq j, k$:

$$\tilde{t}_i^{*NC}(C_{NC}) = \frac{1}{112}\left(-21\alpha + 111\beta_i - 17(\beta_j + \beta_k)\right) \quad (2.29)$$

$$\tilde{\tau}_i^{*}(C_{NC}) = \frac{1}{224}\left(63\alpha + 163\beta_i - 29(\beta_j + \beta_k)\right). \quad (2.30)$$

In this noncooperative equilibrium, each country's emissions tax rate is positively related to its environmental damage parameter and inversely related to the other two countries' parameters. Furthermore, the country with the highest environmental damage parameter sets the highest emissions tax rate as shown here, for i, j, k where $i \neq j, k$:

$$\tilde{t}_i^{*NC} - \tilde{t}_j^{*NC} = \frac{8}{7}(\beta_i - \beta_j) > 0 \qquad \forall \beta_i > \beta_j > \beta_k > 0. \quad (2.31)$$

Comparing emissions taxes under the WTO restricted and the unrestricted tariff scenarios, the difference in country i's emissions tax rates is expressed as follows, for i, j, k where $i \neq j, k$:

$$\tilde{t}_i^{*NC} - t_i^{*NC} = \frac{40}{7\times 43}\left(2\beta_i - (\beta_j + \beta_k)\right) > 0 \qquad \forall \beta_i > \beta_j > \beta_k > 0. \quad (2.32)$$

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[26] Country i's welfare optimization problem as a singleton with WTO-restricted tariffs is detailed in Appendix B2.2.

Equation (2.32) unequivocally illustrates that in the case of tariffs being constrained by WTO regulations, country i consistently imposes a higher emissions tax rate compared to the scenario with unrestricted tariffs. Conversely, country k benefits from the restrictions by enforcing a lower emissions tax rate and takes advantage of the environmental benefits provided by country i.

Country i's local production $\tilde{x}_{ii}(C_{NC})$ and exports $\tilde{x}_{ij}(C_{NC})$ are, respectively as follows, for i, j, k where $i \neq j, k$:

$$\tilde{x}_{ii}(C_{NC}) = \frac{1}{112}\left(49\alpha - 51\beta_i + 29\left(\beta_j + \beta_k\right)\right) \tag{2.33}$$

$$\tilde{x}_{ij}(C_{NC}) = \frac{1}{224}\left(35\alpha - \left(169\beta_i + 9\beta_j\right) + 87\beta_k\right). \tag{2.34}$$

With WTO restricted tariffs, country i is a net importer, while country k is a net exporter, when behaving as singletons, $\forall \beta_i > \beta_j > \beta_k > 0$, as shown here, for i, j, k where $i \neq j, k$:

$$\tilde{Q}_i(C_{NC}) - \tilde{X}_i(C_{NC}) = \frac{5}{7}\left(2\beta_i - \left(\beta_j + \beta_k\right)\right). \tag{2.35}$$

Country i's individual welfare and collective welfare equations with optimal unrestricted and WTO-restricted tariffs are detailed in Appendix B2.1 and B2.2, respectively.

In essence, while the WTO's Most-Favored-Nation (MFN) tariff constraint is intended to promote fairness and non-discrimination among trading partners, the analysis indicates that it fails to enhance their collective welfare, and countries are better off with optimal unrestricted tariffs. Indeed, the collective welfare associated with the WTO Most-Favored-Nation tariff constraint falls short of that in the optimal unrestricted tariff case, as shown by Equation (2.36), where $i \neq j, k$:

$$W(C_{NC}) - \widetilde{W}(C_{NC}) = \frac{2^3 \times 3^2 \times 13}{7^2 \times 43^2}\left[\left(\beta_i - \beta_j\right)^2 + (\beta_i - \beta_k)^2 + \left(\beta_j - \beta_k\right)^2\right]. \tag{2.36}$$

While the three countries do not benefit equally from the WTO tariff regulation and the resulting tariff constraints, Equation (2.36) undoubtedly demonstrates that global welfare is enhanced with optimal unconstrained tariffs, $\forall \beta_i > \beta_j > \beta_k > 0$. Moreover, it is evident from Equation (2.36) that these collective welfare gains become more substantial at higher levels of heterogeneity.

2.3.2 The Grand Coalition Structure C_G - Fully Cooperative Equilibrium

In the grand coalition, countries collectively decide to tax the production of the polluting good at a uniform emissions tax rate, $t_G(C_G)$, that maximizes the joint welfare of all countries, such that,

$$t_i(C_G) = t_j(C_G) = t_k(C_G) = t_G(C_G).$$

Also, members of the grand coalition agree on a common positive tariff rate, $\tau_G(C_G)$, such that,

$$\tau_{i,j}(C_G) = \tau_{i,k}(C_G) = \tau_{j,i}(C_G) = \tau_{j,k}(C_G) = \tau_{k,i}(C_G) = \tau_{k,j}(C_G) = \tau_G(C_G).$$

Hence, the equilibrium quantities produced by the firm operating in country i, given by equations (2.8) and (2.9), can be reduced as follows, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_G) = \frac{1}{4}(\alpha - t_G + 2\tau_G) \quad (2.37)$$

$$x_{ij}(C_G) = x_{ik}(C_G) = \frac{1}{4}(\alpha - t_G - 2\tau_G). \quad (2.38)$$

The restrictions on the model's parameters ensure that all the above optima are interior solutions. Given country i's welfare optimization problem (2.10), the grand coalition's joint welfare optimization problem[27] is given by the following expression:

$$\max_{t_G, \tau_G} W^{C_G} = \max_{t_G, \tau_G} \sum_i \begin{bmatrix} \frac{1}{2} {Q_i}^2(t_G, \tau_G) - \beta_i \left(X_i(t_G, \tau_G) + X_j(t_G, \tau_G) + X_k(t_G, \tau_G) \right) \\ + \tau_G \left(x_{ji}^*(t_G, \tau_G) + x_{ki}^*(t_G, \tau_G) \right) + \left(\alpha - Q_i(t_G, \tau_G) \right) x_{ii}^*(t_G, \tau_G) \\ + \left(\alpha - Q_j(t_G, \tau_G) - \tau_G \right) x_{ij}^*(t_G, \tau_G) + \left(\alpha - Q_k(t_G, \tau_G) - \tau_G \right) x_{ik}^*(t_G, \tau_G) \end{bmatrix}. \quad (2.39)$$

[27] Country i's optimization problem as a member of the grand coalition is detailed in Appendix C2.

The first order conditions of the optimization problem (2.39) yield the following cooperative set of solutions, where any emissions tax and positive import tariff rates, (t_G, τ_G), satisfying Equations (2.40) and (2.41) represent an equilibrium solution:

$$3t_G^*(C_G) + 2\tau_G^*(C_G) = (4\sum_i \beta_i - \alpha) \tag{2.40}$$

$$t_G^*(C_G) \leq \frac{1}{3}(4\sum_i \beta_i - \alpha). \tag{2.41}$$

The fully cooperative agreement denotes that the uniform emissions tax rate is positively related to all three environmental damage parameters and negatively related to the tariff rate τ_G. Moreover, assuming that members of the grand coalition create a custom union, such that $\tau_G = 0$, then $({t_G}^*, {\tau_G}^*) = \left(\frac{1}{3}(4\sum_i \beta_i - \alpha), 0\right)$ is an equilibrium solution. Alternatively, assuming positive import tariffs, then $({t_G}^*, {\tau_G}^*) = \left(\frac{1}{4}(4\sum_i \beta_i - \alpha), \frac{1}{8}(4\sum_i \beta_i - \alpha)\right)$ is another equilibrium solution. Equation (2.40) clearly indicates that there exists a negative relationship between emissions taxes and import tariffs, since $\frac{\partial t_G^*(C_G)}{\partial \tau_G^*} = -\frac{2}{3} < 0$. This suggests that trade liberalization in the form of lower import tariffs, which entails higher production levels and more substantial environmental damages, requires higher emissions taxes. This inverse relationship between emissions taxes and tariffs is unique to a cooperative equilibrium, where changes in import tariffs are offset by changes in the emissions tax rates. Thus, in a cooperative scenario where taxes and tariffs are substitutes, lower tariffs will increase the emissions tax rate, fostering an environmental "race to the top".

Moreover, when changes in tariffs are offset by changes in taxes, individual production $X_i(C_G)$ and welfare $W_i(C_G)$, as well as global production $\sum_i X_i\,(C_G)$ and collective welfare $\sum_i W_i\,(C_G)$, are all independent of the common tariff rate ${\tau_G}^*(C_G)$. Consequently, the stability conditions outlined in Equations (2.13) and (2.14) are unaffected by the assumed solution $({t_G}^*, {\tau_G}^*)$.

Furthermore, since individual welfare $W_i(C_G)$, for i, j, k where $i \neq j, k$, and collective welfare $W(C_G) = \sum_i W_i(C_G)$ under the grand coalition are independent from $\tau_G{}^*(C_G)$, then these welfares remain affected by whether $\tau_G(C_G)$ is exogenous or endogenous, with the same set of parameters.

The equations detailing a member's total production, consumption, individual welfare, and collective welfare in the grand coalition, are provided in Appendix C2.

Country i's local production $x_{ii}(C_G)$ and exports $x_{ij}(C_G)$ in the grand coalition are, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_G) = \frac{1}{3}(\alpha - \sum_i \beta_i + 2\tau_G) \tag{2.42}$$

$$x_{ij}(C_G) = x_{ik}(C_G) = \frac{1}{3}(\alpha - \sum_i \beta_i - \tau_G). \tag{2.43}$$

To guarantee that local production $x_{ii}(C_G)$ is strictly positive and exports $x_{ij}(C_G)$ and $x_{ik}(C_G)$ are positive, then $\frac{1}{2}(\sum_i \beta_i - \alpha) < \tau_G{}^*(C_G) \leq (\alpha - \sum_i \beta_i)$.

Moreover, if members of the grand coalition create a custom union, where $\tau_G{}^*(C_G) = 0$, then the equilibrium emissions tax rate is given by the following expression:

$$t_G{}^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha). \tag{2.44}$$

Equation (2.44) makes it evident that when the market size, as captured by α, is sufficiently small, where $\alpha \leq 4\sum_i \beta_i$, the grand coalition imposes a positive emissions tax to reduce production and, consequently, global emissions. Conversely, when the market is sufficiently larger, $\forall \alpha > 4\sum_i \beta_i$, the coalition can opt for a subsidy to boost production. Essentially, the coalition can internalize the negative externality associated with the production of the polluting good by implementing a positive emissions tax, reducing production and lowering global emissions. Alternatively, it can enforce a subsidy to counteract the underproduction resulting from the Cournot competition.

2.3.3 The Partial Coalition Structure C_P - Partial Cooperative Equilibrium

In the partial coalition structure C_P, two countries, i and j for example, form a coalition $\mathcal{S}$, and the third country, k in this case, remains a singleton. Pair members cooperatively decide to tax the production of the polluting good at a uniform tax rate, $t_{ij}(C_P^k)$, that maximizes the joint welfare of both members, where $W_{ij}^{C_P^k} = W_i^{C_P^k} + W_j^{C_P^k}$. Hence, for i, j, k where $i \neq j, k$, it is assumed that:

$$t_i(C_P^k) = t_j(C_P^k) = t_{ij}(C_P^k).$$

Environmental cooperation spans over global production and trade flows. It is assumed, therefore, that pair members within a partial coalition structure can have zero tariffs among themselves and levy the same positive tariff rate on imports from the outsider, that is, for i, j, k where $i \neq j, k$:

$$\tau_{i,j}\left(C_P^k\right) = \tau_{j,i}\left(C_P^k\right) = \tau_{ij}\left(C_P^k\right) = 0$$

$$\tau_{i,k}\left(C_P^k\right) = \tau_{j,k}\left(C_P^k\right) = \tau_{ij,k}\left(C_P^k\right).$$

The European Union (EU) commonly employs preferential tariffs as a tool to incentivize adherence to non-trade policy objectives, including environmental policies, human rights, labor standards, narcotics production, and security issues. In 2010, the EU withheld preferential market access with lower tariffs from Sri Lanka for violating UN human rights conventions. Additionally, Venezuela lost preferential access to the European market in 2010 for failing to ratify the UN convention against corruption (Borchert et al. 2021). More recently, in 2020, the EU withdrew Cambodia's duty-free quota-free access to its market due to serious human rights concerns in the country (EC, 2020). In line with these practices, it is assumed that $\tau_{ij}\left(C_P^k\right) = 0$, and pair members can restrict the preferential tariff access to the outsider by imposing a positive tariff rate $\tau_{ij,k}\left(C_P^k\right)$, such that $\tau_{ij,k}\left(C_P^k\right) \geq \tau_{ij}\left(C_P^k\right)$.

Note that the two firms located in the countries forming the coalition $\mathcal{S}$ still act independently of each other and compete à la Cournot in the third stage of the oligopoly game.

Let $\tau_{k,ij}(C_P^k)$ be the positive tariff rate that the singleton charges to the pair of countries in the same coalition structure. The singleton within the partial coalition structure treats the pair as one entity, and charges the same tariff rate to each member of the pair, that is, for i, j, k where $i \neq j, k$:

$$\tau_{k,i}(C_P^k) = \tau_{k,j}(C_P^k) = \tau_{k,ij}(C_P^k).$$

The outsider to the pair, country k in this case, behaves noncooperatively, maximizing its individual welfare function, given the pair's emissions tax rate $t_{ij}(C_P^k)$ and tariff rate $\tau_{ij,k}(C_P^k)$.

There are three possible arrangements under the partial coalition structure, namely $\{\{i,j\},\{k\}\}$, $\{\{i,k\},\{j\}\}$, and $\{\{j,k\},\{i\}\}$. There are, therefore, three pair members emissions taxes $t_{ij}(C_P^k), t_{ik}(C_P^j), t_{jk}(C_P^i)$ and the corresponding outsider's emissions tax $t_k^P(C_P^k)$, $t_j^P(C_P^j)$, and $t_i^P(C_P^i)$. With respect to import tariffs, there are three pair members tariff rates, imposed by the pair on the outsider, $\tau_{ij,k}(C_P^k), \tau_{ik,j}(C_P^j)$, and $\tau_{jk,i}(C_P^i)$, and three import tariffs levied by the outsider on pair members, $\tau_{k,ij}(C_P^k), \tau_{j,ik}(C_P^j)$, and $\tau_{i,jk}(C_P^i)$.

2.3.3.1 The Partial Coalition's Pair

Given the outsider's emissions tax, $t_k^P(C_P^k)$, and tariff, $\tau_{k,ij}(C_P^k)$, the equilibrium quantities produced by the firm operating in a country within the pair, given by Equations (2.8) and (2.9), can be reduced as follows, for i, j, k where $i \neq j, k$:

$$x_{ii}{}^*(C_P^k) = \tfrac{1}{4}(\alpha - 2t_{ij} + t_k^P + \tau_{ij,k}) \tag{2.45}$$

$$x_{ij}{}^*(C_P^k) = \tfrac{1}{4}(\alpha - 2t_{ij} + t_k^P + \tau_{ij,k}) \tag{2.46}$$

$$x_{ik}{}^*(C_P^k) = \tfrac{1}{4}(\alpha - 2t_{ij} + t_k^P - 2\tau_{k,ij}). \tag{2.47}$$

Note that local production ${x_{ii}}^{*}(C_P^k)$ is strictly positive, and exports ${x_{ij}}^{*}(C_P^k)$ and ${x_{ik}}^{*}(C_P^k)$ are positive, given the imposed restrictions on the parameters of the model.

The welfare optimization problem[28] (2.10) of a pair member in the partial coalition structure is expressed as follows, for i, j, k where $i \neq j, k$:

$$\max_{t_{ij},\, \tau_{ij,k}} W_{ij}^{C_P^k} = \max_{t_{ij},\, \tau_{ij,k}} \begin{bmatrix} \frac{1}{2}\left({Q_i}^2(t_{ij}, \tau_{ij,k}) + {Q_j}^2(t_{ij}, \tau_{ij,k})\right) - (\beta_i + \beta_j)\left(X_i(t_{ij}, \tau_{ij,k}) + X_j(t_{ij}, \tau_{ij,k}) + X_k(t_{ij}, \tau_{ij,k})\right) \\ \left(\alpha - Q_i(t_{ij}, \tau_{ij,k})\right)\left(x_{ii}^*(t_{ij}, \tau_{ij,k}) + x_{ji}^*(t_{ij}, \tau_{ij,k})\right) + \left(\alpha - Q_j(t_{ij}, \tau_{ij,k})\right)\left(x_{ij}^*(t_{ij}, \tau_{ij,k}) + x_{jj}^*(t_{ij}, \tau_{ij,k})\right) \\ +(\alpha - Q_k(t_{ij}, \tau_{ij,k}) - \tau_{k,ij})\left(x_{ik}^*(t_{ij}, \tau_{ij,k}) + x_{jk}^*(t_{ij}, \tau_{ij,k})\right) + \left(\tau_{ij,k}\left(x_{ki}^*(t_{ij}, \tau_{ij,k}) + x_{kj}^*(t_{ij}, \tau_{ij,k})\right)\right) \end{bmatrix}. \tag{2.48}$$

The first order conditions of the welfare maximization problem (2.48) with respect to t_{ij} yields the following upward sloping best response function, for i, j, k where $i \neq j, k$:

$$t_{ij}(t_k^P, \tau_{ij,k}) = \frac{1}{10}\left(-3\alpha + 6(\beta_i + \beta_j) + t_k^P + 5\tau_{ij,k}\right). \tag{2.49}$$

Interestingly, a pair member exhibits a positive best response function, indicating a cooperative response towards the outsider, whereas the latter behaves noncooperatively as a singleton. A higher emissions tax rate levied on the firm operating in the noncooperative country, country k in this case, increases the cost and reduces the competitiveness of that firm. Consequently, it encourages pair members to elevate the emissions taxes in their respective countries, fostering more stringent environmental regulations, despite the singleton's behavior.

The best response function (2.49) shows a positive relationship between the pair's emissions tax and the tariff rate imposed on the outsider $\tau_{ij,k}(C_P^k)$. Lower tariffs between the pair and the outsider reduce the emissions tax under this partially cooperative scenario, leading to looser environmental regulations. Intuitively, when tariffs decrease between the pair and the outsider, local production faces intensified competition from foreign imports. Consequently, a lower emissions tax rate

[28] Country i's optimization problem as a pair member in the partial coalition structure is detailed in Appendix D2.1.

supports local production, while a higher emissions tax undermines the local firm, making it less appealing compared to the foreign alternative.

The pair's equilibrium tax $t_{ij}^{*}(C_P^k)$ and endogenous tariff $\tau_{ij,k}{}^{*}(C_P^k)$ are, respectively, as follows, for i, j, k where $i \neq j, k$:

$$t_{ij}^{*}(C_P^k) = \frac{1}{834}\left(-176\alpha + 809(\beta_i + \beta_j) - 72\beta_k\right) \tag{2.50}$$

$$\tau_{ij,k}{}^{*}(C_P^k) = \frac{1}{139}\left(29\alpha + 106(\beta_i + \beta_j) - 45\beta_k\right). \tag{2.51}$$

Pair members in a partial agreement may either impose a tax or provide a subsidy to their local firms. Equation (2.50) shows that when the market size, as captured by α, is sufficiently small, where $\alpha \leq \frac{1}{176}\left(809(\beta_i + \beta_j) - 72\beta_k\right)$, the pair enforces a positive emissions tax. In scenarios with sufficiently larger markets and low damages, the pair can provide a subsidy instead.

The restrictions imposed on the model's parameters warrant positive trade flows and ensure that $\tau_{ij,k}{}^{*}(C_P^k) \geq 0$, for i, j, k where $i \neq j, k$.

Domestic production in a country within the pair is expressed as follows, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_P^k) = x_{jj}(C_P^k) = \frac{1}{834}\left(308\alpha - 269(\beta_i + \beta_j) + 126\beta_k\right), \tag{2.52}$$

and exports among pair members are given by, for i, j, k where $i \neq j, k$:

$$x_{ij}(C_P^k) = x_{ji}(C_P^k) = \frac{1}{834}\left(308\alpha - 269(\beta_i + \beta_j) + 126\beta_k\right). \tag{2.53}$$

While exports from a pair member to the outsider are given by, for i, j, k where $i \neq j, k$:

$$x_{ik}(C_P^k) = x_{jk}(C_P^k) = \frac{3}{834}\left(47\alpha - 111(\beta_i + \beta_j) - 25\beta_k\right). \tag{2.54}$$

The total production, consumption, and welfare equations of country i as a pair member are detailed in Appendix D2.1.

2.3.3.2 The Partial Coalition's Outsider

Given the pair's emissions tax rate, $t_{ij}(C_P^k)$, and tariffs, $\tau_{ij}(C_P^k)$ and $\tau_{ij,k}(C_P^k)$, the equilibrium quantities produced by the outsider, country k in this case, outlined in Equations (2.8) and (2.9), can be reduced as follows, for i, j, k where $i \neq j, k$:

$$x_{kk}^*(C_P^k) = \frac{1}{4}(\alpha - 3t_k^P + 2t_{ij} + 2\tau_{k,ij}) \tag{2.55}$$

$$x_{ki}^*(C_P^k) = x_{kj}^*(C_P^k) = \frac{1}{4}(\alpha - 3t_k^P + 2t_{ij} - 3\tau_{ij,k}). \tag{2.56}$$

The imposed restrictions on the model's parameters guarantee that the outsider's local production $x_{kk}^*(C_P^k)$ is strictly positive, and exports to pair members $x_{ki}^*(C_P^k)$ and $x_{kj}^*(C_P^k)$ are positive.

The outsider behaves noncooperatively, and thus, its optimization problem[29] (2.10) is given by:

$$\max_{t_k^P, \tau_{k,ij}} W_k^{C_P^k} \Rightarrow \max_{t_k^P, \tau_{k,ij}} \begin{bmatrix} \frac{1}{2}Q_k^2(t_k^P, \tau_{k,ij}) - \beta_k\left(X_i(t_k^P, \tau_{k,ij}) + X_j(t_k^P, \tau_{k,ij}) + X_k(t_k^P, \tau_{k,ij})\right) \\ +\tau_{k,ij}\left((x_{ik}^*(t_k^P, \tau_{k,ij}) + x_{jk}^*(t_k^P, \tau_{k,ij})\right) + \left(\alpha - Q_k(t_k^P, \tau_{k,ij})\right)x_{kk}^*(t_k^P, \tau_{k,ij}) \\ +(\alpha - Q_i(t_k^P, \tau_{k,ij}) - \tau_{ij,k})x_{ki}^*(t_k^P, \tau_{k,ij}) + (\alpha - Q_j(t_k^P, \tau_{k,ij}) - \tau_{ij,k})x_{kj}^*(t_k^P, \tau_{k,ij}) \end{bmatrix}. \tag{2.57}$$

The first order condition with respect to t_k^P yields the following negative best response function:

$$t_k^P(t_{ij}, \tau_{ij,k}, \tau_{k,ij}) = \frac{1}{17}\left(12\beta_k - 9\alpha - 10t_{ij} + 6(2\tau_{ij,k} + \tau_{k,ij})\right). \tag{2.58}$$

Unlike countries within the pair, the outsider has a downward sloping best response function, implying a noncooperative behavior and free-riding incentives.

The outsider's equilibrium emissions tax $t_k^{*P}(C_P^k)$ and tariff $\tau_{k,ij}^*(C_P^k)$, are, respectively, for i, j, k where $i \neq j, k$:

$$t_k^{*P}(C_P^k) = \frac{1}{417}(315\beta_k - 47(\beta_i + \beta_j) - 64\alpha) \tag{2.59}$$

$$\tau_{k,ij}^*(C_P^k) = \frac{1}{834}\left(247\alpha + 537\beta_k - 190(\beta_i + \beta_j)\right). \tag{2.60}$$

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[29] Country k's optimization problem as an outsider in the partial coalition structure is detailed in Appendix D2.2.

As indicated by Equation (2.59), the outsider, behaving as a singleton, imposes an emissions tax rate that is directly related to the country's own environmental damage parameter β_k, and indirectly related to the pair's environmental damage parameters, β_i and β_j. The restrictions imposed on the model's parameters warrant positive trade flows and ensure that $\tau_{k,ij}{}^*(C_P^k) \geq 0$.

The outsider's local production and exports are, respectively, for i, j, k where $i \neq j, k$:

$$x_{kk}\left(C_P^k\right) = \frac{10}{417}\left(17\alpha + 19\left(\beta_i + \beta_j\right) - 12\beta_k\right) \tag{2.61}$$

$$x_{ki}\left(C_P^k\right) = x_{kj}\left(C_P^k\right) = \frac{1}{417}\left(43\alpha - \left(\beta_i + \beta_j\right) - 153\beta_k\right). \tag{2.62}$$

The outsider's total production, consumption, and welfare equations are listed in Appendix D2.2.

2.4 Results

After a thorough examination of all potential coalition structures and their equilibria, the goal is to identify stable environmental coalitions among countries and assess the impact of environmental damage heterogeneity on the stability of these coalitions. Due to the complexity of the equations, the analysis had to rely on numerical simulations. The analytical and simulation results are summarized in the following two subsections.

2.4.1 Analytical Results

Proposition 2.4.1.1: *Compared to the singleton and the partial coalition structures, the grand coalition provides environmental gains in terms of lower global emissions, when market sizes are sufficiently small.*

The complete proof of Proposition 2.4.1.1 is delineated to Appendix F2.

Let $X(C_{NC})$, $X(C_G)$, $X(C_P^k)$, represent global production under the singleton structure C_{NC}, the grand coalition structure C_G, and the partial coalition structure C_P^k, respectively. These global production levels are expressed in the following equations, respectively:

$$X(C_{NC}) = \sum_i X_i(C_{NC}) = \frac{3}{4}(3\alpha - \sum \beta_i) \tag{2.63}$$

$$X(C_G) = \sum_i X_i\,(C_G) = 3(\alpha - \sum_i \beta_i) \tag{2.64}$$

$$X(C_P^k) = \sum_i X_i\,(C_P^k) = \frac{1}{417}\left(1013\alpha - 683(\beta_i + \beta_j) - 249\beta_k\right). \tag{2.65}$$

Using (2.63) and (2.64), the collective environmental gains provided by the grand coalition in comparison to the singleton structure are given by the following expression:

$$X(C_{NC}) - X(C_G) = \frac{3}{4}(3\sum_i \beta_i - \alpha). \tag{2.66}$$

Equation (2.66) clearly indicates that the grand coalition yields environmental gains, in terms of lower global emissions, when $\alpha < 3\sum_i \beta_i$, corresponding to a range in which the grand coalition imposes a positive emissions tax rate, as shown by Equation (2.44). These environmental gains arise from higher emissions taxes enforced by all members of the grand coalition, in contrast to the singleton structure. Furthermore, they are unaffected by the degree of heterogeneity but would become more significant as $\sum_i \beta_i$ takes higher values.

Using (2.64) and (2.65), the collective environmental gains provided by the grand coalition in comparison to the partial coalition structure, are as follows, for i, j, k where $i \neq j, k$:

$$X(C_P^k) - X(C_G) = \frac{2}{417}\left(-119\alpha + 284(\beta_i + \beta_j) + 501\beta_k\right). \tag{2.67}$$

Equation (2.67) demonstrates that the grand coalition yields lower global production in comparison to the partial coalition C_P^k, when $\alpha < \frac{1}{119}\left(284(\beta_i + \beta_j) + 501\beta_k\right)$. Notably, these environmental gains are also independent of the degree of heterogeneity, but are directly related to all three marginal environmental damage parameters.

Proposition 2.4.1.2: *A larger value of the marginal environmental damage parameter can increase the individual welfare gains from joining the grand coalition.*

The complete proof of Proposition 2.4.1.2 is delineated to Appendix G2.

Let $W_i^{C_G} - W_i^{C_P^i}$ be country i's welfare gains as a member of the grand coalition compared to being an outsider within the partial coalition C_P^i. These welfare gains are, for i, j, k where $i \neq j, k$:

$$W_i^{C_G} - W_i^{C_P^i} = \frac{1}{2\times(417)^2}\left[\begin{array}{c} \alpha\left(9913\alpha - 215970\beta_i + 117259(\beta_j + \beta_k)\right) \\ +809973\beta_i{}^2 + (\beta_j + \beta_k)\left(166227\beta_i - 312140(\beta_j + \beta_k)\right) \end{array}\right]. \quad (2.68)$$

Using (2.68), the effect of the marginal environmental damage parameter β_i on country i's individual welfare gains is given by the following expression, for i, j, k where $i \neq j, k$:

$$\frac{\partial\left[W_i^{C_G} - W_i^{C_P^i}\right]}{\partial \beta_i} = \frac{1}{2\times3\times139^2}\left[539982\beta_i + 55409(\beta_j + \beta_k) - 71990\alpha\right]. \quad (2.69)$$

Equation (2.69) reveals that country i's individual welfare gains from joining the grand coalition can improve as its marginal environmental damage parameter takes a higher value, when $\beta_i < \alpha < \frac{1}{71990}\left(539982\beta_i + 55409(\beta_j + \beta_k)\right)$, for i, j, k where $i \neq j, k$.

Proposition 2.4.1.3: *A larger value of the parameter α can increase the individual welfare gains from joining the grand coalition.*

Let $W_i^{C_G} - W_i^{C_P^i}$ be country i's individual welfare gains as a member of the grand coalition in comparison to being an outsider within the partial coalition C_P^i, as expressed in Equation (2.68). Using (2.68), the effect of the parameter α on country i's welfare gains is, for i, j, k where $i \neq j, k$:

$$\frac{\partial\left[W_i^{C_G} - W_i^{C_P^i}\right]}{\partial \alpha} = \frac{1}{2\times(417)^2}\left[46(431\alpha - 4695\beta_i) + 117259(\beta_j + \beta_k)\right]. \quad (2.70)$$

Equation (2.70) demonstrates that when $\alpha > \frac{1}{19826}\left[215970\beta_i - 117259(\beta_j + \beta_k)\right]$, its effect on country i's welfare gains is strictly positive. Thus, within this range, a higher α value can lead to more significant individual welfare gains from joining the grand coalition, for i, j, k where $i \neq j, k$.

2.4.2 Simulation Results

The parameters chosen in the numerical simulations strictly comply with the following restrictions. First, the imposed constraints ensure that the market is active, under the assumption that no marginal environmental damage parameter can exceed the maximal marginal utility of good X, denoted by α, that is, $\alpha > \beta_i > \beta_j > \beta_k > 0$. Additionally, the imposed constraints ensure that the market structure is maintained throughout the game, and the model has a positive interior solution, by guaranteeing that X_i, $x_{ii}{}^* \in \mathbb{R}_n^{++}$ and $x_{ij}{}^* \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$. Also, the restricted parameters ensure positive tariff rates and warrant positive trade flows. While the complete set of constraints is detailed in Appendix E2, the most restrictive conditions are given by these two expressions, $\alpha \geq \frac{1}{47}\left(111(\beta_i + \beta_j) + 25\beta_k\right)$ and $\alpha \geq \frac{1}{35}\left(169\beta_i + 9\beta_j - 87\beta_k\right)$, to guarantee positive quantities in the partial coalition and the singleton structures, respectively.

Furthermore, since the singletons' collective welfare associated with the WTO Most-Favored-Nation tariff constraint falls short of that in the optimal unrestricted tariff scenario, as shown by Equation (2.36), the current simulations are based on the model with optimal unrestricted tariffs.

Based on the stability conditions (2.13) and (2.14), numerical simulations of the model reveal that the grand coalition remains stable across varying levels of environmental damage heterogeneity. The key findings from the numerical simulations are summarized in the subsequent remarks.

Remark 2.4.2.1: *There exists a range of parameters where the grand coalition is stable in the homogeneous benchmark case and at different levels of environmental damage heterogeneity.*

Let $(\beta_i - \beta_k)/(\beta_i + \beta_k)$ represents a measure of environmental damage heterogeneity, where β_i refers to the marginal environmental damage experienced by the country suffering the most, and β_k denotes the marginal environmental damage incurred by the country suffering the least damage.

The numerical simulations reveal that the grand coalition is stable over a range of environmental damage heterogeneity, and specifically within the bounds[30] of $0 \leq (\beta_i - \beta_k)/(\beta_i + \beta_k) \leq 1$.

Let $W_i^{C_G} - W_i^{C_P^i}$ be country i's individual welfare gains as a member of the grand coalition in comparison to being an outsider in the partial coalition C_P^i, as expressed in Equation (2.68). Given the stability conditions (2.13) and (2.14), the grand coalition is externally stable by default, and internally stable[31] $\Leftrightarrow W_i^{C_G} - W_i^{C_P^i} \geq 0$, for i, j, k.

Assuming $\alpha = 2.4 \sum_i \beta_i$ and $\sum_i \beta_i = 1$[32], Figure 2.1 depicts the welfare gains of countries i, j, and k, as expressed by Equation (2.68). In this scenario, β_i takes a higher value, β_j has the same value, and β_k takes a lower value, drifting further from β_i and β_j, leading to higher heterogeneity levels.

Figure 2.1: Grand Coalition Stability - Varied Heterogeneity, $\alpha = 2.4\sum\beta i$

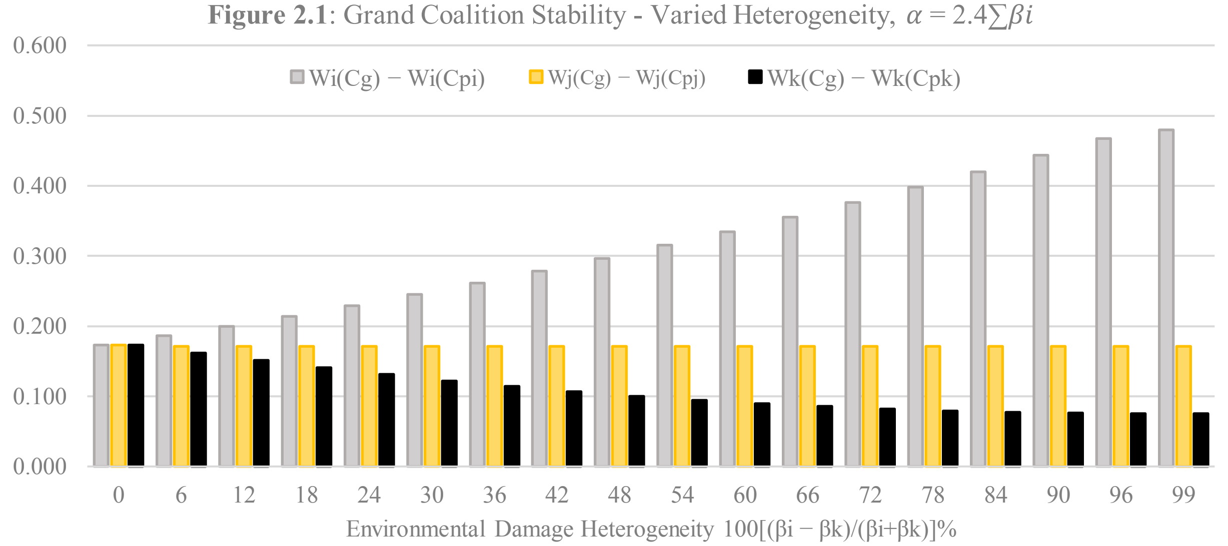


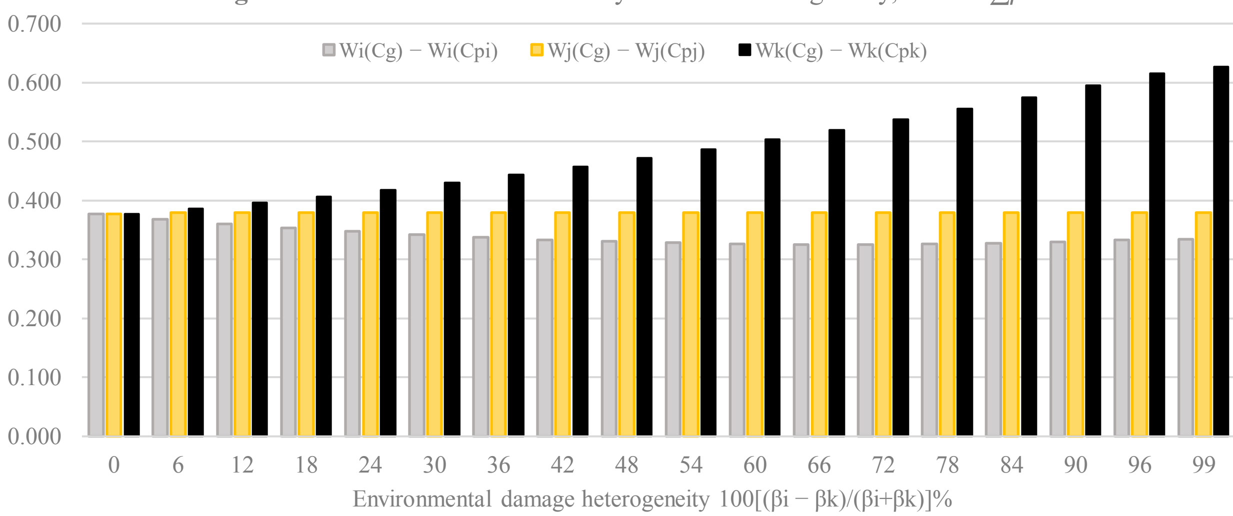
Figure 2.1 demonstrates that all three countries favor the grand coalition, while they do not benefit equally from joining it. A larger value of the marginal environmental damage parameter can increase the welfare gains from joining the grand coalition, as demonstrated in Proposition 2.4.1.2.

[30] The upper bound of this range may vary with the assumed parameters values in the numerical simulations.
[31] The stability of the grand coalition remains unaffected by the WTO constraints imposed on import tariffs within the singleton structure.
[32] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix H2.

For country i, the lower global production resulting from the grand coalition significantly reduces its environmental damage, consequently boosting its net consumer surplus as β_i takes a higher value. These improvements, coupled with higher before-tax profits, outweigh the reduction in tariff revenues brought about by the grand coalition, and thus, lead to increasing welfare gains.

In contrast, country k experiences diminishing welfare gains over the same heterogeneity range, and thus, has weaker incentives to join the grand coalition. As β_k takes a lower value, the welfare gains from reduced production and subsequent lower environmental damage diminish, resulting in a decreased net consumer surplus and less significant welfare gains.

Figure 2.2: Grand Coalition Stability - Varied Heterogeneity, $\alpha = 3.5\sum\beta i$



Assuming $\alpha = 3.5 \sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 2.2 depicts countries i, j, and k's welfare gains, as outlined in Equation (2.68), when the grand coalition does not generate environmental gains. In this case, the grand coalition remains stable across various heterogeneity levels, while country k has the strongest incentives to join the grand coalition. As outlined in Equation (2.70), a larger α value can increase country k's welfare gains, and reinforce the stability of the grand coalition, when $\alpha > \frac{1}{19826}\left[215970\beta_k - 117259(\beta_i + \beta_j)\right]$. However, for country i, larger production in the grand coalition leads to higher damage, and ultimately, decreasing its individual welfare gains.

These results remain consistent when varying α values, where $\alpha \geq \frac{1}{47}\left(111\left(\beta_i + \beta_j\right) + 25\beta_k\right)$ and $\alpha \geq \frac{1}{43}\left(\left(\beta_i + \beta_j\right) + 153\beta_k\right)$, and in the case where $\sum_i \beta_i$ rises. Although it cannot be proven analytically, a range of parameters where the grand coalition is not stable has not been identified. It's also important to note that even with a linear damage function, higher collective welfare gains can be achieved as heterogeneity rises in the grand coalition, as evident from Figures 2.1 and 2.2.

Remark 2.4.2.2: *A member of the grand coalition can be better off individually in comparison to the singleton structure.*

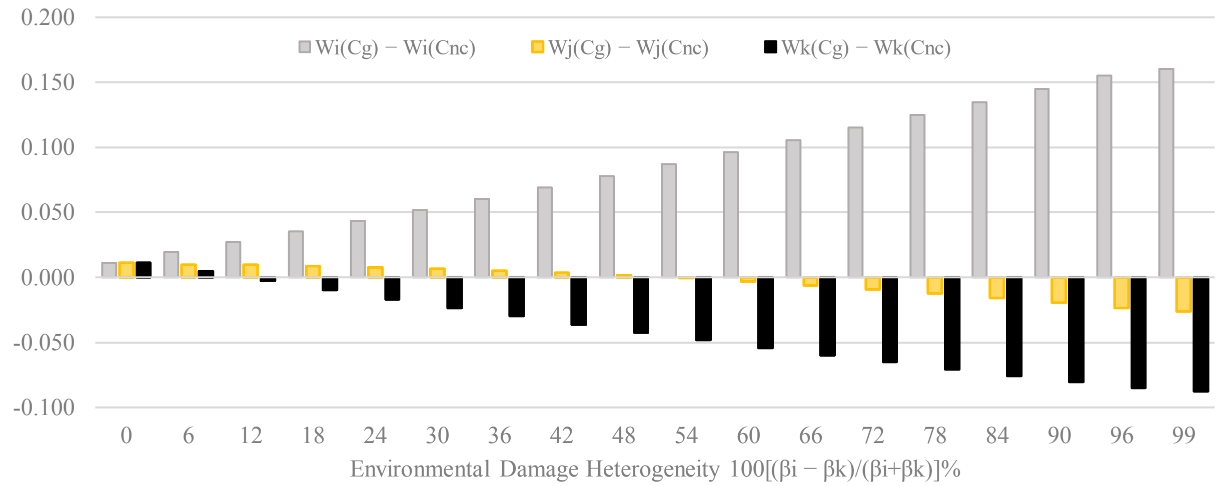
Let $W_i^{C_G} - W_i^{C_{NC}}$ be country i's welfare gains as a member of the grand coalition in comparison to behaving as a singleton. These individual welfare gains are given by, for i, j, k where $i \neq j, k$:

$$W_i^{C_G} - W_i^{C_{NC}} = \frac{1}{2^5 \times 43^2}\begin{bmatrix} 43\alpha\left(43\alpha - 1114\beta_i + 170\left(\beta_j + \beta_k\right)\right) + 76718\beta_i\left(\beta_j + \beta_k\right) \\ +127833\beta_i^2 - 5\left(5599\left(\beta_j + \beta_k\right)^2 + 1952\left({\beta_j}^2 + {\beta_k}^2\right)\right) \end{bmatrix}. \quad (2.71)$$

The simulation results show that members of the grand coalition do not benefit equally from the fully cooperative agreement in comparison to the singleton structure. Assuming $\alpha = 2.4\sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 2.3 depicts the individual welfare gains, for i, j, k where $i \neq j, k$, at varying degrees of heterogeneity. In this scenario, the grand coalition enforces a positive emissions tax rate, leading to environmental benefits, as expressed in Equation (2.66).

The reduction in production and consumption levels within the grand coalition helps alleviate country i's environmental damage as β_i takes a higher value, boosting its net consumer surplus. Additionally, the local firm sees higher pre-tax profits from increased prices and reduced tariffs within the grand coalition, outweighing any loss in government tariff revenues and leading to increasing welfares gain for country i. By contrast, countries j and k see diminishing welfare gains over the same range of heterogeneity. Country k, for instance, experiences welfare losses from reductions in net consumer surplus and tariff revenues, when heterogeneity exceeds 9%, while country j experiences losses beyond 51%. Hence, country i emerges as the primary beneficiary of the grand coalition due to its highest marginal environmental damage parameter.

Figure 2.3: Individual Welfare Gains: Comparing the Grand Coalition to the Singleton Structure - Varied Heterogeneity, $\alpha = 2.4\sum\beta i$



These findings remain consistent when assuming that $\sum_i \beta_i$ increases[33], and when changing the value of the parameter α, where $\frac{1}{47}\left(111(\beta_i + \beta_j) + 25\beta_k\right) \leq \alpha \leq 3\sum_i \beta_i$.

Alternatively, Figure 2.4 depicts the welfare gains in Equation (2.71), for i, j, k where $i \neq j, k$, with $\sum_i \beta_i = 1$ and $\alpha = 3.5\sum_i \beta_i$. Here, the grand coalition enforces a positive emissions tax rate, but it does not generate environmental gains in comparison to the singletons, as shown by (2.66).

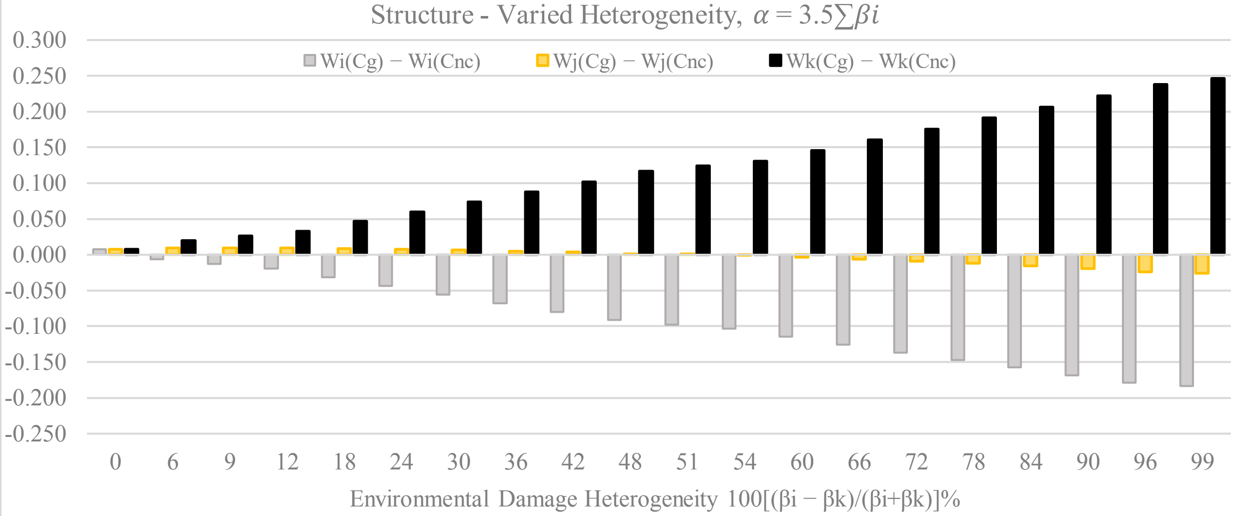
In a sufficiently large market driven by consumption and profits, countries j and k experience more significant welfare gains than country i as shown in Figure 2.4. Here, country k emerges as the main beneficiary of the grand coalition. With the lowest environmental damage parameter, country k's increasing welfare gains stem from significant improvements in net consumer surplus and pre-tax profits. In contrast, country i incurs overall welfare losses when environmental damage

[33] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix H2.

heterogeneity exceeds 3%. As a net importer when behaving as a singleton, as shown in Equation (2.24), country i incurs losses in tariff revenues that outweigh the improvements in net consumer surplus and pre-tax firm profits, resulting in decreasing welfare gains.

Notably, these results are robust to changes in the value of α, where $3\sum_i \beta_i < \alpha$, and when assuming that $\sum_i \beta_i$ increases.

Figure 2.4: Individual Welfare Gains: Comparing the Grand Coalition to the Singleton Structure - Varied Heterogeneity, $\alpha = 3.5\sum\beta i$



Let $W^{C_G} - W^{C_{NC}}$ be the collective welfare gains provided by the grand coalition in comparison to the singletons. These are given by the following expression:

$$W^{C_G} - W^{C_{NC}} = \frac{3}{2^5 \times 43^2}\left[\begin{array}{c} 1849\alpha(\alpha - 6\sum\beta_i) + 17441\left(\beta_i{}^2 + \beta_j{}^2 + \beta_k{}^2\right) \\ 32482(\beta_i\beta_j + \beta_i\beta_k + \beta_j\beta_k) \end{array}\right]. \tag{2.72}$$

The simulations indicate that these collective welfare gains are consistently positive at various heterogeneity levels, where $\alpha \geq \frac{1}{47}\left(111\left(\beta_i + \beta_j\right) + 25\beta_k\right)$ and $\alpha \geq \frac{1}{43}\left(\left(\beta_i + \beta_j\right) + 153\beta_k\right)$. Additionally, they can become more substantial as β_i takes on higher values and heterogeneity increases, even when $\sum_i \beta_i$ is held constant and normalized to one, as demonstrated in Equation (2.72) and in Figures 2.3 and 2.4.

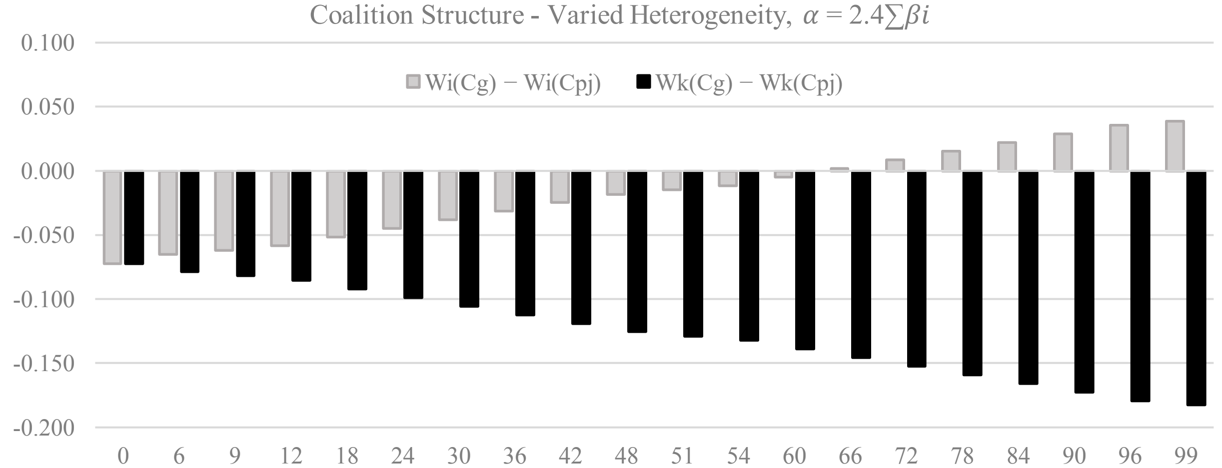
Remark 2.4.2.3: *A member of the grand coalition may experience a lower individual welfare compared to forming a pair in the partial coalition structure.*

Let $W_i^{C_G} - W_i^{C_P^j}$ be country i's welfare gains as a member of the grand coalition in comparison to forming a pair with country k, within the partial coalition C_p^j. These individual welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i^{C_G} - W_i^{C_P^j} = \frac{1}{12\times(139)^2}\begin{bmatrix} 3345\alpha^2 + \beta_j(21982\alpha - 152163\beta_j - 216973\beta_k) \\ -\beta_i(137549\alpha - 301382\beta_i - 340139\beta_j - 286956\beta_k) \\ -\beta_k(5221\alpha + 14426\beta_k) \end{bmatrix}. \quad (2.73)$$

The simulations reveal that a member of the grand coalition can experience lower individual welfare when compared to forming a pair in a partial coalition agreement. Assuming $\sum_i \beta_i = 1$ and $\alpha = 2.4\sum_i \beta_i$, Figure 2.5 depicts countries i and k's welfare gains in the grand coalition to what they would have attained under the partial coalition C_p^j. Here, the grand coalition enforces a positive emissions tax rate and generates environmental gains, as shown in Equation (2.67).

Figure 2.5: Individual Welfare Gains: Comparing the Grand Coalition to the Partial Coalition Structure - Varied Heterogeneity, $\alpha = 2.4\sum\beta i$

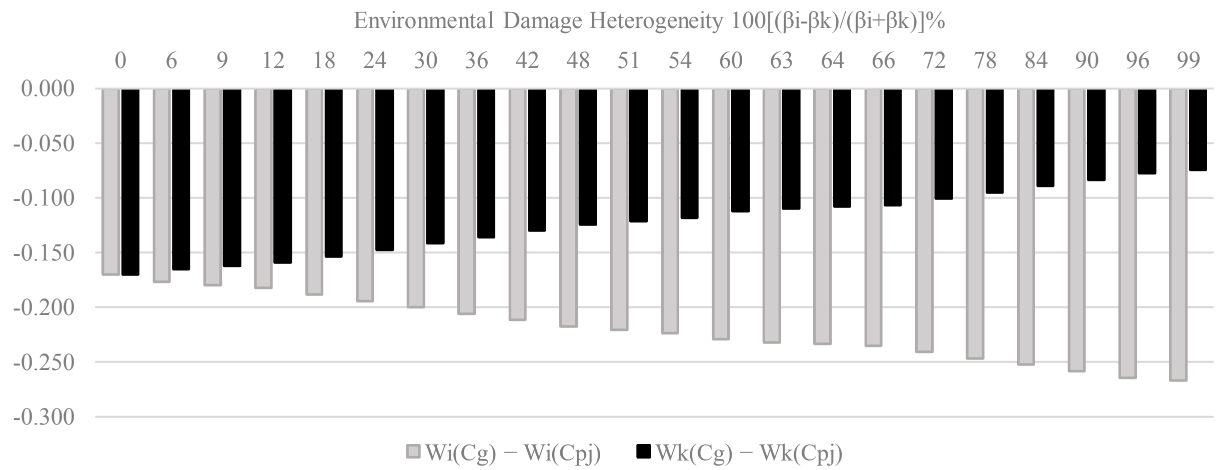


Environmental Damage Heterogeneity 100[(βi-βk)/(βi+βk)]%

As β_i takes a higher value, only country i experiences positive welfare gains, stemming from higher pre-tax profits and lower reductions in net consumer surplus, at heterogeneity levels above

63%. In contrast, country k's reductions in net consumer surplus become more substantial as β_k takes a lower value, leading to continued welfare losses over the same heterogeneity range. These results remain consistent when assuming that $\sum_i \beta_i$ increases[34], and when changing the value of the parameter α, where $\frac{1}{47}\left(111(\beta_i+\beta_k)+25\beta_j\right) \leq \alpha \leq \frac{1}{119}\left(284(\beta_i+\beta_k)+501\beta_j\right)$.

Figure 2.6: Individual Welfare Gains: Comparing the Grand Coalition to the Partial Coalition Structure - Varied Heterogeneity, $\alpha = 3.5\sum\beta i$



Alternatively, Figure 2.6 depicts countries i and k's welfare gains in the grand coalition compared to forming a pair within the partial coalition C_p^j, when $\sum_i \beta_i = 1$ and $\alpha = 3.5\sum_i \beta_i$. In this case, the grand coalition imposes a positive emissions tax[35] but does not yield environmental gains. Both countries are incurring individual welfare losses. As the level of heterogeneity rises, country k's damage parameter is taking a lower value, resulting in smaller reductions in net consumer surplus and hence less significant welfare losses. Conversely, as β_i takes a higher value, country i experiences more substantial reductions in net consumer surplus, driving its welfare losses.

These results remain consistent when assuming that $\sum_i \beta_i$ increases, and when changing the value of the parameter α, where $\frac{1}{119}\left(284(\beta_i+\beta_k)+501\beta_j\right) \leq \alpha \leq 4\sum_i \beta_i$.

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[34] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix H2.

[35] A larger α value, where $\alpha > 4\sum_i \beta_i$ and $t_G{}^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha) < 0$, increases production and consumption in the grand coalition, boosting the welfare gains of country k, while further depressing those of country i.

Let $W^{C_G} - W^{C_P^j}$ be the collective welfare gains provided by the grand coalition in comparison to the partial coalition structure C_p^j. These welfare gains are expressed as follows:

$$W^{C_G} - W^{C_P^j} = \frac{1}{(417)^2}\begin{bmatrix} 9974\alpha^2 + (\beta_i + \beta_k)(59147(\beta_i + \beta_k) - 48448\alpha) \\ 6\beta_j(29248(\beta_i + \beta_k) + 29457\beta_j - 12502\alpha) \end{bmatrix}. \tag{2.74}$$

The simulation results confirm that these collective welfare gains remain positive across various values of α, where $\alpha \geq \frac{1}{47}\left(111(\beta_i + \beta_j) + 25\beta_k\right)$ and $\alpha \geq \frac{1}{43}\left((\beta_i + \beta_j) + 153\beta_k\right)$, and at different degrees of environmental damage heterogeneity.

2.5 Conclusion

The current model's solution with positive endogenous tariffs on imports, demonstrates that a fully cooperative equilibrium is stable when environmental and trade policies are negotiated simultaneously. Considering the model's parameter restrictions, which guarantee an active market, maintain the market structure throughout the game, and ensure an interior solution with positive trade flows, the grand coalition remains stable in the homogeneous benchmark case and in the presence of varying degrees of environmental damage heterogeneity. Although not proven analytically, a range of parameters where the grand coalition is unstable has not been identified, nor has a range where other coalition structures are stable.

The main contribution of this essay to the literature lies in using positive endogenous tariffs on imports within a segmented market setting instead of a global market under free trade conditions. This approach diminishes the free-riding incentives of non-signatories and strengthens the stability of the fully cooperative agreement. These results also align with the concept of establishing a "climate club" to address free-riding behavior in international climate policy, a concept that has gained significant popularity since Nordhaus (2015).

The present essay demonstrates that at sufficiently low market sizes, the grand coalition yields both environmental and overall welfare gains. However, at sufficiently larger market sizes, the grand coalition no longer provides environmental gains but rather delivers collective welfare gains, particularly benefiting monopoly firms with higher profits.

The simplified framework of the current model does introduce certain limitations. To specifically examine the impact of environmental damage heterogeneity, the model assumes that all three countries have the same market size, incur identical marginal production costs, and that each firm can export to the other two foreign markets without any transaction costs. Additionally, it assumes that environmental damage is a linear function of aggregate production, which simplifies the analysis. These simplifications, while necessary for the current study, serve as a foundation for future research to explore potential outcomes when any of these assumptions are relaxed.

Despite the growing recognition of the climate crisis, ambitious climate policies are consistently undermined by government inaction or inadequate responses. While discussions about climate action have certainly grown louder, actual emissions reductions have been limited. Given the alarming levels the climate crisis has reached, it is imperative to strengthen our environmental policies beyond current measures. This essay reflects the current state of global climate action, where international environmental commitments are often weakened by the provision of subsidies to polluting industries, especially in the world's largest economies. It also underscores the value of coordinating environmental and trade policies as a crucial strategy for reducing global emissions, particularly in smaller markets, despite the heterogeneity among countries.

2.6 Appendices

2.6.1 Appendix A2: The Firm's Optimization Problem

The firm's optimization problem (2.7) is expressed as follows, for i, j, k where $i \neq j, k$:

$$\max_{x_{ii}, x_{ij}, x_{ik}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}, x_{ik}} \begin{bmatrix} (\alpha - (x_{ii} + x_{ji} + x_{ki}) - t_i)x_{ii} \\ +(\alpha - (x_{jj} + x_{ij} + x_{kj}) - t_i - \tau_{j,i})x_{ij} \\ +(\alpha - (x_{kk} + x_{ik} + x_{jk}) - t_i - \tau_{k,i})x_{ik} \end{bmatrix}. \tag{A2.1}$$

The first order conditions with respect to local production and exports, respectively, are as follows:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow (\alpha - 2x_{ii} - x_{ji} - x_{ki} - t_i) = 0 \tag{A2.2}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow (\alpha - 2x_{ij} - x_{jj} - x_{kj} - t_i - \tau_{j,i}) = 0 \tag{A2.3}$$

$$\frac{\partial \pi_i}{\partial x_{ik}} = 0 \Rightarrow (\alpha - 2x_{ik} - x_{kk} - x_{jk} - t_i - \tau_{k,i}) = 0. \tag{A2.4}$$

By symmetry, using (A2.3) and (A2.4), the FOCs with respect to x_{ji} and x_{ki}, are, respectively:

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow (\alpha - 2x_{ji} - x_{ii} - x_{ki} - t_j - \tau_{i,j}) = 0 \tag{A2.5}$$

$$\frac{\partial \pi_k}{\partial x_{ki}} = 0 \Rightarrow (\alpha - 2x_{ki} - x_{ii} - x_{ji} - t_k - \tau_{i,k}) = 0 \tag{A2.6}$$

The second order conditions (SOCs) are satisfied, as shown in the following expressions:

$$\frac{\partial^2 \pi_i}{\partial x_{ii}^2} < 0, \frac{\partial^2 \pi_i}{\partial x_{ij}^2} < 0, \text{ and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}} \frac{\partial^2 \pi_i}{\partial x_{ij}^2} - \left(\frac{\partial^2 \pi_i}{\partial x_{ii} \partial x_{ij}}\right) > 0.$$

Using (A2.2), (A2.5), and (A2.6), the equilibrium quantities (2.8) and (2.9) produced by the firm operating in country i, for i, j, k where $i \neq j, k$, are expressed as follows:

$$x_{ii}{}^* = \frac{1}{4}(\alpha - 3t_i + (t_j + t_k) + \tau_{i,j} + \tau_{i,k}) \tag{A2.7}$$

$$x_{ij}{}^* = \frac{1}{4}(\alpha - 3t_i + (t_j + t_k) + \tau_{j,k} - 3\tau_{j,i}). \tag{A2.8}$$

2.6.2 Appendix B2: The Government's Optimization Problem - The Singletons

2.6.2.1 Optimal Unrestricted Tariffs

Let $W_i^{C_{NC}}$ be country i's individual welfare under the singleton structure C_{NC}, then country i's welfare optimization problem (2.10) can be detailed as follows, for i, j, k where $i \neq j, k$:

$$\max_{t_i^{NC},\tau_{i,j},\tau_{i,k}} W_i^{C_{NC}} \Rightarrow \max_{t_i^{NC},\tau_{i,j},\tau_{i,k}} \begin{bmatrix} (15\alpha^2 - 72\alpha\beta_i) \\ +t_i^{NC}\left(-18\alpha + 24\beta_i - 17t_i^{NC} - 10t_j^{NC} - 10t_k^{NC}\right) \\ +\left(t_j^{NC} + t_k^{NC}\right)\left(6\alpha + 24\beta_i + 7t_j^{NC} + 7t_k^{NC}\right) \\ +\tau_{i,j}\left(8\beta_i + 6\alpha + 6t_i^{NC} - 18t_j^{NC} + 14t_k^{NC} + 11\tau_{i,k} - 21\tau_{i,j}\right) \\ +\tau_{i,k}\left(8\beta_i + 6\alpha + 6t_i^{NC} + 14t_j^{NC} - 18t_k^{NC} + 11\tau_{i,j} - 21\tau_{i,k}\right) \\ +\tau_{j,i}\left(8\beta_i - 12\alpha + 12t_i^{NC} - 12t_j^{NC} - 12t_k^{NC} + 18\tau_{j,i} - 6\tau_{j,k}\right) \\ +\tau_{j,k}\left(8\beta_i + 4\alpha - 4t_i^{NC} + 4t_j^{NC} + 4t_k^{NC} + 2\tau_{j,k} - 6\tau_{j,i}\right) \\ +\tau_{k,i}\left(8\beta_i - 12\alpha + 12t_i^{NC} - 12t_j^{NC} - 12t_k^{NC} + 18\tau_{k,i} - 6\tau_{k,j}\right) \\ +\tau_{k,j}\left(8\beta_i + 4\alpha - 4t_i^{NC} + 4t_j^{NC} + 4t_k^{NC} + 2\tau_{k,j} - 6\tau_{k,i}\right) \end{bmatrix} \quad \text{(B2.1.1)}$$

The first order conditions with respect to t_i^{NC} and $\tau_{i,j}$, for i, j, k where $i \neq j, k$, are, respectively:

$$\frac{\delta W_i^{C_{NC}}}{\delta t_i^{NC}} = 0 \Rightarrow \begin{bmatrix} 12\beta_i - 9\alpha - 17t_i^{NC} - 5\left(t_j^{NC} + t_k^{NC}\right) \\ +3(\tau_{i,j} + \tau_{i,k}) + 6(\tau_{j,i} + \tau_{k,i}) - 2(\tau_{j,k} + \tau_{k,j}) \end{bmatrix} = 0 \quad \text{(B2.1.2)}$$

$$\frac{\delta W_i^{C_{NC}}}{\delta \tau_{i,j}} = 0 \Rightarrow \left[4\beta_i + 3\alpha + 3t_i^{NC} - 9t_j^{NC} + 7t_k^{NC} - 21\tau_{i,j} + 11\tau_{i,k}\right] = 0 \quad \text{(B2.1.3)}$$

Using (B2.1.2) and (B2.1.3), and by symmetry, the singleton's equilibrium tax and import tariff rates are given by the following equations, respectively, for i, j, k where $i \neq j, k$:

$$t_i^{*NC}(C_{NC}) = \frac{1}{688}\left(-129\alpha + 499\beta_i - 13\left(\beta_j + \beta_k\right)\right) \quad \text{(B2.1.4)}$$

$$\tau_{i,j}^*(C_{NC}) = \frac{1}{1376}\left(387\alpha + 19\left(45\beta_i - 19\beta_j\right) + 151\beta_k\right). \quad \text{(B2.1.5)}$$

Using (A2.7), (A2.8), (B2.1.4) and (B2.1.5), country i's local production $x_{ii}(C_{NC})$ and exports $x_{ij}(C_{NC})$ are, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_{NC}) = \frac{1}{688}\left(301\alpha - 167\beta_i + 105\left(\beta_j + \beta_k\right)\right) \quad \text{(B2.1.6)}$$

$$x_{ij}(C_{NC}) = \frac{1}{1376}(215\alpha - 453\beta_i - 165\beta_j + 59\beta_k). \quad \text{(B2.1.7)}$$

Country i's total quantity produced $X_i(C_{NC})$ is expressed as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_{NC}) = \frac{1}{172}\Big(129\alpha - 155\beta_i + 13\big(\beta_j + \beta_k\big)\Big). \tag{B2.1.8}$$

Country i's total quantity consumed $Q_i(C_{NC})$ is expressed as follows, for i, j, k where $i \neq j, k$:

$$Q_i(C_{NC}) = \frac{1}{172}\Big(129\alpha - 83\beta_i - 23\big(\beta_j + \beta_k\big)\Big). \tag{B2.1.9}$$

Global production equals global consumption, as shown by the following equation:

$$\textstyle\sum_i X_i(C_{NC}) = \sum_i Q_i\,(C_{NC}) = \frac{3}{4}(3\alpha - \sum \beta_i). \tag{B2.1.10}$$

Country i's individual welfare $W_i(C_{NC})$ and collective welfare $W(C_{NC}) = \sum_i W_i(C_{NC})$ achieved under the singleton structure are, respectively, for i, j, k where $i \neq j, k$:

$$W_i(C_{NC}) = \frac{1}{2^5 \times 43^2}\begin{bmatrix} \alpha\Big(27735\alpha - 129602\beta_i - 7310\big(\beta_j + \beta_k\big)\Big) \\ +\beta_i\Big(20087\beta_i + 41618\big(\beta_j + \beta_k\big)\Big) + 8171\big({\beta_j}^2 + {\beta_k}^2\big) - 3178\beta_j\beta_k \end{bmatrix} \tag{B2.1.11}$$

$$W(C_{NC}) = \frac{3}{2^5 \times 43^2}\begin{bmatrix} \alpha(27735\alpha - 48074\sum_i \beta_i) + \beta_k(12143\beta_k + 26686\beta_i) \\ \beta_i(12143\beta_i + 26686\beta_j) + \beta_j(12143\beta_j + 26686\beta_k) \end{bmatrix}. \tag{B2.1.12}$$

2.6.2.2 WTO-Restricted Tariffs

Let $\widetilde{W}_i^{C_{NC}}$ be country i's welfare under the singleton structure C_{NC}, with WTO-restricted tariffs, then country i's welfare optimization problem (2.10) is as follows, for i, j, k where $i \neq j, k$:

$$\max_{\tilde{t}_i^{NC}, \tilde{\tau}_i} \widetilde{W}_i^{C_{NC}} \Rightarrow \max_{\tilde{t}_i^{NC}, \tilde{\tau}_i} \begin{bmatrix} 3\alpha(5\alpha - 24\beta_i) \\ +\tilde{t}_i^{NC}\Big(-18\alpha + 24\beta_i - 17\tilde{t}_i^{NC} - 10\big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big)\Big) \\ +\big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big)\Big(6\alpha + 24\beta_i + 7\big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big)\Big) \\ +4\tilde{\tau}_i\big(4\beta_i + 3\alpha + 3\tilde{t}_i^{NC} - \big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big) - 5\tilde{\tau}_i\big) \\ +8\tilde{\tau}_j\big(2\beta_i - \alpha + \tilde{t}_i^{NC} - \big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big) + \tilde{\tau}_j\big) \\ +8\tilde{\tau}_k\big(2\beta_i - \alpha + \tilde{t}_i^{NC} - \big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big) + \tilde{\tau}_k\big) \end{bmatrix}. \tag{B2.2.1}$$

The first order conditions with respect to $\tilde{t}_i^{NC}$ and $\tilde{\tau}_i$ are, respectively, for i, j, k where $i \neq j, k$:

$$\frac{\delta \widetilde{W}_i^{C_{NC}}}{\delta \tilde{t}_i^{NC}} = 0 \Rightarrow \big[12\beta_i - 9\alpha - 17\tilde{t}_i^{NC} - 5\big(\tilde{t}_j^{NC} + \tilde{t}_k^{NC}\big) + 6\tilde{\tau}_i + 4\big(\tilde{\tau}_j + \tilde{\tau}_k\big)\big] = 0 \tag{B2.2.2}$$

$$\frac{\delta \widetilde{W}_i^{C_{NC}}}{\delta \tilde{\tau}_i} = 0 \Rightarrow \left[3\alpha + 4\beta_i + 3\tilde{t}_i^{\ NC} - \left(\tilde{t}_j^{\ NC} + \tilde{t}_k^{\ NC}\right) - 10\tilde{\tau}_i\right] = 0. \qquad \text{(B2.2.3)}$$

The first order conditions (B2.2.2), (B2.2.3) and the symmetry yield the following equilibrium emissions tax and import tariff rates, respectively, for i, j, k where $i \neq j, k$:

$$\tilde{t}_i^{\ *NC}(C_{NC}) = \frac{1}{112}\left(-21\alpha + 111\beta_i - 17\left(\beta_j + \beta_k\right)\right) \qquad \text{(B2.2.4)}$$

$$\tilde{\tau}_i^{\ *}(C_{NC}) = \frac{1}{224}\left(63\alpha + 163\beta_i - 29\left(\beta_j + \beta_k\right)\right). \qquad \text{(B2.2.5)}$$

Using (A2.7), (A2.8), (B2.2.4) and (B2.2.5), country i's local production $\tilde{x}_{ii}(C_{NC})$ and exports $\tilde{x}_{ij}(C_{NC})$ are given by the following expressions, respectively, for i, j, k where $i \neq j, k$:

$$\tilde{x}_{ii}(C_{NC}) = \frac{1}{112}\left(49\alpha - 51\beta_i + 29\left(\beta_j + \beta_k\right)\right) \qquad \text{(B2.2.6)}$$

$$\tilde{x}_{ij}(C_{NC}) = \frac{1}{224}\left(35\alpha - \left(169\beta_i + 9\beta_j\right) + 87\beta_k\right). \qquad \text{(B2.2.7)}$$

The total quantity produced in country i, $\tilde{X}_i(C_{NC})$, is as follows, for i, j, k where $i \neq j, k$:

$$\tilde{X}_i(C_{NC}) = \frac{1}{28}\left(21\alpha - 55\beta_i + 17\left(\beta_j + \beta_k\right)\right). \qquad \text{(B2.2.8)}$$

The total quantity consumed in country i, $\tilde{Q}_i(C_{NC})$, is as follows, for i, j, k where $i \neq j, k$:

$$\tilde{Q}_i(C_{NC}) = \frac{3}{28}\left(7\alpha - 5\beta_i - \left(\beta_j + \beta_k\right)\right). \qquad \text{(B2.2.9)}$$

Global production matches global consumption, as demonstrated by the following equation:

$$\sum_i \tilde{X}_i(C_{NC}) = \sum_i \tilde{Q}_i\,(C_{NC}) = \frac{3}{4}\left(3\alpha - \sum \beta_i\right). \qquad \text{(B2.2.10)}$$

Country i's individual welfare, $\widetilde{W}_i(C_{NC})$, and collective welfare, $\widetilde{W}(C_{NC}) = \sum_i \widetilde{W}_i(C_{NC})$, in the singleton structure, are given by the following expressions, respectively, for i, j, k where $i \neq j, k$:

$$\widetilde{W}_i(C_{NC}) = \frac{1}{2^5 \times 7^2}\begin{bmatrix} 735\alpha^2 + \beta_i\left(-3458\alpha + 367\beta_i + 1082\left(\beta_j + \beta_k\right)\right) \\ \beta_j\left(-182\alpha + 283\beta_j - 5\beta_k\right) + \beta_k\left(-182\alpha + 283\beta_k - 5\beta_j\right) \end{bmatrix} \qquad \text{(B2.2.11)}$$

$$\widetilde{W}(C_{NC}) = \frac{3}{2^5 \times 7^2}\begin{bmatrix} 735\alpha^2 + \beta_i\left(-1274\alpha + 311\beta_i + 718\left(\beta_j + \beta_k\right)\right) \\ \beta_j\left(-1274\alpha + 311\beta_j + 718\beta_k\right) + \beta_k\left(-1274\alpha + 311\beta_k\right) \end{bmatrix}. \qquad \text{(B2.2.12)}$$

2.6.3 Appendix C2: The Government's Optimization Problem - The Grand Coalition

Let ${W_i}^{C_G}$ be country i's individual welfare in the grand coalition C_G. It is expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i^{C_G} = \frac{1}{32}\begin{bmatrix}(15\alpha^2 - 72\alpha\beta_i) + t_G(72\beta_i - 6\alpha - 9t_G) \\ +\tau_G(48\beta_i - 4\alpha - 12t_G - 4\tau_G)\end{bmatrix}. \tag{C2.1}$$

Let $W^{C_G} = \sum_i {W_i}^{C_G}$, be the collective welfare of all members within the grand coalition C_G, then their joint welfare optimization problem (2.10) can be detailed as follows:

$$\max_{t_G, \tau_G} W^{C_G} \Rightarrow \max_{t_G, \tau_G}\begin{bmatrix}(15\alpha^2 - 24\alpha\sum_i\beta_i) + t_G(-6\alpha + 24\sum_i\beta_i - 9t_G) \\ +\tau_G(16\sum_i\beta_i - 4\alpha - 12t_G - 4\tau_G)\end{bmatrix}. \tag{C2.2}$$

The first order conditions with respect to t_G and τ_G, are expressed as follows, respectively:

$$\frac{\delta W^{C_G}}{\delta t_G} = 0 \Rightarrow 3t_G = (-\alpha + 4\sum_i\beta_i - 2\tau_G) \tag{C2.3}$$

$$\frac{\delta W^{C_G}}{\delta \tau_G} = 0 \Rightarrow 2\tau_G = (-\alpha + 4\sum_i\beta_i - 3t_G). \tag{C2.4}$$

The first order conditions (C2.3) and (C2.4) yield the following cooperative set of solutions, where any $({t_G}^*, {\tau_G}^*)$ satisfying the following two conditions is an equilibrium solution:

$$3t_G^*(C_G) + 2\tau_G^*(C_G) = (4\sum_i\beta_i - \alpha) \tag{C2.5}$$

$$t_G^*(C_G) \leq \frac{1}{3}(4\sum_i\beta_i - \alpha). \tag{C2.6}$$

Using (A2.7), (A2.8) and (C2.5), country i's local production and exports are, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_G) = \frac{1}{3}(\alpha - \sum_i\beta_i + 2\tau_G) \tag{C2.7}$$

$$x_{ij}(C_G) = x_{ik}(C_G) = \frac{1}{3}(\alpha - \sum_i\beta_i - \tau_G). \tag{C2.8}$$

To guarantee that local production $x_{ii}(C_G)$ is strictly positive, and exports $x_{ij}(C_G)$ and $x_{ik}(C_G)$ are positive, then $\frac{1}{2}(\sum_i\beta_i - \alpha) < {\tau_G}^*(C_G) \leq (\alpha - \sum_i\beta_i)$.

Total production $X_i(C_G)$ and consumption $Q_i(C_G)$ are, respectively, for i, j, k where $i \neq j, k$:

$$X_i(C_G) = Q_i(C_G) = (\alpha - \sum_i \beta_i). \tag{C2.9}$$

Under the assumption that members of the grand coalition agree on a custom union, where $\tau_G{}^*(C_G) = 0$, the equilibrium emissions tax rate $t_G^*(C_G)$ becomes as follows:

$$t_G^*(C_G) = \tfrac{1}{3}(4\sum_i \beta_i - \alpha). \tag{C2.10}$$

Using (A2.7), (A2.8) and (C2.10), local production and exports are as follows, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_G) = x_{ij}(C_G) = x_{ik}(C_G) = \tfrac{1}{3}(\alpha - \sum_i \beta_i). \tag{C2.11}$$

The total quantities produced and consumed in country i, for i, j, k where $i \neq j, k$, are given by:

$$X_i(C_G) = Q_i(C_G) = (\alpha - \sum_i \beta_i). \tag{C2.12}$$

The global production level, which is equal to the global consumption level, is equal to:

$$\sum_i X_i\,(C_G) = \sum_i Q_i\,(C_G) = 3(\alpha - \sum_i \beta_i). \tag{C2.13}$$

Country i's welfare as a member of the grand coalition, $W_i(C_G)$ is, for i, j, k where $i \neq j, k$:

$$W_i(C_G) = \tfrac{1}{2}(\alpha - \sum_i \beta_i)\left(\alpha - 5\beta_i + \left(\beta_j + \beta_k\right)\right). \tag{C2.14}$$

The grand coalition's collective welfare, $W(C_G) = \sum_i W_i\,(C_G)$, is expressed as follows:

$$W(C_G) = \tfrac{3}{2}(\alpha - \sum_i \beta_i)^2. \tag{C2.15}$$

Individual production $X_i(C_G)$, global production $X(C_G) = \sum_i X_i\,(C_G)$, individual welfare $W_i(C_G)$, and collective welfare $W(C_G)$, are all independent of the tariff $\tau_G(C_G)$, since changes in tariffs are offset by changes in the emissions tax, as indicated by equation (C2.3). Thus, the stability condition (2.13) is not affected by the assumed solution $(t_G{}^*, \tau_G{}^*) = \left(\tfrac{1}{3}(4\sum_i \beta_i - \alpha), 0\right)$.

2.6.4 Appendix D2: The Government's Optimization Problem - The Partial Coalition

2.6.4.1 The Partial Coalition's Pair

Let ${W_i}^{C_P^k}$ be country i's individual welfare as a pair member in the partial coalition structure C_P^k. It is expressed as follows, for i, j, k where $i \neq j, k$:

$$
{W_i}^{C_P^k} = \frac{1}{32}\begin{bmatrix} (15\alpha^2 - 72\alpha\beta_i) \\ +t_{ij}(-12\alpha + 48\beta_i - 20t_{ij} - 3{t_k}^P) + {t_k}^P(6\alpha + 24\beta_i + 7t_{ij} + 7{t_k}^P) \\ +\tau_{ij}(16\beta_i - 6\alpha - 12t_{ij} + 2{t_k}^P + 5\tau_{ij,k} - 3\tau_{ij}) \\ +\tau_{ij,k}(16\beta_i + 10\alpha + 20t_{ij} - 14{t_k}^P + \tau_{ij} - 19\tau_{ij,k}) \\ +\tau_{k,ij}(16\beta_i - 8\alpha - 8{t_k}^P + 8\tau_{k,ij}) \end{bmatrix} \quad \text{(D2.1.1)}
$$

Let ${W_{ij}}^{C_P^k} = {W_i}^{C_P^k} + {W_j}^{C_P^k}$ be the pair's joint welfare in the partial coalition C_P^k. Assuming $\tau_{ij}(C_P^k) = 0$, the pair's optimization problem (2.10) is detailed as follows, for i, j, k where $i \neq j, k$:

$$
\max_{t_{ij},\, \tau_{ij,k}} {W_{ij}}^{C_P^k} \Rightarrow \max_{t_{ij},\, \tau_{ij,k}} \begin{bmatrix} 3\left(5\alpha^2 - 12\alpha(\beta_i + \beta_j)\right) \\ +2t_{ij}(-6\alpha + 12(\beta_i + \beta_j) - 10t_{ij} + t_k^P) \\ +t_k^P(6\alpha + 12(\beta_i + \beta_j) + 2t_{ji} + 7t_k^P) \\ +\tau_{ij,k}(8(\beta_i + \beta_j) + 10\alpha + 20t_{ij} - 14t_k^P - 19\tau_{ij,k}) \\ +8\tau_{k,ij}\left((\beta_i + \beta_j) - \alpha - t_k^P + \tau_{k,ij}\right) \end{bmatrix}. \quad \text{(D2.1.2)}
$$

The first order conditions with respect to $t_{ij}(C_P^k)$ and $\tau_{ij,k}(C_P^k)$ are as follows:

$$
\frac{\delta {W_{ij}}^{C_P^k}}{\delta t_{ij}} = 0 \Rightarrow 10t_{ij} = \left(6(\beta_i + \beta_j) - 3\alpha + t_k^P + 5\tau_{ij,k}\right) \quad \text{(D2.1.3)}
$$

$$
\frac{\delta {W_{ij}}^{C_P^k}}{\delta \tau_{ij,k}} = 0 \Rightarrow 19\tau_{ij,k} = \left(4(\beta_i + \beta_j) + 5\alpha + 10t_{ij} - 7t_k^P\right). \quad \text{(D2.1.4)}
$$

Using the first order conditions (D2.1.3), (D2.1.4), (D2.2.2), and (D2.2.3), the pair's equilibrium emissions tax $t_{ij}^*(C_P^k)$ and tariff ${\tau_{ij,k}}^*(C_P^k)$, are as follows, for i, j, k where $i \neq j, k$:

$$
t_{ij}^*(C_P^k) = \frac{1}{834}\left(-176\alpha + 809(\beta_i + \beta_j) - 72\beta_k\right) \quad \text{(D2.1.5)}
$$

$$
{\tau_{ij,k}}^*(C_P^k) = \frac{1}{139}\left(29\alpha + 106(\beta_i + \beta_j) - 45\beta_k\right). \quad \text{(D2.1.6)}
$$

A pair member domestic production and exports, are, respectively, for i, j, k where $i \neq j, k$:

$$x_{ii}(C_P^k) = x_{jj}(C_P^k) = \frac{1}{834}(308\alpha - 269(\beta_i + \beta_j) + 126\beta_k) \tag{D2.1.7}$$

$$x_{ij}(C_P^k) = x_{ji}(C_P^k) = \frac{1}{834}(308\alpha - 269(\beta_i + \beta_j) + 126\beta_k) \tag{D2.1.8}$$

$$x_{ik}(C_P^k) = x_{jk}(C_P^k) = \frac{3}{834}(47\alpha - 111(\beta_i + \beta_j) - 25\beta_k). \tag{D2.1.9}$$

The total quantity produced in a country within the pair is as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_P^k) = X_j(C_P^k) = \frac{1}{834}(757\alpha - 871(\beta_i + \beta_j) + 177\beta_k). \tag{D2.1.10}$$

The total quantity consumed in a country within the pair is as follows, for i, j, k where $i \neq j, k$:

$$Q_i(C_P^k) = Q_j(C_P^k) = \frac{9}{139}(13\alpha - 10(\beta_i + \beta_j) - \beta_k). \tag{D2.1.11}$$

The joint production level generated by the pair is as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_P^k) + X_j(C_P^k) = \frac{1}{417}(757\alpha - 871(\beta_i + \beta_j) + 177\beta_k). \tag{D2.1.12}$$

The welfare of country i in the pair, $W_i(C_P^k)$, is expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i(C_P^k) = \frac{1}{12 \times (139)^2}\begin{bmatrix} 112581\alpha^2 + \beta_k(36237\beta_k - 21982\alpha) \\ \beta_i(278248(\beta_i + \beta_j) + 123565\beta_k - 558007\alpha) \\ +\beta_j(5221\alpha - 101500(\beta_i + \beta_j) - 14879\beta_k) \end{bmatrix}. \tag{D2.1.13}$$

2.6.2.1 The Partial Coalition's Outsider

Given $\tau_{ij}(C_P^k) = 0$, $t_{ij}(C_P^k)$, and $\tau_{ij,k}(C_P^k)$, the outsider behaves as a singleton, and its welfare optimization problem (2.10) can be detailed as follows:

$$\underset{t_k^P, \tau_{k,ij}}{\text{Max}}\ W_k^{C_P^k} = \underset{t_k^P, \tau_{k,ij}}{\text{Max}}\begin{bmatrix} 3(5\alpha^2 - 24\alpha\beta_k) \\ +t_k^P(-18\alpha + 24\beta_k - 10t_{ij} - 17t_k^P) \\ +2t_{ij}(6\alpha + 24\beta_k - 5t_k^P + 14t_{ij}) \\ +4\tau_{k,ij}(4\beta_k + 3\alpha + 3t_k^P - 2t_{ij} - 5\tau_{k,ij}) \\ +4\tau_{ij,k}(4\beta_k - 6\alpha + 6t_k^P - 12t_{ij} + 9\tau_{ij,k}) \end{bmatrix}. \tag{D2.2.1}$$

The first order conditions with respect to t_k^P and $\tau_{k,ij}$, respectively, are as follows:

$$\frac{\delta W_k{}^{C_P^k}}{\delta t_k^P} = 0 \Rightarrow 17t_k^P = \left(12\beta_k - 9\alpha - 10t_{ij} + 12\tau_{ij,k} + 6\tau_{k,ij}\right) \quad \text{(D2.2.2)}$$

$$\frac{\delta W_k{}^{C_P^k}}{\delta \tau_{k,ij}} = 0 \Rightarrow 10\tau_{k,ij} = \left(4\beta_k + 3\alpha + 3t_k^P - 2t_{ij}\right). \quad \text{(D2.2.3)}$$

Using the FOCs (D2.1.3), (D2.1.4), (D2.2.2), and (D2.2.3), the outsider's equilibrium solution $t_k^{P^*}\left(C_P^k\right)$ and $\tau_{k,ij}{}^*\left(C_P^k\right)$, is as follows, for i, j, k where $i \neq j, k$:

$$t_k^{P^*}\left(C_P^k\right) = \frac{1}{417}\left(315\beta_k - 47\left(\beta_i + \beta_j\right) - 64\alpha\right) \quad \text{(D2.2.4)}$$

$$\tau_{k,ij}{}^*\left(C_P^k\right) = \frac{1}{834}\left(247\alpha + 537\beta_k - 190\left(\beta_i + \beta_j\right)\right). \quad \text{(D2.2.5)}$$

The outsider's local production and exports are, respectively, for i, j, k where $i \neq j, k$:

$$x_{kk}\left(C_P^k\right) = \frac{10}{417}\left(17\alpha + 19\left(\beta_i + \beta_j\right) - 12\beta_k\right) \quad \text{(D2.2.6)}$$

$$x_{ki}\left(C_P^k\right) = x_{kj}\left(C_P^k\right) = \frac{1}{417}\left(43\alpha - \left(\beta_i + \beta_j\right) - 153\beta_k\right). \quad \text{(D2.2.7)}$$

The outsider's total quantities produced and consumed are, respectively, for i, j, k where $i \neq j, k$:

$$X_k(C_P^k) = \frac{1}{417}\left(256\alpha + 188\left(\beta_i + \beta_j\right) - 426\beta_k\right) \quad \text{(D2.2.8)}$$

$$Q_k\left(C_P^k\right) = \frac{1}{417}\left(311\alpha - 143\left(\beta_i + \beta_j\right) - 195\beta_k\right). \quad \text{(D2.2.9)}$$

The world market clears, as global production equals global consumption, as shown here,

$$\textstyle\sum_i X_i\left(C_P^k\right) = \sum_i Q_i\left(C_P^k\right) = \frac{1}{417}\left(1013\alpha - 683\left(\beta_i + \beta_j\right) - 249\beta_k\right). \quad \text{(D2.2.10)}$$

The outsider's welfare $W_k\left(C_P^k\right)$ is expressed as follows, for i, j, k where $i \neq j, k$:

$$W_k\left(C_P^k\right) = \frac{1}{2\times(417)^2}\begin{bmatrix} 163976\alpha^2 + 12\beta_k(-68947\alpha + 4956\beta_k) \\ \left(\beta_i + \beta_j\right)\left(-117259\alpha + 138251\left(\beta_i + \beta_j\right) + 529329\beta_k\right) \end{bmatrix}. \quad \text{(D2.2.11)}$$

The partial coalition's collective welfare $W\left(C_P^k\right) = \sum_i W_i(C_P^k)$ is expressed as follows:

$$W\left(C_P^k\right) = \frac{1}{2\times(417)^2}\begin{bmatrix} 501719\alpha^2 + \left(\beta_i + \beta_j\right)\left(403373\left(\beta_i + \beta_j\right) - 946438\alpha\right) \\ +3\beta_k\left(230786\left(\beta_i + \beta_j\right) + 56061\beta_k - 297770\alpha\right) \end{bmatrix}. \quad \text{(D2.2.12)}$$

2.6.5 Appendix E2: Restrictions on the Model's Parameters

The parameters chosen in the simulations strictly adhere to these conditions, aiming to guarantee:

- An active market, by ensuring that $\alpha > \beta_i > \beta_j > \beta_k > 0$.
- A positive interior solution maintaining the market structure throughout the game, by ensuring that X_i, $x_{ii}{}^* \in \mathbb{R}_n^{++}$ and $x_{ij}{}^* \in \mathbb{R}_n^{+}$, for i, j, k where $i \neq j, k$.
- Positive import tariff rates and trade flows.
- The most restrictive conditions: $\alpha \geq \frac{1}{47}\left(111\left(\beta_i + \beta_j\right) + 25\beta_k\right)$; $\alpha \geq \frac{1}{35}\left(169\beta_i + 9\beta_j - 87\beta_k\right)$.

The complete set of the most restrictive constraints pertaining to each structure is detailed here:

- From the Singleton Structure with Optimal Unrestricted Tariffs:

$$x_{ii}(C_{NC}) > 0 \Rightarrow \alpha > \frac{1}{301}\left(167\beta_i - 105\left(\beta_j + \beta_k\right)\right) \tag{E2.1}$$

$$x_{ij}(C_{NC}) \geq 0 \Rightarrow \alpha \geq \frac{1}{215}(453\beta_i + 165\beta_j - 59\beta_k) \tag{E2.2}$$

$$\tau_{i,j}{}^*(C_{NC}) \geq 0 \Rightarrow \alpha \geq -\frac{1}{387}\left(19\left(45\beta_i - 19\beta_j\right) + 151\beta_k\right). \tag{E2.3}$$

- From the Singleton Structure with WTO-Restricted Tariffs:

$$\tilde{x}_{ii}(C_{NC}) > 0 \Rightarrow \alpha > \frac{1}{49}\left(51\beta_i - 29\left(\beta_j + \beta_k\right)\right) \tag{E2.4}$$

$$\tilde{x}_{ij}(C_{NC}) \geq 0 \Rightarrow \alpha \geq \frac{1}{35}\left(169\beta_i + 9\beta_j - 87\beta_k\right) \tag{E2.5}$$

$$\tilde{\tau}_i{}^*(C_{NC}) \geq 0 \Rightarrow \alpha \geq \frac{1}{63}\left(29\left(\beta_j + \beta_k\right) - 163\beta_i\right). \tag{E2.6}$$

- From the Grand Coalition Structure:

$$x_{ii}(C_G) = x_{ij}(C_G) = x_{ik}(C_G) > 0 \Rightarrow \alpha > \textstyle\sum_i \beta_i \tag{E2.7}$$

$$\tau_G{}^*(C_G) \geq 0 \Rightarrow t_G{}^* \leq \frac{1}{3}(4\textstyle\sum_i \beta_i - \alpha). \tag{E2.8}$$

- From the Partial Coalition Structure - The Pair:

$$x_{ii}\left(C_P^k\right) = x_{jj}\left(C_P^k\right) > 0 \Rightarrow \alpha > \frac{1}{308}\left(269\left(\beta_i + \beta_j\right) - 126\beta_k\right) \tag{E2.9}$$

$$x_{ij}\left(C_P^k\right) = x_{ji}\left(C_P^k\right) \geq 0 \Rightarrow \alpha \geq \frac{1}{308}\left(269\left(\beta_i + \beta_j\right) - 126\beta_k\right) \tag{E2.10}$$

$$x_{ik}\left(C_P^k\right) = x_{jk}\left(C_P^k\right) \geq 0 \Rightarrow \alpha \geq \frac{1}{47}\left(111\left(\beta_i + \beta_j\right) + 25\beta_k\right) \tag{E2.11}$$

$$\tau_{ij,k}{}^{*}(C_P^k) \geq 0 \Rightarrow \alpha > \frac{1}{29}\left(45\beta_k - 106\left(\beta_i + \beta_j\right)\right). \tag{E2.12}$$

- From the Partial Coalition Structure - The Outsider:

$$x_{kk}\left(C_P^k\right) > 0 \Rightarrow \alpha > \frac{1}{17}\left(12\beta_k - 19\left(\beta_i + \beta_j\right)\right) \tag{E2.13}$$

$$x_{ki}\left(C_P^k\right) = x_{kj}\left(C_P^k\right) \geq 0 \Rightarrow \alpha \geq \frac{1}{43}\left(\left(\beta_i + \beta_j\right) + 153\beta_k\right) \tag{E2.14}$$

$$\tau_{k,ij}{}^{*}\left(C_P^k\right) \geq 0 \Rightarrow \alpha \geq \frac{1}{247}\left(190\left(\beta_i + \beta_j\right) - 537\beta_k\right) \tag{E2.15}$$

2.6.6 Appendix F2: Proof of Proposition 2.4.1.1

Using (2.1), (B2.1.6), and (B2.1.7), country i's total quantity produced as a singleton is as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_{NC}) = \frac{1}{172}\left(129\alpha - 155\beta_i + 13(\beta_j + \beta_k)\right). \tag{F2.1}$$

Using (F2.1) and the symmetry, the singletons' global production, $X(C_{NC}) = \sum_i X_i(C_{NC})$, is:

$$X(C_{NC}) = \sum_i X_i(C_{NC}) = \frac{3}{4}(3\alpha - \sum \beta_i). \tag{F2.2}$$

Using (2.1), (C2.7), and (C2.8), country i's total production in the grand coalition is as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_G) = (\alpha - \sum_i \beta_i). \tag{F2.3}$$

Using (F2.3), the global production in the grand coalition, $X(C_G) = \sum_i X_i\,(C_G)$, is as follows:

$$X(C_G) = \sum_i X_i\,(C_G) = 3(\alpha - \sum_i \beta_i). \tag{F2.4}$$

Using (F2.2) and (F2.4), the environmental gains provided by the grand coalition in comparison to the singleton structure are:

$$X(C_{NC}) - X(C_G) = \frac{3}{4}(3\sum_i \beta_i - \alpha). \tag{F2.5}$$

Equation (F2.5) proves that $X(C_{NC}) - X(C_G) > 0$, when $\alpha < 3\sum_i \beta_i$.

Using (2.1), (D2.1.7), (D2.1.8), and (D2.1.9), country i's total production within the pair in the partial coalition C_P^k, is as follows, for i, j, k where $i \neq j, k$:

$$X_i(C_P^k) = X_j(C_P^k) = \frac{1}{834}\left(757\alpha - 871(\beta_i + \beta_j) + 177\beta_k\right). \tag{F2.6}$$

Using (F2.6), the joint production level within the pair is as follows, for i, j, k where $i \neq j, k$:

$$X_i\left(C_P^k\right) + X_j\left(C_P^k\right) = \frac{1}{417}\left(757\alpha - 871\left(\beta_i + \beta_j\right) + 177\beta_k\right). \quad \text{(F2.7)}$$

Using (2.1), (D2.2.6), and (D2.2.7), country k's total quantity produced as an outsider to a pair, is expressed as follows, for i, j, k where $i \neq j, k$:

$$X_k\left(C_P^k\right) = \frac{1}{417}\left(256\alpha + 188\left(\beta_i + \beta_j\right) - 426\beta_k\right). \quad \text{(F2.8)}$$

Using (F2.7) and (F2.8), global production in the partial coalition C_P^k, and by symmetry for C_P^j and C_P^i, is given by:

$$X\left(C_P^k\right) = \sum_i X_i\left(C_P^k\right) = \frac{1}{417}\left(1013\alpha - 683\left(\beta_i + \beta_j\right) - 249\beta_k\right). \quad \text{(F2.9)}$$

Using (F2.4) and (F2.9), the environmental gains in terms of lower global emissions, provided by the grand coalition when compared to the partial coalition C_P^k, and by symmetry for C_P^j and C_P^i, are expressed as follows:

$$X\left(C_P^k\right) - X(C_G) = \frac{2}{417}\left(-119\alpha + 284\left(\beta_i + \beta_j\right) + 501\beta_k\right). \quad \text{(F2.10)}$$

Equation (F2.10) proves that $X\left(C_P^k\right) - X(C_G) > 0$, when $\alpha < \frac{1}{119}\left(284\left(\beta_i + \beta_j\right) + 501\beta_k\right)$.

It is worth mentioning that the condition $\alpha < \frac{1}{119}\left(284\left(\beta_i + \beta_j\right) + 501\beta_k\right)$ is more restrictive than $\alpha < 3\sum_i \beta_i$, when $\sum_i \beta_i = 1$, and hence, when $\alpha < \frac{1}{119}\left(284\left(\beta_i + \beta_j\right) + 501\beta_k\right)$, the grand coalition results in lower global emissions in comparison to both the singleton and the partial coalition structures. • Q.E.D.

2.6.7 Appendix G2: Proof of Proposition 2.4.1.2

Using (D2.2.11), country i's individual welfare as an outsider to a pair in the partial coalition C_P^i, is as follows:

$$W_i(C_P^i) = \frac{1}{2\times(417)^2}\begin{bmatrix} 163976\alpha^2 + 12\beta_i(-68947\alpha + 4956\beta_i) \\ (\beta_j+\beta_k)(-117259\alpha + 138251(\beta_j+\beta_k) + 529329\beta_i) \end{bmatrix}. \quad \text{(G2.1)}$$

Let $W_i^{C_G} - W_i^{C_P^i}$ be country i's individual welfare gains as a member of the grand coalition in comparison to being an outsider to a pair within the partial coalition C_P^i.

Using (C2.14) and (G2.1), these welfare gains are expressed as follows, for i, j, k where $i \neq j, k$:

$$W_i^{C_G} - W_i^{C_P^i} = \frac{1}{2\times(417)^2}\begin{bmatrix} \alpha\left(9913\alpha - 215970\beta_i + 117259(\beta_j+\beta_k)\right) \\ +809973{\beta_i}^2 + (\beta_j+\beta_k)\left(166227\beta_i - 312140(\beta_j+\beta_k)\right) \end{bmatrix}. \quad \text{(G2.2)}$$

Using (G2.2), the first order condition with respect to β_i, is given by the following expression, for i, j, k where $i \neq j, k$:

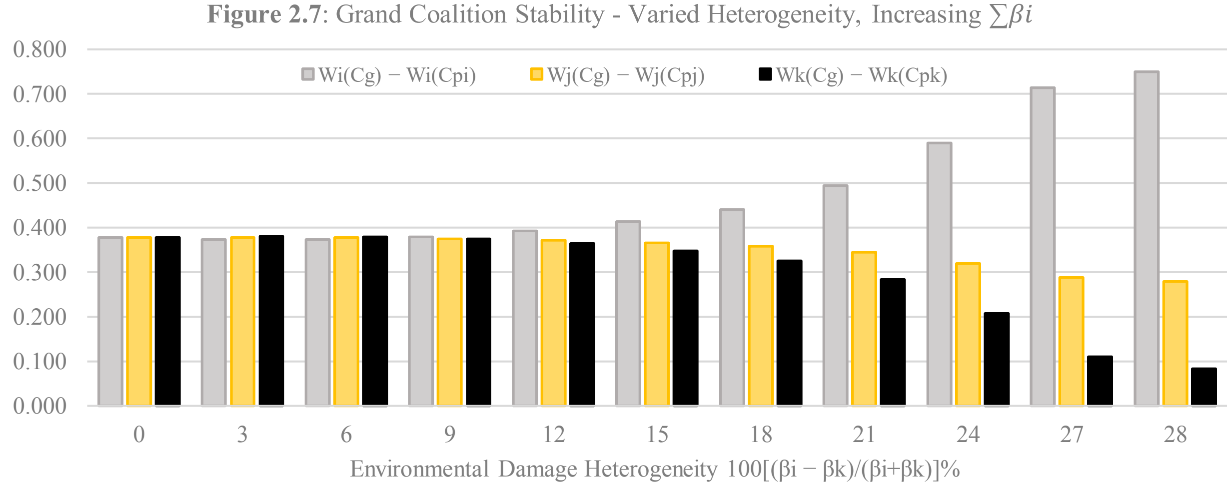
$$\frac{\partial\left[W_i^{C_G} - W_i^{C_P^i}\right]}{\partial\beta_i} = \frac{1}{2\times3\times139^2}\left[539982\beta_i + 55409(\beta_j+\beta_k) - 71990\alpha\right]. \quad \text{(G2.3)}$$

Equation (G2.3) clearly indicates that a country's individual welfare gains from joining the grand coalition can improve as its marginal environmental damage parameter takes a higher value, when $\beta_i < \alpha < \frac{1}{71990}\left(539982\beta_i + 55409(\beta_j+\beta_k)\right)$, for i, j, k where $i \neq j, k$. • Q.E.D.

2.6.8 Appendix H2: Simulation Results with Increasing $\sum_i \boldsymbol{\beta}_i$

The analysis and figures presented here depict the simulation results assuming that $\sum_i \beta_i$ increases compared to the case where $\sum_i \beta_i = 1$. As β_i, β_j, and β_k take higher values, while maintaining the heterogeneity assumption where $\beta_i > \beta_j > \beta_k > 0$, $\sum_i \beta_i$ increases. Keeping the value of α constant to explore the effect of heterogeneity restricts the range of parameters that satisfy all the conditions imposed on the model's parameters, as outlined in Appendix E2, and specifically the most restrictive condition expressed in Equation (E2.11). Hence, the comparison is only possible within a limited range of heterogeneity. For instance, with $\alpha = 2.4$, the range where the restrictions are met diminishes to a 14% heterogeneity level. Thus, $\alpha = 3.5$ will be used in the current numerical simulations, where all the restrictions are met up to a 28% heterogeneity level. Nevertheless, the simulation results remain consistent when assuming that $\sum_i \beta_i$ increases, in contrast to when $\sum_i \beta_i$ is held constant and normalized to 1.

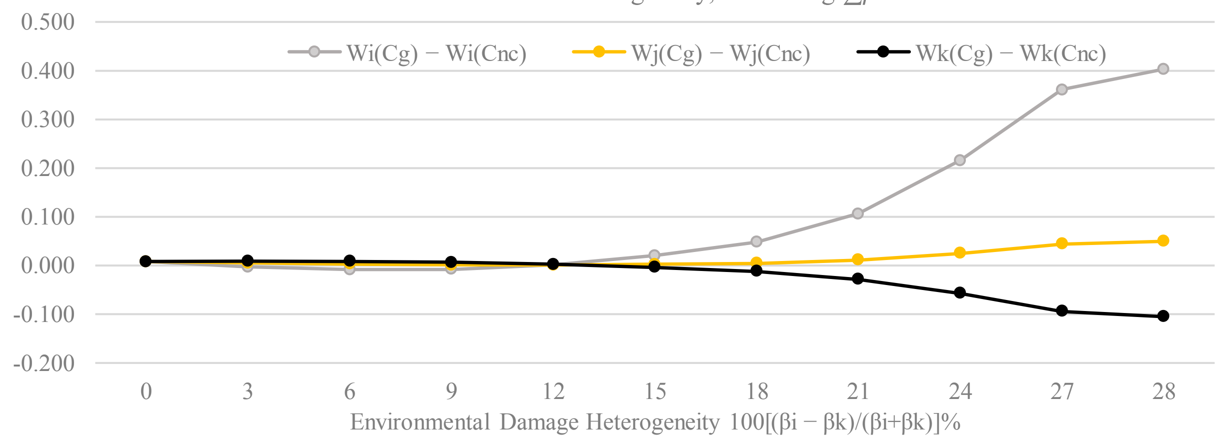
Figure 2.7: Grand Coalition Stability - Varied Heterogeneity, Increasing $\sum \beta i$



Assuming $\alpha = 3.5$, Figure 2.7 illustrates the welfare gains of countries i, j, and k, as expressed by Equation (2.68), when $\sum_i \beta_i$ increases. Similar to Figures 2.1 and 2.2, Figure 2.7 indicates that the grand coalition is stable across various heterogeneity levels. Country i's welfare gains significantly increase when the grand coalition reduces global production and thus damage, while countries j and k see diminishing welfare gains over the same range. The simulations reveal that the stability of the grand coalition can be reinforced by a larger α value, confirming proposition 2.4.1.3. These results remain consistent when varying α values, where $\alpha \geq \frac{1}{47}\left(111\left(\beta_i + \beta_j\right) + 25\beta_k\right)$.

Similar to the scenario where $\sum_i \beta_i = 1$, a range of parameters where the grand coalition is unstable has not been identified when assuming $\sum_i \beta_i$ increases.

Figure 2.8: Individual Welfare Gains: Comparing the Grand Coalition to the Singleton Structure - Varied Heterogeneity, Increasing $\sum\beta i$

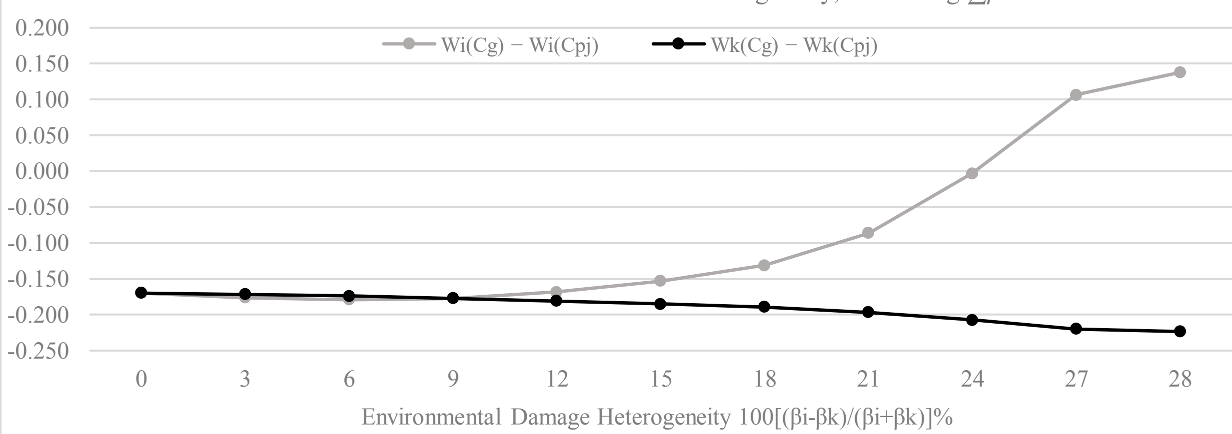


Assuming $\alpha = 3.5$, Figure 2.8 depicts the individual welfare gains of countries i, j, and k as outlined in equation (2.71), as members of the grand coalition in comparison to the singletons. In this case, the grand coalition is stable, with $t_G^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha) > 0$. As $\sum_i \beta_i$ takes higher values, while α is held constant, the grand coalition deliver environmental benefits in terms of lower production (emissions), when $\alpha < 3\sum_i \beta_i$, since $X(C_{NC}) - X(C_G) = \frac{3}{4}(3\sum_i \beta_i - \alpha)$.

When it does (above 9% in Figure 2.8), country i sees increasing welfare gains associated with lower production levels. When it doesn't (at or below 9% in Figure 2.8), country k is the main beneficiary. Similar to Figures 2.3 and 2.4, Figure 2.8 confirms remark 2.4.2.2 that a member of the grand coalition may be better off when compared to behaving as a singleton. These results are robust to changes in the value of α, where $\alpha \geq \frac{1}{47}\left(111\left(\beta_i+\beta_j\right)+25\beta_k\right)$.

Alternatively, Figure 2.9 depicts countries i and k's individual welfare gains in the grand coalition compared to forming a pair within the partial coalition C_p^j, when β_i, β_j, and β_k, take higher values and $\alpha = 3.5$. With $t_G^*(C_G) = \frac{1}{3}(4\sum_i \beta_i - \alpha) > 0$, the grand coalition imposes a positive emissions tax rate. Given Equation (2.67), the grand coalition provides environmental gains compared to C_p^j, when $\alpha < \frac{1}{119}\left(284(\beta_i+\beta_k)+501\beta_j\right)$. Similar to Figure 2.6, Figure 2.9 indicates that both countries are experiencing individual welfare losses up to 24% heterogeneity.

Figure 2.9: Individual Welfare Gains of Countries i and k: Comparing the Grand Coalition to the Partial Coalition Structure - Varied Heterogeneity, Increasing $\sum\beta i$



As β_i takes a higher value, country i sees improving welfare gains after 6% heterogeneity, stemming from the environmental gains brought about by the grand coalition after this level. In contrast, as β_k takes a higher value, country k experiences increasing welfare losses over the full range of heterogeneity. Similar to Figures 2.5 and 2.6, Figure 2.9 confirms remark 2.4.2.3 that a member of the grand coalition can be often worth off than a pair member in a partial coalition.

These results are robust to changes in the values of α, where $\alpha \geq \frac{1}{47}\left(111\left(\beta_i+\beta_j\right)+25\beta_k\right)$.

ESSAY 3

THE IMPACTS OF UNILATERAL CARBON BORDER ADJUSTMENTS AMONG HETEROGENEOUS COUNTRIES

3.1 Introduction

The pressing demand for swift global climate action aligns with the necessity to rectify disparities in current carbon pricing. Within this framework, the present essay examines the impacts of unilateral Carbon Border Adjustments (CBAs) on global emissions and welfare, as well as their potential to promote increased international environmental cooperation among heterogeneous trading partners, with a focus on addressing environmental damage heterogeneity.

The main objectives of this essay are, therefore: i) To investigate whether unilateral CBAs lead to environmental gains, overall welfare gains, or both. ii) To assess the potential of CBAs to encourage convergence of environmental standards among heterogeneous countries. iii) To evaluate the ability of CBAs to incentivize international cooperation, considering the effects of environmental damage heterogeneity on the likelihood of cooperation.

The essay introduces a novel focus by examining the time sensitivity of CBAs, distinguishing between farsighted and myopic CBAs, considering the potential for retaliation in myopic CBAs, and comparing their effectiveness to the basic trade model with bilateral endogenous tariffs.

The current essay examines an open economy featuring two countries, each with a single firm producing a homogeneous emission-intensive good and generating transboundary emissions such as carbon dioxide. Consumers in each country are affected by global emissions, and every unit produced generates exactly one unit of emissions. The firm's choice variable is production, which also represents emissions. As such, abatement[36] is not modelled as a separate choice variable, but forgone profit is the firm's abatement cost. Firms compete à la Cournot in a segmented market rather than a shared global market.

Each government uses a per-unit of production (emissions) tax rate as an environmental policy tool. The two countries experience varying consequences from environmental damage, resulting in different marginal environmental damage parameters.

The game consists of two main stages, encompassing the optimization of governments' welfares and the maximization of firms' profits. In the first stage, each country determines the emissions tax rate that maximizes its individual welfare. The country with the highest emissions tax rate unilaterally implements a carbon border adjustment that requires the foreign firm to pay the difference between the emissions tax rates on its exports. In the second stage, each firm noncooperatively chooses its production level to maximize profits. The game is solved by backward induction, starting from the second stage and progressing backward to the first stage.

In comparison to the basic trade model with bilateral endogenous tariffs, the numerical simulations demonstrate that farsighted CBAs can generate environmental gains and overall welfare gains, but only under specific conditions, and lead to higher emissions taxes in both countries. On the other hand, myopic CBAs without retaliation offer a greater potential for cooperation, regardless of the level of heterogeneity in environmental damages. However, myopic CBAs with retaliation can result in collective welfare gains under specific conditions.

The main policy implications of this essay suggest that farsighted CBAs can be an effective approach to reducing global emissions, particularly in sufficiently small markets, while myopic

[36] Following Anouliès (2015), Baksi and Chaudhuri (2017), Hecht and Peters (2018), Al Khourdajie and Finus (2020), and Elboghdadly and Finus (2020), abatement is not modelled as a separate choice variable to simplify the model.

CBAs fall short in delivering environmental gains when compared to alternative noncooperative measures, such as farsighted CBAs and bilateral endogenous tariffs. Additionally, the analysis shows that myopic CBAs can foster greater international cooperation among trading partners, even in the presence of heterogeneity among countries.

The primary contribution of this essay to the literature lies in presenting evidence that the effectiveness of CBAs is inherently tied to their time sensitivity. Additionally, the essay assesses the environmental and welfare impacts of unilateral CBAs, emphasizing their divergence from the bilateral endogenous tariff approach.

The rest of the essay is structured as follows: Section 2 describes the model; Section 3 examines the noncooperative solutions; Section 4 explores the cooperative solution; Section 5 summarizes the main findings, and Section 6 concludes the essay.

3.2 The Model

The model examines an open economy comprising two heterogeneous countries, $N = \{i, j\}$. In each country, there exists a single profit-maximizing firm producing an emission-intensive homogeneous good X. The total production of the firm located in country i is given by the following expression, for i, j where $i \neq j$:

$$X_i = \left(x_{ii} + x_{ij}\right), \tag{3.1}$$

where x_{ii} is produced and sold in country i, and x_{ij} is produced in country i and exported to country j, for i, j where $i \neq j$. For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that X_i, ${x_{ii}}^* \in \mathbb{R}_n^{++}$ and ${x_{ij}}^* \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$. The production process generates transboundary air pollution such as carbon dioxide. It is assumed that every unit produced generates one unit of global emissions. The firm's choice variables are local production and exports, which also represent emissions. Firms can reduce total emissions by producing less output at the expense of reducing profits. Hence, abatement is neither an option nor a choice variable, but forgone profits would be the firm's abatement cost.

Total consumption in country i, for i, j where $i \neq j$, is denoted by the following expression:

$$Q_i = \left(x_{ii} + x_{ji}\right), \tag{3.2}$$

where x_{ii} is locally produced and x_{ji} is imported from country j, where $i \neq j$.

Firms compete à la Cournot in a segmented market, where each firm faces linear market-specific demands, rather than a shared global market demand. The market demand in country i, is given by, for i, j where $i \neq j$:

$$Q_i = (\alpha - P_i), \tag{3.3}$$

where Q_i is the total consumption of the polluting good in country i, P_i is the price of the good in market i, and α is the maximal marginal utility derived from its consumption.

For simplification, it is assumed that the marginal cost of production is equal to zero, and each firm can export to the other foreign market at no transaction costs.

Pollution generates environmental damage in each country; the social cost of pollution is a linear function of global emissions:

$$D_i(X) = \beta_i(X_i + X_j), \tag{3.4}$$

where β_i is the marginal environmental damage in country i caused by aggregate production, that is, by global emissions. The linear environmental damage function makes the analysis more readable and the model more tractable. For the market to be active, it is assumed that the marginal environmental damage parameter cannot be higher than the maximal marginal utility of good X, given by α, and thus $\beta_i \in (0, \alpha)$, for i, j. Consumers in each country are affected by the global level of emissions. As such, variance in environmental damages does not manifest through different emissions exposure levels, but how the same amount of emissions translates into costs, given the underlying determinants of heterogeneity, such as income, health stock, defensive investment, or baseline exposure (Hsiang et al., 2019).

The model is solved by backward induction. First, the government in any country i enforces a per-unit of production (emissions) tax rate t_i that is imposed on the local firm as an environmental policy instrument. Since every unit produced precisely generates a unit of emissions, then a tax per unit of production t_i is equivalent to a tax per unit of emissions. Thus, the government in country i collects emissions tax revenues, for i, j where $i \neq j$, defined as:

$$ER_i = t_i(x_{ii} + x_{ij}) = t_i X_i. \tag{3.5}$$

Given that the two countries have different environmental damage parameters, they are likely to apply different tax rates on the production of polluting good. The country with the highest environmental damage parameter will impose a higher emissions tax. Consequently, the country with the highest emissions tax rate will unilaterally implement a border adjustment mechanism, which entails adjusting for the differences in emissions tax rates on imports. The firm producing in the country with the lowest emissions tax will be required to pay the difference between the domestic and the foreign emissions tax rates on its exports. The objective of this carbon border adjustment (CBA) is to equalize the emissions taxes between the two firms. This mechanism has been carefully designed to comply with WTO rules. Therefore, the foreign firm will be charged precisely the difference between the emissions tax rates as a means of achieving emissions tax parity. The carbon border adjustment (CBA) is, therefore, defined as:

$$\omega_i = (t_i - t_j), \qquad \forall\, t_i > t_j \tag{3.6}$$

The country with the highest emissions tax collects fiscal revenues from the adjustment, given by:

$$CBR_i = \omega_i x_{ji} = (t_i - t_j) x_{ji}, \qquad \forall\, t_i > t_j \tag{3.7}$$

It is assumed that there are no transfer payments between countries and fiscal revenues remain in the state of origin, since allowing for transfers can alter the incentive behind cooperation.

In this essay, a novel perspective is presented, focusing on the time sensitivity of Carbon Border Adjustments (CBAs). Consequently, the study investigates two types of carbon border adjustments, namely Farsighted and Myopic CBAs, and compares them with the basic trade model with bilateral endogenous tariffs. Farsighted CBAs involve a scenario where the government's welfare optimization problem and the resulting optimal emissions tax rate consider ex-ante the potential for carbon adjustments. In contrast, in the myopic CBA scenario, the government's welfare optimization problem and the resulting optimal emissions tax rate initially ignore the potential for carbon adjustments, but these adjustments are accounted for subsequently. The current essay also explores the possibility of retaliation in the context of myopic CBAs.

Moreover, the two noncooperative CBA scenarios are compared with the basic trade model with bilateral endogenous tariffs. In the context of using bilateral endogenous tariffs as a trade policy tool, the government in country i imposes a positive tariff τ_i per unit of imports from country j. The collected tariff revenues, retained in the state of origin, are as follows, for i, j where $i \neq j$:

$$TR_i = (\tau_i x_{ji}). \tag{3.8}$$

The welfare function of country i, denoted by W_i, consists of the domestic consumer surplus CS_i, the profits of local firm π_i, the government's tariff revenues TR_i or the revenues from carbon border adjustments CBR_i, and the emissions tax revenues ER_i, subtracting the environmental damage D_i caused by global emissions. Thus, country i's welfare function in the case of bilateral tariffs, can be expressed as follows, for i, j where $i \neq j$:

$$W_i(t^\tau, \tau) = (CS_i + \pi_i + ER_i + TR_i - D_i). \tag{3.9}$$

However, in the case of unilateral border adjustments imposed by country i on imports from country j, $\forall\ t_i > t_j$, the welfare functions of countries i and j become, respectively, as follows:

$$W_i(t, \omega_i) = (CS_i + \pi_i + ER_i + CBR_i - D_i) \tag{3.10}$$

$$W_j(t, \omega_i) = \left(CS_j + \pi_j + ER_j - D_j\right). \tag{3.11}$$

Subsequently, each firm noncooperatively selects its profit-maximizing production rate, while considering the policies enforced by both governments and the other firm's output decisions.

The essay, therefore, examines the fully cooperative case and four noncooperative scenarios: unilateral myopic CBAs without retaliation, unilateral myopic CBAs with retaliation, unilateral farsighted CBAs, and the basic trade model with bilateral endogenous tariffs.

3.3 Noncooperative Solutions

In the upcoming subsections, the analysis delves into the diverse strategies pursued within the noncooperative framework. These strategies include unilateral myopic CBAs with and without retaliation, unilateral farsighted CBAs, and the basic trade model with bilateral endogenous tariffs. Each strategy represents distinct approaches taken by individual countries to optimize their welfare amidst environmental concerns and economic objectives.

3.3.1 The Firm's Optimization Problem

Each single firm independently determines its profit-maximizing output, while considering the policies established by both governments and the output decisions made by the other foreign firm.

Firms compete à la Cournot in domestic markets, and each firm has two choice variables: production for the local market x_{ii} and exports to the foreign market x_{ij}. The firm's total profit function in country i comprises revenues from both its domestic market i and foreign market j, deducting domestic emissions taxes on production in all cases, and tariffs on exports only in the context of the bilateral tariff model. The firm in country j subtracts from total revenues either the tariff or the adjustment on exports in the CBA case, in addition to emissions taxes. Consequently, firms' i and j optimization problems can be formulated, respectively, as follows:

$$\max_{x_{ii},x_{ij}} \pi_i \Rightarrow \max_{x_{ii},x_{ij}} \left[(\alpha - Q_i - t_i)x_{ii} + \left(\alpha - Q_j - t_i\right)x_{ij} - \tau_j x_{ij}\right] \tag{3.12}$$

$$\max_{x_{jj},x_{ji}} \pi_j \Rightarrow \max_{x_{jj},x_{ji}} \left[\left(\alpha - Q_j - t_j\right)x_{jj} + \left(\alpha - Q_i - t_j\right)x_{ji} - \tau_i x_{ji} - \omega_i x_{ji}\right]. \tag{3.13}$$

The welfare function of country i, for i, j where $i \neq j$, is determined based on the optimal Cournot quantities obtained here. The firms' optimization problems[37] under each noncooperative scenario are described in the following subsections.

3.3.1.1 Under Myopic Carbon Border Adjustments

In the myopic CBA scenario, the firm's optimization problem initially does not consider the potential for carbon border adjustments. The total profit function of the firm located in country i includes the total revenues from its domestic market i and the foreign market j, where $i \neq j$.

Let ${t_i}^m$ be the noncooperative emissions tax rate enforced by country i, then the local firm deducts only the domestic emissions tax imposed on total production. These initial Cournot quantities are, subsequently, readjusted to allow for the unilateral CBA imposed by the government in country i on imports from country j, to equalize emissions tax rates.

[37]The firms' optimization problems under each noncooperative scenario are detailed in Appendix A3.

In this case, in Equations (3.12) and (3.13), $\tau_i = 0$, for i, j and $\omega_i = 0$. The optimization problems of firms i and j, stated in (3.12) and (3.13), respectively, are reduced to, for i, j where $i \neq j$:

$$\max_{x_{ij}\ j\in N} \pi_i \Rightarrow \max_{x_{ij}\ j\in N} \left[\sum_{j\in N}\left(P_j\left(x_{ij}\right) - t_i{}^m\right)x_{ij}\right]. \tag{3.14}$$

The equilibrium quantities produced by the firm operating in country i, for i, j where $i \neq j$, are:

$$x_{ii}{}^*(t^m) = x_{ij}{}^*(t^m) = \tfrac{1}{3}\left(\alpha - 2t_i{}^m + t_j{}^m\right). \tag{3.15}$$

For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that $x_{ii}{}^*(t^m) \in \mathbb{R}_n^{++}$and $x_{ij}{}^*(t^m) \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$. The Cournot equilibrium quantities demonstrate noncooperative behavior, where domestic production and exports decrease with the local emissions tax $t_i{}^m$, and increase with the foreign emissions tax $t_j{}^m$.

3.3.1.2 Under Farsighted Carbon Border Adjustments

In the farsighted CBA scenario, the firm's optimization problem considers ex-ante the carbon border adjustment. Country i, possessing the highest environmental damage parameter, and consequently, enforcing a higher emissions tax rate, unilaterally introduces a border adjustment mechanism to rectify the disparity in emissions taxes on imports from country j.

Let $t_i{}^f$ be the emissions tax rate enforced by country i. The firm operating in country j will need to pay the domestic emissions tax imposed by the government in country j on total production, denoted by $t_j{}^f$, as well as the carbon border adjustment on its exports, denoted as $\omega_i{}^f$, such that:

$$\omega_i{}^f\left(t_i{}^f, t_j{}^f\right) = \begin{Bmatrix} \left(t_i{}^f - t_j{}^f\right) & \forall\, t_i{}^f > t_j{}^f \\ 0 & \forall\, t_i{}^f \leq t_j{}^f \end{Bmatrix}.$$

The carbon border adjustment revenues CBR_i are collected by the government in country i. In this case, in Equations (3.12) and (3.13), $\omega_i{}^f = \left(t_i{}^f - t_j{}^f\right)$, $\forall\, t_i{}^f > t_j{}^f$, and $\tau_i = \tau_j = 0$.

Firms i and j's optimization problems, stated in (3.12) and (3.13), respectively, are rewritten as:

$$\max_{x_{ij}\ j\in N} \pi_i \Rightarrow \max_{x_{ij}\ j\in N} \left[\sum_{j\in N}\left(P_j\left(x_{ij}\right)x_{ij} - t_i{}^f x_{ij}\right)\right] \tag{3.16}$$

$$\max_{x_{ji}\ i\in N} \pi_j \Rightarrow \max_{x_{ji}\ i\in N} \left[\sum_{i\in N}\left(P_i\left(x_{ji}\right)x_{ji} - t_j{}^f x_{ji}\right) - \left(\left(t_i{}^f - t_j{}^f\right)\right)x_{ji}\right]. \tag{3.17}$$

The equilibrium quantities produced by the firm operating in country i are as follows:

$$x_{ii}{}^*(t^f, \omega_i) = \frac{1}{3}(\alpha - t_i{}^f) \tag{3.18}$$

$$x_{ij}{}^*(t^f, \omega_i) = \frac{1}{3}\left(\alpha - 2t_i{}^f + t_j{}^f\right). \tag{3.19}$$

While the equilibrium quantities produced by the firm operating in country j are given by:

$$x_{jj}{}^*(t^f, \omega_i) = \frac{1}{3}(\alpha + t_i{}^f - 2t_j{}^f) \tag{3.20}$$

$$x_{ji}{}^*(t^f, \omega_i) = \frac{1}{3}(\alpha - t_i{}^f). \tag{3.21}$$

Local production is constrained to be strictly positive, that is, $x_{ii}(t^f, \omega_i) \in \mathbb{R}_n^{++}$, and exports are required to be positive, such that, $x_{ij}(t^f, \omega_i) \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$.

Compared to myopic CBAs, the farsighted anticipation of the adjustment maintains the exports of country i and country j's domestic production unchanged. However, the CBA imposes identical emissions taxes on country i's domestic production and country j's exports, making the latter solely dependent on the emissions tax rate enforced in country i. Essentially, the anticipated CBA equalizes the emissions tax between country i's local production and its imports from country j.

3.3.1.3 Under Endogenous Bilateral Tariffs

Let $t_i{}^\tau$ and τ_i be the emissions tax and tariff enforced by country i in the basic trade model with bilateral endogenous tariffs, respectively. The firm located in country i deducts from total revenues the domestic emissions tax, t_i^{τ}, imposed on total production, and the tariff, τ_j, imposed on its exports to country j. Hence, in Equations (3.12) and (3.13), $\tau_i \geq 0$, $\tau_j \geq 0$, and $\omega_i = 0$. The optimization problems of firms i and j, expressed in (3.12) and (3.13), respectively, can be reduced as follows, for i, j where $i \neq j$:

$$\max_{x_{ij}\ j \in N} \pi_i \Rightarrow \max_{x_{ij}\ j \in N} \left[\sum_{j \in N}\left(P_j(x_{ij})x_{ij} - t_i^{\tau} x_{ij}\right) - \tau_j x_{ij}\right]. \tag{3.22}$$

The equilibrium quantities produced by the firm operating in country i, for i, j where $i \neq j$, are:

$$x_{ii}^*(t^{\tau}, \tau) = \frac{1}{3}(\alpha - 2t_i^{\tau} + t_j^{\tau} + \tau_i) \tag{3.23}$$

$$x_{ij}^*(t^{\tau}, \tau) = \frac{1}{3}\left(\alpha - 2t_i^{\tau} + t_j^{\tau} - 2\tau_j\right). \tag{3.24}$$

The Cournot equilibrium implies that production decrease with the local emissions tax rate, t_i^{τ}, and increase with the tax rate imposed on the foreign firm, t_j^{τ}. As anticipated, domestic production increases with the local tariff rate, τ_i, while exports decrease with the foreign tariff, τ_j. Local production is constrained to be strictly positive, that is, $x_{ii}(t^{\tau}, \tau) \in \mathbb{R}_n^{++}$, and exports are required to be positive, $x_{ij}(t^{\tau}, \tau) \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$.

3.3.2 The Government's Optimization Problem

In this essay, the central premise revolves around the assumption that both countries exhibit distinct marginal environmental damage parameters, denoted as β_i and β_j, where $\beta_i > \beta_j > 0$. If countries were homogeneous, that is with identical environmental damage parameters, they would enforce the same emissions tax rate. However, due to their heterogeneity, the country with the highest environmental damage parameter β_i, will implement a higher emissions tax rate t_i. Consequently, the disparity in emissions taxes calls for a carbon border adjustment to be imposed by country i on its imports from country j, given that country j has a lower emissions tax. In the basic trade model, there is an additional aspect at play - the inclusion of bilateral endogenous tariffs on imports. This tariff can be used strategically by a country to protect its domestic industry from foreign competition while also accounting for the environmental impact of imported goods.

3.3.2.1 Myopic Carbon Border Adjustments

The case of myopic carbon border adjustments assumes that the government's optimization problem and the resulting optimal emissions tax do not take into consideration ex-ante the potential for CBAs. This adjustment is applied after the government's optimization process, and production quantities are adjusted subsequently. Therefore, the firm producing in country j and exporting to country i, will be required to pay on its exports, the difference between the foreign emissions tax ${t_i}^m$ and the domestic tax ${t_j}^m$. To be compatible with WTO rules, it will be charged precisely the difference between the emissions tax rates as a means of achieving emissions tax parity.

3.3.2.1.1 Without Retaliation

In the myopic CBA case, country i noncooperatively sets an emissions tax rate, denoted by ${t_i}^m$. Given the equilibrium quantities produced by the firms, described in Equation (3.15), country i's welfare optimization problem[38] can be expressed as follows, for i, j where $i \neq j$:

$$\max_{t_i^m} {W_i}^m \Rightarrow \max_{t_i^m} \begin{bmatrix} \frac{1}{2}\left(Q_i(t_i^m)\right)^2 - \beta_i\left(X_i(t_i^m) + X_j(t_i^m)\right) \\ +\left(\alpha - Q_i(t_i^m)\right)x_{ii}^*(t_i^m) + \left(\alpha - Q_j(t_i^m)\right)x_{ij}^*(t_i^m) \end{bmatrix}. \tag{3.25}$$

The first order condition of the welfare maximization problem (3.25) with respect to the emissions tax rate, t_i^m, yields the following negative best response function, for i, j where $i \neq j$:

$${t_i}^m\left({t_j}^m\right) = \frac{1}{7}\left(-4\alpha + 6\beta_i - {t_j}^m\right). \tag{3.26}$$

Equation (3.26) demonstrates each country's noncooperative behavior with a negative best response function.

[38] Country i's optimization problem with myopic CBAs without retaliation is detailed in Appendix B3.1.

The equilibrium emissions tax rate, for i, j where $i \neq j$, is given by the following expression:

$$t_i{}^{*m} = \frac{1}{8}\left(-4\alpha + \left(7\beta_i - \beta_j\right)\right). \tag{3.27}$$

In this noncooperative equilibrium, each country's emissions tax rate is positively related to its own environmental damage parameter while inversely related to the other country's parameter, implying solid free-riding incentives. Equation (3.27) also demonstrates that the difference in emissions tax rates boils down exactly to the difference in environmental damage parameters, where $\left(t_i{}^{*m} - t_j{}^{*m}\right) = (\beta_i - \beta_j) > 0$, since $\beta_i > \beta_j > 0$.

With myopic CBAs, firms react to current government policies. If governments are myopic and their emissions taxes ignore the potential for such adjustments, then, the firms' initial optimal quantities, expressed in Equation (3.15), do not account for the CBA, but these need to be adjusted subsequently to account for the unilateral carbon border adjustment, $w_i^m = \left(t_i{}^{*m} - t_j{}^{*m}\right)$. The adjusted equilibrium quantities are detailed in Appendix B3.1.

After the adjustment, country i's local production and exports are, respectively, as follows:

$$x_{ii}{}^{m} = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right) \tag{3.28}$$

$$x_{ij}{}^{m} = \frac{1}{8}\left(4\alpha - 5\beta_i + 3\beta_j\right). \tag{3.29}$$

Country j's local production and exports are expressed, respectively, as follows:

$$x_{jj}{}^{m} = \frac{1}{8}\left(4\alpha - 5\beta_j + 3\beta_i\right) \tag{3.30}$$

$$x_{ji}{}^{m} = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right). \tag{3.31}$$

From country i's perspective, the carbon adjustment reduces country i's imports and increase its domestic production, enhancing its total production level. On the other hand, the carbon border adjustment decreases country j's exports as well as its total production[39].

[39] Countries i and j's production, consumption, and welfare equations are detailed in Appendix B3.1.

3.3.2.1.2 With Retaliation

The country with lower taxes can either comply with the unilateral adjustment and pay the difference between the emissions tax rates on its exports, or it can retaliate by imposing an endogenous positive tariff on imports from the other country. Few empirical studies (Böhringer et al., 2016; Fouré et al., 2016) have notably highlighted the potential risk of non-EU countries retaliating in response to the unilateral implementation of the EU CBAM.

In the myopic case, country i's decision to unilaterally harmonize emissions taxes across borders, as well as country j's retaliation, both occur after governments have finalized their emissions tax rates. At this point, the optimal taxes, as expressed in Equation (3.27), have been determined without accounting for the possibility of unilateral carbon adjustment and retaliation.

Moreover, firms initially do not consider the potential for CBAs or the possibility of retaliation in their optimization problem, as they react to current policies. However, the quantities they produce will eventually be influenced by the unilateral carbon adjustment, $w_i^m = \left(t_i{}^{*m} - t_j{}^{*m}\right)$, and the retaliatory tariff $\tau_j^{\breve{m}}$, imposed by country j on its imports from country i. These changes will impact both firms' production decisions, as they will need to adapt to the new cost structures and trade conditions resulting from these policy measures. Therefore, the equilibrium quantities produced by the firm operating in country i, for i, j where $i \neq j$, expressed in Equation (3.15) are adjusted to account for $w_i^m = \left(t_i{}^{*m} - t_j{}^{*m}\right)$ and $\tau_j^{\breve{m}}$. The adjusted quantities are detailed in Appendix B3.2.

Subsequently, based on the adjusted quantities, country j's welfare optimization problem to determine the endogenous retaliatory tariff, denoted by $\tau_j^{\breve{m}}$, is expressed as follows:

$$\max_{\tau_j^{\breve{m}}} W_j{}^{\breve{m}} \Rightarrow \max_{\tau_j^{\breve{m}}} \begin{bmatrix} \frac{1}{2}\left(Q_j\left(\tau_j^{\breve{m}}\right)\right)^2 - \beta_j\left(X_i\left(\tau_j^{\breve{m}}\right) + X_j\left(\tau_j^{\breve{m}}\right)\right) + \tau_j^{\breve{m}} x_{ij}^*\left(\tau_j^{\breve{m}}\right) \\ + \left(\alpha - Q_j\left(\tau_j^{\breve{m}}\right)\right) x_{jj}^*\left(\tau_j^{\breve{m}}\right) + \left(\alpha - Q_i\left(\tau_j^{\breve{m}}\right) - \left(t_i^m - t_j^m\right)\right) x_{ji}^*\left(\tau_j^{\breve{m}}\right) \end{bmatrix}. \tag{3.32}$$

The first order condition[40] with respect to the tariff rate $\tau_j^{\breve{m}}$ yields the following positive tariff rate:

$$\tau_j^{*\breve{m}} = \frac{1}{3}\left(\alpha - \beta_i + 2\beta_j\right). \tag{3.33}$$

Given the assumption that $\alpha > \beta_i > \beta_j > 0$, it follows that $\tau_j^{*\breve{m}} > 0$, $\forall\ \alpha, \beta_i, \beta_j$.

Hence, following the retaliation by country j, the local production and exports produced by the firm operating in country i become, respectively, as follows:

$$x_{ii}{}^{\breve{m}} = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right) \tag{3.34}$$

$$x_{ij}{}^{\breve{m}} = \frac{1}{72}\left(20\alpha - 29\beta_i - 5\beta_j\right). \tag{3.35}$$

Country j's local production and exports are given, respectively, by the following equations:

$$x_{jj}{}^{\breve{m}} = \frac{1}{72}\left(44\alpha + 19\beta_i - 29\beta_j\right) \tag{3.36}$$

$$x_{ji}{}^{\breve{m}} = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right). \tag{3.37}$$

Country j's retaliation to country i's unilateral CBA reduces country i's total production as expressed by the following expression, $\forall \alpha > \beta_i > 0$:

$$X_i{}^{\breve{m}} - X_i{}^{m} = -\frac{2}{9}\left(\alpha - \beta_i + 2\beta_j\right). \tag{3.38}$$

While retaliation increases country j's total production as shown by this equation, $\forall \alpha > \beta_i > 0$:

$$X_j{}^{\breve{m}} - X_j{}^{m} = \frac{1}{9}(\alpha - \beta_i + 2\beta_j). \tag{3.39}$$

The equations detailing total production, consumption, and welfares of countries i and j are provided in Appendix B3.2.

[40]Country j's optimization problem with myopic CBAs with retaliation is detailed in Appendix B3.2.

3.3.2.2 Farsighted Carbon Border Adjustments

With farsighted carbon border adjustments, the government in country i selects noncooperatively an emissions tax rate, denoted by ${t_i}^f$. Given the equilibrium quantities expressed by Equations (3.18), (3.19), (3.20) and (3.21), country i's welfare optimization problem[41] can be expressed as:

$$\max_{t_i^f} {W_i}^f \Rightarrow \max_{t_i^f} \begin{bmatrix} \frac{1}{2}\left(Q_i\left(t_i^f\right)\right)^2 - \beta_i\left(X_i\left(t_i^f\right) + X_j\left(t_i^f\right)\right) + \left(\alpha - Q_i\left(t_i^f\right)\right)x_{ii}^*\left(t_i^f\right) \\ + \left(\alpha - Q_j\left(t_i^f\right)\right)x_{ij}^*\left(t_i^f\right) + \left(t_i^f - t_j^f\right)x_{ji}^*\left(t_i^f\right) \end{bmatrix}. \quad (3.40)$$

The first order condition with respect to the tax rate t_i^f yields the following positive best response:

$${t_i}^f\left({t_j}^f\right) = \frac{1}{10}\left((9\beta_i - \alpha) + 2{t_j}^f\right). \quad (3.41)$$

On the other hand, given the equilibrium quantities described in Equations (3.18), (3.19), (3.20) and (3.21), country j's welfare maximization problem can be expressed as follows:

$$\max_{t_j^f} {W_j}^f \Rightarrow \max_{t_j^f} \begin{bmatrix} \frac{1}{2}\left(Q_j\left(t_j^f\right)\right)^2 - \beta_j\left(X_i\left(t_j^f\right) + X_j\left(t_j^f\right)\right) \\ + \left(\alpha - Q_j\left(t_j^f\right)\right)x_{jj}^*\left(t_j^f\right) + \left(\alpha - Q_i\left(t_j^f\right) - \left(t_i^f - t_j^f\right)\right)x_{ji}^*\left(t_j^f\right) \end{bmatrix}. \quad (3.42)$$

The first order condition with respect to the tax rate t_j^f yields the following negative best response:

$$t_j^f\left({t_i}^f\right) = \left(\beta_j - {t_i}^f\right). \quad (3.43)$$

Country i demonstrates a positive best response function, whereas country j exhibits a negative best response, indicating a tendency towards free-riding behavior. Using (3.41) and (3.43), the optimal equilibrium emissions tax rates of countries i and j are, respectively, as follows:

$${t_i}^{*f} = \frac{1}{12}\left(-\alpha + \left(9\beta_i + 2\beta_j\right)\right) \quad (3.44)$$

$${t_j}^{*f} = \frac{1}{12}\left(\alpha - 9\beta_i + 10\beta_j\right). \quad (3.45)$$

[41]Countries i and j's optimization problems with farsighted CBAs are detailed in Appendix C3.

With such anticipated adjustments[42], ${t_i}^{*f} > {t_j}^{*f}$, $\forall 0 < \beta_j < \beta_i < \alpha < (9\beta_i - 4\beta_j)$.

Country i's local production and exports are, respectively, expressed by the following equations:

$$ {x_{ii}}^{f} = \frac{1}{36}\left(13\alpha - 9\beta_i - 2\beta_j\right) \tag{3.46} $$

$$ {x_{ij}}^{f} = \frac{1}{12}\left(5\alpha - 9\beta_i + 2\beta_j\right). \tag{3.47} $$

Country j's local production and exports are, respectively, expressed by the following equations:

$$ {x_{jj}}^{f} = \frac{1}{12}\left(3\alpha + 9\beta_i - 6\beta_j\right) \tag{3.48} $$

$$ {x_{ji}}^{f} = \frac{1}{36}\left(13\alpha - 9\beta_i - 2\beta_j\right). \tag{3.49} $$

Countries i and j's production, consumption, and welfares equations are detailed in Appendix C3.

3.3.2.3 Endogenous Bilateral Tariffs

With endogenous bilateral tariffs, a government selects noncooperatively an emissions tax ${t_i}^{\tau}$, and an import tariff rate τ_i, for i, j. Given the equilibrium quantities expressed by Equations (3.23) and (3.24), country i's welfare optimization problem[43] is as follows, for i, j where $i \neq j$:

$$ \max_{t_i^\tau, \tau_i} {W_i}^{\tau} \Rightarrow \max_{t_i^\tau, \tau_i} \begin{bmatrix} \frac{1}{2}\left(Q_i(t_i^\tau, \tau_i)\right)^2 - \beta_i\left(X_i(t_i^\tau, \tau_i) + X_j(t_i^\tau, \tau_i)\right) + \tau_i x_{ji}^*(t_i^\tau, \tau_i) \\ +\left(\alpha - Q_i(t_i^\tau, \tau_i)\right)x_{ii}^*(t_i^\tau, \tau_i) + \left(\alpha - Q_j(t_i^\tau, \tau_i) - \tau_j(t_i^\tau, \tau_i)\right)x_{ij}^*(t_i^\tau, \tau_i) \end{bmatrix}. \tag{3.50} $$

The first order condition with respect to the tax rate t_i^τ yields the following negative best response:

$$ t_i^\tau\left(t_j^\tau, \tau\right) = \frac{1}{7}\left(-4\alpha + 6\beta_i - t_j^\tau + \left(3\tau_i + 2\tau_j\right)\right). \tag{3.51} $$

Country i's equilibrium emissions tax rate, for i, j where $i \neq j$, is expressed as follows:

$$ {t_i}^{*\tau} = \frac{1}{96}(-28\alpha + 103\beta_i - 11\beta_j). \tag{3.52} $$

While the equilibrium import tariff rate is expressed as follows, for i, j where $i \neq j$:

$$ {\tau_i}^{*} = \frac{1}{48}(16\alpha + 35\beta_i - 19\beta_j). \tag{3.53} $$

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[42] The model's parameters have been restricted to ensure that $\left({t_i}^{*f} - {t_j}^{*f}\right) > 0$ throughout the simulations.

[43] Country i's welfare optimization problem with endogenous bilateral tariffs is detailed in Appendix D3.

Under this noncooperative equilibrium, each country's emissions tax rate is positively related to its own environmental damage parameter while inversely related to the other country's parameter. Equation (3.52) clearly indicates that country i consistently enforces a higher emissions tax rate compared to country j, since $\left(t_i^{*\tau} - t_j^{*\tau}\right) = \frac{19}{16}\left(\beta_i - \beta_j\right)$ and $\beta_i > \beta_j > 0$ by assumption.

Country i's local production and exports are, respectively, as follows, for i, j where $i \neq j$:

$$x_{ii}^{\tau} = \frac{1}{96}(52\alpha - 49\beta_i + 29\beta_j) \tag{3.54}$$

$$x_{ij}^{\tau} = \frac{1}{96}(20\alpha - 47\beta_i - 5\beta_j). \tag{3.55}$$

Country i's total production, consumption, and welfare equations are detailed in Appendix D3.

3.4 The Cooperative Solution

In the cooperative scenario, it is assumed that countries collectively agree to impose a uniform emissions tax on the production of the polluting good, denoted as t^C, such that, $t_i^C = t_j^C = t^C$. This tax rate is chosen to maximize the joint welfare of both countries, where $W^C = \sum_{i \in N} W_i$.

Scholars have frequently advocated for uniform emissions tax solutions as an efficient policy instrument to address global environmental issues (Hoel 1992, Finus and Rundshagen 1998, Nordhaus 2006, Weitzman 2014). Indeed, uniform emissions tax solutions have gained support for several reasons. Firstly, they offer a straightforward approach. Unlike differentiated solutions, uniform taxes simplify the decision-making process and reduce the time required for negotiations, thereby lowering transaction costs and making it more appealing for countries to engage in cooperative efforts. Equity is another key aspect of uniform solutions. When all countries face the same tax rate, there is a sense of fairness and equal burden-sharing. This uniformity can enhance public acceptance and support for such policies, as it avoids perceptions of one country being unfairly favored over another (Finus and Rundshagen 1998, McEvoy and McGinty 2018).

Moreover, the enforcement and verification of uniform taxes in an agreement are relatively straightforward. Consequently, the uniform tax rate acts as a focal point (Schelling, 1960), a solution that stands out as an obvious choice, making it more likely for bargaining partners to converge and reach an agreement (Finus and Rundshagen 1998).

Due to the adoption of a uniform tax rate in both countries in a cooperative agreement, the necessity for carbon border adjustments is eliminated. Furthermore, the need for bilateral tariffs is also obviated, as changes in tariffs can be accounted for through changes in the emissions tax rate. Consequently, it is assumed that countries eliminate import tariffs, leading to the formation of a custom union, where ${\tau_i}^C = {\tau_j}^C = \tau^C = 0$.

In the current duopoly game, however, the firms continue to compete à la Cournot, where they set their production rates independently of each other. Thus, the optimization problems of firms i and j, given respectively by Equations (3.12) and (3.13), are reduced as follows, for i, j where $i \neq j$:

$$\max_{x_{ij}\ j \in N} \pi_i \Rightarrow \max_{x_{ij}\ j \in N} \sum_{j \in N} \left(P_j\left(x_{ij}\right) - t^C\right) x_{ij}. \tag{3.56}$$

The equilibrium quantities produced by the firm operating in country i are, for i, j where $i \neq j$:

$${x_{ii}}^*(t^C) = {x_{ij}}^*(t^C) = \frac{1}{3}(\alpha - t^C). \tag{3.57}$$

The above optima represent positive interior solutions, considering the constraints imposed on the model's parameters.

With cooperation, a uniform emissions tax rate t^C is chosen to maximize the joint welfare of both countries, and thus the maximization problem[44] of countries i and j can be expressed as follows:

$$\max_{t^C} \sum_i W_i^C \Rightarrow \max_{t^C} \sum_i \begin{bmatrix} \frac{1}{2}\left(Q_i(t^C)\right)^2 - \beta_i \left(X_i(t^C) + X_j(t^C)\right) \\ +\left(\alpha - Q_i(t^C)\right) x_{ii}^*(t^C) + \left(\alpha - Q_j(t^C)\right) x_{ij}^*(t^C) \end{bmatrix}. \tag{3.58}$$

[44] The fully cooperative optimization problem is detailed in Appendix E3.

The first order condition yields the following equilibrium emissions tax rate:

$$t^{*C} = \frac{1}{2}\left(-\alpha + 3(\beta_i + \beta_j)\right). \tag{3.59}$$

The cooperative equilibrium implies that the uniform emissions tax is positively related to both environmental damage parameters. It is evident that when the market size, as captured by the parameter α, is sufficiently small, where $\alpha \leq 3(\beta_i + \beta_j)$, the uniform tax rate is positive. However, when the market is sufficiently larger, the emissions tax rate becomes negative, where $\alpha > 3(\beta_i + \beta_j)$. Essentially, the cooperative equilibrium addresses the negative externality linked to the production of the polluting good by implementing a positive emissions tax rate. This tax reduces aggregate production, consequently lowering global emissions. Alternatively, the cooperative agreement may enforce a subsidy if the production of the polluting good is deemed insufficient due to the dynamics of Cournot competition.

Country i's local production and exports, for i, j where $i \neq j$, are given by the following equation:

$$x_{ii}{}^{*C} = x_{ij}{}^{*C} = \frac{1}{2}\left(\alpha - (\beta_i + \beta_j)\right). \tag{3.60}$$

Country i's total production, consumption, and welfare equations are detailed in Appendix E3.

3.5 Results

Having thoroughly examined the case of unilateral myopic carbon border adjustments (CBAs) with and without retaliation, the goal is to analyze the impacts of myopic CBAs on global welfare and emissions. This analysis will be compared to the basic trade model with bilateral endogenous tariffs and the model with farsighted CBAs. Specifically, the aim is to evaluate the effectiveness of myopic CBAs in reducing global emissions, their ability to level up the playing field concerning the convergence of environmental standards, their role in encouraging international environmental cooperation, their capacity to generate collective welfare gains, and their divergence from the bilateral tariff-based and the farsighted CBA approaches.

3.5.1 Analytical Results

Proposition 3.5.1.1: *Myopic CBAs, with and without retaliation, do not generate environmental gains in terms of lower global emissions, when compared to the farsighted CBA and bilateral endogenous tariff approaches.*

The complete proof of Proposition 3.5.1.1 is delineated to Appendix G3.

Let X^m, $X^{\breve{m}}$, X^f, and X^τ, represent global production under the myopic CBA without retaliation, myopic CBA with retaliation, farsighted CBA, and endogenous bilateral tariff scenarios, respectively. These global production levels are expressed in the following equations, respectively:

$$X^m = \sum_i X_i{}^m = \tfrac{1}{6}\Big(12\alpha - \big(5\beta_i + \beta_j\big)\Big) \tag{3.61}$$

$$X^{\breve{m}} = \sum_i X_i{}^{\breve{m}} = \tfrac{1}{18}\big(34\alpha - \big(13\beta_i + 7\beta_j\big)\big) \tag{3.62}$$

$$X^f = \sum_i X_i{}^f = \tfrac{1}{18}\Big(25\alpha - \big(9\beta_i + 8\beta_j\big)\Big) \tag{3.63}$$

$$X^\tau = \sum_i X_i{}^\tau = \tfrac{3}{4}\big(2\alpha - \big(\beta_i + \beta_j\big)\big). \tag{3.64}$$

Using (3.61) and (3.63), global production with myopic CBAs without retaliation always exceeds what would occur with farsighted CBAs, as expressed by this equation, $\forall \alpha > \beta_i > \beta_j > 0$:

$$X^m - X^f = \tfrac{1}{18}(11\alpha - 6\beta_i + 5\beta_j). \tag{3.65}$$

Using (3.61) and (3.64), global production with myopic CBAs without retaliation always exceeds what would be the case with bilateral endogenous tariffs, $\forall \alpha > \beta_i > \beta_j > 0$, as shown here:

$$X^m - X^\tau = \tfrac{1}{12}(6\alpha - \beta_i + 7\beta_j). \tag{3.66}$$

Notably, Equations (3.65) and (3.66) are strictly positive, since $\alpha > \beta_i > \beta_j > 0$, by assumption.

Similar results are obtained when considering the myopic CBA scenario with retaliation. Using (3.62), (3.63), and (3.64), global production with myopic CBAs with retaliation consistently exceeds what would be the case with farsighted CBA and bilateral endogenous tariff approaches, as expressed by the following equations, respectively, $\forall \alpha > \beta_i > \beta_j > 0$:

$$X^{\breve{m}} - X^f = \frac{1}{18}(9\alpha - 4\beta_i + \beta_j) \tag{3.67}$$

$$X^{\breve{m}} - X^\tau = \frac{1}{36}(14\alpha + \beta_i + 13\beta_j). \tag{3.68}$$

Thus, myopic CBAs, regardless of retaliation, when compared to farsighted CBA and bilateral tariff approaches, are less effective in reducing global emissions. Unlike farsighted CBAs, environmental taxes under the myopic CBA model do not account ex-ante for carbon adjustments; instead, these adjustments occur after the welfare optimization process.

In terms of the capacity of carbon border adjustments to reduce global emissions beyond the scope of the bilateral trade model, only farsighted CBAs demonstrate this potential. However, this potential is only realized under certain conditions, where $\frac{1}{4}\left(9\beta_i + 11\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$, $\forall 0 < \beta_j < \beta_i < 25\beta_j$, or where, $\frac{1}{20}\left(47\beta_i + 5\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$, $\forall 0 < \beta_j < 25\beta_j < \beta_i$.

Proposition 3.5.1.2: *Myopic CBAs do not lead to higher environmental taxes, when compared to the farsighted CBA and bilateral endogenous tariff approaches.*

The complete proof of Proposition 3.5.1.2 is delineated to Appendix H3.

Using (3.27), (3.44), and (3.45), countries i and j's emissions tax rates with myopic CBAs, compared to the farsighted CBA case, are expressed by the following equations, respectively:

$$t_i^{*f} - t_i^{*m} = \frac{1}{24}(10\alpha - 3\beta_i + 7\beta_j) \tag{3.69}$$

$$t_j^{*f} - t_j^{*m} = \frac{1}{24}\left(14\alpha - \left(15\beta_i + \beta_j\right)\right). \tag{3.70}$$

It is evident from Equation (3.69), that country i consistently enforces a lower tax with myopic CBAs in comparison to the farsighted CBA scenario, since $t_i^{*f} - t_i^{*m} > 0, \forall \alpha > \beta_i > \beta_j > 0$.

Equation (3.70) shows that $t_j^{*f} - t_j{}^{*m} > 0$, if $\alpha > \frac{1}{14}\left(15\beta_i + \beta_j\right)$. Since the farsighted CBA case requires that $15\alpha \geq \left(27\beta_i - 6\beta_j\right)$, then $t_j^{*f} - t_j{}^{*m} > 0$, $\forall \frac{1}{15}\left(27\beta_i - 6\beta_j\right) \leq \alpha < (9\beta_i - 4\beta_j)$.

Using (3.27) and (3.52), country i's emissions tax rate with myopic CBAs is consistently lower than the bilateral tariff model, as demonstrated by the following equation, for i, j where $i \neq j$:

$$t_i^{*\tau} - t_i{}^{*m} = \frac{1}{96}(20\alpha + 19\beta_i + \beta_j). \tag{3.71}$$

It follows that $t_i^{*\tau} - t_i{}^{*m} > 0, \forall \alpha > \beta_i > \beta_j > 0$, for i, j where $i \neq j$. Equation (3.71) shows that any country implements a lower emissions tax with myopic CBAs in comparison to the tariff model, while the difference widens when the marginal damage parameters take higher values.

Hence, given the model's restrictions, specifically $\alpha > \beta_i > \beta_j > 0$ and $\alpha \geq \frac{1}{15}\left(27\beta_i - 6\beta_j\right)$, emissions taxes with myopic CBAs are lower compared to the other noncooperative scenarios, regardless of retaliation and irrespective of the extent of heterogeneity in environmental damages.

Bear in consideration that emissions taxes remain unchanged with or without retaliation, given that unilateral carbon border adjustments introduced by country i and the subsequent retaliation by country j, both occur after the emissions taxes of both governments have already been established.

When assessing the ability of CBAs to promote a convergence in environmental standards, only farsighted CBAs, subject to specific conditions, demonstrate the capability to increase emissions tax rates in both countries beyond what would occur in the basic endogenous tariff model.

Using (3.44), (3.45), and (3.52), countries i and j's emissions tax rates with farsighted CBAs, compared to the bilateral tariff case, are, respectively, expressed by the following equations:

$$t_i{}^{*f} - t_i{}^{*\tau} = \frac{1}{96}(20\alpha - 31\beta_i + 27\beta_j) \tag{3.72}$$

$$t_j^{*f} - t_j{}^{*\tau} = \frac{1}{96}(36\alpha - 61\beta_i - 23\beta_j). \tag{3.73}$$

Given the parameters constraints, specifically $\alpha > \beta_i > \beta_j > 0$ and $\alpha \geq \frac{1}{20}(47\beta_i + 5\beta_j)$, equations (3.72) and (3.73) are strictly positive, indicating that both countries impose higher emissions taxes when anticipating carbon border adjustments in comparison to endogenous tariffs. For country i, a positive best response with farsighted CBAs, raises the tax above the tariff model, while the difference widens as β_j rises, since $\frac{\partial(t_i{}^{*f} - t_i{}^{*\tau})}{\partial \beta_j} > 0$. For country j, a domestic higher tax, lowers the adjustment bill paid to country i and raises its welfare, since $\frac{\partial W_j{}^f}{\partial t_j^f} > 0$.

These findings are in close agreement with Hecht and Peters (2018), who observed that CBAs support the implementation of more stringent environmental policies across countries.

Proposition 3.5.1.3: *In the context of Myopic CBAs, collective welfare can be higher when country j retaliates, as opposed to the scenario without retaliation.*

The complete proof of Proposition 3.5.1.3 is delineated to Appendix I3.

Let W^m be the collective welfare with myopic CBAs without retaliation. It is expressed as follows:

$$W^m = \sum_i W_i^m = \frac{1}{2^4 \times 3^2}\left[144\alpha^2 + \beta_i(-288\alpha + 91\beta_i + 142\beta_j) + \beta_j(-288\alpha + 19\beta_j)\right]. \quad (3.74)$$

Let $W^{\tilde{m}}$ be the collective welfare with myopic CBAs with retaliation. It is expressed as follows:

$$W^{\tilde{m}} = \sum_i W_i^{\tilde{m}} = \frac{1}{2^4 \times 3^4}\left[1288\alpha^2 + \beta_i(703\beta_i + 1418\beta_j - 2468\alpha) + \beta_j(355\beta_j - 2516\alpha)\right]. \quad (3.75)$$

Using (3.74) and (3.75), the collective welfare gains from retaliation are expressed as follows:

$$W^{\tilde{m}} - W^m = \frac{-1}{2^2 \times 3^4}\left(\left(2\alpha - 29\beta_i - 23\beta_j\right)\left(\alpha - \beta_i + 2\beta_j\right)\right). \quad (3.76)$$

Since $(\alpha - \beta_i + 2\beta_j) > 0$, $\forall \alpha > \beta_i > \beta_j > 0$, these welfare gains are strictly positive, when $\frac{1}{20}(29\beta_i + 5\beta_j) \leq \alpha < \frac{1}{2}(29\beta_i + 23\beta_j)$. Also, they become more significant as β_j takes a higher value, since $\frac{\partial[W^{\tilde{m}} - W^m]}{\partial \beta_j} = \frac{(92\beta_j + 35\beta_i + 19\alpha)}{2^2 \times 3^4} > 0$, $\forall\ \alpha > \beta_i > \beta_j > 0$.

Moreover, they are associated with environmental gains measured in terms of lower global emissions, as shown by the following expression, $\forall \alpha > \beta_i > \beta_j > 0$:

$$\sum_i X_i{}^m - \sum_i X_i{}^{\tilde{m}} = \frac{1}{9}\left(\alpha - \beta_i + 2\beta_j\right). \tag{3.77}$$

These collective welfare improvements in the retaliatory scenario stem from country j's post-retaliation individual welfare gains. The reduced global production after retaliation, as outlined in (3.77), comes at the expense of country i, as the reductions in country i's production, as shown in (3.38), outweigh the post-retaliation improvement in production for country j, as shown in (3.39). This leads to higher prices and profits in country j, driving its welfare gains, while country i incurs welfare losses primarily due to lower before-tax profits.

3.5.2 Simulation Results

Due to the complexities of the equations, the analysis had to rely on numerical simulations, which are limited by certain parameter constraints[45]. The model ensures an active market by assuming that any marginal environmental damage parameter cannot exceed the maximal marginal utility of good X, that is, $\alpha > \beta_i > \beta_j > 0$. Additionally, it imposes certain restrictions to maintain the market structure throughout the game and guarantee a positive interior solution. Therefore, X_i, $x_{ii}{}^* \in \mathbb{R}_n^{++}$ and $x_{ij}{}^* \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$. Also, the constrained parameters warrant positive trade flows and positive import tariffs.

The main findings of this essay reveal that myopic CBAs, with or without retaliation, do not generate environmental gains. In contrast, farsighted CBAs can lead to both environmental gains and overall welfare gains, but only under specific conditions. They also result in higher emissions

[45]The most restrictive conditions on the model's parameters are summarized in Appendix F3, with the most restrictive on α's lower bound (F3.5), where $\alpha \geq \frac{1}{20}\left(47\beta_i + 5\beta_j\right)$, and on α's upper bound (F3.4), where $\alpha < \left(9\beta_i - 4\beta_j\right)$.

tax rates in both countries. However, myopic CBAs without retaliation offer a greater potential for cooperation, across various levels of heterogeneity. On the other hand, myopic CBAs with retaliation can lead to collective welfare gains under specific conditions. The numerical simulation results are summarized in the following remarks.

Remark 3.5.2.1: *Myopic CBAs without retaliation generate greater incentives for environmental cooperation, when compared to farsighted CBA and bilateral endogenous tariff approaches.*

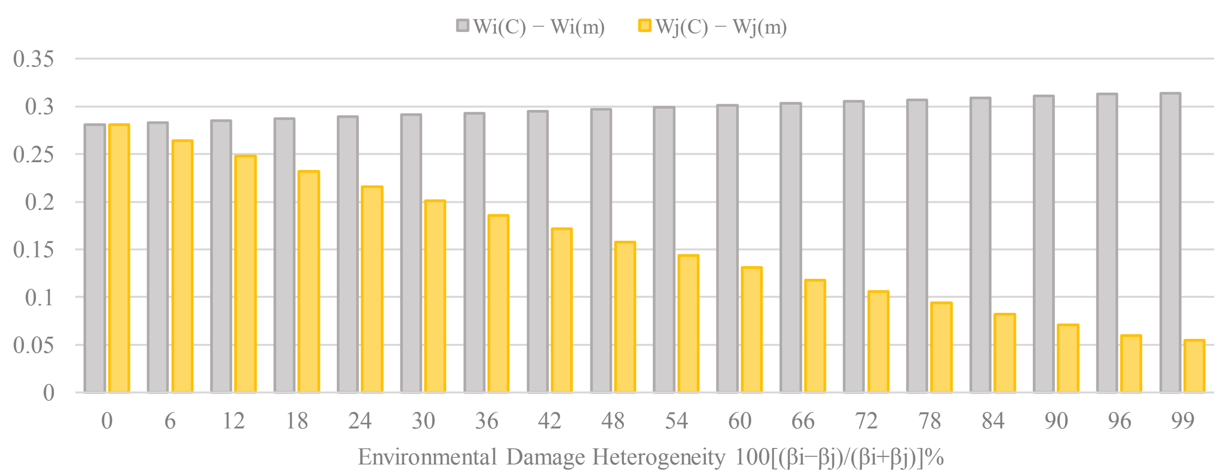
Let W_i^C and W_i^m represent country i's welfares under the cooperative and myopic CBA without retaliation scenarios, respectively, for i, j where $i \neq j$. The individual welfare gains of countries i and j from cooperation are expressed in the following equations, respectively:

$$W_i^C - W_i^m = \frac{1}{2^5 \times 3}\left[\left(107\beta_i - 53\beta_j\right)\left(\beta_i + \beta_j\right) - 32\alpha\left(\beta_i - \beta_j\right)\right] \tag{3.78}$$

$$W_j^C - W_j^m = \frac{1}{2^5 \times 3^2}\left[96\alpha\left(\beta_i - \beta_j\right) - 215{\beta_i}^2 + 130\beta_i\beta_j + 409{\beta_j}^2\right]. \tag{3.79}$$

The numerical simulations reveal that both countries derive positive welfare gains with cooperation when compared to the myopic CBA case without retaliation. This holds true across varying degrees of heterogeneity and various values of α, where $\alpha \geq \frac{1}{4}\left(5\beta_i - 3\beta_j\right)$ and $\alpha > \sum_i \beta_i$.

Figure 3.1: Individual Welfare Gains: Comparing Cooperation to Myopic CBAs - Varied Heterogeneity



Assuming $\alpha = 2.4 \sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 3.1 depicts Equations (3.78) and (3.79), where β_i takes a higher value and β_j takes a lower value as the degree of heterogeneity increases. As clearly depicted in Figure 3.1, while their benefits may not be equal, both countries still prefer the cooperative scenario to the myopic CBA case. This preference holds true not only in the homogeneous benchmark case, but also over a wide range of environmental damage heterogeneity. For country i, having the highest damage parameter, lower production and consumption under cooperation, lead to improvements in net consumer surplus and before-tax profits, enhancing its welfare gains. A higher damage parameter promotes increasing welfare gains from cooperation compared to myopic CBAs, when $\alpha < \frac{1}{16}\left(107\beta_i + 27\beta_j\right)$. Still, as the market becomes larger, as captured by α, these welfare gains will diminish, since $\frac{\partial\left[W_i^C - W_i^m\right]}{\partial\alpha} = \frac{(\beta_j - \beta_i)}{3} < 0, \forall \beta_i > \beta_j$.

For country j, the benefits mainly arise from enhanced before-tax profits and savings on border adjustment payments, leading to lower welfare gains from cooperation. As β_j takes a lower value, country j sees diminishing welfare gains, as long as $\alpha < \frac{1}{48}\left(65\beta_i + 409\beta_j\right)$. Unlike country i, country j benefits from a larger market size, since $\frac{\partial\left[W_j^C - W_j^m\right]}{\partial\alpha} = \frac{(\beta_i - \beta_j)}{3} > 0, \forall \beta_i > \beta_j$.

Alternatively, let $W_i^C - W_i^f$ represent country i's individual welfare gains from cooperation in comparison to the farsighted CBA case. These welfare gains are as follows, for i, j where $i \neq j$:

$$W_i{}^C - W_i{}^f = \frac{1}{216}\left(13\alpha^2 - 5\alpha\left(30\beta_i - 4\beta_j\right) + 297\beta_i{}^2 + 156\beta_i\beta_j - 128\beta_j{}^2\right) \quad (3.80)$$

$$W_j{}^C - W_j{}^f = \frac{1}{324}\left(11\alpha^2 + \alpha\left(72\beta_i - 182\beta_j\right) - 243\beta_i{}^2 + 126\beta_i\beta_j + 392\beta_j{}^2\right). \quad (3.81)$$

Figure 3.2 depicts Equations (3.80) and (3.81) with the same conditions as Figure 3.1. It clearly indicates that the potential for cooperation is confined to a narrow window, primarily within the homogeneous case, beyond which countries i and j consistently exhibit divergent preferences for the cooperative agreement. In this case, country i benefits from rising net consumer surplus and pre-tax profits, enhancing its welfare gains. In contrast, country j saves the CBA payment to country i, but faces more significant declines in net consumer surplus and pre-tax profits, leading to individual welfare losses, since cooperation reduces its production and consumption.

Let $W_i^C - W_i^\tau$ represent country i's individual welfare gains from cooperation in comparison to the bilateral tariff model. These individual welfare gains are as follows, for i, j where $i \neq j$:

$$W_i^C - W_i^\tau = \frac{1}{2^9 \times 3}\left[48\alpha^2 + \beta_i(1847\beta_i + 546\beta_j - 848\alpha) + \beta_j(368\alpha - 1193\beta_j)\right]. \quad (3.82)$$

Figure 3.2: Individual Welfare Gains: Comparing Cooperation to Farsighted CBAs - Varied Heterogeneity

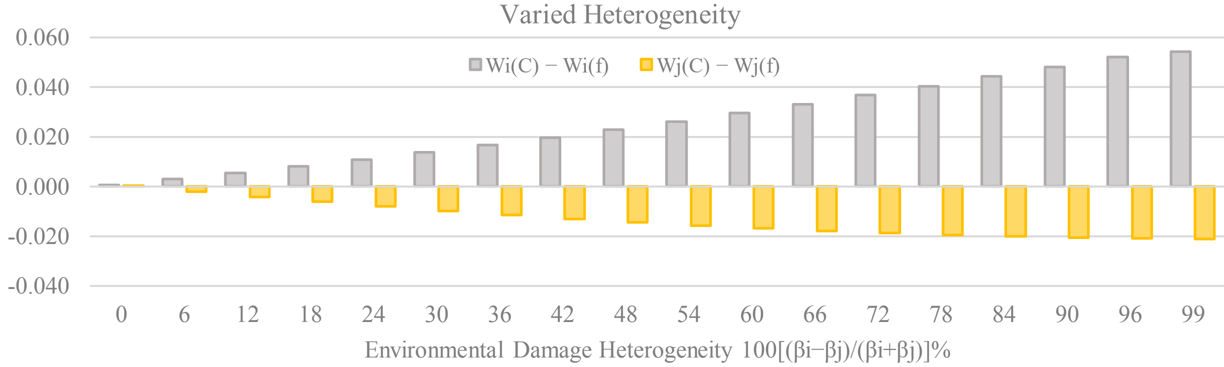


Figure 3.3: Individual Welfare Gains: Comparing Cooperation to Bilateral Endogenous Tariffs - Varied Heterogeneity

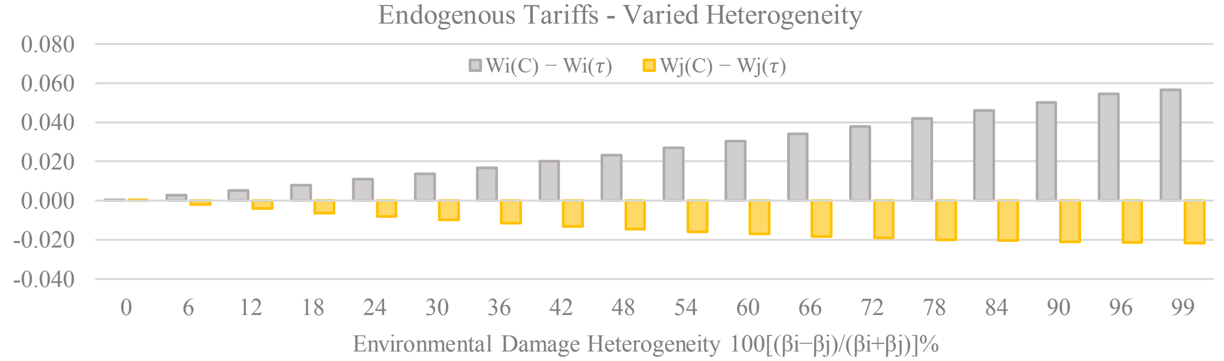


Figure 3.3 depicts Equation (3.82) for both countries, with the same conditions as Figures 3.1 and 3.2. It's noteworthy that the range of cooperation with bilateral endogenous tariffs closely mirrors that of farsighted CBAs, where countries mostly display divergent preferences for the cooperative scenario, across various degrees of heterogeneity. These findings are consistent when assuming

that $\sum_i \beta_i$ increases[46] compared to where $\sum_i \beta_i = 1$, and when changing the value of α, where $\frac{1}{20}(47\beta_i + 5\beta_j) \leq \alpha < (9\beta_i - 4\beta_j)$.

Remark 3.5.2.2: *In the presence of heterogeneity, myopic CBAs with retaliation can eliminate any prospects for international environmental cooperation.*

Let W_i^C and $W_i^{\breve{m}}$ denote country i's individual welfare, under the cooperative and the myopic CBA retaliatory scenarios, respectively. The individual welfare gains stemming from cooperation, compared to the myopic CBA case with retaliation, for countries i and j, are, respectively:

$$W_i{}^C - W_i^{\breve{m}} = \frac{1}{2^5 \times 3^4}\left[160\alpha^2 - 56\alpha(25\beta_i - 23\beta_j) + 3265\beta_i{}^2 - 1223\beta_j{}^2 + 602\beta_i\beta_j\right] \quad (3.83)$$

$$W_j{}^C - W_j^{\breve{m}} = \frac{-1}{2^5 \times 3^2}\left[16\alpha^2 + \beta_i(231\beta_i - 194\beta_j - 128\alpha) + \beta_j(160\alpha - 345\beta_j)\right]. \quad (3.84)$$

The simulations reveal that country i consistently benefits from cooperation, while country j mostly prefers the retaliatory scenario, across varying degrees of heterogeneity and various values of α, where $\alpha \geq \frac{1}{20}(29\beta_i + 5\beta_j)$ and $\alpha > \sum_i \beta_i$.

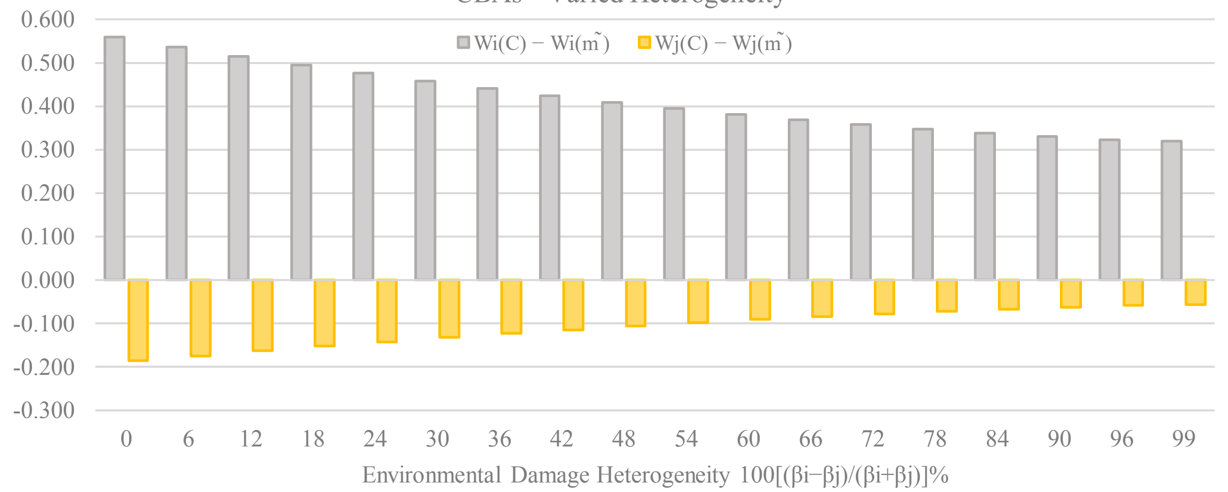
Assuming $\alpha = 2.4\sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 3.4 depicts Equations (3.83) and (3.84), where β_i takes a higher value and β_j takes a lower value, as the degree of heterogeneity increases. In this case, the simulations do not reveal any range of parameters where cooperation is feasible.

As β_i takes a higher value, country i experiences welfare gains from cooperation. These gains primarily stem from reduced production and consumption, notably boosting its net consumer surplus and the local firm's pre-tax profits, which outweigh the losses in CBA revenues. However, as β_i drifts further away from β_j, the losses in CBA revenues become more significant reducing country i's overall welfare gains.

[46] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix J3.

In contrast, country j experiences a decrease in net consumer surplus, which, combined with losses retaliatory tariff revenues, outweigh the improvement in pre-tax profits, leading to overall welfare losses. Nevertheless, as β_j takes a lower value with higher degrees of heterogeneity, country j faces diminishing losses in retaliatory tariff revenues, reducing its overall welfare losses.

Figure 3.4: Individual Welfare Gains: Comparing Cooperation to Myopic Retaliatory CBAs - Varied Heterogeneity



These results are consistent when assuming that $\sum_i \beta_i$ increases[47] compared to where $\sum_i \beta_i = 1$, and when changing the value of the parameter α, where $\alpha \geq \frac{1}{20}\left(29\beta_i + 5\beta_j\right)$ and $\alpha > \sum_i \beta_i$.

Remark 3.5.2.3: *Based on the numerical simulations, in the absence of cooperation, collective welfare is mostly highest under the basic trade model with bilateral endogenous tariffs.*

Let W^{τ}, W^{f}, and W^{C} represent collective welfare under bilateral endogenous tariffs, farsighted CBAs, and cooperation, respectively. These are expressed in the following equations:

$$W^{\tau} = \sum_i W_i^{\tau} = \frac{1}{2^8}\left[240\alpha^2 + \beta_i(-432\alpha + 147\beta_i + 330\beta_j) + \beta_j\left(-432\alpha + 147\beta_j\right)\right] \quad (3.85)$$

$$W^{f} = \sum_i W^{f}{}_i = \frac{1}{2^3 \times 3^4}\left[587\alpha^2 + \beta_i(-990\alpha + 243\beta_i + 576\beta_j) + \beta_j(-992\alpha + 248\beta_j)\right] \quad (3.86)$$

$$W^{C} = \sum_i W_i^{C} = (\alpha - \sum_i \beta_i)^2. \quad (3.87)$$

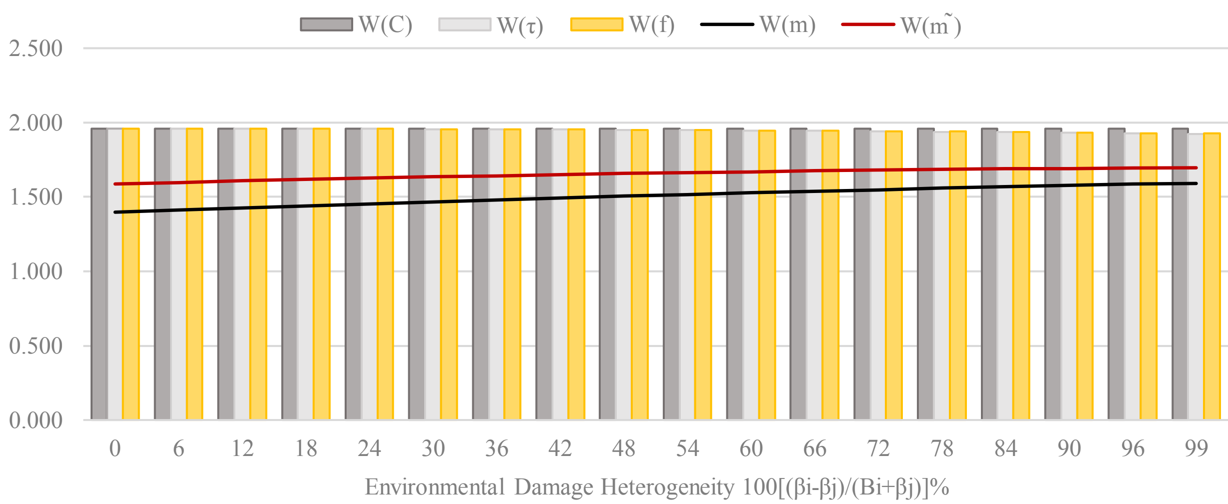
[47] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix J3.

The numerical simulations demonstrate that the cooperative equilibrium consistently leads to the highest collective welfare at alternative degrees of heterogeneity. However, beyond cooperation, the basic trade model with endogenous tariffs achieves the highest collective welfare. This holds true across varying degrees of heterogeneity and various values of the parameter α, where either

$\frac{1}{164}\left(459\beta_i + 361\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$, or

$\forall\, 0 < \beta_j < \beta_i < 25\beta_j, \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \le \alpha < \frac{1}{4}\left(9\beta_i + 11\beta_j\right)$.

Figure 3.5: Cooperative and Noncooperative Collective Welfares - Varied Heterogeneity



Assuming $\alpha = 2.4\sum_i \beta_i$ and $\sum_i \beta_i = 1$, Figure 3.5 illustrates collective welfare under cooperation (3.87) and all noncooperative scenarios: bilateral tariff model (3.85), farsighted CBA case (3.86), and myopic CBA cases without (3.74) and with (3.75) retaliation. It is evident that collective welfare is highest with cooperation, regardless of heterogeneity levels.

Beyond cooperation, the basic trade model incorporating endogenous bilateral tariffs emerges as the strongest contributor to substantial collective welfare. These findings support Markusen's (1975) argument that addressing the externality caused by a global pollutant without global cooperation requires a mix of Pigouvian taxes and import tariffs.

However, the farsighted CBA case emerges as a viable alternative, representing a second-best option. It closely mirrors outcomes akin to the endogenous bilateral tariff model, as CBA adjustments are anticipated and integrated into optimal emissions tax rates, while providing environmental and collective welfare gains, in some specific conditions[48]. This potential is realized within a narrow range of parameters, specifically, where either:

$\forall\ 0 < \beta_j < \beta_i < 25\beta_j, \frac{1}{4}\left(9\beta_i + 11\beta_j\right) < \alpha < \frac{1}{164}\left(459\beta_i + 361\beta_j\right)$, or

$\forall\ 0 < \beta_j < 25\beta_j < \beta_i, \frac{1}{20}\left(47\beta_i + 5\beta_j\right) < \alpha < \frac{1}{164}\left(459\beta_i + 361\beta_j\right)$.

These results closely align with Eyland and Zaccour (2014) who demonstrated that CBAs could serve as a credible threat to achieve an outcome that closely resembles the cooperative outcome.

Conversely, as detailed in Proposition 3.5.1.3, the myopic CBA case with retaliation can outperform the scenario without retaliation in terms of collective welfare under specific conditions, where $\frac{1}{20}\left(29\beta_i + 5\beta_j\right) \leq \alpha < \frac{1}{2}\left(29\beta_i + 23\beta_j\right)$.

These results remain consistent at alternative degrees of environmental damage heterogeneity and when assuming $\sum_i \beta_i$ is increasing[49] as opposed to $\sum_i \beta_i = 1$.

3.6 Conclusion

The present essay demonstrates that the effectiveness and outcomes of unilateral carbon border adjustments ultimately depends on their time sensitivity. Notably, myopic CBAs fall short in delivering environmental gains when compared to alternative noncooperative climate measures, such as farsighted CBA and bilateral tariff approaches. In terms of promoting convergence in

[48] The collective welfare comparison between bilateral tariff and farsighted CBA cases is provided in Appendix D3.
[49] The simulation results, assuming $\sum_i \beta_i$ is increasing as opposed to $\sum_i \beta_i = 1$, are detailed in Appendix J3.

environmental standards, myopic CBAs do not contribute to an environmental race to the top. However, it is farsighted CBAs that exhibit the potential, under specific conditions, to elevate emissions taxes beyond the confines of the reciprocal trade model with endogenous tariffs. When it comes to fostering international environmental cooperation, myopic CBAs without retaliation offer strong incentives for such cooperation. Conversely, myopic CBAs with retaliation can significantly reduce the prospects for international environmental cooperation. Finally, in the context of generating collective welfare gains in the absence of cooperation, the basic model with bilateral endogenous tariffs stands out as the most favorable option. Only the farsighted CBA case closely mirrors the outcomes of the reciprocal tariff model since CBA adjustments are anticipated and incorporated into optimal emissions tax rates.

The simplified framework of the current model does introduce certain limitations. To specifically examine the impact of environmental damage heterogeneity, the model assumes that both countries have the same market size, incur identical marginal production costs, and that each firm can export to the other foreign market without any transportation costs. Additionally, it assumes that environmental damage is a linear function of aggregate production, which makes the model more tractable. These simplifications, while necessary for the current study, pave the way for many research questions that can be addressed in the future, to explore potential outcomes when any of these assumptions are relaxed.

Despite the increased recognition of the climate crisis, significant disparities persist in environmental standards and regulations. The proliferation of carbon pricing schemes is certainly becoming more evident in both affluent and less affluent countries. However, the impacts of many of these schemes on global emissions require time, particularly in regions where environmental regulations remain too lax to drive substantial and immediate changes. The pressing need for accelerated global climate action calls unequivocally for a reduction in these disparities. In the absence of a quick-fix solution, owing to the diversity of the regulatory landscape and substantial differences in environmental regulations, carbon border adjustment (CBA) measures emerge as a viable alternative for immediate climate action. This essay reveals, however, that only farsighted CBAs can effectively reduce global emissions in sufficiently small markets and generate overall welfare gains. It also highlights the role of myopic CBAs in promoting international environmental cooperation, despite the differences in environmental damages across countries.

3.7 Appendices

3.7.1 Appendix A3: Noncooperative Solutions - The Firm's Optimization Problem

The firms' optimization problems in countries i and j, are expressed, respectively, as follows:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[(\alpha - Q_i - t_i)x_{ii} + \left(\alpha - Q_j - t_i\right)x_{ij} - \tau_j x_{ij}\right] \quad \text{(A3.1)}$$

$$\max_{x_{jj}, x_{ji}} \pi_j \Rightarrow \max_{x_{jj}, x_{ji}} \left[\left(\alpha - Q_j - t_j\right)x_{jj} + \left(\alpha - Q_i - t_j\right)x_{ji} - \tau_i x_{ji} - \omega_i x_{ji}\right]. \quad \text{(A3.2)}$$

The firms' optimization problems in each scenario are described in the following subsections. For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed in each case that $X_i, x_{ii} \in \mathbb{R}_n^{++}$ and $x_{ij} \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$.

3.7.1.1 Under Myopic Carbon Border Adjustments

With myopic CBAs, Equations (A3.1) and (A3.2) are reduced as follows, for i, j where $i \neq j$:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[(\alpha - Q_i - t_i{}^m)x_{ii} + \left(\alpha - Q_j - t_i{}^m\right)x_{ij}\right]. \quad \text{(A3.1.1)}$$

The first order conditions (FOCs) with respect to country i's local production and exports are:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow 2x_{ii}{}^* = \left(\alpha - x_{ji} - t_i{}^m\right) \quad \text{(A3.1.2)}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow 2x_{ij}{}^* = \left(\alpha - x_{jj} - t_i{}^m\right). \quad \text{(A3.1.3)}$$

By symmetry, the FOCs with respect to country j's local production and exports are:

$$\frac{\partial \pi_j}{\partial x_{jj}} = 0 \Rightarrow 2x_{jj}{}^* = \left(\alpha - x_{ij} - t_j{}^m\right) \quad \text{(A3.1.4)}$$

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow 2x_{ji}{}^* = \left(\alpha - x_{ii} - t_j{}^m\right). \quad \text{(A3.1.5)}$$

The second order conditions (SOCs) are satisfied, as shown here, for i, j where $i \neq j$:

$$\frac{\partial^2 \pi_i}{\partial x_{ii}{}^2} < 0; \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} < 0; \text{and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}} \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} - \left(\frac{\partial^2 \pi_i}{\partial x_{ii} \partial x_{ij}}\right) > 0.$$

Using (A3.1.2), (A3.1.3), (A3.1.4), and (A3.1.5), the Cournot equilibrium quantities produced by the firm operating in country i, for i, j where $i \neq j$, are given by the following expressions:

$$x_{ii}{}^{*}(t^{m}) = \frac{1}{3}\left(\alpha - 2t_i{}^{m} + t_j{}^{m}\right) \tag{A3.1.6}$$

$$x_{ij}{}^{*}(t^{m}) = \frac{1}{3}\left(\alpha - 2t_i{}^{m} + t_j{}^{m}\right). \tag{A3.1.7}$$

3.7.1.2 Under Farsighted Carbon Border Adjustments

With farsighted CBAs, Equations (A3.1) and (A3.2) are reduced to the following equations:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[(\alpha - Q_i - t_i{}^{f})x_{ii} + \left(\alpha - Q_j - t_i{}^{f}\right)x_{ij}\right] \tag{A3.2.1}$$

$$\max_{x_{jj}, x_{ji}} \pi_j \Rightarrow \max_{x_{jj}, x_{ji}} \left[\left(\alpha - Q_j - t_j{}^{f}\right)x_{jj} + (\alpha - Q_i - t_i{}^{f})x_{ji}\right]. \tag{A3.2.2}$$

The first order conditions (FOCs) with respect to country i's local production and exports are:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow x_{ii}{}^{*} = \frac{1}{2}\left(\alpha - x_{ji} - t_i{}^{f}\right) \tag{A3.2.3}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow x_{ij}{}^{*} = \frac{1}{2}\left(\alpha - x_{jj} - t_i{}^{f}\right). \tag{A3.2.4}$$

The first order conditions (FOCs) with respect to country j's local production and exports are:

$$\frac{\partial \pi_j}{\partial x_{jj}} = 0 \Rightarrow x_{jj}{}^{*} = \frac{1}{2}\left(\alpha - x_{ij} - t_j{}^{f}\right) \tag{A3.2.5}$$

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow x_{ji}{}^{*} = \frac{1}{2}(\alpha - x_{ii} - t_i{}^{f}). \tag{A3.2.6}$$

The second order conditions (SOCs) are satisfied, as shown here:

$$\frac{\partial^2 \pi_i}{\partial x_{ii}{}^2} < 0, \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} < 0, \text{ and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}} \frac{\partial^2 \pi_i}{\partial x_{ij}{}^2} - \left(\frac{\partial^2 \pi_i}{\partial x_{ii} \partial x_{ij}}\right) > 0.$$

Using (A3.2.3), (A3.2.4), (A3.2.5), and (A3.2.6), the Cournot equilibrium quantities produced by the firms operating in countries i and j, respectively, are given by the following equations:

$$x_{ii}{}^{*}\left(t^{f}, \left(t_i{}^{f} - t_j{}^{f}\right)\right) = \frac{1}{3}(\alpha - t_i{}^{f}) \tag{A3.2.7}$$

$$x_{ij}{}^{*}\left(t^{f}, \left(t_i{}^{f} - t_j{}^{f}\right)\right) = \frac{1}{4}\left(\alpha - 2t_i{}^{f} + t_j{}^{f}\right) \tag{A3.2.8}$$

$$x_{jj}^{*}\left(t^{f},\left(t_i^{f}-t_j^{f}\right)\right)=\tfrac{1}{3}\left(\alpha+t_i^{f}-2t_j^{f}\right) \tag{A3.2.9}$$

$$x_{ji}^{*}\left(t^{f},\left(t_i^{f}-t_j^{f}\right)\right)=\tfrac{1}{3}(\alpha-t_i^{f}). \tag{A3.2.10}$$

3.7.1.3 Under Endogenous Bilateral Tariffs

With positive endogenous tariffs, Equations (A3.1) and (A3.2) are reduced to, for i, j where $i \neq j$:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[(\alpha-Q_i-t_i^{\tau})x_{ii}+\left(\alpha-Q_j-t_i^{\tau}\right)x_{ij}-\tau_j x_{ij}\right]. \tag{A3.3.1}$$

The first order conditions (FOCs) with respect to country i's local production and exports are:

$$\frac{\partial \pi_i}{\partial x_{ii}}=0 \Rightarrow 2x_{ii}^{*}=\left(\alpha-x_{ji}-t_i^{\tau}\right) \tag{A3.3.2}$$

$$\frac{\partial \pi_i}{\partial x_{ij}}=0 \Rightarrow 2x_{ij}^{*}=\left(\alpha-x_{jj}-t_i^{\tau}-\tau_j\right). \tag{A3.3.3}$$

By symmetry, the FOCs with respect to country j's local production and exports are as follows:

$$\frac{\partial \pi_j}{\partial x_{jj}}=0 \Rightarrow 2x_{jj}^{*}=\left(\alpha-x_{ij}-t_j^{\tau}\right) \tag{A3.3.4}$$

$$\frac{\partial \pi_j}{\partial x_{ji}}=0 \Rightarrow 2x_{ji}^{*}=\left(\alpha-x_{ii}-t_j^{\tau}-\tau_i\right). \tag{A3.3.5}$$

The second order conditions (SOCs) are satisfied, as we have:

$$\frac{\partial^2 \pi_i}{\partial x_{ii}^2}<0; \frac{\partial^2 \pi_i}{\partial x_{ij}^2}<0; \text{ and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}}\,\frac{\partial^2 \pi_i}{\partial x_{ij}^2}-\left(\frac{\partial^2 \pi_i}{\partial x_{ii}\partial x_{ij}}\right)>0.$$

Using (A3.3.2), (A3.3.3), (A3.3.4), and (A3.3.5), the Cournot equilibrium quantities produced by the firm operating in country i are given by the following expressions, for i, j where $i \neq j$:

$$x_{ii}^{*}(t^{\tau},\tau)=\tfrac{1}{3}\left(\alpha-2t_i^{\tau}+t_j^{\tau}+\tau_i\right) \tag{A3.3.6}$$

$$x_{ij}^{*}(t^{\tau},\tau)=\tfrac{1}{3}\left(\alpha-2t_i^{\tau}+t_j^{\tau}-2\tau_j\right). \tag{A3.3.7}$$

3.7.2 Appendix B3: Noncooperative Solutions - The Government's Optimization Problem, Myopic CBAs

3.7.2.1 Myopic Carbon Border Adjustments without Retaliation

Let $t_i{}^m$ be country i's emissions tax rate in the myopic CBA case, then country i's welfare maximization problem can be expressed as follows, for i, j where $i \neq j$:

$$\max_{t_i^m} W_i{}^m \Rightarrow \max_{t_i^m}\left[8\alpha(\alpha - 3\beta_i) + t_i^m\left(12\beta_i - 7t_i^m - 2t_j^m - 8\alpha\right) + t_j^m\left(4\alpha + 12\beta_i + 5t_j^m\right)\right]. \quad \text{(B3.1.1)}$$

The first order condition with respect to the emissions tax rate t_i^m, for i, j where $i \neq j$, is as follows:

$$\frac{\partial W_i{}^m}{\partial t_i{}^m} = 0 \Rightarrow (-8\alpha + 12\beta_i - 14t_i^m - 2t_j{}^m) = 0. \quad \text{(B3.1.2)}$$

Using (B3.1.2), country i's equilibrium emissions tax rate is as follows, for i, j where $i \neq j$:

$$t_i{}^{*m} = \frac{1}{8}(-4\alpha + 7\beta_i - \beta_j). \quad \text{(B3.1.3)}$$

Equation (B3.1.3) indicates that $\left(t_i{}^{*m} - t_j{}^{*m}\right) = (\beta_i - \beta_j) > 0$, since $\beta_i > \beta_j$ by assumption.

The initial equilibrium quantities (A3.1.6) and (A3.1.7) produced by the firm operating in country i, for i, j where $i \neq j$, are adjusted to account for the CBA, $\omega_i{}^m = \left(t_i{}^{*m} - t_j{}^{*m}\right)$, imposed by country i on imports from country j. These adjusted quantities are expressed as follows:

$$x_{ii}{}^*(t^m, \omega_i{}^m) = \frac{1}{3}(\alpha - t_i{}^m) \quad \text{(B3.1.4)}$$

$$x_{ij}{}^*(t^m, \omega_i{}^m) = \frac{1}{3}\left(\alpha - 2t_i{}^m + t_j{}^m\right) \quad \text{(B3.1.5)}$$

$$x_{jj}{}^*(t^m, \omega_i{}^m) = \frac{1}{3}(\alpha - 2t_j{}^m + t_i{}^m) \quad \text{(B3.1.6)}$$

$$x_{ji}{}^*(t^m, \omega_i{}^m) = \frac{1}{3}(\alpha - t_i{}^m). \quad \text{(B3.1.7)}$$

Substituting for $t_i{}^{*m}$ given by (B3.1.3), country i's local production and exports are, respectively:

$$x_{ii}{}^m = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right) \quad \text{(B3.1.8)}$$

$$x_{ij}{}^m = \frac{1}{8}\left(4\alpha - 5\beta_i + 3\beta_j\right). \quad \text{(B3.1.9)}$$

Using (B3.1.3), country j's local production and exports are expressed, respectively, as follows:

$$x_{jj}{}^{m} = \frac{1}{8}\left(4\alpha - 5\beta_j + 3\beta_i\right) \quad \text{(B3.1.10)}$$

$$x_{ji}{}^{m} = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right). \quad \text{(B3.1.11)}$$

CBAs reduce country i's imports, increase its local production, increasing its total production. Country i's total quantity produced, $X_i{}^{m}$, and total quantity consumed, $Q_i{}^{m}$, are, respectively:

$$X_i{}^{m} = \frac{1}{12}\left(12\alpha - 11\beta_i + 5\beta_j\right) \quad \text{(B3.1.12)}$$

$$Q_i{}^{m} = \frac{1}{12}\left(12\alpha - 7\beta_i + \beta_j\right). \quad \text{(B3.1.13)}$$

For country j, the CBA decreases its exports and its total production. Country j's total quantity produced, $X_j{}^{m}$, and total quantity consumed, $Q_j{}^{m}$, are given, respectively, as follows:

$$X_j{}^{m} = \frac{1}{12}\left(12\alpha - 7\beta_j + \beta_i\right) \quad \text{(B3.1.14)}$$

$$Q_j{}^{m} = \frac{1}{4}\left(4\alpha - \left(\beta_i + \beta_j\right)\right). \quad \text{(B3.1.15)}$$

The world market clears, as global production equals global consumption, as expressed by:

$$\sum_i X_i{}^{m} = \sum_i Q_i{}^{m} = \frac{1}{6}\left(12\alpha - \left(5\beta_i + \beta_j\right)\right). \quad \text{(B3.1.16)}$$

Given the assumption that every unit of production generates exactly one unit of global emissions, then Equation (B3.1.16) represents global emissions as well.

Countries i and j's individual welfares, W_i^{m} and W_j^{m}, respectively, are expressed as follows:

$$W_i^{m} = \frac{1}{2^5}\frac{1}{3^2}\left[144\alpha^2 + \beta_i(-480\alpha + 111\beta_i + 126\beta_j) + \beta_j(-96\alpha + 15\beta_j)\right] \quad \text{(B3.1.17)}$$

$$W_j^{m} = \frac{1}{2^5}\frac{1}{3^2}\left[144\alpha^2 + \beta_i(-96\alpha + 71\beta_i + 158\beta_j) + \beta_j(-480\alpha + 23\beta_j)\right]. \quad \text{(B3.1.18)}$$

Collective welfare, $W^{m} = \sum_i W_i^{m}$, with myopic CBAs without retaliation is as follows:

$$W^{m} = \frac{1}{2^4 \times 3^2}\left[144\alpha^2 + \beta_i(-288\alpha + 91\beta_i + 142\beta_j) + \beta_j(-288\alpha + 19\beta_j)\right]. \quad \text{(B3.1.19)}$$

3.7.2.2 Myopic Carbon Border Adjustments with Retaliation

With myopic CBAs, the government's welfare optimization problem and the resulting optimal emissions taxes precede country i's implementation of the adjustments and country j's retaliation. The equilibrium emissions tax (B3.1.3) is unchanged, that is $t_i{}^{*\breve{m}} = t_i{}^{*m}$, for i, j where $i \neq j$. The initial equilibrium quantities (A3.1.6) and (A3.1.7) produced by the firm operating in country i, for i, j where $i \neq j$, are adjusted to account for the CBA, $w_i^m = \left(t_i{}^{*m} - t_j{}^{*m}\right)$, and the retaliatory tariff imposed by country j, $\tau_j^{\breve{m}}$.

Firms i and j's optimization problems are expressed, respectively, as follows:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[\left(\alpha - \left(x_{ii} + x_{ji}\right) - t_i{}^m\right)x_{ii} + \left(\alpha - \left(x_{jj} + x_{ij}\right) - t_i{}^m - \tau_j^{\breve{m}}\right)x_{ij}\right] \quad \text{(B3.2.1)}$$

$$\max_{x_{jj}, x_{ji}} \pi_j \Rightarrow \max_{x_{jj}, x_{ji}} \left[\left(\alpha - \left(x_{jj} + x_{ij}\right) - t_j{}^m\right)x_{jj} + \left(\alpha - \left(x_{ii} + x_{ji}\right) - t_j{}^m - \left(t_i{}^m - t_j{}^m\right)\right)x_{ji}\right]. \quad \text{(B3.2.2)}$$

The first order conditions with respect to x_{ii} and x_{ij} are expressed, respectively, as follows:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow 2x_{ii} = \left(\alpha - x_{ji} - t_i{}^m\right) \quad \text{(B3.2.3)}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow 2x_{ij} = \left(\alpha - x_{jj} - t_i{}^m - \tau_j^{\breve{m}}\right). \quad \text{(B3.2.4)}$$

The first order conditions with respect to x_{jj} and x_{ji} are expressed, respectively, as follows:

$$\frac{\partial \pi_j}{\partial x_{jj}} = 0 \Rightarrow 2x_{jj} = \left(\alpha - x_{ij} - t_j{}^m\right) \quad \text{(B3.2.5)}$$

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow 2x_{ji} = \left(\alpha - x_{ii} - t_i{}^m\right). \quad \text{(B3.2.6)}$$

Using (B3.2.3), (B3.2.4), (B3.2.5), and (B3.2.6), the quantities (A3.1.6) and (A3.1.7) produced by the firm operating in country i, for i, j where $i \neq j$, are adjusted as follows:

$$x_{ii}{}^*\left(t^m, \left(t_i{}^m - t_j{}^m\right), \tau_j^{\breve{m}}\right) = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right) \quad \text{(B3.2.7)}$$

$$x_{ij}{}^*\left(t^m, \left(t_i{}^m - t_j{}^m\right), \tau_j^{\breve{m}}\right) = \frac{1}{24}\left(12\alpha - 15\beta_i + 9\beta_j - 16\tau_j^{\breve{m}}\right) \quad \text{(B3.2.8)}$$

$$x_{jj}{}^*\left(t^m, \left(t_i{}^m - t_j{}^m\right), \tau_j^{\breve{m}}\right) = \frac{1}{24}\left(12\alpha + 9\beta_i - 15\beta_j + 8\tau_j^{\breve{m}}\right) \quad \text{(B3.2.9)}$$

$$x_{ji}{}^*\left(t^m, \left(t_i{}^m - t_j{}^m\right), \tau_j^{\breve{m}}\right) = \frac{1}{24}\left(12\alpha - 7\beta_i + \beta_j\right). \quad \text{(B3.2.10)}$$

Given (B3.2.7), (B3.2.8), (B3.2.9), and (B3.2.10), country j's welfare maximization problem to determine the endogenous retaliatory tariff rate, denoted by $\tau_j^{\breve{m}}$, can be written as follows:

$$\max_{\tau_j^{\breve{m}}} W_j^{\breve{m}} \Rightarrow \max_{\tau_j^{\breve{m}}} \begin{bmatrix} 144\alpha(\alpha - 4\beta_j) + \beta_i(-96\alpha + 71\beta_i + 158\beta_j) \\ +\beta_j(96\alpha + 23\beta_j) + \tau_j^{\breve{m}}(96\alpha - 96\beta_i + 192\beta_j - 144\tau_j^{\breve{m}}) \end{bmatrix}. \quad \text{(B3.2.11)}$$

The first order condition with respect to the tariff rate, $\tau_j^{\breve{m}}$, is given by the following equation:

$$\frac{\partial W_j^{\breve{m}}}{\partial \tau_j^{\breve{m}}} = 0 \Rightarrow (96\alpha - 96\beta_i + 192\beta_j - 288\tau_j^{\breve{m}}) = 0 \quad \text{(B3.2.12)}$$

Using (B3.2.12), the endogenous positive retaliatory tariff, $\forall\ \alpha > \beta_i > \beta_j$, is as follows:

$$\tau_j^{*\breve{m}} = \frac{1}{3}(\alpha - \beta_i + 2\beta_j). \quad \text{(B3.2.13)}$$

Following the retaliation by country j, country i's local production and exports are, respectively:

$$x_{ii}^{\breve{m}} = \frac{1}{24}(12\alpha - 7\beta_i + \beta_j) \quad \text{(B3.2.14)}$$

$$x_{ij}^{\breve{m}} = \frac{1}{72}(20\alpha - 29\beta_i - 5\beta_j). \quad \text{(B3.2.15)}$$

Country j's local production and exports become, respectively, as follows:

$$x_{jj}^{\breve{m}} = \frac{1}{72}(44\alpha + 19\beta_i - 29\beta_j) \quad \text{(B3.2.16)}$$

$$x_{ji}^{\breve{m}} = \frac{1}{24}(12\alpha - 7\beta_i + \beta_j). \quad \text{(B3.2.17)}$$

Country i's total production $X_i^{\breve{m}}$ and consumption $Q_i^{\breve{m}}$ are, respectively:

$$X_i^{\breve{m}} = \frac{1}{36}(28\alpha - 25\beta_i - \beta_j) \quad \text{(B3.2.18)}$$

$$Q_i^{\breve{m}} = \frac{1}{12}(12\alpha - 7\beta_i + \beta_j). \quad \text{(B3.2.19)}$$

Country j's retaliation to country i's unilateral CBA reduces country i's total production as expressed by the following expression, $\forall \alpha > \beta_i > 0$:

$$X_i{}^{\breve{m}} - X_i{}^{m} = -\frac{2}{9}\left(\alpha - \beta_i + 2\beta_j\right). \tag{B3.2.20}$$

Country j's post-retaliation total production $X_j{}^{\breve{m}}$ and consumption $Q_j{}^{\breve{m}}$ are, respectively:

$$X_j{}^{\breve{m}} = \frac{1}{36}(40\alpha - \beta_i - 13\beta_j) \tag{B3.2.21}$$

$$Q_j{}^{\breve{m}} = \frac{1}{36}(32\alpha - 5\beta_i - 17\beta_j). \tag{B3.2.22}$$

Retaliation increases country j's total production as shown by this equation, $\forall \alpha > \beta_i > 0$:

$$X_j{}^{\breve{m}} - X_j{}^{m} = \frac{1}{9}(\alpha - \beta_i + 2\beta_j). \tag{B3.2.23}$$

The world market clears, and global production equals global consumption, as expressed by:

$$\sum_i X_i{}^{\breve{m}} = \sum_i Q_i{}^{\breve{m}} = \frac{1}{18}(34\alpha - 13\beta_i - 7\beta_j). \tag{B3.2.24}$$

Under the assumption that every unit of production generates exactly one unit of global emissions, Equation (B3.2.24) also represents global emissions.

Countries i and j's individual welfares, $W_i^{\breve{m}}$ and $W_j^{\breve{m}}$, are expressed, respectively, as follows:

$$W_i^{\breve{m}} = \frac{1}{2^5 3^4}\left[1136\alpha^2 + \beta_i\left(-3784\alpha + 623\beta_i + 1990\beta_j\right) + \beta_j(-1288\alpha - 73\beta_j)\right] \tag{B3.2.25}$$

$$W_j^{\breve{m}} = \frac{1}{2^5 3^2}\left[160\alpha^2 + \beta_i(-128\alpha + 87\beta_i + 94\beta_j) + \beta_j(-416\alpha + 87\beta_j)\right]. \tag{B3.2.26}$$

Collective welfare, $W^{\breve{m}} = \sum_i W_i^{\breve{m}}$, with myopic CBAs with retaliation is expressed as follows:

$$W^{\breve{m}} = \frac{1}{2^4 \times 3^4}\left[1288\alpha^2 + \beta_i(703\beta_i + 1418\beta_j - 2468\alpha) + \beta_j(355\beta_j - 2516\alpha)\right]. \tag{B3.2.27}$$

3.7.3 Appendix C3: Noncooperative Solutions - The Government's Optimization Problem, Farsighted CBAs

With farsighted CBAs, the government in country i selects noncooperatively an emissions tax rate denoted by $t_i{}^f$. Given the equilibrium quantities (A3.2.7), (A3.2.8), (A3.2.9) and (A3.2.10), countries i and j's welfare optimization problems can be expressed as follows:

$$\max_{t_i^f} W_i{}^f \Rightarrow \max_{t_i^f}\left[4\alpha(\alpha-3\beta_i)+t_i^f\left(9\beta_i-\alpha-5t_i^f+2t_j^f\right)+t_j^f\left(3\beta_i-\alpha+t_j^f\right)\right] \quad \text{(C3.1)}$$

$$\max_{t_j^f} W_j{}^f \Rightarrow \max_{t_j^f}\left[8\alpha\left(\alpha-3\beta_j\right)+t_i^f\left(18\beta_j-4\alpha+5t_i^f-6t_j^f\right)+t_j^f\left(6\beta_j-3t_j^f\right)\right]. \quad \text{(C3.2)}$$

The first order conditions with respect to t_i^f and t_j^f, respectively, yield the following equations:

$$\frac{\partial W_i{}^f}{\partial t_i{}^f}=0 \Rightarrow 10t_i^f=\left(-\alpha+9\beta_i+2t_j^f\right) \quad \text{(C3.3)}$$

$$\frac{\partial W_j{}^f}{\partial t_j{}^f}=0 \Rightarrow t_j^f=\left(\beta_j-t_i^f\right). \quad \text{(C3.4)}$$

Using (C3.3) and (C3.4), countries i and j's equilibrium emissions taxes are, respectively:

$$t_i{}^{*f}=\frac{1}{12}(-\alpha+9\beta_i+2\beta_j) \quad \text{(C3.5)}$$

$$t_j{}^{*f}=\frac{1}{12}(\alpha-9\beta_i+10\beta_j). \quad \text{(C3.6)}$$

Country i's local production and exports are given, respectively, by the following equations:

$$x_{ii}{}^f=\frac{1}{36}\left(13\alpha-9\beta_i-2\beta_j\right) \quad \text{(C3.7)}$$

$$x_{ij}{}^f=\frac{1}{12}\left(5\alpha-9\beta_i+2\beta_j\right). \quad \text{(C3.8)}$$

Country j's local production and exports are as follows, respectively:

$$x_{jj}{}^f=\frac{1}{12}\left(3\alpha+9\beta_i-6\beta_j\right) \quad \text{(C3.9)}$$

$$x_{ji}{}^f=\frac{1}{36}\left(13\alpha-9\beta_i-2\beta_j\right). \quad \text{(C3.10)}$$

Country i's total production $X_i{}^f$ and consumption $Q_i{}^f$ are expressed as follows, respectively:

$$X_i{}^f = \frac{1}{9}(7\alpha - 9\beta_i + \beta_j) \tag{C3.11}$$

$$Q_i{}^f = \frac{1}{18}\left(13\alpha - 9\beta_i - 2\beta_j\right). \tag{C3.12}$$

Country j's total production $X_j{}^f$ and consumption $Q_j{}^f$ are as follows, respectively:

$$X_j{}^f = \frac{1}{18}(11\alpha + 9\beta_i - 10\beta_j) \tag{C3.13}$$

$$Q_j{}^f = \frac{1}{3}\left(2\alpha - \beta_j\right). \tag{C3.14}$$

The world market clears, as global production equals global consumption, as expressed by:

$$\sum_i X_i{}^f = \sum_i Q_i{}^f = \frac{1}{18}\left(25\alpha - 9\beta_i - 8\beta_j\right). \tag{C3.15}$$

Under the assumption that every unit of production generates exactly one unit of global emissions, Equation (C3.15) also represents global emissions.

Countries i and j's individual welfares with farsighted CBAs, W_i^f and W_j^f, respectively, are:

$$W_i^f = \frac{1}{216}\left[95\alpha^2 + \beta_i(-282\alpha + 27\beta_i + 60\beta_j) + \beta_j(-20\alpha + 20\beta_j)\right] \tag{C3.16}$$

$$W_j^f = \frac{1}{324}\left[151\alpha^2 + \beta_i(-72\alpha + 81\beta_i + 198\beta_j) + \beta_j(-466\alpha + 94\beta_j)\right]. \tag{C3.17}$$

Collective welfare with farsighted CBAs, $W^f = \sum_i W_i^f$, is expressed as follows:

$$W^f = \frac{1}{2^3 \times 3^4}\left[587\alpha^2 + \beta_i(-990\alpha + 243\beta_i + 576\beta_j) + \beta_j(-992\alpha + 248\beta_j)\right]. \tag{C3.18}$$

3.7.4 Appendix D3: Noncooperative Solutions - The Government's Optimization Problem, Bilateral Endogenous Tariffs

With bilateral endogenous tariffs, each government selects an emissions tax rate, ${t_i}^{\tau}$, and a positive endogenous tariff, τ_i, for i, j where $i \neq j$. Given the equilibrium quantities (A3.3.6) and (A3.3.7), country i's welfare optimization problem is expressed as follows, for i, j where $i \neq j$:

$$\max_{t_i^\tau,\tau_i} {W_i}^{\tau} \Rightarrow \max_{t_i^\tau,\tau_i} \begin{bmatrix} 8\alpha^2 - 24\alpha\beta_i + t_i^\tau\left(-8\alpha + 12\beta_i - 7t_i^\tau - 2t_j^\tau\right) + t_j^\tau\left(4\alpha + 12\beta_i + 5t_j^\tau\right) \\ +\tau_i\left(6\alpha + 6\beta_i + 6t_i^\tau - 6t_j^\tau - 9\tau_i\right) + \tau_j\left(-8\alpha + 6\beta_i + 4t_i^\tau - 8t_j^\tau + 8\tau_j\right) \end{bmatrix}. \quad \text{(D3.1)}$$

The first order condition with respect to the emissions tax rate, t_i^τ, yields the following equation:

$$\frac{\partial {W_i}^{\tau}}{\partial t_i^\tau} = 0 \Rightarrow 7t_i^\tau = \left(-4\alpha + 6\beta_i - t_j^\tau + 3\tau_i + 2\tau_j\right). \quad \text{(D3.2)}$$

The first order condition with respect to the tariff rate, τ_i, yields the following equation:

$$\frac{\partial {W_i}^{\tau}}{\partial \tau_i} = 0 \Rightarrow 3\tau_i = (\alpha + \beta_i + t_i^\tau - t_j^\tau). \quad \text{(D3.3)}$$

Using (D3.2) and (D3.3), country i's equilibrium emissions tax and tariff rates are, respectively, for i, j where $i \neq j$:

$${t_i}^{*\tau} = \frac{1}{96}(-28\alpha + 103\beta_i - 11\beta_j) \quad \text{(D3.4)}$$

$${\tau_i}^{*} = \frac{1}{48}(16\alpha + 35\beta_i - 19\beta_j). \quad \text{(D3.5)}$$

Using (D3.4), country i's emissions tax rate exceeds that of country j, since $\beta_i > \beta_j > 0$:

$${t_i}^{*\tau} - {t_j}^{*\tau} = \frac{19}{16}(\beta_i - \beta_j). \quad \text{(D3.6)}$$

Country i's local production and exports are, respectively, for i, j where $i \neq j$:

$${x_{ii}}^{\tau} = \frac{1}{96}(52\alpha - 49\beta_i + 29\beta_j) \quad \text{(D3.7)}$$

$${x_{ij}}^{\tau} = \frac{1}{96}(20\alpha - 47\beta_i - 5\beta_j). \quad \text{(D3.8)}$$

Country i's total production $X_i{}^\tau$ and consumption $Q_i{}^\tau$ are, respectively, for i, j where $i \neq j$:

$$X_i{}^\tau = \frac{1}{4}(3\alpha - 4\beta_i + \beta_j) \tag{D3.9}$$

$$Q_i{}^\tau = \frac{3}{16}\left(4\alpha - \left(3\beta_i + \beta_j\right)\right). \tag{D3.10}$$

The world market clears, as global production equals global consumption, as expressed by:

$$\sum_i X_i{}^\tau = \sum_i Q_i{}^\tau = \frac{3}{4}\left(2\alpha - \left(\beta_i + \beta_j\right)\right). \tag{D3.11}$$

Under the assumption that every unit of production generates exactly one unit of global emissions, Equation (D3.11) also represents global emissions.

Countries i's individual welfare, W_i^τ, is expressed as follows, for i, j where $i \neq j$:

$$W_i^\tau = \frac{1}{1536}\left[720\alpha^2 + \beta_i(457\beta_i + 990\beta_j - 2224\alpha) + \beta_j(425\beta_j - 368\alpha)\right]. \tag{D3.12}$$

Collective welfare with bilateral endogenous tariffs, $W^\tau = \sum_i W_i{}^\tau$, is expressed as follows:

$$W^\tau = \frac{1}{2^8}\left[240\alpha^2 + \beta_i(-432\alpha + 147\beta_i + 330\beta_j) + \beta_j\left(-432\alpha + 147\beta_j\right)\right]. \tag{D3.13}$$

Using (C3.18) and (D3.13), the collective welfare gains with endogenous tariffs in comparison to the farsighted CBA case, are given by the following expression:

$$W^\tau - W^f = \frac{1}{2^8 \times 3^4}\left(\left(164\alpha - 459\beta_i - 361\beta_j\right)\left(4\alpha - 9\beta_i - 11\beta_j\right)\right). \tag{D3.14}$$

Given (D3.14) and restrictions (F3.4) and (F3.5), then $W^\tau - W^f > 0$, in any of these two cases:

i) $\left(164\alpha - 459\beta_i - 361\beta_j\right) > 0$ and $\left(4\alpha - 9\beta_i - 11\beta_j\right) > 0$.

$$164\alpha - 459\beta_i - 361\beta_j > 0 \Rightarrow 164\alpha > \left(459\beta_i + 361\beta_j\right)$$

$$\left(4\alpha - 9\beta_i - 11\beta_j\right) > 0 \Rightarrow 4\alpha > \left(9\beta_i + 11\beta_j\right) \Rightarrow 164\alpha > \left(369\beta_i + 451\beta_j\right)$$

$\left[\left(459\beta_i + 361\beta_j\right) - \left(369\beta_i + 451\beta_j\right)\right] = 90\left(\beta_i - \beta_j\right) > 0, \forall \beta_i > \beta_j > 0.$

$\Rightarrow 164\alpha > \left(459\beta_i + 361\beta_j\right)$ is more restrictive than $4\alpha > \left(9\beta_i + 11\beta_j\right)$.

$\Rightarrow W^{\tau} - W^{f} > 0, \forall \frac{1}{164}\left(459\beta_i + 361\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$.

ii) $\left(164\alpha - 459\beta_i - 361\beta_j\right) < 0$ and $\left(4\alpha - 9\beta_i - 11\beta_j\right) < 0$

$\Rightarrow W^{\tau} - W^{f} > 0, \forall\ 4\alpha < \left(9\beta_i + 11\beta_j\right)$, that is, when $20\alpha < \left(45\beta_i + 55\beta_j\right)$.

The tariff model restricts $20\alpha \geq \left(47\beta_i + 5\beta_j\right)$.

Thus, this case requires in addition that: $\left(45\beta_i + 55\beta_j\right) > \left(47\beta_i + 5\beta_j\right)$

$\Rightarrow 0 < \beta_j < \beta_i < 25\beta_j$.

$\Rightarrow W^{\tau} - W^{f} > 0, \forall \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \leq \alpha < \frac{1}{4}\left(9\beta_i + 11\beta_j\right)$.

3.7.5 Appendix E3: The Cooperative Solution

In the cooperative case, it is assumed that ${t_i}^C = {t_j}^C = t^C$ and ${\tau_i}^C = {\tau_j}^C = \tau^C = 0$. The firm's optimization problem, expressed in (A3.1) and (A3.2), is reduced as follows, for i, j where $i \neq j$:

$$\max_{x_{ii}, x_{ij}} \pi_i \Rightarrow \max_{x_{ii}, x_{ij}} \left[(\alpha - Q_i - t^C)x_{ii} + \left(\alpha - Q_j - t^C\right)x_{ij}\right]. \tag{E3.1}$$

The first order conditions with respect to country i's local production and exports are as follows:

$$\frac{\partial \pi_i}{\partial x_{ii}} = 0 \Rightarrow 2{x_{ii}}^* = \left(\alpha - x_{ji} - t^C\right) \tag{E3.2}$$

$$\frac{\partial \pi_i}{\partial x_{ij}} = 0 \Rightarrow 2{x_{ij}}^* = \left(\alpha - x_{jj} - t^C\right). \tag{E3.3}$$

By symmetry, the FOCs with respect to country j's local production and exports are as follows:

$$\frac{\partial \pi_j}{\partial x_{jj}} = 0 \Rightarrow 2{x_{jj}}^* = \left(\alpha - x_{ij} - t^C\right) \tag{E3.4}$$

$$\frac{\partial \pi_j}{\partial x_{ji}} = 0 \Rightarrow 2{x_{ji}}^* = (\alpha - x_{ii} - t^C). \tag{E3.5}$$

The second order conditions (SOCs) are satisfied, as we have:

$$\frac{\partial^2 \pi_i}{\partial {x_{ii}}^2} < 0, \frac{\partial^2 \pi_i}{\partial {x_{ij}}^2} < 0, \text{ and } \frac{\partial^2 \pi_i}{\partial^2 x_{ii}} \frac{\partial^2 \pi_i}{\partial {x_{ij}}^2} - \left(\frac{\partial^2 \pi_i}{\partial x_{ii} \partial x_{ij}}\right) > 0.$$

Using (E3.2), (E3.3), (E3.4), and (E3.5), the equilibrium quantities produced by the firm operating in country i are, for i, j where $i \neq j$:

$$x_{ii}{}^*(t^C) = x_{ij}{}^*(t^C) = \frac{1}{3}(\alpha - t^C). \tag{E3.6}$$

Given (E3.6), country i's welfare function is as follows, for i, j where $i \neq j$:

$$W_i^C = \frac{2}{9}[2\alpha(\alpha - 3\beta_i) + t^C(-\alpha + 6\beta_i - t^C)]. \tag{E3.7}$$

Let $W^C = \sum_i W_i^C$ be the joint welfare function of both countries; their maximization problem can be expressed as follows, for i, j where $i \neq j$:

$$\max_{t^C} W^C \Rightarrow \max_{t^C}\left[2\alpha^2 - 3\alpha\left(\beta_i + \beta_j\right) + t^C\left(-\alpha + 3\left(\beta_i + \beta_j\right) - t^C\right)\right]. \tag{E3.8}$$

The first order condition of the joint welfare maximization problem (E3.8) with respect to t^C is:

$$\frac{\delta W^C}{\delta t^C} = 0 \Rightarrow \left(-\alpha + 3(\beta_i + \beta_j) - 2t^C\right) = 0. \quad \text{(E3.9)}$$

The first order condition yields the following cooperative emissions tax rate:

$$t^{*C} = \frac{1}{2}\left(-\alpha + 3(\beta_i + \beta_j)\right). \quad \text{(E3.10)}$$

Country i's local production and exports are as follows, respectively, for i, j where $i \neq j$:

$$x_{ii}{}^{*C} = x_{ij}{}^{*C} = \frac{1}{2}\left(\alpha - (\beta_i + \beta_j)\right). \quad \text{(E3.11)}$$

Country i's total production $X_i{}^C$ and consumption $Q_i{}^C$ are equal, for i, j where $i \neq j$:

$$X_i{}^C = Q_i{}^C = (\alpha - \textstyle\sum_i \beta_i). \quad \text{(E3.12)}$$

The world market clears, as global production equals global consumption, as expressed by:

$$\textstyle\sum_i X_i{}^C = \sum_i Q_i{}^C = 2(\alpha - \sum_i \beta_i). \quad \text{(E3.13)}$$

Given the assumption that every unit of production generates one unit of emissions, then Equation (E3.13) also represents the cooperative global level of emissions.

Under the cooperative agreement, country i's welfare W_i^C, for i, j where $i \neq j$, is as follows:

$$W_i{}^C = \frac{1}{2}\left[\alpha(\alpha - 4\beta_i) + (\beta_i + \beta_j)(3\beta_i - \beta_j)\right]. \quad \text{(E3.14)}$$

The collective welfare, $W^C = \sum_i W_i^C$, is expressed as:

$$W^C = (\alpha - \textstyle\sum_i \beta_i)^2. \quad \text{(E3.15)}$$

Equation (E3.15) demonstrates that collective welfare with cooperation is unambiguously positive. Given the restrictions imposed on the model's parameters, $W^C > 0, \forall \alpha > \sum_i \beta_i$ and $\alpha > \beta_i > \beta_j$.

Collective welfare is also independent from the degree of environmental damage heterogeneity, but rather negatively related to $\sum_i \beta_i$.

3.7.6 Appendix F3: Restrictions on the Model's Parameter

The model ensures an active market by assuming that any marginal environmental damage parameter cannot exceed the maximal marginal utility of good X, that is, $\alpha > \beta_i > \beta_j > 0$.

For the market structure to be maintained throughout the game and to guarantee a positive interior solution, it is assumed that $X_i, x_{ii} \in \mathbb{R}_n^{++}$ and $x_{ij} \in \mathbb{R}_n^{+}$, for i, j where $i \neq j$.

These restrictions also ensure positive import tariffs and warrant positive trade flows.

The complete set of the most restrictive constraints pertaining to each scenario is detailed here:

- Myopic Carbon Border Adjustments, without Retaliation:

$$x_{ij}{}^{m} \geq 0 \Rightarrow \alpha \geq \frac{1}{4}\left(5\beta_i - 3\beta_j\right) \tag{F3.1}$$

- Myopic Carbon Border Adjustments, with Retaliation:

$$x_{ij}{}^{\tilde{m}} \geq 0 \Rightarrow \alpha \geq \frac{1}{20}\left(29\beta_i + 5\beta_j\right) \tag{F3.2}$$

- Farsighted Carbon Border Adjustments:

$$x_{ij}{}^{f} \geq 0 \Rightarrow \alpha \geq \frac{1}{15}\left(27\beta_i - 6\beta_j\right) \tag{F3.3}$$

$$t_i{}^{*f} - t_j{}^{*f} > 0 \Rightarrow \alpha < \left(9\beta_i - 4\beta_j\right) \tag{F3.4}$$

- Bilateral Endogenous Tariffs:

$$x_{ij}{}^{\tau} \geq 0 \Rightarrow \alpha \geq \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \tag{F3.5}$$

- Cooperation:

$$x_{ii}{}^{C} > 0 \Rightarrow \alpha > \textstyle\sum_i \beta_i \tag{F3.6}$$

3.7.7 Appendix G3: Proof of Proposition 3.5.1.1

Using (B3.1.16), global production with myopic CBAs without retaliation is given by:

$$\sum_i X_i^{m} = \frac{1}{6}\left(12\alpha - \left(5\beta_i + \beta_j\right)\right). \tag{G3.1}$$

Using (C3.15), global production with farsighted CBAs is expressed as follows:

$$\sum_i X_i^{f} = \frac{1}{18}\left(25\alpha - 9\beta_i - 8\beta_j\right). \tag{G3.2}$$

Using (G3.1) and (G3.2), global production with myopic CBAs without retaliation always exceeds what would occur with farsighted CBAs, as given by the following equation, $\forall \alpha > \beta_i > \beta_j > 0$:

$$\sum_i X_i^{m} - \sum_i X_i^{f} = \frac{1}{18}(11\alpha - 6\beta_i + 5\beta_j). \tag{G3.3}$$

Using (D3.11), global production with bilateral endogenous tariffs is expressed as follows:

$$\sum_i X_i^{\tau} = \frac{3}{4}\left(2\alpha - \left(\beta_i + \beta_j\right)\right). \tag{G3.4}$$

Using (G3.1) and (G3.4), global production with myopic CBAs without retaliation always exceeds what would be the case with bilateral endogenous tariffs, $\forall \alpha > \beta_i > \beta_j > 0$, as expressed here:

$$\sum_i X_i^{m} - \sum_i X_i^{\tau} = \frac{1}{12}(6\alpha - \beta_i + 7\beta_j). \tag{G3.5}$$

Using (B3.2.24), global production with myopic CBAs with retaliation is as follows:

$$\sum_i X_i^{\breve{m}} = \frac{1}{18}(34\alpha - 13\beta_i - 7\beta_j). \tag{G3.6}$$

Using (G3.2) and (G3.6), global production with myopic CBAs with retaliation consistently surpasses that of farsighted CBAs, $\forall \alpha > \beta_i > \beta_j > 0$:

$$\sum_i X_i^{\breve{m}} - \sum_i X_i^{f} = \frac{1}{18}(9\alpha - 4\beta_i + \beta_j) \tag{G3.7}$$

Using (G3.4) and (G3.6), global production with myopic CBAs with retaliation consistently surpasses that of bilateral endogenous tariffs, $\forall \alpha > \beta_i > \beta_j > 0$:

$$\sum_i X_i^{\breve{m}} - \sum_i X_i^{\tau} = \frac{1}{36}(14\alpha + \beta_i + 13\beta_j). \tag{G3.8}$$

Hence, myopic CBAs, regardless of retaliation, when compared to farsighted CBA and bilateral tariff approaches, are less effective in reducing global emissions.

Using (G3.2) and (G3.4), farsighted CBAs can reduce global emissions beyond the scope of the bilateral trade model, under specific conditions, as detailed in the following equation:

$$\sum_i X_i^{\tau} - \sum_i X_i^{f} = \frac{1}{36}\left(4\alpha - \left(9\beta_i + 11\beta_j\right)\right). \tag{G3.9}$$

Equation (G3.9) shows that $\sum_i X_i^{\tau} - \sum_i X_i^{f} > 0, \forall \alpha > \frac{1}{4}\left(9\beta_i + 11\beta_j\right)$.

Given the restrictions (F3.4) and (F3.5), the farsighted CBA and bilateral tariff models require, respectively, that $\alpha < \left(9\beta_i - 4\beta_j\right)$ and $20\alpha \geq \left(47\beta_i + 5\beta_j\right)$. It follows that $\sum_i X_i^{\tau} - \sum_i X_i^{f} > 0$, under these two conditions:

$\forall 0 < \beta_j < \beta_i < 25\beta_j \Rightarrow \frac{1}{4}\left(9\beta_i + 11\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$, or

$\forall 0 < \beta_j < 25\beta_j < \beta_i \Rightarrow \frac{1}{20}\left(47\beta_i + 5\beta_j\right) < \alpha < \left(9\beta_i - 4\beta_j\right)$. • Q.E.D.

3.7.8 Appendix H3: Proof of Proposition 3.5.1.2

Given the welfare optimization problem (B3.1.1) in the myopic CBA case, country i's optimal emissions tax is given by the following equation, for i, j where $i \neq j$:

$$t_i{}^{*m} = \frac{1}{8}(-4\alpha + 7\beta_i - \beta_j). \tag{H3.1}$$

Given the welfare optimization problems (C3.1) and (C3.2) in the farsighted CBA case, the optimal emissions taxes of countries i and j, are given by the following equations, respectively:

$$t_i{}^{*f} = \frac{1}{12}(-\alpha + 9\beta_i + 2\beta_j) \tag{H3.2}$$

$$t_j{}^{*f} = \frac{1}{12}(\alpha - 9\beta_i + 10\beta_j). \tag{H3.3}$$

The CBA requires that $t_i{}^{*f} > t_j{}^{*f}$. Since $t_i{}^{*f} - t_j{}^{*f} = \frac{1}{6}(9\beta_i - 4\beta_j - \alpha)$, the parameters are constrained to guarantee that, $0 < \alpha < (9\beta_i - 4\beta_j), \forall \alpha > \beta_i > \beta_j > 0$.

Using (H3.1), (H3.2), and (H3.3), countries i and j's emissions taxes with myopic CBAs, in comparison to farsighted CBAs, are, respectively, expressed by the following equations:

$$t_i^{*f} - t_i{}^{*m} = \frac{1}{24}(10\alpha - 3\beta_i + 7\beta_j) \tag{H3.4}$$

$$t_j^{*f} - t_j{}^{*m} = \frac{1}{24}\left(14\alpha - \left(15\beta_i + \beta_j\right)\right). \tag{H3.5}$$

It is evident from equation (H3.4), that country i consistently enforces a lower tax with myopic CBAs in comparison to farsighted CBAs, since $t_i^{*f} - t_i{}^{*m} > 0, \forall \alpha > \beta_i > \beta_j > 0$.

Equation (H3.5) shows that $t_j^{*f} - t_j{}^{*m} > 0 \Rightarrow \alpha > \frac{1}{14}\left(15\beta_i + \beta_j\right)$.

Since the farsighted CBA case requires that $15\alpha \geq \left(27\beta_i - 6\beta_j\right)$, which is more restrictive than $\alpha > \frac{1}{14}\left(15\beta_i + \beta_j\right) \Rightarrow t_j^{*f} - t_j{}^{*m} > 0, \forall \frac{1}{15}\left(27\beta_i - 6\beta_j\right) \leq \alpha < (9\beta_i - 4\beta_j)$.

Since, $t_i{}^{*m} = t_i{}^{*\breve{m}}$, for i, j where $i \neq j$, then equations (H3.4) and (H3.5) also imply that both countries implement lower emissions taxes in the case of myopic CBAs, regardless of retaliation.

Given the welfare optimization problem (D3.1) with bilateral endogenous tariffs, the optimal emissions tax rate of country i, for i, j where $i \neq j$, is as follows:

$$t_i^{*\tau} = \frac{1}{96}(-28\alpha + 103\beta_i - 11\beta_j). \quad \text{(H3.6)}$$

Using (H3.1) and (H3.6), country i's emissions tax rate with myopic CBAs in comparison to the bilateral tariff model, is given by the following equation, for i, j where $i \neq j$:

$$t_i^{*\tau} - t_i^{*m} = \frac{1}{96}(20\alpha + 19\beta_i + \beta_j). \quad \text{(H3.7)}$$

Since $\alpha > \beta_i > \beta_j > 0$ by assumption, then $t_i^{*\tau} - t_i^{*m} > 0$, for i, j where $i \neq j$.

Equation (H3.7) indicates that any country implements a lower emissions tax with myopic CBAs in comparison to the tariff model.

Using (H3.2), (H3.3), and (H3.6), countries i and j's emissions taxes with farsighted CBAs in comparison to the bilateral tariff model, are, respectively, expressed by the following equations:

$$t_i^{*f} - t_i^{*\tau} = \frac{1}{96}(20\alpha - 31\beta_i + 27\beta_j) \quad \text{(H3.8)}$$

$$t_j^{*f} - t_j^{*\tau} = \frac{1}{96}(36\alpha - 61\beta_i - 23\beta_j). \quad \text{(H3.9)}$$

Equation (H3.8) shows that $t_i^{*f} - t_i^{*\tau} > 0$, $\forall\, \alpha > \frac{1}{20}\left(31\beta_i - 27\beta_j\right)$. The farsighted CBA and bilateral tariff models require, respectively, that $\alpha < \left(9\beta_i - 4\beta_j\right)$ and $20\alpha \geq \left(47\beta_i + 5\beta_j\right)$.

Since $\alpha \geq \frac{1}{20}\left(47\beta_i + 5\beta_j\right)$ is more restrictive $\alpha > \frac{1}{20}\left(31\beta_i - 27\beta_j\right)$,

$\Rightarrow t_i^{*f} - t_i^{*\tau} > 0, \forall \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \leq \alpha < (9\beta_i - 4\beta_j)$.

Equation (H3.9) shows that $t_j^{*f} - t_j^{*\tau} > 0$, $\forall\, \alpha > \frac{1}{36}\left(61\beta_i + 23\beta_j\right)$.

Since $\alpha \geq \frac{1}{20}\left(47\beta_i + 5\beta_j\right)$ is more restrictive than $\alpha > \frac{1}{36}\left(61\beta_i + 23\beta_j\right)$,

$\Rightarrow t_j^{*f} - t_j^{*\tau} > 0, \forall \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \leq \alpha < (9\beta_i - 4\beta_j)$

$\Rightarrow t_i^{*f} - t_i^{*\tau} > 0$, for i, j where $i \neq j$, $\forall \frac{1}{20}\left(47\beta_i + 5\beta_j\right) \leq \alpha < (9\beta_i - 4\beta_j)$ • Q.E.D.

3.7.9 Appendix I3: Proof of Proposition 3.5.1.3

Using (B3.1.19) and (B3.2.27), the collective welfare gains from retaliation are expressed by:

$$W^{\breve{m}} - W^{m} = \frac{-1}{2^2 \times 3^4}\left(\left(2\alpha - 29\beta_i - 23\beta_j\right)\left(\alpha - \beta_i + 2\beta_j\right)\right). \tag{I3.1}$$

Using (I3.1), $W^{\breve{m}} - W^{m} > 0$, if $\left(2\alpha - 29\beta_i - 23\beta_j\right)\left(\alpha - \beta_i + 2\beta_j\right) < 0$.

Since $\alpha > \beta_i > \beta_j > 0$, by assumption, then $\left(\alpha - \beta_i + 2\beta_j\right) > 0, \forall\ \alpha > \beta_i > \beta_j > 0$.

If $\left(\alpha - \beta_i + 2\beta_j\right) > 0, \forall\ \alpha > \beta_i > \beta_j > 0$, then $W^{\breve{m}} - W^{m} > 0 \Rightarrow \left(2\alpha - 29\beta_i - 23\beta_j\right) < 0$.

$\left(2\alpha - 29\beta_i - 23\beta_j\right) < 0 \Rightarrow \alpha < \frac{1}{2}\left(29\beta_i + 23\beta_j\right)$.

Given the restrictions (F3.1) and (F3.2), that is, $\alpha \geq \frac{1}{4}\left(5\beta_i - 3\beta_j\right)$ and $\alpha \geq \frac{1}{20}\left(29\beta_i + 5\beta_j\right)$, respectively, $\alpha \geq \frac{1}{20}\left(29\beta_i + 5\beta_j\right)$ is more restrictive than $\alpha \geq \frac{1}{4}\left(5\beta_i - 3\beta_j\right)$.

It follows that $W^{\breve{m}} - W^{m} > 0$, when $\frac{1}{20}\left(29\beta_i + 5\beta_j\right) \leq \alpha < \frac{1}{2}\left(29\beta_i + 23\beta_j\right)$.

Taking the first order condition of (I3.1) with respect to β_j yields the following equation:

$$\frac{\partial\left(W^{\breve{m}} - W^{m}\right)}{\partial \beta_j} = \frac{1}{2^2 \times 3^4}\left(92\beta_j + 35\beta_i + 19\alpha\right). \tag{I3.2}$$

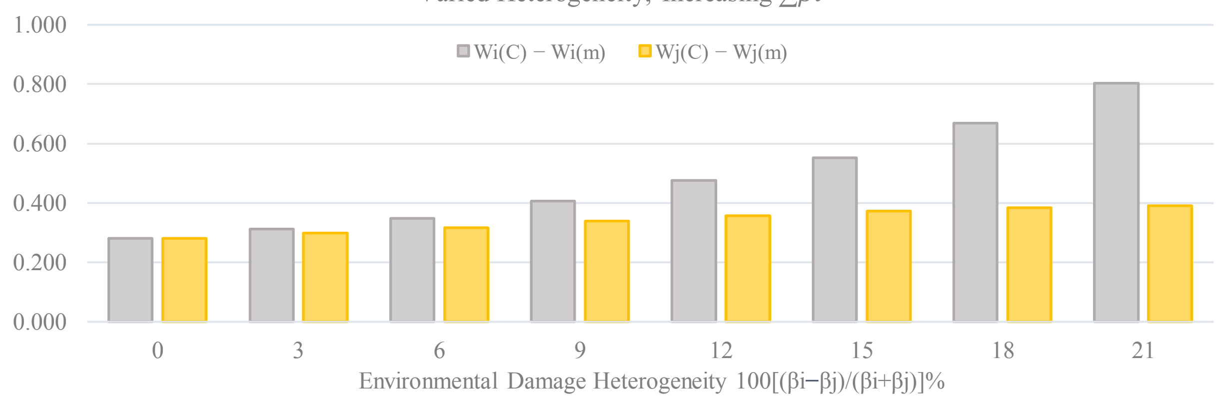
Since $\alpha > \beta_i > \beta_j > 0$, by assumption, then $\frac{\partial\left(W^{\breve{m}} - W^{m}\right)}{\partial \beta_j} > 0,\ \forall\ \alpha > \beta_i > \beta_j > 0 \Rightarrow$ collective welfare gains from retaliation can improve as β_j takes on a higher value. • Q.E.D.

3.7.10 Appendix J3 : Simulation Results with Increasing $\sum_i \boldsymbol{\beta_i}$

The analysis and figures presented here depict the simulation results assuming that $\sum_i \beta_i$ increases compared to the case where $\sum_i \beta_i = 1$. As β_i and β_j take higher values, while maintaining the heterogeneity assumption where $\beta_i > \beta_j > 0$, $\sum_i \beta_i$ increases. However, keeping the value of α constant to explore the effect of heterogeneity restricts the range of parameters that satisfy all the conditions imposed on the model's parameters, as outlined in Appendix F3, and specifically the most restrictive conditions expressed in Equations (F3.4) and (F3.5).

Hence, for any particular α value, the comparison is only possible within a limited range of heterogeneity. For instance, with $\alpha = 2.4$, the range where all the restrictions are satisfied is up to 21% heterogeneity. Nevertheless, the simulation results remain consistent when assuming that $\sum_i \beta_i$ increases, in contrast to when $\sum_i \beta_i$ is held constant and normalized to 1.

Figure 3.6: Individual Welfare Gains: Comparing Cooperation to Myopic CBAs - Varied Heterogeneity, Increasing $\sum \beta i$



Assuming $\alpha = 2.4$ and $\sum_i \beta_i$ increases, Figure 3.6 depicts Equations (3.78) and (3.79), where both β_i and β_j take higher values as the degree of heterogeneity increases. Similar to Figure 3.1, while both countries do not experience the same benefits, they still prefer the cooperative scenario to the myopic CBA case. This preference holds true not only in the homogeneous benchmark case, but also over the full range of environmental damage heterogeneity, where the restrictions are met.

Alternatively, Figure 3.7 depicts Equations (3.80) and (3.81) with the same conditions as Figure 3.6. Similar to Figure 3.2, it clearly indicates that the potential for cooperation is confined to a narrow window, primarily within the homogeneous case and up to 1% heterogeneity, beyond which countries i and j consistently exhibit divergent preferences for the cooperative agreement.

Figure 3.7: Individual Welfare Gains: Comparing Cooperation to Farsighted CBAs - Varied Heterogeneity, Increasing $\sum \beta i$

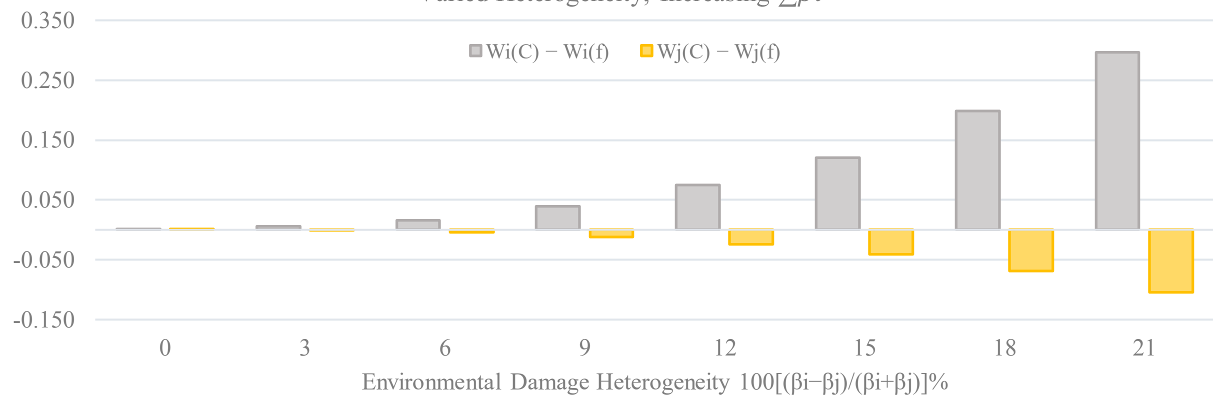
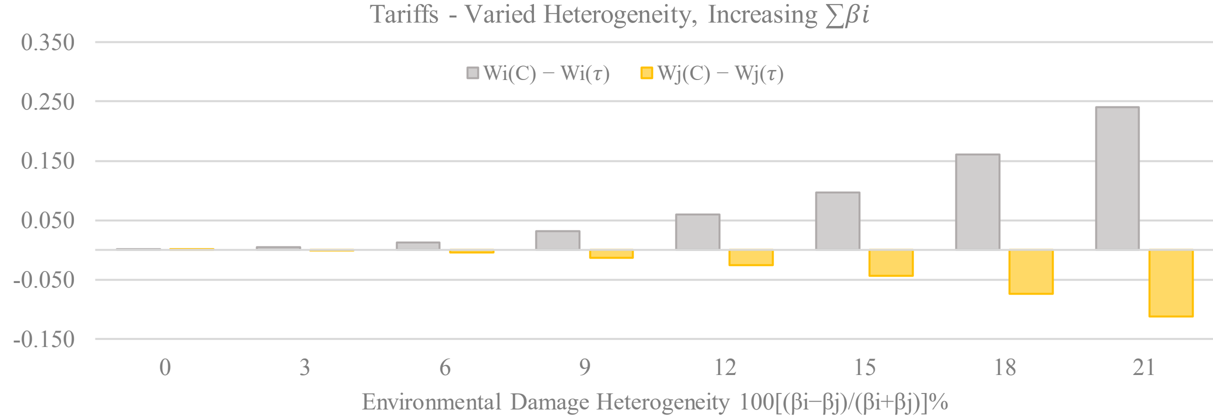


Figure 3.8 depicts Equation (3.82) for both countries, with the same conditions as Figures 3.6 and 3.7. Similar to Figure 3.3, it is evident that the range of cooperation with bilateral endogenous tariffs closely mirrors that of farsighted CBAs, being mainly in the homogeneous case. Both countries display divergent preferences for the cooperative scenario, above 1% heterogeneity.

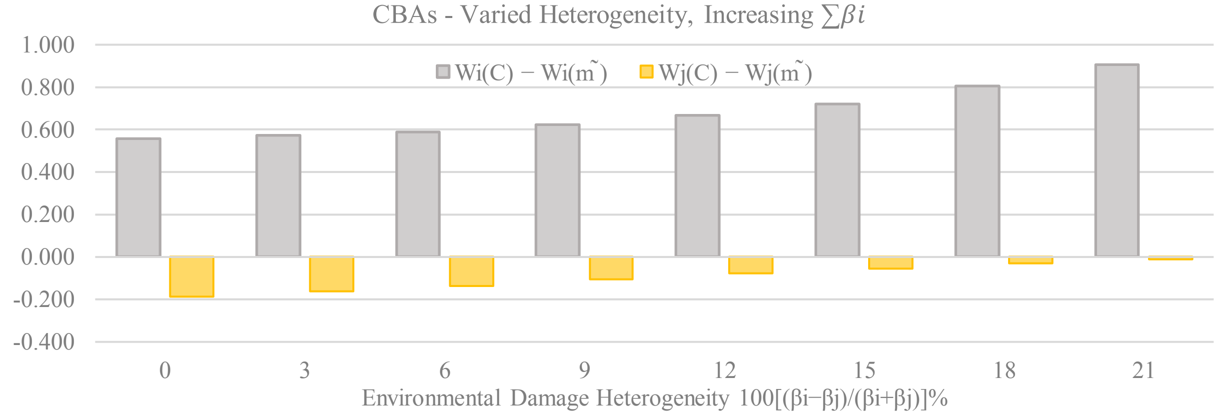
Figure 3.8: Individual Welfare Gains: Comparing Cooperation to Bilateral Endogenous Tariffs - Varied Heterogeneity, Increasing $\sum \beta i$



These findings remain consistent when changing α, where $\frac{1}{20}(47\beta_i + 5\beta_j) \leq \alpha < (9\beta_i - 4\beta_j)$.

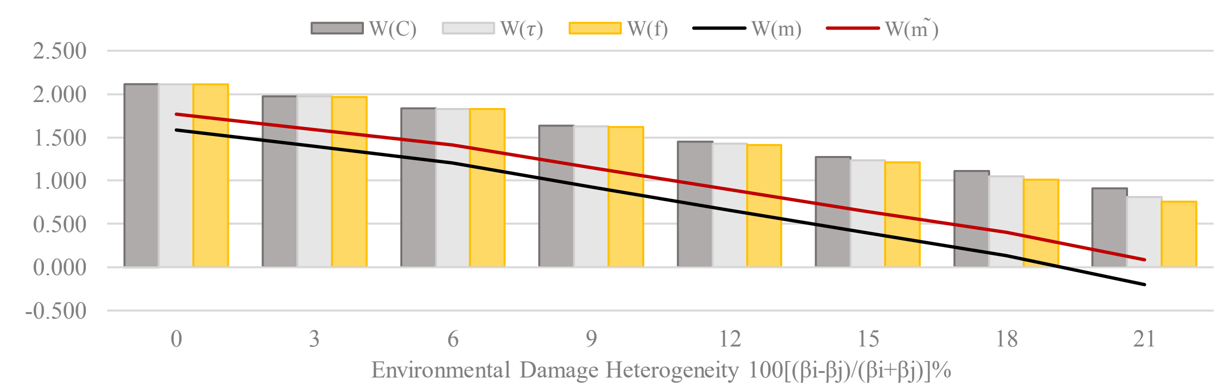
Assuming $\alpha = 2.4$ and $\sum_i \beta_i$ increases, Figure 3.9 depicts Equations (3.83) and (3.84), where β_i and β_j take higher values as the degree of heterogeneity increases. Like Figure 3.4, it is evident that there isn't a range of parameters where both countries would cooperate. They display divergent preferences for the cooperative scenario across various levels of heterogeneity. These findings remain consistent when changing α, where $\frac{1}{20}\left(47\beta_i + 5\beta_j\right) \leq \alpha < \left(9\beta_i - 4\beta_j\right)$.

Figure 3.9: Individual Welfare Gains: Comparing Cooperation to Myopic Retaliatory CBAs - Varied Heterogeneity, Increasing $\sum\beta i$



Assuming $\alpha = 2.4$ and $\sum_i \beta_i$ increases, Figure 3.10 illustrates collective welfare under cooperation (3.87) and all noncooperative scenarios: bilateral tariffs (3.85), farsighted CBAs (3.86), and myopic CBAs without (3.74) and with (3.75) retaliation.

Figure 3.10: Cooperative and Noncooperative Collective Welfares - Varied Heterogeneity, Increasing $\sum\beta i$



Similar to Figure 3.5, it is evident from Figure 3.10 that collective welfare is always highest with cooperation, regardless of heterogeneity levels. Since $W^C = (\alpha - \sum_i \beta_i)^2$, collective welfare in the cooperative scenario decreases as $\sum_i \beta_i$ takes a higher value. However, in the absence of cooperation, the endogenous bilateral tariff and the farsighted CBA cases emerge as the strongest contributor to substantial collective welfare. While the myopic CBA case with retaliation can outperform the scenario without retaliation in terms of collective welfare, as detailed in Proposition 3.5.1.3. However, as both marginal environmental damage parameters take higher values here, collective welfare in each scenario diminishes.

BIBLIOGRAPHY

1. Al Khourdajie, A., & Finus, M. (2020). Measures to enhance the effectiveness of international climate agreements: The case of border carbon adjustments. *European Economic Review, 24,* 103405.
2. Anouliès, L. (2015). The strategic and effective dimensions of the border tax adjustment. *Journal of Public Economic Theory*, *17*(6), 824-847.
3. Baghdadi, L., Martinez-Zarzoso, I., & Zitouna, H. (2013). Are RTA agreements with environmental provisions reducing emissions? *Journal of International Economics*, *90*(2), 378-390.
4. Bakalova, I., & Eyckmans, J. (2019). Simulating the impact of heterogeneity on stability and effectiveness of international environmental agreements. *European Journal of Operational Research*, *277*(3), 1151-1162.
5. Baksi, S., & Chaudhuri, A. R. (2017). International trade and environmental cooperation among heterogeneous countries. In *Economics of International Environmental Agreements - A Critical Approach* (1st ed., pp. 97-115). Routledge.
6. Baksi, S., & Chaudhuri, A. R. (2020). Imperfect Competition, Border Carbon Adjustments, and Stability of a Global Climate Agreement. *Departmental Working Papers 2020-03, The University of Winnipeg, Department of Economics*.
7. Barrett, S. (1994). Strategic environmental policy and international trade. *Journal of Public Economics*, *54*(3), 325-338.
8. Barrett, S. (1997). The strategy of trade sanctions in international environmental agreements. *Resource and Energy Economics*, *19*(4), 345-361.
9. Barrett, S. (2001). International cooperation for sale. *European Economic Review*, *45*(10), 1835-1850.

10. Bernheim, B. D., Peleg, B., & Whinston, M. D. (1987). Coalition-Proof nash equilibria i. concepts. *Journal of Economic Theory*, *42*(1), 1-12.

11. Biancardi, M., & Villani, G. (2010). International environmental agreements with asymmetric countries. *Computational Economics*, *36*(1), 69-92.

12. Biancardi, M., & Villani, G. (2018). Sharing R&D investments in international environmental agreements with asymmetric countries. *Communication in Nonlinear Sciences and Numerical Simulation*, *58*, 249-261.

13. Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2016). The strategic value of carbon tariffs. *American Economic Journal: Economic Policy*, *8*(1), 28-51.

14. Borchert, I., Conconi, P., Di Ubaldo, M., & Herghelegiu, C. (2021). The pursuit of non-trade policy objectives in EU trade policy. *World Trade Review*, *20*(5), 623-647.

15. Brandi, C., Schwab, J., Berger, A., & Morin, J. F. (2020). Do environmental provisions in trade agreements make exports from developing countries greener? *World Development*, *129*, 104899.

16. Carter, A. V., & Dordi, T. (2021). Correcting Canada's "One eye shut" climate policy: Meeting Canada's climate commitments requires ending supports for, and beginning a gradual phase out of, oil and gas production. *Cascade Institute Technical Paper No.* 2021.4, *1*(1), 1-26.

17. Cheikbossian, G. (2010). Revue Économique. *Cheikbossian, Guillaume, La Coordination des Politiques Environnementales Entre Deux Pays De Taille Asymétrique*, *61*(1), 11-30.

18. Cheikbossian, G., & Cavagnac, M. (2017). Stable environmental agreements and international trade in asymmetric oligopoly markets. In *Economics of International Environmental Agreements - A Critical Approach* (1st ed., pp. 35-60). Routledge.

19. Climate Action Tracker (CAT). (2021). *Global update: Climate target updates slow as science demands action*. https://climateactiontracker.org/documents/871/CAT_2021-09_Briefing_GlobalUpdate.pdf

20. Conrad, K. (1993). Taxes and subsidies for Pollution-Intensive industries as trade policy. *Journal of Environmental Economics and Management*, *25*(2), 121-135.

21. D'Aspremont, C., Jacquemin, A., Gabszewicz, J. J., & Weymark, J. A. (1983). On the stability of collusive price leadership. *The Canadian Journal of Economics*, *16*(1), 17-25.

22. Diamantoudi, E., Sartzetakis, E. S., & Strantza, S. (2018a). International environmental agreements - stability with transfers among countries. *FEEM Working Paper No. 20.2018.*

23. Diamantoudi, E., Sartzetakis, E. S., & Strantza, S. (2018b). International environmental agreements - the impact of heterogeneity among countries on stability. *FEEM Working Paper No. 22.2018.*

24. Diamantoudi, E., Sartzetakis, E. S., & Strantza, S. (2018c). International environmental agreements and trading blocs - can issue linkage enhance cooperation? *FEEM Working Paper No. 23.2018.*

25. Duval, Y., & Hamilton, S. (2002). Strategic environmental policy and international trade in asymmetric oligopoly markets. *International Tax and Public Finance*, *9*, 259-271.

26. Eichner, T., & Kollenbach, G. (2021). Environmental agreements, research and technological spillovers. *European Journal of Operational Research*, *300*(1), 366-377.

27. Elboghdadly, N., & Finus, M. (2020). Enforcing Climate Agreements: The Role of Escalating Border Carbon Adjustments. *Graz Economics Papers No. 2020.11, University of Graz, Department of Economics.*

28. European Commission. (2020, August 12). *Cambodia loses duty-free access to the EU market over human rights concerns* [Press release]. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1469

29. European Commission (EC). (2023). *Carbon Border Adjustment Mechanism*. Taxation and Customs Union. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en#latest-developments

30. Evans, S., Gabbatiss, J., McSweeney, R., Chandrasekhar, A., Tandon, A., Viglione, Hausfather, Z., You, X., Goodman, J., & Hayes, S. (2021, November 15). COP26: Key outcomes agreed at the UN climate talks in Glasgow. *Carbon Brief*. https://www.carbonbrief.org/cop26-key-outcomes-agreed-at-the-un-climate-talks-in-glasgow
31. Eyland, T., & Zaccour, G. (2014). Carbon tariffs and cooperative outcomes. *Energy Policy*, *65*, 718-728.
32. Finus, M., & McGinty, M. (2019). The anti-paradox of cooperation: Diversity may pay! *Journal of Economic Behavior & Organization*, *157*, 541-559.
33. Finus, M., & Rundshagen, B. (1998). Toward a positive theory of coalition formation and endogenous instrumental choice in global pollution control. *Public Choice*, *96*(1-2), 145-186.
34. Finus, M., & Rundshagen, B. (2003). How the rules of coalition formation affect stability of international environmental agreements. *FEEM Working Paper No. 62.2003.*
35. Fouré, J., Guimbard, H., & Monjon, S. (2016). Border carbon adjustment and trade retaliation: What would be the cost for the European Union? *Energy Economics*, *54*, 349-362.
36. Gautier, L. (2017). Abatement level in environmental agreements when firms are heterogeneous in abatement costs. In *Economics of International Environmental Agreements - A Critical Approach* (1st ed., pp. 145-164). Routledge.
37. Hagen, A., & Eisenack, K. (2015). International environmental agreements with asymmetric countries: Climate clubs vs. Global cooperation. *FEEM Working Paper No. 58.2015.*
38. Hagen, A., & Schneider, J. (2021). Trade sanctions and the stability of climate coalitions. *Journal of Environmental Economics and Management*, *109*, 102504.
39. Hecht, M., & Peters, W. (2018). Border adjustments supplementing nationally determined carbon pricing. *Environmental and Resource Economics*, *73*(1), 93-109.
40. Hoel, M. (1992). International environment conventions: the case of uniform reductions of emissions. *Environmental & Resource Economics*, *2*, 141-159.

41. Hsiang, S., Oliva, P., & Walker, R. (2019). The distribution of environmental damages. *Review of Environmental Economics and Policy*, *13*(1), 83-103.

42. ICAP (2023). *Emissions Trading Worldwide: Status Report 2023.* Berlin: International Carbon Action Partnership.

43. IPCC, 2023: Summary for Policymakers. In *Climate* Change *2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34.

44. Kennedy, P. G. E. (1994). Equilibrium Pollution Taxes in Open Economies with Imperfect Competition. *Journal of Environmental Economics and Management*, *27*(1), 49-63.

45. Magacho, G., Espagne, E., & Godin, A. (2023). Impacts of the CBAM on EU trade partners: consequences for developing countries. *Climate Policy*, 1-17.

46. Maliszewska, M., Chepeliev, M., Fischer, C., & Jung, E. (2023, June 13). How developing countries can measure exposure to the EU's carbon border adjustment mechanism. *World Bank Blogs*. https://blogs.worldbank.org/trade/how-developing-countries-can-measure-exposure-eus-carbon-border-adjustment-mechanism

47. Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics*, *5*(1), 15-29.

48. Martínez-Zarzoso, I., & Oueslati, W. (2018). Do deep and comprehensive regional trade agreements help in reducing air pollution? *International Environmental Agreements: Politics, Law and Economics*, *18*(6), 743-777.

49. Mathieu, C. (Ed.). (2021). Can the biggest emitters set up a climate club? A review of international carbon pricing debates. *Études De L'Ifri*, *Ifri,* June 2021.

50. McEvoy, D. M., & McGinty, M. (2018). Negotiating a uniform emissions tax in international environmental agreements. *Journal of Environmental Economics and Management*, *90*, 217-231.

51. Morin, J. F., Dür, A., & Lechner, L. (2018). Mapping the Trade and Environment Nexus: Insights from a New Data Set. *Global Environmental Politics*, *18*(1), 122-139.

52. Morin, J. F., & Jinnah, S. (2018). The untapped potential of preferential trade agreements for climate governance. *Environmental Politics*, *27*(3), 541-565.

53. Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, *105*(4), 1339-1370.

54. Nordhaus, W. D. (2006). After Kyoto: Alternative mechanisms to control global warming. *American Economic Review*, *96*(2), 31-34.

55. Pavlova, Y., & De Zeeuw, A. (2013). Asymmetries in international environmental agreements. *Environment and Development Economics*, *18*(1), 51-68.

56. Schelling, T. C. (1960). *The strategy of conflict*. Cambridge: Harvard University Press.

57. Sorgho, Z., & Tharakan, J. (2022). Do PTAs with environmental provisions reduce GHG emissions? Distinguishing the role of Climate-Related provisions. *Environmental and Resource Economics*, *83*(3), 709-732.

58. Standaert, M. (2021, March 24). *Despite pledges to cut emissions, China goes on a coal spree*. Yale Environment 360. https://e360.yale.edu/features/despite-pledges-to-cut-emissions-china-goes-on-a-coal-spree

59. Tagliapietra, S., & Veugelers, R. (2021). Fostering the industrial component of the European Green Deal: key principles and policy options. *Intereconomics*, *56*(6), 305-310.

60. Tanguay, G. A. (2001). Strategic environmental policies under international duopolistic competition. *International Tax and Public Finance*, *8*(5), 793-811.

61. UN Environment Programme. (2019). *Emissions gap report 2019.* https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf

62. Weitzman, M. L. (2014). Can negotiating a uniform carbon price help to internalize the global warming externality? *Journal of the Association of Environmental and Resource Economists*, *1*(1–2), 29-49.

63. World Meteorological Organization (WMO). (2022, September 13). *United in science 2022*. https://library.wmo.int/records/item/58075-united-in-science-2022#.ZCa3y-zMI0h

64. World Meteorological Organization (WMO). (2023, January 12). *Past eight years confirmed to be the eight warmest on record* [Press release]. https://public-old.wmo.int/en/media/press-release/past-eight-years-confirmed-be-eight-warmest-record

65. World Meteorological Organization (WMO). (2024, January 12). *WMO confirms that 2023 smashes global temperature record* [Press release]. https://wmo.int/news/media-centre/wmo-confirms-2023-smashes-global-temperature-record

66. Zhong, J., & Pei, J. (2022). Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's proposed carbon border adjustment mechanism. *Energy Policy*, *162*, 112802.

67. Zhou, L., Tian, X., & Zhou, Z. (2017). The effects of environmental provisions in RTAs on PM2.5 air pollution. *Applied Economics*, *49*(27), 2630-2641.