Three Essays on Information and Transboundary Problems in Environmental and Resource Economics

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Declaration

I hereby declare that the work contained within has been composed by me, and the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This thesis is entirely my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the Acknowledgements.

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To:

The Mother Earth

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Abstract

The thesis contains three chapters on environmental and natural resource economics and focuses on situations where agents receive private or public information.

The first chapter analyses the problem of transboundary fisheries, where harvesting countries behave non-cooperatively. In addition to biological uncertainty, countries may face strategic uncertainty. A country that receives negative assessments about the current level of the fish stock, may become "pessimistic" about the assessment of the other harvesting country, which can ignite "panic-based" overfishing. In such a coordination problem, multiplicity of equilibria is a generic characteristic of the solution. Both strategic uncertainty and equilibrium selection, relatively, have been given less attention in the theoretical literature of common-property natural resources. In this model, in the limit as the harvesting countries observe more and more precise information, rationality ensures the unique "global game" equilibrium, a la Carlsson and van Damme (1993). The improved predictive power of the model helps a potential intergovernmental manager of the stock understand the threshold behaviour of harvesting countries. The global game threshold coincides with the risk-dominance threshold of a precise information model, as if there was no strategic uncertainty, and implies that the countries select the corresponding risk-dominant action for any level of assessment of the stock. Gaining from the risk-dominance equivalence, I derive policy suggestions for the overfishing cost and the property rights in common-property fisheries.

The second chapter develops a theoretical framework to examine the role of public information in dynamic self-enforcing international environmental agreements (IEAs) on climate change. The countries choose self-enforcing emission abatement strategies

in an infinite-horizon repeated game. In a stochastic model, where the social cost of greenhouse gasses (GHG) is a random variable, a central authority, as an information sender, can control release of information about the unknown state to the countries. In the literature on stochastic IEAs, it is shown that comparison of different scenarios of learning by the countries, depends on ex-ante difference of true social cost of GHG from the prior belief of countries. Here, I try to understand, in a signalling game between the informed sender and the countries, whether the no-learning or imperfect-learning scenarios, can be an equilibrium outcome. It is shown that the equilibrium strategy of the sender, who is constrained to a specific randomisation device and tries to induce an incentive-compatible abatement level which is Pareto superior, leads to full learning of social cost of GHG of symmetric and asymmetric countries.

Finally, in the third chapter, I again examine a setting, where a central authority, as an information sender, conducts research on the true social cost of climate change, and releases information to the countries. However, in this chapter, instead of restricting the sender to a specific signalling structure, the sender, who has commitment power, by designing an information mechanism (a set of signals and a probability distribution over them), maximises his payoff, which depends on the mitigation action of countries and the social cost of green-house gases(GHG). The countries, given the information policy (the probability distribution over signals) and the public signal, update their beliefs about the social cost of GHG and take a mitigation action. I derive the optimal information mechanism from the general set of public information mechanisms, in coalition formation games. I show that the coalition size, as a function of beliefs, is an endogenous variable, induced by the information sender. If the sender maximises the expected payoff of either of non-signatories or signatories of the climate treaty, then full revelation is the optimal information policy, while if the sender attempts to reduce the global level of GHG, then optimal information policy leads to imperfect disclosure of the social cost. Furthermore, given any of the specifications of the sender's payoff, the optimal information policy leads to the socially optimal mitigation and membership outcomes.

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Chapter 1

Introduction

1.1 Overview

The thesis contains three essays on transboundary environmental and resource economics and, using non-cooperative game theory frameworks, it attempts to shed light on the significance of information on the interaction of countries facing the problem of commons. The second chapter examines the role of private information on harvesting actions of countries sharing common-pool fisheries. The third and fourth chapters study climate change and transboundary emission games, where the source of information is public. In these two chapters, in addition to the interaction of countries, the possibility of affecting the countries' mitigation actions by communication of public information is investigated.

In the subsequent sections, each chapter is briefly reviewed, and in addition to highlighting the research questions, I describe how they are tackled, and present the main results and contributions.

1.2 Second Chapter: Panic-Based Overfishing In Transboundary Fisheries

In this chapter, I try to understand one of the underlying reasons for overfishing in transboundary fisheries, which is overlooked in the theory of resource economics. I suggest a new approach to study fisheries by including strategic risk in the analysis, as a driving force of overfishing.

I examine a coordination resource game between two countries sharing a common-pool fishery. The countries, by assessing the stock individually, obtain private information about the level of fish stock. Realistically, their information is noisy (imprecise) but correlated, so each country has beliefs (opinion) about both the stock and the belief of the other country, which leads to strategic uncertainty.

As a coordination game, the model has a multiplicity of equilibrium outcomes. In addition to addressing the interaction of countries under strategic uncertainty, the main objective of this chapter is to drive unique prediction about the harvesting outcome of countries for every level of assessment of the stock of fish.

More specifically, I focus on a two-period fishery, where, at the beginning of each period, the stock is observed publicly. Then the fish stock reproduces and is subject to biological shocks. As a result of biological uncertainty, the countries assess the stock privately, and obtain their noisy private information. After updating their beliefs, they simultaneously choose between two actions of sustainable fishing and overfishing. The first is fishing a pre-committed share of the stock, which implies preserving the stock for the next period, but overfishing leads to depletion of the stock. In the final period, overfishing is dominant, and I focus on the equilibrium of the game in the first period, when the countries, by overfishing, lose the continuation payoff of the second period.

The chapter shows that there are ranges of low and high levels of assessment of the fish stock, where overfishing and sustainable fishing are respectively dominant actions. However, there is an intermediate range of the stock, where beliefs about each other's assessment determine the equilibrium outcome, and negative beliefs can give rise to "panic-based" overfishing, while the stock is not at a low level and overfishing is not a dominant action. Furthermore, in the absence of any equilibrium refinement, there is a multiplicity of equilibria in the intermediate range of assessments, and no prediction about the harvesting outcome can be derived.

The chapter suggests applying the global game equilibrium-selection of Carlsson and Van Damme (1993), upon the possibility that the countries (in the limit) are able to receive extremely precise private information. Therefore, given the binary-action assumption, the equilibrium selection technique leads to a unique threshold of assessments. Hence, for every level of assessment, it is possible to uniquely predict the harvesting action of countries. Furthermore, comparative-static analysis on the threshold provides insight into the effect of the underlying parameters of the model on the harvesting outcome.

In addition, it is shown that in our resource game, the threshold of global-game analysis coincides with the threshold of risk-dominance equilibrium-selection criterion in a complete-information game. The property of global games provides tractability for a potential (intergovernmental) manager of the stock in computing the threshold and analysing the interaction of countries as if there was no strategic uncertainty. Given the uniqueness results, some policy suggestions on the sustainable sharing rule and cost of overfishing are presented.

1.3 Third Chapter: The Economics of Climate Change and The Role of Public Information

This chapter develops a model about another renewable resource, which is global green-house gases (GHG). Similar to the second chapter, the stock is assumed to accumulate over time, and here, in the context of international environmental agreements (IEA), a repeated game among countries is examined.

It is assumed that the countries minimise their loss of private abatements, in addition to the social cost of GHG, and choose their emission abatement strategies.

A set of self-enforceable abatements given punishment by reversion to the history-independent strategy, is derived. The chapter offers equilibrium-selection analysis from this set, if the countries target a level of abatement which minimises their joint loss.

The second aspect of this chapter is addressing equilibrium selection with respect to uncertainty about the marginal social cost of GHG, which is a parameter in models of the third and fourth chapters, about which the countries receive public information. In the third chapter, the countries are either symmetric with respect to the social cost (known as level uncertainty), or asymmetric (known as distributional uncertainty).

In the literature on stochastic IEAs, different scenarios of full-learning and no learning about the marginal social cost of GHG with regards to social welfare, mitigation actions, number of countries in coalitions, etc. are studied, and it is shown that the results depend on the difference in the true realisation of social cost and its ex-ante expectation. Relative to the theory of stochastic IEAs, where different public information structures are compared, this chapter attempts to show which information structure can be an equilibrium outcome of a game between the countries and a potential information sender. Examples of information senders can be intergovernmental research institutes into climate change. In other words, in this chapter, full learning and no learning are possible equilibrium outcomes of a signalling game, where the sender is informed, and accordingly, is aware of the difference of true social cost and the prior expected value.

More specifically, the expected loss of the sender depends on abatement action of the countries and the social cost of GHG. The sender, by releasing public information on the social cost of GHG, tries to induce an abatement strategy which is closer to the social-optimal level. In order to derive the equilibrium learning scenario, I restrict attention to a specific signalling strategy, which includes full revelation and no disclosure. In the resulted incomplete information game, the countries given the publicly communicated information structure, update their beliefs about the social cost of GHG and choose a self-enforceable abatement action. It is shown that the game has a unique equilibrium which leads to full learning of the state.

1.4 Fourth Chapter: Optimal Communication of Climate Change With The Public

Similar to the third chapter, this chapter studies public information on the social cost of GHG, and the possibility of affecting actions of the countries by communication of this variable with the countries. However, instead of a repeated game, here the countries are involved in a coalition game, and they maximise their expected payoff, which depends on their (individual and collective) mitigation strategies, and the social cost of GHG, which is a random variable in the model. The sender's payoff also depends on the mitigation action of countries and the social cost variable. Furthermore, the payoffs of both sides of communication are common knowledge.

In contrast to the third chapter, the sender, at the time of announcing the information strategy, is not informed about the state of social cost. Furthermore, relative to the third chapter, instead of choosing an information strategy from a specific set, in the fourth chapter, the sender designs an optimal information policy (a probability distribution over signals) from the unrestricted set of public information policies, and the sender commits to it. This is indeed a generalisation of the theory of information design, introduced by Kamenica and Gentzkow (2011), to coalition formation in the context of climate change.

This chapter assumes that the sender, before observing the true social cost, communicates an information policy with the countries. After observing the state, the sender sends a signal realisation according to the chosen information policy. Countries given the information policy and the signal, update their beliefs and decide on joining a coalition. Subsequently, the non-signatories and signatories of the coalition choose their abatement or emission actions.

Therefore, the sender tries to induce a desirable mitigation and membership action, by affecting the countries' beliefs. It is shown that as the size of coalition is a function of beliefs, and here beliefs are endogenous variables, the coalition size is an endogenous variable, affected by the information policy of the sender.

Compared to the third chapter, here, other payoffs for the sender are assumed. It is shown that if the sender maximises an expected payoff which coincides with the expected payoff of either or both signatories or non-signatories, the optimal information policy leads to full revelation of the social cost. On the contrary, if the sender minimises the total level of GHG, then imperfect disclosure is an optimal action for the sender. However, under all of these payoff specifications, the communication of information leads to the formation of a grand coalition, where all countries cooperate on the social-optimal mitigation strategy.

1.5 Synthesis of The Research

The thesis is centred around information and learning by countries in transoundary fisheries and climate change economics. In the various essays of the thesis, the source of information is either private, or there is an active information sender, who communicates publicly with the countries.

All chapters attempt to show how information can affect the interaction of countries. In the third chapter, in addition to studying the role of information on equilibrium selection, an information sender is introduced to the strategic interaction of countries, who has limited signalling choices, and tries to affect the actions of countries. In the final chapter, from an information design perspective, the sender, by choosing the optimal game, induces the most desirable outcome of the interaction of countries. In other words, in the last chapter, the information structure and the corresponding selected equilibrium are choice variables of the sender.

Chapter 2

Panic-Based Overfishing In Transboundary Fisheries

Abstract

The chapter analyses the problem of transboundary fisheries, where harvesting countries behave non-cooperatively. In addition to biological uncertainty, countries may face strategic uncertainty. A country that receives negative assessments about the current level of the fish stock, may become "pessimistic" about the assessment of the other harvesting country, which can ignite "panic-based" overfishing. In such a coordination problem, multiplicity of equilibria is a generic characteristic of the solution. Both strategic uncertainty and equilibrium selection, relatively, have been given less attention in the theoretical literature of common-property natural resources. In this model, in the limit as the harvesting countries observe more and more precise information, rationality ensures the unique "global game" equilibrium, a la Carlsson and van Damme (1993). The improved predictive power of the model helps a potential intergovernmental manager of the stock understand the threshold behaviour of harvesting countries. The global game threshold coincides with the risk-dominance threshold of a precise information model, as if there is no strategic uncertainty, and implies that the countries select the corresponding risk-dominant action for any level of assessment of the stock. Gaining from the risk-dominance equivalence, I derive policy suggestions for the overfishing cost and the property rights in common-property fisheries.

Key words: Fishery, Biological and Strategic Uncertainties, Equilibrium Refinement, Risk Dominance, Global Games

JEL Classification: Q22; C72; C73; D82

2.1 Introduction

Despite the fact that countries have access to more and more sophisticated assessment technologies to estimate the fish population and are aware of the threatening situation of marine fisheries, "the great fish war" is increasing worldwide. According to FAO statistics[1], from 1980 to 2012, the total marine catch has grown by 62%.

In this research, I develop a theoretical framework to understand the economic forces behind the decision-making of harvesting countries in transboundary fisheries[2], where the harvesters receive information about the situation of the habitat. The results of the theoretical model, help a potential (intergovernmental) manger of the stock to explain the driving forces of overfishing, in addition to obtaining some policy solutions to tackle it.

Here, I study the behaviour of two countries, which share a fishery and interact non-cooperatively in a two-period model. After recruitment of the resource[3], the stock is publicly observed and then the appropriators face the biological shocks affecting the stock of fish[4]. The main sources of biological uncertainty in the marine ecosystem, as listed in the literature, are migration of the fish stock, predation by other animals, changes of temperature etc.[5]

The model distinguishes between the effects of different sources of uncertainty on the behaviour of fishing agents. In contrast to the biological uncertainty, the strategic uncertainty, relatively, had been given less attention in the theoretical literature of common-property natural resources. In the present research, after facing the biological shocks, the harvesting agents are modelled to obtain private noisy information about

[1] Yearbook of fishery statistics 2013

[2] By transboundary fisheries I refer to the resources overlapping the 200-mile Exclusive Economic Zones of more than one country, which are shared as common-pool resources among some countries.

[3] Similar to the literature, recruitment of the fishery refers to it reproduction.

[4] As a result of the chosen sequence of events, the term biological uncertainty is chosen instead of recruitment uncertainty. This is similar to Roughgarden and Smith (1996) and Sethi et al. (2005), who distinguish between uncertainty due to the migration of the stock or recruitment uncertainty and the measurement error in estimate of the stock.

[5] By the two-period setup, in fact I model a fishery which is destined to undergo a catastrophic situation of depletion at a certain point in the future, as the result of an exogenous reason, such as climate change. However, the countries may trigger the catastrophe at an earlier date, and I focus on their harvesting decision-making before the destined catastrophe.

the current stock. This private information may be a result of the individual research of the countries. In reality, the private assessments[6], although highly correlated among countries, have an individual measurement error or noise. The noisy private information leads to strategic uncertainty about the behaviour of the other harvesting country. In fact, the countries form higher-order beliefs about information of the other country, and second guess its harvesting decision. I am interested in the outcome of interaction of countries in this resource game, where there is a strategic risk about their partners' behaviour.

The uncertainties are introduced in two steps. In the first step, the model is analysed under the assumption of complete information about the current state of the fishery. However, there are random biological shocks that may affect the stock in the future period[7].

In this chapter, the interaction of harvesting countries is modelled in a coordination setup, hence, the payoffs have strategic complementarities. Indeed, while coordination and trust play a crucial role in the environmental economics, models of coordination under the assumption of precise information have multiplicity of equilibria, which reduces the predictive power of the model. The first equilibrium selection technique which is suggested in the chapter, is the risk-dominance criterion of Harsanyi and Selten (1988), which leads to a unique pair of threshold-type equilibrium strategies under precise information.

In the next step, I assume that the fishing countries do not observe the state of the environment precisely in any period, but they receive noisy private signals about it. Such a model helps us to understand how in a situation where overfishing is not a dominant strategy and the fishery may even have the potential for preservation, the pessimistic belief of the countries about each other's beliefs, can lead to panic-based overfishing. Indeed, higher-order beliefs can play a significant role in explaining the

[6]Throughout the chapter, assessment and signal are used as synonyms.

[7]This timing is similar to Clark and Kirkwood (1985), but here the non- regulated agents rather than the manager face the uncertainty.

observed overharvest of natural resources and here it is the result of noisy private observation of the fish stock.

Here I analyse the model when both realistic underlying biological and strategic uncertainties are present in the model. Furthermore, as the private information becomes extremely precise (although the level of the stock will never be common knowledge), the coordination game will naturally have the unique equilibrium of global games of Carlsson and van Damme (1993), and Morris and Shin (1998). Since, the unique equilibrium of global games is the only equilibrium strategy in the set of rationalisable strategies, the beliefs of the harvesters are consistent with their rationality and common knowledge of rationality. In other words, if private information is extremely precise, there is no need to justify applying the global game equilibrium-selection technique to this fishery game, but the rationality naturally enforces it. Obtaining very precise information is not an abstract assumption in the renewable resources. For example, see Costello et al. (1998), and Costello et al. (2001) for improvement in the accuracy of forecast of the fish stocks.

Accordingly, it is shown that the results of Carlsson and van Damme (1993), and Morris and Shin (1998) generalise to the case of renewable resources that the state variable (here the fish stock) in the current period depends on its previous level. It is discussed how reducing the noise of private information helps the researcher or the potential manager of the resource in deriving a conclusion about the interaction of the harvesting agents. The equilibrium takes a threshold form, and it is discussed under which conditions the harvesters coordinate on preserving the stock, and when their negative beliefs about the other country and the fishery, enforces depletion of the resource. Indeed, the refined threshold-type strategies explain the flipping behaviour of harvesting countries of the resource as the result of a change in their beliefs about the other country and sustainablity of resource. It also sheds light on the economic rationale of different harvesting levels by different countries in the same fishery. In fact, the global game analysis can explain the real-world (on the equilibrium path) chaotic mis-coordination behaviour around the threshold level.

In addition, as the global game equilibrium threshold coincides with the risk-dominant threshold in the precise-signal model[8], it provides a tractable framework for policy implications in common-property fisheries. Consequently, I present comparative-static analysis on the critical level of habitat, also I derive policy suggestions for the overfishing cost and the property rights of transboundary fisheries.

The structure of the chapter will be as follows: The related literature is reviewed in section 4.2. Then, the model is introduced in section 4.3. First, it is analysed under biological uncertainty in section 2.4. Then, in section 2.5, strategic uncertainty is added to the setup, and the global game equilibrium-refinement is introduced. Section 4.6 concludes and finally extended proofs are provided in the appendix.

2.2 Related Literature

The literature on game theory and fisheries is better surveyed by Munro (2009), Bailey et al. (2010), van Long (2011), Hannesson (2011) and Miller et al. (2013). This chapter is related to two main strands of the literature of resource extraction: the stochastic resource games and the literature on regime shifts (or catastrophe).

The pioneer in the area of the stochastic resource games is Reed (1978, 1979), who introduced the stochastic fluctuations in the stock recruitment of a renewable resource.[9] Since then the role of uncertainties and imperfect information has been extensively studied. However, there are a few authors who examine the role of asymmetric information. Laukkanen (2003,2005), Mckelvey et al. (2003) and Tarui et al. (2008), investigate situations where the harvesting action or some share of the stock are not observable by other players. In the model considered in this chapter, the source of asymmetry of information is observing noisy private signals about the state of the habitat by both harvesting countries. Golubtsov and McKelvey (2007) study an infinite-

[8]The risk-dominance equivalence of the global game equilibrium, was first proved by Carlsson and van Damme (1993) for the class of static 2×2 games.

[9]For stochastic games of resource extraction with recruitment uncertainty, to name a few among the pioneers, see Spulber (1982, 1985), Mirman and Spulber (1985), Clark and Kirkwood (1985), Clemhout and Wan (1985), Clarke and Reed (1994), Roughgarden and Smith (1996).

horizon fishery game, where the fishing fleets observe private noisy signals about the stock growth and stock-split parameters. There results are based on simulations that derive MPE and Nash bargaining solutions, and assign numeric precisions to signals of harvesting fleets to represent the incomplete information. In contrast, I construct a game which is simplified in many aspects, however, I derive analytical solutions to the problem, and prove uniqueness of the equilibrium[10].

The second strand is the extensive literature on the effect of risk of adverse events which cause a regime shift. This literature, which includes either control theory or coalition formation studies, is better reviewed by Crepin et al. (2012), Barrett (2013), Ren and Polasky (2014) and van der Ploeg (2014). As classified by Polasky et al. (2011), either system dynamics admits a fixed point or the underlying stock has an exogenous threshold (or tipping point). However, this chapter is classified under a third group of economic models of regime shifts, which is the global games. In fact, in these models, the binary action of players leads to an equilibrium which takes a threshold form with respect to (signals about) the underlying state variable. Hence, the threshold in the model is endogenous, and enables us to derive comparative-static analysis on the threshold.

As mentioned, the global-game analysis was first introduced by Carlsson and van Damme (1993) and then Morris and Shin (1998, 2003) generalised the theory. Common applications of global games are currency crises (Morris and Shin, 1998), bank runs (Morris and Shin, 2001; Rochet and Vives, 2004; Goldstein and Pauzner, 2005), foreign direct investment (Dasgupta, 2007), political regime change (Angeletos et al. 2007; Edmond, 2011) and debt-pricing (Morris and Shin, 2004; Corsetti, Guimaraes and Roubini, 2006), which all refer to real-world situations where a small change in the beliefs of agents can trigger a sudden change in their economic behaviour and lead to a regime shift.[11]

[10]The main simplification in the present setup is the two-period assumption. Handling the strategic uncertainty implies a great deal of complication, and a two-period model is sufficient to capture the idea of regime shift to depletion, in addition to the stock recruitment.

[11]As an experimental study supporting the theory see Heinemann et al. (2004).

Therefore, the present chapter also contributes to the strand of equilibrium refinement. The multiplicity of equilibria has been intensively investigated in the literature of common property resources. Among all, Dutta (1995) generalised the Folk Theorem of Aumann and Shapley (1994) to the stochastic games, also Benhabib and Radner (1992), Dutta and Sundaram (1993), Dockner and Sorger (1996) and Sorger (1998) show multiplicity of perfect equilibria in deterministic dynamic games. Although equilibrium selection has been one of the main challenges of game theory since the 1980s, to the best of my knowledge, equilibrium refinement in coordination games has not been addressed explicitly in the applications of natural resources and environmental economics. Here, I construct a resource game, where the uniqueness of equilibrium is owed to the risk-dominance and global-game equilibrium-selection methods.

Most of the literature on global games is about static settings. The growing literature of dynamic global games can be classified into two main strands. In the first strand, which was originally studied by Morris and Shin (1999,2001) and Chamley (1999), fundamentals are the driving force of the dynamics. In such frameworks, in each period the state variable, about which players obtain private information, is evolving according to a one-step random-walk process. They show that each period of the dynamic model can be considered an independent static game, with a unique threshold equilibrium in the limit, which is a random variable itself. Morris and Shin (2003) call this type of dynamic settings “Recurring Incomplete Information” global games. As Steiner (2008b) and Chassang (2010) have pointed out, the dynamics of outcomes in the models of this generation are produced exogenously by the fundamentals.

The other strand in dynamic global game literature, includes models that endogenise the underlying dynamics. This idea was first proposed by Angeletos, Hellwig and Pavan (2007) who studied a multi-period regime-change game where the fundamentals were i.i.d. Survival of the status quo in at least one period weakens the posterior beliefs about the possibility of abandoning the regime. So players’ beliefs about the fundamentals are the endogenous source of the dynamics. Similar to Morris and Shin (1999), they also assume fundamental-independent payoffs for the safe action.

Therefore, this type of endogeneity is completely related to the evolution of beliefs. Steiner (2008a) captured the idea of endogeneity of dynamics by introducing another state variable in the payoff functions. Chassang (2010) and Dasgupta et al. (2012) study respectively, infinite and finite-horizon global games, in which all payoffs are functions of an i.i.d. state variable and players' incentives through the payoff structure are the source of endogeneity of dynamics.[12].

The present work is a combination of these two strands. First, as a renewable resource, the state of a fishery depends on its previous value through the growth function[13]. Beside the exogenous evolution of the fishery, all of the payoffs depend on the state of the resource. Hence the players' incentives are the other driving force of the dynamics of outcomes.

2.3 The General Framework

In each period, a 2×2 game with stay-exit structure is played[14]. Two countries share a stock of fish $w_t \in (0, 1)$, where subscript t refers to time. They choose between two actions: sustainable-fishing, S, and overfishing, O. If the countries decide to maintain the resource then the game will continue to the next period, but they may choose to exhaust the stock in any period and end the game. If there is no uncertainty in the environment, then the stock of fish grows according to the specific, but commonly-used growth function of Levhari and Mirman (1980), as an increasing, strictly concave and bounded growth function, $w_t = (\bar{w}_{t-1})^{\alpha}$, where $0 < \alpha < 1$, and $\bar{w}_{t-1} \in (0, 1)$ is the escapement level of the stock at the end of period $t - 1$. Also $\bar{w}_0$ is the initial stock which is chosen by nature. Furthermore, α and the growth function are common knowledge among the harvesting countries.

[12]There is another strand in the dynamic global games, where two-period models are considered. For example, see Goldstein and Pauzner (2005), Heidhues and Melissas (2006), Dasgupta (2007), and Kovac and Steiner (2012).

[13]Not completely similar to Morris and Shin(1999) and Chamley (1999), since the state variable does not follow a random-walk process.

[14]This is similar to the theoretical global game paper of Chassang (2010). In contrast to his model, where the sate variable is i.i.d. here the state grows over time.

However, in this model there are uncertainties about both the stock of fish and the harvesting action of the other player. The timing of the game is as follows:

At the beginning of the game, nature chooses the state of the fishery, $\bar{w}_0$. Then at the beginning of each period t, for $t \in \{1,2\}$, the escapement level, $\bar{w}_{t-1}$, which is the parent fish stock left from the previous period, reproduces and the countries receive a public signal, $y_t \equiv (\bar{w}_{t-1})^{\alpha}$, about the state of the fishery, which is in fact the population of fish in the stock.[15] Then the fishery will be subject to biological shocks, ξ_t, which I model as an additive shock to the stock of the transboundary fishery. Therefore, $w_t = y_t + \xi_t$.[16] Also, $\Xi \sim U[-c, c]$, where $0 < c < 1$ and $U[.]$ refers to the uniform probability density function[17]. The biological shocks are serially uncorrelated and independent of w_t. It is assumed that if the stock is fully depleted, then there will not be any immigration to the stock, and the fishery can never recover.

In every period $t \in \{1,2\}$ and after the biological shocks, country i as a result of its own independent research, obtains a noisy private signal, x_t^i, about the size of the stock, where $x_t^i = w_t + \varepsilon_t^i$, also $E \sim U[-a, a]$. The superscript $i \in \{1,2\}$ refers to countries' index, where $i \in \{1,2\}$, and in future $-i$ refers to the other country. Since ε_t^i can be interpreted as the private measurement error in the assessment of the fish stock, parameter a is referred as the precision of private information. These noises are i.i.d. and independent of w_t. Although the signals of the two countries are highly correlated, they are private information. The structure of payoffs, the distributional assumptions of the private signals and the noise technology of the state of the fishery are common knowledge among the countries.

Finally, players choose between the two harvesting levels simultaneously, and at the end of each period[18], actions are observed and payoffs are determined. In period $t \in \{1,2\}$, when the countries are making decisions the true level of stock is w_t. As

[15] It can be assumed that the public signal is communicated by benevolent (intergovernmental) research institutes which conduct research about the fisheries and publish their results.

[16] Henceforth, upper case letters denote random variables, and lower case letters refer to the realised values that the random variables map onto.

[17] In Appendix 2.7.3, the assumption of uniform distributions is relaxed.

[18] I refer to the described framework as a two-period model, as $t = 0$ is used for the sake of completeness and defining the initial values. So, the first period is denoted by $t = 1$.

mentioned earlier, if in the first period, the players coordinate on sustainable-fishing, then the game continues to the next period, and if one or both countries overfish in any period, the game ends, both players receive the termination payoffs of that period, the habitat will be extinguished to a level below the minimum viable population, and no further positive or negative shocks in subsequent period will affect the stock.

Table 2.1 depicts the payoffs of the first period (without continuation values). The payoff of the sustainable harvesting is equal to the countries' yield or the amount of fish that they catch. Sustainable-fishing is harvesting according to a pre-committed harvest fraction, r, for each country, where $r \in (0, \frac{1}{2})$. At the moment this fraction is exogenously fixed and if both counties choose the sustainable harvest, then indeed they share the total catch, $2r$, symmetrically.[19] While, overfishing in the first period is catching whatever is left in the stock and it leads to an extraction cost, $\frac{\kappa}{w_1}$, as well, where κ is a positive constant. This cost captures extra costs of illegal harvesting or the international pressure from breaching the agreement, and it is negatively related to the size of population.

In fact, because of the growth function, existence of such an overfishing cost implies that if the fishery is small in size, where reproduction rate is high, overfishing causes a larger loss. For example, for a small stock which is mainly parental fish, there is more public awareness and international pressure to protect it. Conversely, the richness of the habitat reduces the overfishing cost, and decreases the conservation incentives. Sensitivity of the results to the existence of this cost, and its specific functional form is discussed for the model with biological uncertainty in section 2.4, and with biological and strategic uncertainty in section 2.5. The payoff of (O,O) in the first period is sharing the resource equally minus the overfishing cost.

It is implicitly assumed that the price of fish is normalised to one, and there is no market externality. In addition, the cost of acquiring information is normalised to zero.

[19] Conventionally, sustainable yield refers to a level of catch such that the stock remains constant over time, however here I define sustainable catch as harvesting in compliance with the agreed harvest fraction and the sharing rule.

These simplifying assumptions provide us with a tractable model to study the strategic interaction of countries in the transboundary fisheries.

Table 2.1 Normal-form representation of the game in the first period

		Country 2: S	Country 2: O
Country 1	S	$rw_1,\, rw_1$	$rw_1,\, (1-r)w_1 - \frac{\kappa}{w_1}$
	O	$(1-r)w_1 - \frac{\kappa}{w_1},\, rw_1$	$\frac{w_1}{2} - \frac{\kappa}{w_1},\, \frac{w_1}{2} - \frac{\kappa}{w_1}$

In the last period, there is no continuation value, hence there is no overfishing cost either. The strictly dominant strategy for both players is overfishing. Hence, given the symmetry of the game, they share the stock equally in the last period. Appealing to sequential rationality, by backward induction, the total payoff of country i in the first period of a two-period game by playing (S, S) is $rw_1 + \frac{\beta}{2}\mathbb{E}[w_2|y_1,\, x_1^1,\, \sigma_1^1 = \sigma_1^2 = 1]$, where $\beta \in (0, 1)$ is the discount factor, which is identical for both harvesting agents, and σ_t^i is the strategy of country i in period t, such that $\sigma_t^i : X_t \times Y_t \to [0, 1]$, and the range $[0, 1]$ refers to the probability of sustainable fishing by country i given its signals. The stay-exit structure implies that the other payoffs in the first period of a two-period game, remain the same as table 2.1, i.e. there is no continuation value if at least one of the countries chooses overfishing in the first period. The first period of the two-period model is analysed as a one-shot game augmented with the continuation payoff of a dominant action in the second period.

This setup fits into the literature of stochastic games, where the stage game changes from period to period and the transition function, showing the evolution of stock, depends on both the actions and the random biological shocks. The explained stochastic resource game can be denoted by $G(\bar{w}_0, a, c, r, \alpha, \beta, \kappa)$, and henceforth I suppress notation and express it as G.

Finally it is assumed that X_t and W_t map into $(0, 1)$. This is because first, the stock variable must be non-negative, and second the growth of the stock occurs only in the range $(0, 1)$. Since $x_t^i = w_t + \varepsilon_t^i$, restricting x_t^i is sufficient and is achieved by assuming

$0 < x_1^i < 1$ and $0 < x_2^i < 1$. The first assumption implies $0 < (\bar{w}_0)^\alpha \pm c \pm a < 1$, and the second implies $0 < b[(\bar{w}_0)^\alpha \pm c]^\alpha \pm c \pm a < 1$, where $b \equiv (1-2r)^\alpha$. Because depending on r and α, the state variable in the first period, w_1, can be both greater or less than w_2, both restrictions are needed and they can be rephrased to $(\bar{w}_0)^\alpha - c - a > 0$, $(\bar{w}_0)^\alpha + c + a < 1$, $b[(\bar{w}_0)^\alpha - c]^\alpha - c - a > 0$ and $b[(\bar{w}_0)^\alpha + c]^\alpha + c + a < 1$. These indeed mean that the maximum level of noise of each period, $a + c$, must be small enough relative of the initial stock to guarantee that $x_t^i \in (0, 1)$.

As a definition, a strategy σ_t^i is a threshold strategy for player i, if there exists a cutoff, below which the countries sustainably harvest, and above which they overfish. Indeed, the reason for defining the threshold strategies with sustainable fishing for low levels of the stock is concavity of the growth function and the existence of overfishing cost, which lead to greater conservation incentive where the fishery, although small in size, has a high reproduction rate. Finally, since the game is symmetric, the equilibrium refers to a pair of equilibrium strategies.

The uncertainty is introduced in two steps in the analysis. In the first step, I focus on precise private signals. Therefore, the countries can assess the current state of the fishery perfectly, but the biological shocks in future period may still affect the fishery. In the second step, where the general case with noisy private signals is studied, there will be both biological and strategic uncertainties in the first period.

2.4 Biological Uncertainty

In this section I will examine the decision of countries in the first period, under the assumption of $a = 0$. Hence, $x_1^i = w_1$ for both i. In other words, in equilibrium, there is complete and perfect information about the action of the other country, and the current state of the fishery, but there is biological uncertainty about the future stock.

Given game G with payoffs depicted in Table 2.1 and taking into account the continuation payoffs, the countries compare the expected payoff of sustainable fishing versus overfishing in the first period. Let us define two functions representing the expected payoff differential of a country given that the other country chooses sustainable harvesting and overfishing respectively:

$$\underline{\Delta}^0(w_1) \equiv rw_1 + \frac{\beta}{2}\mathbb{E}[w_2|w_1,\, \sigma_1^1 = \sigma_1^2 = 1] - (1-r)w_1 + \frac{\kappa}{w_1} \tag{2.4.1}$$

$$\bar{\Delta}^0(w_1) \equiv rw_1 - \frac{w_1}{2} + \frac{\kappa}{w_1} \tag{2.4.2}$$

where $\mathbb{E}[w_2|w_1,\sigma_t^1 = \sigma_t^2 = 1] = b(w_1)^\alpha$, and superscript 0 refers to the precise-signal case.

2.4.1 Dominance and intermediate regions

There is a low level of fish population, $\underline{w}_1$, below which due to the high overfishing cost also the high reproduction rate of the fishery, sustainable harvest is a dominant action. I call $(0, \underline{w}_1)$ the lower dominance region. In other words, for any $w_1 \in (0, \underline{w}_1)$, independent of the action of the other country, the payoff of sustainable extraction is strictly larger than overfishing, i.e. $\underline{\Delta}^0(w_1) > 0$ and $\bar{\Delta}^0(w_1) > 0$.

Similarly, there exists an upper dominance region, $(\bar{w}_1, 1)$, where overfishing in the first period is a dominant action. Indeed, in this region, if one of the players is going to exit the game, there is a first-mover advantage to do so. In fact, for any $w_1 > \bar{w}_1$, $\underline{\Delta}^0(w_1) < 0$ and $\bar{\Delta}^0(w_1) < 0$.

This leads to the existence of an intermediate region of fish population, $[\underline{w}_1, \bar{w}_1]$, in which there is no dominant action. The continuation payoff and the overfishing cost are such that the game in the first period is a coordination game, i.e $\underline{\Delta}^0(w_1) \geq 0$, with equality at $\bar{w}_1$ and $\bar{\Delta}^0(w_1) \leq 0$, with equality at $\underline{w}_1$. Therefore, in this region, on which I will focus, the game has two pure Nash equilibrium actions of (S, S) and (O, O).

To characterise this region, it is sufficient to solve for $\underline{w}_1$ and $\bar{w}_1$. Solving $\bar{\Delta}^0(\underline{w}_1) = 0$ implies $\underline{w}_1 = \sqrt{\kappa/(\frac{1}{2} - r)}$. Likewise, $\bar{w}_1$ solves $\underline{\Delta}^0(\bar{w}_1) = 0$. There is no explicit solution for $\bar{w}_1$, but note that $\underline{\Delta}^0(w_1)$ is continuous in w_1, also $\lim_{w_1 \to 0} \underline{\Delta}^0(w_1) = +\infty$. I impose the following assumption to ensure strict monotonicity of $\underline{\Delta}^0(w_1)$ and existence of its unique real root in between $(\underline{w}_1, 1)$.

Assumption 1. *Game G is such that for all* $w_1 \in (0,1)$, $\frac{\partial \underline{\Delta}^0(w_1)}{\partial w_1} < 0$, *also* $\underline{\Delta}^0(w_1 = 1) < 0$.

Indeed, $\underline{\Delta}^0(w_1)$ is a strictly decreasing function with respect to w_1, if $\frac{\partial \underline{\Delta}^0(w_1)}{\partial w_1} = \frac{\beta}{2} b\alpha w_1^{\alpha-1} - (1-2r) - \frac{\kappa}{w_1^2} < 0$, which is satisfied if and only if $\frac{\beta}{2} b\alpha w_1^{\alpha+1} - b^{\frac{1}{\alpha}} w_1^2 < \kappa$. Recall that $\underline{\Delta}^0(w_1)$ is the expected payoff differential of a country where the other country is harvesting sustainably, hence this assumption implies that, for all $w_1 \in (0,1)$, that the fish population is growing, if the other country harvests sustainably, then as the stock increases, the overfishing cost parameter, κ, is large enough such that marginal net benefit of overfishing is more than marginal net benefit of sustainable harvesting[20]. Furthermore, if the LHS of the inequality is negative, then this assumption is reduced to $\kappa > 0$. In addition, $\underline{\Delta}^0(w_1 = 1) < 0$ reassures the single crossing of $\underline{\Delta}^0(w_1)$ in between $(\underline{w}_1, 1)$. Indeed $\underline{\Delta}^0(w_1 = 1) = \frac{\beta}{2} b - (1-2r) + \kappa$ is negative if and only if $\kappa < (1-2r) - \frac{\beta}{2} b$. This can be rewritten as $\frac{\beta}{2}(1-2r)^{\alpha} < (1-2r) - \kappa$, which states that κ should be small enough such that if the stock is not growing, i.e. $w_1 = 1$, then the payoff of catching the left share today, $(1-2r) - \kappa$, is greater than the tomorrow's share. Therefore, the two parts of assumption 1 can be jointly rephrased as $\frac{\beta}{2} b\alpha w_1^{\alpha+1} - b^{\frac{1}{\alpha}} w_1^2 < \kappa < b^{\frac{1}{\alpha}} - \frac{\beta}{2} b$.

Given Assumption 1, there exist a unique real root, $\bar{w}_1 \in (0,1)$, solving $\underline{\Delta}^0(\bar{w}_1) = 0$. Finally, I need to assume $\underline{\Delta}^0(\underline{w}_1) > \bar{\Delta}^0(\underline{w}_1)$, to guarantee that $\underline{w}_1 < \bar{w}_1$.

Assumption 2. *Game G is such that* $\underline{\Delta}^0(\underline{w}_1) > 0$.

Intuitively, in the lower dominance region, sustainable harvest is a cooperative action, and increases the conservative incentive of the other country. Comparison of (2.4.1) and (2.4.2) shows that Assumption 2 is satisfied if and only if $(\frac{1}{2} - r)\underline{w}_1 < \frac{\beta}{2} b \underline{w}_1^{\alpha}$.

[20] Note that as κ increases, marginal net benefit of overfishing, $(1-r) + \frac{\kappa}{w_1^2}$, increases.

Therefore, $0 < \underline{w}_1 < \bar{w}_1 < 1$, and thus game G admits lower and upper dominance regions, and an intermediate region of fish population in between.[21]

Thus, in the intermediate region, where there is no dominant action, although there are only two periods in the model, because the fish stock is reproducing and the considerable overfishing cost, depending on the current level of the stock, countries may choose to wait in the first period, and in the most cooperative equilibrium, both countries sustainably harvest up to $\bar{w}_1$. Despite the fact that in the dominance regions there were unique outcomes, for any state of fishery (or precise signal) in between the upper-bound and lower-bound thresholds there is multiplicity of equilibrium outcomes that players either play (O,O) or (S,S) or randomise (at the thresholds).

Therefore, if there is complete information about the current stock of fish, then the theory cannot predict the action of harvesting agents. This multiplicity of equilibrium outcome, which is the natural characteristic of coordination games under precise information, in the absence of any equilibrium refinement, reduces the predictive power of the model to zero for any value of the stock $w_1 \in [\underline{w}_1, \bar{w}_1]$.

2.4.2 Comparative statics on the upper-bound and lower-bound thresholds

The discount factor, β, and the reproduction rate, α, through the channel of continuation value of sustainable harvest, only affect $\underline{\Delta}^0(w_1)$, but not $\bar{\Delta}^0(w_1)$. Since $\underline{\Delta}^0(w_1)$ is an increasing function of both of these parameters, if the countries become more patient, i.e. the discount factor increases, or if the reproduction rate of the fishery increases, i.e. α decreases, for any given level of fish population, $\underline{\Delta}^0(w_1)$ shifts up, so its crossing which is $\bar{w}_1$, moves to the right. Therefore, there would be a smaller upper dominance region, while $\underline{w}_1$ is constant.

However, the overfishing cost parameter, κ, and the harvest fraction, r, affect both $\underline{w}_1$ and $\bar{w}_1$, and indeed these two parameters are important for practice pathways.

[21] As a numeric example, if $\beta = 0.9$, $\kappa = 0.01$, $r = 0.3$, and $\alpha = 0.5$, then $\underline{w}_1 = 0.2$ and $\bar{w}_1 = 0.6$.

Since

$$\frac{\partial\underline{\Delta}^0(w_1)}{\partial\kappa} = \frac{\partial\bar{\Delta}^0(w_1)}{\partial\kappa} = \frac{1}{w_1}$$

increasing the cost parameter, shifts both $\underline{w}_1$ and $\bar{w}_1$ to the right. Hence, by expanding the lower dominance region and shrinking the upper dominance region, a larger overfishing cost implies a safer habitat on average[22].

Finally because $\frac{\partial\bar{\Delta}^0(w_1)}{\partial r} = w_1$, if the countries agree on a larger harvest fraction for sustainable catch, i.e. if r increases, $\underline{w}_1$ increases, so up to a larger level of fish population, the sustainable extraction is a dominant action. However, because

$$\frac{\partial\underline{\Delta}^0(w_1)}{\partial r} = 2w_1 - \alpha\beta(1-2r)^{\alpha-1}w_1^{\alpha}$$

can be either positive or negative, also $\frac{\partial^2\underline{\Delta}^0(w_1)}{\partial r^2} < 0$, $\underline{\Delta}^0(w_1)$ is not monotone in r, and there is a trade off. Increasing the harvest fraction of sustainable catch, on one hand reduces the continuation payoff, $rw_1 + \frac{\beta}{2}bw_1^{\alpha}$, and on the other hand reduces the temptation for unilateral deviation $(1-r)w_1$. Indeed, there is a critical harvest fraction, $\bar{r} = \frac{1}{2} - (\frac{\alpha\beta}{2})^{\frac{1}{1-\alpha}}\frac{1}{2w_1}$, which solves $\frac{\partial\underline{\Delta}^0(w_1)}{\partial r} = 0$, and below which increasing the shares of sustainable fishing reduces the temptation for overfishing, so for any level of fish stock, $\underline{\Delta}^0(w_1)$ shifts up, pushing $\bar{w}_1$ to the right. Increasing the shares beyond the critical $\bar{r}$, decreases the upper-bound threshold as it reduces the continuation payoffs.

2.4.3 Equilibrium refinement with biological uncertainty

A relevant equilibrium-selection technique in this game with precise information is the risk-dominance criterion of Harsanyi and Selten (1988). In the first period of any game G, sustainable-fishing weakly risk-dominates overfishing if the product of deviation losses of sustainable-fishing is weakly greater than those of overfishing, i.e.

$$\left[rw_1 + \frac{\beta}{2}\mathbb{E}[w_2|w_1,\sigma_1^1 = \sigma_1^2 = 1] - (1-r)w_1 + \frac{\kappa}{w_1}\right]^2 - \left[\frac{w_1}{2} - \frac{\kappa}{w_1} - rw_1\right]^2 \geq 0 \quad (2.4.3)$$

[22]Despite the fact that there is no prediction about the equilibrium selection by the harvesting agents in the intermediate region.

Indeed, the terms inside the brackets are $\underline{\Delta}^0(w_1)$ in (2.4.1) and negative of $\bar{\Delta}^0(w_1)$ in (2.4.2), respectively. As explained, in the dominance regions, there exists a unique prediction, therefore, I focus on the intermediate region. Since for any $w_1 \in (\underline{w}_1, \bar{w}_1)$ any game G is a coordination game, i.e. (S,S) and (O,O) are pure Nash equilibria of the game, thus both expressions inside the brackets in (2.4.3) are positive in this region. Furthermore, a fish population equal to the upper-bound threshold, $\bar{w}_1$, does not satisfy the risk-dominance criterion in (2.4.3). Hence, for any $w_1 \in [\underline{w}_1, \bar{w}_1)$, the inequality in (2.4.3) can be written as $\Delta^{RD}(w_1) \geq 0$, where

$$\Delta^{RD}(w_1) \equiv 2rw_1 + \frac{\beta}{2}b(w_1)^{\alpha} - (1-r)w_1 + \frac{2\kappa}{w_1} - \frac{w_1}{2} \tag{2.4.4}$$

Proposition 1. *In the first period of any game in G, under the precise signals, there exists a unique symmetric risk-dominant threshold, w^{RD}, below which sustainable harvest is risk-dominant and above which overfishing is risk-dominant.*

Proof. The first part of Assumption 1 is sufficient for $\frac{\partial \Delta^{RD}(w_1)}{\partial w_1} < 0$. In fact, $\frac{\partial \Delta^{RD}(w_1)}{\partial w_1} < 0$ implies $\frac{1}{2}[\frac{\beta}{2}b\alpha w_1^{\alpha+1} - b^{\frac{1}{\alpha}} w_1^2 - (\frac{1}{2} - r)w_1^2] < \kappa$, and if the LHS of this inequality is negative, then $\kappa > 0$ ensures strict monotonicity of $\Delta^{RD}(w_1)$. Recall that (2.4.4) is sum of $\underline{\Delta}^0(w_1)$ and $\bar{\Delta}^0(w_1)$. Since $\bar{\Delta}^0(w_1 = \bar{w}_1) < 0$, also $\underline{\Delta}^0(w_1 = \bar{w}_1) = 0$, $\Delta^{RD}(w_1 = \bar{w}_1) < 0$. In addition, $\underline{\Delta}^0(\underline{w}_1) > 0$, and $\bar{\Delta}^0(\underline{w}_1) = 0$, imply that $\Delta^{RD}(w_1 = \underline{w}_1) > 0$. Hence, $\Delta^{RD}(w_1)$ has a unique real root, say $w^{RD} \in (\underline{w}_1, \bar{w}_1)$ and the risk-dominant equilibrium admits a threshold form, below w^{RD} the countries fish sustainably and above it they overfish. □

In terms of comparative statics, the sensitivity of $\Delta^{RD}(w_1)$ and therefore w^{RD} to the discount factor and reproduction rate are similar to $\underline{\Delta}^0(w_1)$ and $\bar{w}_1$. So as β increases, or as α decreases, w^{RD} shifts to the right, so in a larger set of fish population, the unique action of sustainable extraction is risk dominant.

Furthermore, because $\frac{\partial \Delta^{RD}(w_1)}{\partial \kappa} = \frac{2}{w_1}$, relative to $\underline{w}_1$ and $\bar{w}_1$ thresholds, w^{RD} is more sensitive to the overfishing cost. So, when κ increases, all of these three thresholds shift to the right, but w^{RD} responds more, implying coordination on the conservative action for a larger range of fish population. Without the overfishing cost, i.e. if $\kappa = 0$, there would be no lower dominance region, and $\Delta^{RD}(w_1)$ would be a hump-shape function, but still it admits a single real root at w^{RD}, and at any level of the stock above w^{RD}, $\Delta^{RD}(w_1) < 0$, and below it, $\Delta^{RD}(w_1) > 0$. Therefore, proposition 1 holds. Furthermore, with any other functional form for the overfishing cost, as long as the single-crossing property, and the mentioned signs of $\Delta^{RD}(w_1)$ hold, the risk-dominance criterion leads to a unique threshold-form equilibrium. Clearly, a cost function which is negatively related to the stock, provides monotonicity of $\Delta^{RD}(w_1)$ as well.

Finally, the risk-dominance threshold does not respond monotonically to the harvest fraction, r, and indeed

$$\frac{\partial \Delta^{RD}(w_1)}{\partial r} = 3w_1 - \alpha\beta(1-2r)^{\alpha-1}w_1^{\alpha} = 0$$

implies existence of a critical harvest fraction, $r^{RD} = \frac{1}{2} - (\frac{\alpha\beta}{3})^{\frac{1}{1-\alpha}}\frac{1}{2w_1}$. Note that $\frac{\partial^2 \Delta^{RD}(w_1)}{\partial r^2} < 0$, hence, below r^{RD}, increasing the harvest fraction increases $\Delta^{RD}(w_1)$ and therefore w^{RD}, and above the critical level, increasing r, decreases the risk-dominance threshold. Furthermore, comparison of r^{RD} with the critical harvest fraction in section 2.4.2, implies $\bar{r} < r^{RD}$.

To sum up, according to Harsanyi and Selten (1988), if the players coordinate on the less risky action, then the risk-dominance equilibrium-selection criterion provides a unique prediction. However, it is known that in a model with precise information, selection of risk-dominance criterion is a matter of opinion, and in fact the global game provides a justification for the risk-dominance selection. In addition, the assumption of observing the state of the fishery precisely is very strong. In the next section, by allowing for noisy private information acquisition, in addition to explaining the equilibrium coordination failure, which is observed in reality, I derive a unique prediction about the outcome of the countries' interaction.

2.5 Biological and Strategic Uncertainty

Under precise information, the fishing countries could perfectly anticipate the harvesting decision of the other country in equilibrium. However, in reality the harvesting countries do not share either precise or common information about the stock of resource. In this section, the model is analysed under the more plausible assumption that the fishing firms do not assess the state of the environment precisely in any period, but they obtain the public signals, y_t, before the biological shocks and the noisy private signals, x_t^i, after the shocks. In fact, since the private signals about the stock of the fishery are highly correlated between the two countries, each signal conveys some information about the signal and therefore the action of the other country. On the other hand, this information is noisy and leads to strategic uncertainty and possibility of coordination failure in equilibrium.

In such an environment, in which the countries face both biological and strategic uncertainties, they form higher-order beliefs about each other's beliefs about the stock of fish. Carlsson and van Damme (1993) and Morris and Shin (1998) provide a tractable method, which ends up with a simple monotone-strategy equilibrium, which just depends on the countries' private assessments. Their analysis is based on vanishing noise of the private signals, although the state variable will never become common knowledge. In the next subsections, the global game equilibrium is derived, then its result is compared with the risk-dominance criterion of Harsanyi and Selten (1988) for the precise information game. Finally given these results, I derive the optimal harvest fraction of sustainable yield and overfishing cost.

2.5.1 Equilibrium with biological and strategic uncertainty

Before characterising the global-game equilibrium strategies, let us examine the probability of sustainable yield in the dominance regions given private and noisy information. If country i observes a signal $x_1^i < \underline{w}_1 - a$, then it believes that $w_1 < \underline{w}_1$, so regardless of its belief about the other country, as a dominant strategy, chooses sustainable harvest with probability one. If any country has a private assessment $x_1^i < \underline{w}_1 - 2a$, then it believes definitely that the other country is also receiving a signal $x_1^{-i} < \underline{w}_1$. Hence for any $w_1 < \underline{w}_1 - 2a$, probability of (S, S) is one. By the same argument, in the upper dominance region, for any $w_1 > \bar{w}_1 + 2a$, the probability of (S, S) is zero. I assume there exist levels of fish stock $\underline{w}_1 - 2a > 0$, also $\bar{w}_1 + 2a < 1$. If $w_1 \geq \underline{w}_1$, no country has an assessment $x_1^i < \underline{w}_1 - a$. Likewise, where $w_1 \leq \bar{w}_1$, neither of them have a signal $x_1^i > \bar{w}_1 + a$. Thus, for any $w_1 \in [\underline{w}_1, \bar{w}_1]$, there is no dominant strategy and the countries' beliefs about each other determine the probability of (S, S), and it varies between its upper bound (one) and its lower bound (zero).

Hence, overfishing in the first period, may occur for two reasons. First, the private noisy assessment of resource may provide some information that the population of fish stock implies that overfishing is a dominant action. Therefore, for example, if the stock of resource in the first period is above $\bar{w}_1 + 2a$, as mentioned above, overfishing happens because the countries observe high signals about the stock (where the fishery has a low reproduction and overfishing cost is relatively low). In addition, the correlated assessments convey noisy information regarding the assessment and therefore the belief of the other country. Hence, overfishing may happen because a country believes that the other country has observed a high signal, although the stock is not fragile, i.e. where it is not dominant to overfish. Indeed, in the intermediate region of $[\underline{w}_1, \bar{w}_1]$, the fear of mis-coordination on the equilibrium path, which translates to "pessimism" about the possibility of unilateral overfishing by the other country, is the result of observing noisy private signals[23]. I refer to overfishing in the intermediate region as "panic-based" overfishing, which is the result of pessimism about the belief of the other harvesting country and it is not dominant to overfish[24]. Therefore, in the absence of any equilibrium refinement, in the intermediate region, there is multiplicity of equilibria.

[23]The term "fear of mis-coordination" is borrowed from Chassang (2010), who explains that although the probability of actual mis-coordination in the equilibrium of a global game is very small, the "fear" of mis-coordination influences the equilibrium actions.

[24]The term "panic-based" action is also borrowed from the bank run paper of Goldstein and Pauzner (2005) on the literature of Global games.

Because the signals affect the countries' beliefs about both the state of the fishery and the action of the other country, the expected payoff of countries and therefore their equilibrium actions depend on their private assessments. To find the equilibrium strategies, again each country compares the expected payoff of sustainable fishing and overfishing, which depend on its own belief about the stock of the fishery, in addition to its belief about the belief of the other country about the state. Let $\Delta^i(w_1,\, x_1^{-i}(x_1^i,\, y_1) \mid x_1^i,\, y_1)$ be the difference of expected payoff of sustainable fishing versus overfishing for country i in period 1, given the observed signals and holding belief x_1^{-i} about the signal of the other country. Indeed,

$$\Delta^i(w_1,\, x_1^{-i}(.) \mid x_1^i,\, y_1) \equiv$$
$$\mathbb{E}\left[(rw_1 + \frac{\beta}{2}w_2)\mathbf{1}_{\substack{\sigma_1^i=1\\ \sigma_1^{-i}=1}} + (rw_1)\mathbf{1}_{\substack{\sigma_1^i=1\\ \sigma_1^{-i}=0}} - ((1-r)w_1 - \frac{\kappa}{w_1})\mathbf{1}_{\substack{\sigma_1^i=0\\ \sigma_1^{-i}=1}} - (\frac{w_1}{2} - \frac{\kappa}{w_1})\mathbf{1}_{\substack{\sigma_1^i=0\\ \sigma_1^{-i}=0}} \,\middle|\, x_1^i, y_1\right] \tag{2.5.1}$$

I claim there exists a symmetric equilibrium threshold, w^*. If there exists such a threshold perfect Bayes Nahs equilibrium (PBNE), then in equilibrium, country i by observing a signal below $w^* - a$ (above $w^* + a$), chooses sustainable fishing, i.e. $\sigma_1^i = 1$, (overfishing, i.e. $\sigma_1^i = 0$), where $\Delta^i(w_1,\, x_1^{-i}(.) \mid x_1^i,\, y_1)$ is positive (negative) for that country. Furthermore, if the country exactly receives the critical signal of $x_1^i = w^*$, then country i must be indifferent between sustainable fishing and overfishing in equilibrium, i.e. $0 \le \sigma_1^i \le 1$. Hence, given the properties of the indifference equation, examined in Appendix 2.7.2, a sufficient condition for existence of a threshold PBNE is $\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*,\, y_1) = 0$. In addition, in equilibrium both countries choose the same level of harvest unless at least one country observes a signal which is very close to the critical signal, where mis-coordination might happen.

Before formalising this result in the next proposition, in order to shed light on the importance of global-game technique in analysing the behaviour of countries encapsulated in (2.5.1), assume that country i could observe the stock precisely, but assumes that the other country has a private signal x_1^{-i}. From the point of view of such a country, equation (2.5.1) would be reduced to[25]

$$\Delta^0(w_1,\, x_1^{-i}(.) \mid x_1^i) \equiv \begin{cases} rw_1 + \frac{\beta}{2}w_2 - (1-r)w_1 + \frac{\kappa}{w_1} & \text{if } x_1^{-i} \leq w^* \\ (r - \frac{1}{2})w_1 + \frac{\kappa}{w_1} & \text{if } x_1^{-i} \geq w^* \end{cases} \tag{2.5.2}$$

and probability of sustainable fishing by the other country could be pinned down by

$$Pr(x^{-i} < w^* \mid w_1) = Pr(w_1 + \epsilon_1^{-i} < w^* \mid w_1) = F(w^* - w_1 \mid w_1)$$

where $F(.)$ is the uniform cumulative distribution function of ϵ_t^i. Therefore, if the current level of stock was not a random variable for the countries, but they assume that the other country has private information, it was possible to compute the probability of sustainable fishing or overfishing for any level of the stock. So, $\Delta^i(w_1,\, x_1^{-i}(.) \mid x_1^i,\, y_1)$ in (2.5.1) would be simply sum of the expected value of two parts of $\Delta^0(w_1,\, x_1^{-i}(.) \mid x_1^i)$ over the support of x_1^{-i}.

However, in an environment where the countries cannot assess the stock of the fishery absolutely precisely, the expected payoffs in (2.5.1) and $Pr(x_1^{-i} < w^* \mid x_1^i)$ are difficult to compute. In Appendix 2.7.1, the conditional probability densities of the stock and the belief of harvesting partner for a uniform (non-vanishing) noise and biological shock, are derived. Here, I am interested in an equilibrium refinement, in order to improve the predictive power of the model. Therefore, given the possibility of accessing almost precise assessment technologies, I gain from the global-game analysis, which by focusing on very precise private information (although never common knowledge), indeed leads to analysing the model using $\mathbb{E}_{x_1^{-i}}\Delta^0(w_1,\, x_1^{-i}(.) \mid x_1^i)$.

In global-game equilibrium it may happen that the two countries choose asymmetric actions, because their signals are very close to the common threshold. This chaos is

[25]The implicitly assumed monotone strategy and the uniqueness of threshold are justified later.

rare, but with noisy private information, it happens around the equilibrium threshold. This helps to understand the observed heterogeneity of fishing activities in the same fishery, for example, some countries impose targets to stop overfishing, but at the same fishery some other countries have significantly more fishing fleets.

In equilibrium, both countries, which have private assessments about the state of habitat from $[\underline{w}_1, \bar{w}_1]$, solve the problem for a threshold-type player, for whom $\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*,\, y_1) = 0$, and after deriving the common threshold, w^*, each country compares its signal with w^* and chooses an action.

Assume the countries receive very precise signals, such that a is sufficiently small, (but it is not equal to zero). Then from the point of view of the threshold-type country, the stock of fishery in the first period is uniformly distributed over $[w^* - a, w^* + a]$. Furthermore, vanishing noise leads to a situation where not only the fundamental uncertainty is vanishing, but also the strategic uncertainty is extremely large. Thus, country i with $x_1^i = w^*$, would assign uniform probability to the signal of the other country, which is known as holding Laplacian belief. Given this insight, I summarise the results of this equilibrium selection in the next proposition and the proof is provided in Appendix 2.7.2.

Proposition 2. *Under private information, there exists $\bar{a} > 0$, such that for all $a < \bar{a}$, in the first period of any game in G, there exists a unique equilibrium which admits a symmetric PBNE threshold, w^*, such that country i, for any signal $x_1^i < w^* - a$, fishes sustainably and for $x_1^i > w^* + a$, chooses overfishing.*

Given the unique threshold, for both countries, it is best response to follow the described strategies for any level of the signals. More precisely, in the limit[26], country i which has a private assessment of the stock above w^*, inferring that the fishery is not productive, also the overfishing cost is relatively low, has more incentive to overfish. In addition to that, its highly correlated private information with the signal of the other country implies that the other country is also likely to choose overfishing and given the

[26]Note that by the limit, I refer to the unique equilibrium for all a sufficiently small, and not to the uniqueness of the limit of equilibrium strategies.

strategic complementarity in the payoffs, overfishing is reinforced. Therefore, for any $x_1^i > w^* + a$, $\Delta^i(w_1,\, x_1^{-i}(.) \mid x_1^i)$ is negative and overfishing is chosen in equilibrium[27]. By a similar argument, for a country with an assessment below the critical level i.e. $x_1^i < w^* - a$, the expected payoff differential is positive, hence it chooses sustainable fishing. The refined threshold-form strategy is consistent with the observed behaviour of agents in many renewable resources, where a slight change in the beliefs about the state of the resource and the belief of others can lead to a sudden flip in their decisions.

Indeed, apart from the region very close to the threshold, as the noise of private signal converges to zero, the probability that the two countries obtain private signals from the two sides of the threshold converges to zero, although they do not know the ranking of their signals. Thus, for any level of stock $w_1 \in (0, w^* - a)$ the probability of sustainable fishing is one, and for any $w_1 \in (w^* + a, 1)$ they would overfish with probability one. If $w_1 \in (w^* - a, w^* + a)$, the probability of sustainable fishing belongs to $[0, 1]$. Note that these probabilities are independent of the specification of upper-bound and lower-bound thresholds, though their existence is important in deriving the uniqueness result.

It is the dominance solvability of global games, which rules out any equilibrium other than the monotone strategies. Intuitively, as explained, for country i which obtains an assessment from the lower dominance region, i.e. if $x_1^i < \underline{w}_1 - a$, overfishing is strictly dominated. Knowing that the other country has the same strategy for such a level of observation of habitat, if country i receives a signal slightly to the right of this range, i.e. $\underline{w}_1 - a < x_1^i < \underline{w}_1 - a + \eta$, for a small η, it believes in such a situation the other country would be more likely to choose sustainable harvest as a dominant action, so $\Delta^i(w_1,\, x_1^{-i}(.) \mid x_1^i)$ will be positive and it leads to another round of deletion of strictly dominated strategies. By continuity, the same argument goes for $\underline{w}_1 - a < x_1^i < \underline{w}_1 - a + 2\eta$ and the iterated deletion goes on. The same argument starts from the upper dominance region and both cease around the threshold. Indeed,

[27]Note that when the private information is extremely precise, the public signal (which was observed before the biological shocks) is ignored.

it is the existence of dominance regions which ignites this “contagious effect”, and results in a unique prediction for any level of fish stock.

The fact that the equilibrium is the unique rationalisable strategy implies that the harvesting agents need not have common expectations about each others’ strategies in equilibrium, and it is sufficient to assume rationality and common knowledge of rationality.[28] Therefore, by assuming very precise private information, the rationality of harvesting agents automatically enforces the unique rationalisable strategy of global games.

Finally, the results are independent of the precision of public signal, c. In fact, where the private assessments are extremely informative, the countries ignore their prior beliefs and the public signal.

2.5.2 Selection of risk-dominant actions with imprecise private information

The global-game threshold coincides with the risk-dominant threshold of the precise-signal case[29]. Indeed, the predictions of both models are similar, although here it is the private signal (rather than simply the state) which determines the unique equilibrium action, and players on the global-game equilibrium will always coordinate on the less-risky action. As explained by Carlsson and van Damme (1993), the rationality leads to selection of the risk-dominance equilibrium, and it provides a justification for the selection of less risky actions in equilibrium, suggested by Harsanyi and Selten (1988).

Intuitively, under the biological and strategic uncertainties, the harvesting countries prefer the risk-dominant action where their beliefs about the state of the fishery and their inferred information about the other country are consistent with their beliefs in the dominance regions. This (non-arbitrary) coincidence of thresholds is particularly

[28] In that regards, the model can be generalised to include the behaviour of harvesting firms in a common-property fishery, which, in contrast to countries, may not benefit from sophisticated research institutions.

[29] See the characterisation of equilibrium in Appendix 2.7.2.

interesting for policy implications. Although the harvesters acquire private assessments of the fishery, the manager of the stock, which can be an intergovernmental institution, can simply compute the risk-dominant threshold of the precise-signal situation and derive unique predictions about the rational behaviour of countries.

Lastly, as mentioned in section 2.4, without the overfishing cost, there would not be any lower dominance region, but still relying on the single crossing of $\Delta^{RD}(w_1)$, the game has a unique threshold-form PBNE. However, lack of the lower dominance region implies that the unique monotone-strategy PBNE is not necessarily the unique rationalisable equilibrium of the game, and therefore the game does not necessarily have uniqueness of equilibrium.

2.5.3 Optimal policy

If the information is very precise, the comparative statics result of the risk-dominant threshold can be applied to the case of biological and strategic uncertainty. In this subsection, I focus on the contribution of the results to the policy-related parameters, κ and r.

As discussed, the increase in the cost of illegal fishing increases the lower-bound, the upper-bound, the risk-dominant and consequently, the global-game thresholds. Therefore, according to the model, no matter whether the harvesting countries are affected by biological or strategic uncertainties, undoubtedly, by increasing the overfishing cost, the fishery becomes less vulnerable to panic-based harvest, i.e. overfishing where it is not a dominant action. This can be achieved by improving international awareness by campaigns and NGOs, more cooperation by the international legislative institutions and better intergovernmental monitoring of the transboundary fisheries.

In contrast to the overfishing cost, expected payoff differential is not monotone in the harvest fraction. Again, as the information becomes extremely precise, the analysis of the risk-dominance harvest fraction applies. The potential manager of the stock may target the critical harvest fraction corresponding to the maximum threshold, r^{RD}, and for example through intergovernmental negotiations about the harvest fraction, can balance the conservative incentives and the overfishing temptation.

However, the overfishing cost or the harvest fraction which leads to the maximum threshold level, w^*, may not necessarily be chosen. Different institutional frameworks may determine the overfishing cost and the harvest fraction of sustainable yield, and it is possible that the countries (and the potential manager of the stock) follow different objectives[30]. If the net benefit is targeted[31], then as the noise in the private information and consequently the probability of mis-coordination converge to zero, $\lim_{a\to 0} B(\kappa, r)$ determines net benefit of a representative country on the equilibrium path, where $B(\kappa, r)$ is defined as

$$B(\kappa, r) \equiv \int_0^{w^{RD}(\kappa,r)} [rw_1 + \frac{\beta}{2} b w_1^\alpha] f_{W_1}(w_1 \mid x_1^i) dw_1 + \int_{w^{RD}(\kappa,r)}^1 [\frac{w_1}{2} - \frac{\kappa}{w_1}] f_{W_1}(w_1 \mid x_1^i) dw_1 \tag{2.5.3}$$

In other words, knowing that for all levels of fish population below the PBNE threshold, both countries harvest sustainably and above it, they both overfish, in the limit, it is possible to uniquely define the net benefit of the countries, and if it is used in determining the optimal policy, then $\frac{\partial B(\kappa,r)}{\partial \kappa} = 0$, and $\frac{\partial B(\kappa,r)}{\partial r} = 0$ are the necessary conditions of the optimal overfishing cost and harvest fraction, respectively.

The way the harvesting countries agree on these parameters is a normative question. In the model, the welfare is defined by the net benefit from yield of a representative country in a resource which exhausts in the future. This model was to derive a unique prediction of the behaviour of harvesting countries which face biological and strategic uncertainties, the insight can be used in political economy settings and possible institutional arrangements to answer questions related to the optimality.

[30]For example, for bargaining process in fisheries see Golubtsov and McKelvey (2007)
[31]Like the bank run model of Goldstein and Pauzner (2005).

2.6 Conclusions

This chapter studies the behaviour of two harvesting countries in a transboundary fishery, by a two-period game with strategic complementarities in their payoffs. The chapter in addition to investigating equilibrium refinement of a resource game where biological and strategic uncertainties are embedded in the model, tries to explain overfishing decisions of countries driven by pessimistic expectations about the other harvester as a rational behaviour. In fact, private information acquisition results in the risk of mis-coordination, and induces pessimism about the sustainability of the resource, which can increase the temptation for overfishing.

First, I develop a setting where the countries can obtain precise information about the population of the habitat, and the resulting multiplicity of equilibria reduces the predictive power of the model about the level of harvest of countries to zero. Hence, the risk-dominance equilibrium selection of Harsanyi and Selten (1988) is suggested which leads to a monotone strategy.

In the second step, the model is analysed under the more realistic assumption of noisy private information, which leads to the existence of strategic uncertainty in addition to the biological uncertainty. It is shown that apart from very low and very high levels of fish population, where the countries have dominant strategies, the expectation of countries about each other's assessments determines their fishing decisions. Thus the fishery may be exhausted by a panic-based harvest, although it is not dominant to deplete the resource and the true level of fish stock is still productive and could be preserved for the next period. From the point of view of a central authority or an intergovernmental manager of the fishery, overfishing in this region can be explained by taking into account the pessimistic beliefs of the countries about each other's behaviour and the fear of mis-coordination.

In such a setting, without any equilibrium refinement, no prediction can be derived about the outcome of interaction of the countries. The perturbed game provides a suitable framework to apply the equilibrium-selection of Carlsson and van Damme (1993) and Morris and Shin (1998). It is shown that in a setting where the state of the resource depends on its previous level, and all payoffs are state-dependant, the extremely precise private information of harvesting countries leads to the unique global game equilibrium as the unique rationalisable strategy. Accordingly, for any level of the private assessment of countries, the theory is able to uniquely predict the equilibrium outcome. The global game refinement results in a simple monotone strategy with a threshold which coincides with the risk-dominant threshold. Therefore, although the model with strategic uncertainty is a complicated setup, the risk-dominance equivalence provides a tractable framework for the policy analysis. Therefore, I derive comparative-static results on the threshold level, in addition to policy implications for the overfishing cost and the harvest fraction of sustainable catch.

The refined self-fulfilling equilibrium prescribes sustainable harvest for all private assessments below the risk-dominant threshold. In fact, sustainable fishing is risk dominant where the expectation of a high reproduction rate of the fishery and relatively high overfishing cost is reinforced by optimistic opinion about the assessment of the other country. Conversely, above the critical level, the fear of mis-coordination by the other country reinforces low expectations about the reproduction rate of the fishery combined with low overfishing cost. This result provides a possible explanation for the catastrophic situation of many fisheries around the world, where increasing the common knowledge about the adverse state of the environment does not prevent its collapse, because all harvesting agents, taking into account the strategic uncertainty, have economically chosen to exhaust the resource.

Similar to the literature on threshold behaviour in resource economics, the resulting monotone strategies explain the flipping behaviour of countries in transboundary fisheries around the critical level of fish population, that a small change in the belief about the state of the fishery may lead to a radical change of fishing activities. However, the model with noisy information, is also able to explain the mis-coordiantion around the critical level along the equilibrium path. Indeed, relative to a precise information setting, the refined global game equilibrium, can justify the simultaneous overfishing and sustainable harvest of countries in one fishery, as their equilibrium behaviour where their assessments are very close to the threshold.

Finally, given the significant role of equilibrium refinement in resource economics, there are many possible extensions which could lead to a more interesting model to explain the reality. Although for the case of transboundary fisheries, a two-player game is not far from reality, the setup can be extended to a multiple-agent framework. Furthermore, research in which the countries can harvest in multiple periods is another possibility to generalise the model to a more realistic framework.

2.7 Appendix

2.7.1 Conditional probability density functions with imprecise signals

Recall that $w_t = y_t + \xi_t$ and $x_t^i = w_t + \varepsilon_t^i$. Furthermore, $f_\nu(.)$ refers to the probability density function and $F_\nu(.)$ is the cumulative distribution function of any random variable ν. As the main ingredients for analysing the model, I derive the conditional probability density function of the state of the fishery and the signal of the other country for a general noise, i.e. out of the limit.

Since the fishing agents are Bayesian learners, their posterior belief about state of the fishery can be obtained by a simple Bayes rule or the following formula,

$$f_{W_t}(w_t \mid y_t, x_t^i) = \frac{f_\Xi(w_t - y_t) f_E(x_t^i - w_t)}{\int f_\Xi(q - y_t) f_E(x_t^i - q)\mathbf{d}\mathrm{q}} \tag{2.7.1}$$

$$= \frac{1}{\int_{\max\{y_t - c, x_t^i - a\}}^{\min\{y_t + c, x_t^i + a\}} \mathbf{d}\mathrm{q}} \tag{2.7.2}$$

Assuming the private signal to be more precise than the public signal, i.e. if $a < c$,

$$f_{W_t}(w_t \mid y_t, x_t^i) = \begin{cases} \frac{1}{x_t^i + a - y_t + c} & \text{if } w_t \in [y_t - c,\, x_t^i + a] \text{ and } x_t^i - a < y_t - c < x_t^i + a < y_t + c \\ \frac{1}{2a} & \text{if } w_t \in [x_t^i - a,\, x_t^i + a] \text{ and } y_t - c < x_t^i - a < x_t^i + a < y_t + c \\ \frac{1}{y_t + c - x_t^i + a} & \text{if } w_t \in [x_t^i - a,\, y_t + c] \text{ and } y_t - c < x_t^i - a < y_t + c < x_t^i + a \end{cases} \tag{2.7.3}$$

In addition, from the point of view of player i, the conditional probability density of signal of the other player can be derived by calculating the convolution of two independent distributions, i.e.

$$f_{X_t^{-i}}(x_t^{-i} \mid y_t, x_t^i) = \int f_{W_t}(x_t^{-i} - p \mid y_t, x_t^i) f_E(p) \mathbf{d}\mathrm{p} \tag{2.7.4}$$

which depending on the support of W_t, admits three possible cases.

***Case I*:** If $w_t \in [y_t - c,\, x_t^i + a]$ and $x_t^i - a < y_t - c < x_t^i + a < y_t + c$,

$$\begin{aligned} f_{X_t^{-i}}(x_t^{-i} \mid y_t, x_t^i) &= \frac{1}{2a(x_t^i + a - y_t + c)} \int_{\max\{-a, x_t^{-i} - x_t^i - a\}}^{\min\{a, x_t^{-i} - y_t + c\}} \mathbf{d}\mathrm{p} \\ &= \frac{1}{2a(x_t^i + a - y_t + c)} \begin{cases} x_t^{-i} - y_t + c + a & \text{if } x_t^{-i} \in [y_t - c - a,\, x_t^i] \\ 2a & \text{if } x_t^{-i} \in [x_t^i,\, y_t - c + a] \\ 2a - x_t^{-i} + x_t^i & \text{if } x_t^{-i} \in [y_t - c + a,\, x_t^i + 2a] \end{cases} \end{aligned} \tag{2.7.5}$$

***Case II*:** If $w_t \in [x_t^i - a,\, x_t^i + a]$ and $y_t - c < x_t^i - a < x_t^i + a < y_t + c$,

$$\begin{aligned} f_{X_t^{-i}}(x_t^{-i} \mid y_t, x_t^i) &= \frac{1}{4a^2} \int_{\max\{-a, x_t^{-i} - x_t^i - a\}}^{\min\{a, x_t^{-i} - x_t^i + a\}} \mathbf{d}\mathrm{p} \\ &= \frac{1}{4a^2} \begin{cases} x_t^{-i} - x_t^i + 2a & \text{if } x_t^{-i} \in [x_t^i - 2a,\, x_t^i] \\ x_t^i - x_t^{-i} + 2a & \text{if } x_t^{-i} \in [x_t^i,\, x_t^i + 2a] \end{cases} \end{aligned} \tag{2.7.6}$$

***Case III*:** If $w_t \in [x_t^i - a,\, y_t + c]$ and $y_t - c < x_t^i - a < y_t + c < x_t^i + a$,

$$f_{X_t^{-i}}(x_t^{-i} \mid y_t, x_t^i) = \frac{1}{2a(y_t + c - x_t^i + a)} \int_{\max\{-a, x_t^{-i} - y_t - c\}}^{\min\{a, x_t^{-i} - x_t^i + a\}} \mathbf{d}\mathrm{p}$$
$$= \frac{1}{2a(y_t + c - x_t^i + a)} \begin{cases} x_t^{-i} - x_t^i + 2a & \text{if } x_t^{-i} \in [x_t^i - 2a,\, y_t + c - a] \\ 2a & \text{if } x_t^{-i} \in [y_t + c - a,\, x_t^i] \\ a - x_t^{-i} + y_t + c & \text{if } x_t^{-i} \in [x_t^i,\, a + y_t + c] \end{cases} \tag{2.7.7}$$

Clearly, case *I* and *III* of $f_{X_t^{-i}}(x_t^{-i} \mid y_t, x_t^i)$ are trapezoidal distributions and case *II* is a symmetric triangular distribution. All cases are possible, and they can be used in the indifference condition of player i, defined in (2.5.1).

2.7.2 Global game analysis with Uniform biological shocks and noise of private signals

In the limit that $a \to 0$, I focus on case *II* of appendix 2.7.1, where $w_t \in [x_t^i - a,\, x_t^i + a]$ and $y_t - c < x_t^i - a < x_t^i + a < y_t + c$. Clearly, its cumulative distribution at player i's signal will be $F_{X_t^{-i}}(x_t^{-i} \mid x_t^i) = 1 - F_{X_t^{-i}}(x_t^{-i} \mid x_t^i) = \frac{1}{2}$, which translates to holding the Laplacian belief.

I first focus on threshold-type player, and characterise the equilibrium threshold. I shown that there exists a unique threshold PBNE. Then, in order to preclude any other type of equilibrium, I examine the sufficient conditions to show that threshold-type PBNE is the only strategy surviving iterated deletion of strictly dominated strategy.

In the limit that the information is extremely precise, i.e. as $a \to 0$, the country which observes the critical signal holds uniform belief about the state of the fishery over $[w^* - a, w^* + a]$. Therefore, for the threshold-type country the expected payoff in (2.5.1) will be reduced to

$$\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*) = \frac{1}{2a} \int_{w^*-a}^{w^*+a} \mathbb{E}_{x_1^{-i}} \Delta^0(w_1,\, x_1^{-i}(.) \mid w^*)) dw_1 \tag{2.7.8}$$

where $\Delta^0(w_1,\, x_1^{-i}(.) \mid w^*)$ is defined in (2.5.2).

Since, the two random variables X^{-i} and W_1 are highly correlated, in the limit that $a \to 0$, and consequently $w_1 \to w^*$, all uncertainty can be expressed in terms of strategic uncertainty. Hence, in the limit,

$$\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*) = \mathbb{E}_{x_1^{-i}} \Delta^0(w^*,\, x_1^{-i}(.) \mid w^*) \tag{2.7.9}$$

Furthermore, Laplacian belief about signal of the other country, implies

$$\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*) = \frac{1}{2}[2rw^* + \frac{\beta}{2} b(w^*)^\alpha - (1-r)w^* + \frac{2\kappa}{w^*} - \frac{w^*}{2}] \tag{2.7.10}$$

which by definition, must be equal to zero. In fact, the term inside the brackets is $\Delta^{RD}(w^*)$ defined in (2.4.4). Thus, the indifference condition of the threshold-type player in the limit is reduced to $\Delta^{RD}(w^*) = 0$, which as stated in proposition 1, admits a unique real solution in $(\underline{w}_1, \bar{w}_1)$.

Now I provide the sufficient conditions which are satisfied in the model to apply proposition 2.2 of Morris and Shin (2003) to show that the characterised threshold-type PBNE satisfies dominance solvability conditions, and therefore it is the unique equilibrium of the game.

(1) State monotonicity: $\Delta^{RD}(w_1)$, which is sum of $\underline{\Delta}^0(w_1)$ and $\bar{\Delta}^0(w_1)$, is strictly decreasing in the state of the fishery. (2) Action monotonicity: Game G is a coordination game and therefore the harvesting levels of countries are strategic complements. (3) Strict Laplacian state monotonicity: For a country with Laplacian belief, $\mathbb{E}_{x_1^{-i}} \Delta^0(w^*,\, x_1^{-i}(.) \mid w^*)$ has a single crossing at w^*. (4) Uniform limit dominance: There exists $\underline{x} = \underline{w}_1 - a$ such that for all $x_1^i < \underline{x}$, $\Delta^{RD} > 0$, also there exists $\bar{x} = \bar{w}_1 + a$ such that for all $x_1^i > \bar{x}$, $\Delta^{RD} < 0$.[32] (5) Continuity: $\mathbb{E}_{x_1^{-i}} \Delta^0(w_1,\, x_1^{-i}(.) \mid x_1^i)$ is contin-

[32] This is stronger than existence of dominance regions, and it is sufficient to apply proposition 2.2 of Morris and Shin (2003).

uous with respect to the signal and probability density of X^{-i}. (6) Finite expectation of signals: The distribution of noise is integrable.

2.7.3 Characterisation of global-game equilibrium with general distributions of biological shocks and noise of private signals

The global-game analysis in the limit is independent of distribution of noise and prior, and indeed locally any distribution is uniform. These facts are helpful in applying the theory to real-life issues, such as decision making in common-property fisheries.

Assume $\Xi \sim g$ on $[-c, c]$, and $E \sim h$ on $[-a, a]$, where $g(.)$ and $h(.)$ are continuous probability density functions, also $f(.)$ is integrable.

In contrast to the uniform case, here necessarily the countries in the limit do not have uniform belief about the signal of the other country, but the threshold-type country holds Laplacian belief[33].

From the point of view of both countries or the manager of the stock, the country, which would observe the threshold signal, would be the most uncertain country about the action of the other country. Indeed, in the limit of vanishing noise, $Pr(x_1^{-i} < w^* \mid w^*) = \frac{1}{2}$. Hence, the indifference condition of the threshold-type country, i.e.

$$\Delta^i(w_1,\, x_1^{-i}(.) \mid w^*, y_1) = \int_{w^*-a}^{w^*+a} \mathbb{E}_{x_1^{-i}} \Delta^0(w_1,\, x_1^{-i}(.) \mid w^*, y_1)) f_{w_1}(w_1 \mid w^*, y_1) dw_1 \tag{2.7.11}$$

in the limit that W_1 and X_1^{-i} are highly correlated, is simplified to $\mathbb{E}_{x_1^{-i}} \Delta^0(w^*,\, x_1^{-i}(.) \mid w^*) = 0$, and given Laplacian belief, it is further reduced to $\Delta^{RD}(w^*) = 0$.

[33]See appendix B of Morris and Shin (2003) for the proof of Laplacian belief with finite number of players.

Chapter 3

The Economics of Climate Change and The Role of Public Information

Abstract

This chapter develops a theoretical framework to examine the role of public information in dynamic self-enforcing international environmental agreements (IEAs) on climate change. The countries choose self-enforcing emission abatement strategies in an infinite-horizon repeated game. In a stochastic model, where the social cost of greenhouse gasses (GHG) is a random variable, a central authority, as an information sender, can control release of information about the unknown state to the countries. In the literature on stochastic IEAs, it is shown that comparison of different scenarios of learning by the countries, depends on ex-ante difference of true social cost of GHG from the prior belief of countries. Here, I try to understand, in a signalling game between the informed sender and the countries, whether the no-learning or imperfect-learning scenarios, can be an equilibrium outcome. It is shown that the equilibrium strategy of the sender, who is constrained to a specific randomisation device and tries to induce an incentive-compatible abatement level which is Pareto superior, leads to full learning of social cost of GHG of symmetric and asymmetric countries.
Key words: Climate change, International Environmental Agreements, Uncertainty, Signalling, Self-enforcing agreements, Equilibrium selection
JEL Classification: Q54, C72, C73, D62, D83, H41

3.1 Introduction

Consumption of fossil fuels increases stocks of GHG, and there is wide disagreement among economists about the magnitude of the social cost of GHG. For example, according to Pindyck (2013), the range of estimates varies from \$10 to \$200 per ton of CO_2. In this chapter using a theoretical framework, I look into the behaviour of countries in regards to a climate change model, and try to investigate how the incentives of the countries in dynamic international agreements depend on their beliefs about the social cost of GHG.

There are benevolent intergovernmental entities, like the Intergovernmental Panel on Climate Change (IPCC), which conduct research into climate change and communicate their research results to the public. This chapter provides an IEA setting in which the involved countries receive public information on social cost of GHG from a central authority, as an information sender. In addition to studying the effect of learning on the selected mitigation actions of countries and social welfare, the research aims to derive the equilibrium learning outcome and precision of public information, in a signalling game between the sender and the countries.

The chapter contributes two main analyses. First, I am interested in the effects of the potential public information on selection of mitigation actions by the countries. Hence, a stochastic dynamic model of transboundary pollution is presented, where the countries are involved in a self-enforcing relationship to abate their emissions. In terms of IEA literature, the current research is similar to Dutta and Radner (2006, 2009, 2012) and Polasky et al. (2006), because instead of focusing on the coalition formation, an infinite-horizon renewable-resource game is studied and the range of sustainable equilibria under threat of a punishment path are derived. However, in contrast to the setup of this chapter, these models are deterministic.

Here, the set of self-enforceable abatement strategies given reversion to the business-as-usual (BAU), upon any deviation, is derived, where the BAU abatement refers to the history-independent strategy. It is shown that the countries are able to sustain payoffs higher than the BAU level of abatement. The countries select an equilibrium abatement which maximises their joint expected payoff, given the set of sustainable abatements. In this respect, the contribution of this chapter is presentation of the set of sustainable abatements in a metric space and examining how this set and the selected equilibrium change with respect to the social cost of GHG, which can be affected in the learning process.

The second aspect of the analysis focuses on the interaction of the information sender and the countries with regards to the information on social cost of GHG, as the state variable. In a game framework, I examine a situation where the sender tries to induce a particular mitigation action. The sender is benevolent, in the sense that his objective is inducing an abatement action which is the closest to the social optimal level, but this objective does not coincide with the constrained objective of the countries, and I assume that the payoffs of both sides are common knowledge.

In the relatively small literature on stochastic IEAs, the welfare implications of observing precise public signal (full learning), and no signal (no learning) are studied. Their results depend on the comparison of the true social cost of GHG and its prior expectation. Therefore, to implement the best learning scenario, ex-ante the true state variable should be known. Hence, in this chapter, I assume that at the beginning of the game, the sender privately observes the true social cost of GHG, and depending on comparison of the true realisation with the prior of countries, he chooses precision of public information to be communicated. Thus, relative to the literature, where the focus is on comparative static of full-learning and no-learning scenarios in coalition games, in this game, I derive the equilibrium learning outcome.

In this chapter, in order to examine whether full-learning and no-learning can be equilibrium, a specific signalling structure is studied, where the information sender is constrained to choose among certain signalling strategies. At the beginning of period zero, and before choosing the level of abatement investments, the information sender privately observes the state and decides between revealing the true social cost of GHG or being silent. Alternatively, in another game, I assume that the sender can randomise between sending the truthful signal or a meaningless signal (or noise), thus, the choice of signalling strategy determines the precision of signal realisation. The countries after observing the signalling choice of the sender, update their beliefs about the social cost of GHG, and select a self-enforcing mitigation action. It is shown that the incomplete-information game does not have any pooling equilibrium where the information structure can lead to no learning or imperfect learning. Instead, the unique equilibrium strategy of the sender is full disclosure of the state[34].

Furthermore, in the stochastic IEA literature, effects of delay in learning are studied. Here in the signalling games, I examine possibility of delay in sending the (fully-revealing) signal realisations to the countries. It is shown that after the sender privately observes the state in the beginning of the game, the equilibrium time of sending the fully-revealing signal is immediately after selection of the signalling choice. In other words, in these games, any delay falls off the equilibrium path.

Finally, the results are generalised to a case of asymmetric countries, where the countries differ with respect to the social cost of GHG, and the results of signalling games are reinforced for the case of asymmetric countries.

The subsequent section reviews the related literature, then the general framework is introduced in section 3.3, and the interaction of countries under assumption of a precise-signal about the social cost of GHG, is analysed in section 3.4. Then, the uncertainty and the signalling games for the symmetric and asymmetric countries are studied in section 3.5 and 3.6, respectively. The chapter closes with conclusions, and proofs are provided in the appendix.

3.2 Related Literature

First, the economics of climate change and IEAs are extensively studied, and the literature is reviewed by Toman (1998), Wagner (2002), Kolstad and Toman (2001), Aldy and Stavins (2009) and most recently by Benchekroun and Long (2012), among others. Here I am interested in game theory and especially the non-cooperative methodological approach to the IEAs. Almost all authors in the field believe that in the

[34] This chapter does not study the optimal information policy , and the mentioned information structures clearly are not optimal. Designing the optimal public information structure is the topic of the next chapter.

absence of a supra-national authority and where individual actions are not verifiable by a third party, the agreements should be self-enforcing.

There are a few instances in the existing literature, which assume observable outputs and binding contracts. Kerr (1995) formalises the relationship of developed and developing countries in a one-period principal-agent contract setup, and investigates the optimal time for designing a contract. Harstad (2012) referring to the Kyoto Protocol and Durban Platform, assumes the accountability of governments, and suggests writing explicit incomplete contracts on emissions, where countries may invest in a substitute green technology.

The main focus of self-enforcing climate change literature is coalition formation of non-cooperative agents. This chapter, instead of coalition formation, studies implicit contract of countries in a repeated game and focuses on the range of sustainable mitigation strategies. Long (2011) reviews the literature on dynamic renewable games. To name a few, Ploeg and Zeeuw (1992) and Dockner and Long (1993) are seminal papers which study dynamic transboundary games, and compare socially optimal and non-cooperative outcomes. Thomas (1992), by examining an infinite-horizon oligopolistic non-renewable resource game, derives the optimal punishment path to sustain an implicit agreement such that the joint profit of a cartel is maximised. More recently, Polasky et al. (2006) in a dynamic common property renewable resource game, derive the set of sustainable equilibria given punishment by the worst perfect equilibrium. Dutta and Radner (2009) in dynamic climate change models, characterise the set of subgame perfect equilibrium emissions given BAU sanction also reversion to a the worst equilibrium. Dutta and Radner (2006, 2012) derive the set of sustainable equilibria given BAU reversion, in models which allow technological change and capital accumulation, respectively. Relative to their models, instead of emissions, I focus on the investment in abatement technologies, and I examine the properties of the set of sustainable equilibria. Harstad et al. (2015) study a repeated game, where in each period, the countries decide on investment in environmental technologies and subsequently on emission strategies, they also characterise the set of sustainable equilibria where any deviation triggers reversion to the worst equilibrium.

The literature on IEAs mainly focuses on deterministic setups, and stochastic IEAs is given relatively less attention. The literature on stochastic IEAs, generally examines coalition formation, where uncertainty is resolved either after negotiation (no learning) or before negotiation (full learning), and the maximum number of countries in the stable coalition, the emissions and welfare under these scenarios of learning are compared.

The literature deals with uncertainty in imperfect information setups. Indeed, the scientific uncertainty is studied as a common, fundamental uncertainty, and is modelled in two ways. Either there is uncertainty about the level of a payoff-relevant variable or there is a common uncertainty about the distribution of the cost of damage. The latter is known as distributional uncertainty, and refers to situations where countries are ex-ante identical, but after that uncertainty is resolved (by perfect learning), they may have different costs ex-post, which will be known by all.

The most cited paper in this strand is Na and Shin (1998) which proposes the idea of distributional uncertainty and derives optimal time of negotiation for coalition formation in a static model of three countries. Ulph (2004) studies the level uncertainty and the effect of learning in a fixed and variable membership model of IEA. He has a two-period model which allows for studying the dynamics of the stocks. Kolstad (2007) adds the idea of partial (interim) learning to a one-period coalition formation model, which refers to (perfect) learning of the state of the world after the membership stage and before the emission stage. In all of these papers the fundamental variable is either binary or admits three states; Finus and Pintassilgo (2013) generalise it to a continuum action space in a model of both level and distributional uncertainty, and they check full, no and partial (interim) learning scenarios, though they do not model the stock accumulation.

Furthermore, in the literature on uncertainty, learning and climate change, Hammitt et al. (1992), Kolstad (1996), Ulph and Ulph (1997), Na and Shin (1998), Scott et al.

(1999), Keller et al. (2004), Ulph (2004) and Kolstad and Ulph (2008, 2011) generally conclude that there is an adverse effect of learning on the emission level. For example, in the case of distributional uncertainty, it is shown that ex-ante uncertainty about the payoff-relevant parameter, facilitates the negotiation. Kolstad (2007) and Finus and Pintassilgo (2013) who have more general models, show that this effect of learning is not a general rule.

The chapter is also related to the broad literature on signalling by an informed sender. Classic examples are Crawford and Sobel (1982) or Spence (1973). In this strand of literature, the sender does not have any commitment power, and sending a signal is either costless or there is a cost which restricts the sender. In this chapter, it is not the cost of signalling, but it is preference and selection of the fully-revealing signal of the state under some situations, which blocks the possibility of imperfect transmission of information under other situations.

3.3 The Model

Countries, indexed $i = 1, 2, ..., I$, choose their emission abatement levels, q_{it}, where time index is $t = 0, 1, 2, ...$. Their abatements contribute to a reduction in the total stock of GHG in the next period. The stock of GHG has the following equation of motion,

$$Q_{t+1} = \delta Q_t + \Psi - \sum_i q_{it} \tag{3.3.1}$$

where Q_t is the GHG in period t, $(1 - \delta)$ is the rate of decay of GHG, and $0 < \delta < 1$. Assume the initial level of GHG, Q_0, is given. Furthermore, Ψ is the unabated emission of GHG, and I assume it is a constant over time. By $\mathbf{q}_t = (q_{1t}, q_{2t}, ..., q_{It})$, where $q_{it} \in \mathbb{R}_+$, I refer to the vector of pollution abatements undertaken by the countries, and can be interpreted as investment in abatement technologies, green technologies, or reforestation to reduce the emission of GHG. In fact, $\Psi - \sum_i q_{it}$ is the actual emission level, and $\mathbf{q}_t$ can be targeted quantitatively by the countries as a climate change mitigation policy. From this point on, I refer to q_{it} as the abatement level.

In the dynamic game, where the stock of GHG changes over time, the countries minimise their expected discounted loss function, which is additive separable in the total stock of GHG, and the private cost of abatement. The flow loss function is

$$\Pi_{it} = C(q_{it}) + \gamma_i Q_t \tag{3.3.2}$$

where $C(.)$ refers to the private cost of emission abatement, which is independent of i. In addition, γ_i is the marginal social cost of GHG, in the literature it is also known as the cost ratio parameter[35]. I assume that γ_i and the choice variable q_i belong to intervals in $\mathbb{R}_+$. Furthermore, the common discount factor is $0 < \beta < 1$.

It is assumed that $C(.)$ is a strictly increasing and strictly convex function. In other words, $C'(.) > 0$, also $C''(.) > 0$. Therefore, $C'^{-1}(.)$ is a function.[36] Moreover, I assume $C(0) = 0$.

Later I examine situations where the marginal social cost of GHG is a random variable, about which the countries receive public information. However, I begin the analysis with the assumption that the countries know the true value of marginal social cost of GHG - equivalently they receive a precise public signal about it at the beginning of the game.

Additive separability and linearity of the equation of motion of GHG and the loss function are fairly standard in the climate change literature, and provide a specifically tractable framework.[37]

I assume that the countries at the end of each period observe the individual actions, so the deviations can be detected unambiguously, and it is a perfect-monitoring repeated game. There is no private information, and public history includes all past actions and the initial value of GHG. For simplicity, it is assumed that the countries take

[35] If the flow loss function is $\widehat{\Pi}_{it} = \widehat{a}_i C(q_{it}) + \widehat{b}_i Q_t$, then $\Pi_{it} \equiv \frac{\widehat{\Pi}_{it}}{\widehat{a}_i}$ and the cost-ratio parameter is $\gamma_i \equiv \frac{\widehat{b}_i}{\widehat{a}_i}$.

[36] Na and Shin(1998) and Finus and Pintassilgo (2013), assume $C(q_{it}) = \frac{q_{it}^2}{2}$. They study coalition formation in static and two-period models, respectively.

[37] Because of the resulting certainty equivalence in the stochastic analysis, the model is similar to the deterministic model of Dutta and Radner (2009).

action simultaneously, hence I abstract from any social learning or any leader-follower interactions within each period.

In the infinite-horizon game, the equilibrium concept is subgmae perfect equilibrium (SPE).[38] In the following sections, the model is analysed under different information structures.

3.4 A precise public signal in period zero

Assume that at $t = 0$, the countries receive a precise public signal about the true value of γ. This is known as full learning, and because of certainty equivalence, the analysis of the stochastic model under this assumption is identical to a deterministic setup.

In the next two subsections, I define the social optimum, and the BAU abatement levels, and calculate each of them. Then the set of SPE abatements is verified. All derivations and proofs are in the appendix.

3.4.1 The socially optimal abatement

A potential social planner or a country which internalises the stock externality would choose a sequence of $\{q_{it}\}_{t=0}^{\infty}$ to minimise the discounted sum of the losses of all countries, that is

$$\sum_{t=0}^{\infty} \beta^t \sum_{i} x_i [C(q_{it}) + \gamma Q_t] \tag{3.4.1}$$

such that the equation of motion in (3.3.1) holds. In addition, $x_i > 0$ for every i, and it signifies weight of country i in the social welfare, where the weights are normalised such that $\sum_i x_i = I$, so I refer to x_i as the Pareto share of country i. Furthermore, recall that β is the common discount factor.

[38]In a finite-horizon model, using backward induction, and given the loss is increasing in the abatement level, in the last period, zero abatement is the dominant action for all countries. So, independent of whether one deviates in the previous period or not, they will choose zero abatement in the last period. Therefore, there is no credible punishment available and non-interestingly no history-dependent strategy can sustain a positive amount of abatement.

The solution to this problem is referred as the socially optimal abatement, $\mathbf{q}^*$. The problem has a recursive structure and the standard dynamic programming tools can be applied[39]. The socially optimal level of abatement, q_i^* is

$$q_i^* = C'^{-1}(\frac{\beta B_i^*}{x_i}) \tag{3.4.2}$$

where $B_i^* = \frac{\sum_i x_i \gamma_i}{1-\beta\delta}$, and if $\gamma_i = \gamma$, then B^* is reduced to $\frac{\gamma I}{1-\beta\delta}$. Also, if $x_i = 1$ for all i, then there is a unique symmetric solution such that $q_i^* = q^*$ for all i.

Given the assumptions about the private abatement cost function, $\mathbf{q}^*$ is unique, for any given Pareto share, x_i. The policy is stationary, and independent of the stock of GHG.[40] Intuitively, the level of abatement today affects the stock of GHG tomorrow, and the countries compute the geometric series of future losses. Indeed, given the equation of motion of GHG in (3.3.1), there is a unique long-run equilibrium (steady state) of GHG, $\tilde{Q} = \frac{\Psi - \sum_i^I q_i}{1-\delta}$, where q_i is the level of abatement in the long run, and here it is the stationary socially optimal strategy. The general solution to the difference equation of (3.3.1) is $Q_t = \delta^t Q_0 + (1-\delta^t)\tilde{Q}$. Recall that $0 < \delta < 1$, thus the stock of GHG converges smoothly to the long-run $\tilde{Q}$, and because $\lim_{t\to\infty} Q_t = \tilde{Q}$ for any Q_0, the stock has a global stability. It is plausible to assume that $Q_0 < \tilde{Q}$, thus Q_t over time increases smoothly and converges to $\tilde{Q}$. In order to choose the level of abatement which minimises their joint loss, the countries compare the marginal cost and benefit of abatement. Marginally, by abating less, the private cost of abating will be smaller today, however, because of the additive separability of the loss function and the difference equation of GHG, the marginal cost of abatement is constant for all levels of abatement. Therefore, the solution of their marginal cost and benefit analysis is independent of the level of GHG.

Given the strict convexity of private cost, $C'^{-1}(.)$ is a strictly increasing function. Hence, equation (3.4.2) implies that the socially optimal abatement is increasing in the marginal social cost of GHG, γ, the discount factor, β, the persistence rate of GHG, δ,

[39] See the appendix for the proof.
[40] This is also seen by Dutta and Radner (2009).

and the number of countries, I. In addition, a country of smaller Pareto share should abate more.

Let us define the "Pareto frontier" as $\{\mathbf{q} \mid \mathbf{q} = \mathbf{q}^*$, for all $x_i > 0$, for all $i \in I$, where $\sum_i x_i = I\}$.[41] In general and given any symmetric or asymmetric Pareto share, the resultant Pareto frontier is a hypersurface of dimension I.

3.4.2 The BAU abatement

The BAU abatement, $\overline{\mathbf{q}}$, is the history-independent strategy of the game. Taking the action of the others as constant and minimising their own loss, obtains the BAU abatement, and choosing the BAU level in all periods is a SPE. Again the problem can be solved as a dynamic programming problem. The resulting reaction function of country i is $C'(\overline{q}_{it}) - \beta\overline{B}_i = 0$, where $\overline{B}_i = \frac{\gamma_i}{1-\beta\delta}$. Thus, again the solution is unique and the BAU abatement level, $\overline{q}_i$ is

$$\overline{q}_i = C'^{-1}(\beta\overline{B}_i) \tag{3.4.3}$$

In addition, under the assumption of $\gamma_i = \gamma$, $\overline{\mathbf{q}}$ is a symmetric equilibrium. Finally, the stock-independency of the solutions is the result of linearity in the model, and therefore, similar to the socially optimal, the BAU abatement is a constant.[42]

Moreover, by restricting attention to the history-independent strategies, the reaction functions of the countries are independent of each other's abatements. In other words, the BAU solution, as a history-independent strategy, is a dominant strategy. Indeed, the uniqueness of the BAU solution is a result of the orthogonality of reaction functions at $\overline{\mathbf{q}}$.

In terms of comparison of the socially optimal, q_i^*, and the BAU abatement, $\overline{q}_i$, as explained, since $C(.)$ is increasing and strictly convex, the inverse of its first derivative is

[41] Indeed, it is the set of abatements which correspond to the Pareto frontier in the loss space. An example of the Pareto frontier of two countries with quadratic private cost is plotted in Figure 3.1.

[42] In the stochastic setup, the BAU abatement is equivalent to the Markov perfect equilibrium with constant strategies.

an increasing function as well. Therefore, q_i^* is strictly larger than $\overline{q}_i$, for all parameter values.

3.4.3 The set of sustainable abatement levels as SPE

The possibility of deviation and the subsequent punishment path is absent in the whole strand of stochastic IEAs. Here, specifically, I derive the set of abatement levels which survive as SPE when deviations are punished by reversion to the BAU abatement from the next period. The reversion to the BAU seems to be a realistic assumption.[43]

In this section, I derive the incentive-compatibility constraint of adopting a general stock-independent abatement level, $\mathbf{q} = (q_1, q_2, ..., q_I)$, such that any deviation from the constant targeted level of $\mathbf{q}$ will be punished by reverting to the BAU abatement from the following period. As mentioned earlier, I check unilateral deviations and I abstract from coalition formation.

Every country i, computes the resultant geometric series of GHG, and the short-run and long-run losses of following the constant abatement, q_i in every period. Let us denote the total loss of this strategy by $V(Q_t)$. Country i compares $V(Q_t)$ with the optimal loss of deviation path, where $\overline{V}(Q_{t+1})$ denotes the optimal continuation loss of the BAU strategy.

If the following condition holds for every country i, then the corresponding loss of abating according to $\mathbf{q}$, can be sustained as a SPE loss, by the trigger-type stationary strategy profile of playing q_i at all subgames at which there has not been a deviation from $\mathbf{q}$ in the past, and playing $\overline{q}_i$ otherwise. The incentive compatibility constraint (as a sufficient condition) for every i is[44]

$$\begin{aligned} & C(q_i) + \gamma_i Q_t + \beta[V(\delta Q_t + \Psi - q_{it} - \sum_{j \neq i} q_{jt})] \leq \\ & C(q_i^{BR}) + \gamma_i Q_t + \beta[\overline{V}_i(\delta Q_t + \Psi - q_{it}^{BR} - \sum_{j \neq i} q_{jt})] \end{aligned} \tag{3.4.4}$$

[43] Dutta and Radner (2009) derive this set, and I examine its properties.
[44] Note that both sides of the inequality are the losses of one country.

where q_i^{BR} is the best-response level of abatement to $\sum_{j\neq i} q_j$. In the appendix it is shown that the level of abatement which is the best response to $\sum_{j\neq i} q_j$, is also $\overline{q}_i$. Indeed, as explained, because there is no interaction in the reaction functions, the stationary strategies of other countries, i.e. q_j for all $j \neq i$, only affect the level of GHG, but best responses are independent. Moreover, the minimum sustainable abatement level as a SPE is clearly, the BAU abatement.

Again the linearity of the short-run loss and the equation of motion of GHG leads to a linear optimal loss of the stationary strategy, say $V(Q_t) = A_i + B_t Q_t$, which in turn implies a constant marginal cost. Thus, $B_i = \frac{\gamma_i}{1-\beta\delta}$ for all i. In other words, $\frac{dV(Q_t)}{dQ_t}$ is constant for any stationary strategy. Since the BAU abatement is also a stationary strategy, $B_i = \overline{B}_i$. The incentive compatibility constraint in (3.4.4) can be simplified to

$$C(q_i) - \beta B_i(\beta \sum_{j\neq i} q_j + q_i) \leq C(\overline{q}_i) - \beta B_i(\beta \sum_{j\neq i} \overline{q}_j + \overline{q}_i) \tag{3.4.5}$$

and this condition should hold for all countries.

In order to verify the set of sustainable abatement levels as SPE abatements, let us define IC_i as the combination of abatement levels which are incentive-compatible for country i, given the trigger strategy specified above,

$$IC_i \equiv \{\mathbf{q} \mid C(q_i) - \beta B_i(\beta \sum_{j\neq i} q_j + q_i) - C(\overline{q}_i) + \beta B_i(\beta \sum_{j\neq i} \overline{q}_j + \overline{q}_i) \leq 0\} \tag{3.4.6}$$

Because of the strict convexity of $C(q_i)$, IC_i is strictly quasi-convex. In addition, I define set IC_i^0 for every i as

$$IC_i^0 \equiv \{\mathbf{q} \mid C(q_i) - \beta B_i(\beta \sum_{j\neq i} q_j + q_i) - C(\overline{q}_i) + \beta B_i(\beta \sum_{j\neq i} \overline{q}_j + \overline{q}_i) = 0\} \tag{3.4.7}$$

Indeed IC_i^0 is a level set such that (3.4.5) binds for country i, and it is strictly convex. For any country i, any combination of abatements $\mathbf{q} \geq \overline{\mathbf{q}}$, which are on the lower contour sets inside IC_i^0 satisfy the incentive-compatibility of country i. Let us call these combinations of abatements D_i for i, and the intersection of all D_i sets D. Indeed, adoption of any abatement level $\mathbf{q}$ in the closure of D is a SPE abatement strategy and the resulting loss sustains a SPE loss under the threat of BAU reversion.

Let us call the derivative of $\frac{dq_i}{dq_j}$ along IC_i^0 the marginal rate of compliance of country i with country j, MRC_{ij} for any $j \neq i$. In fact, MRC_{ij} is the amount of increase in q_i which is incentive-compatible for country i, following an infinitesimal increase in the abatement of country j, where other coordinates are constant. By total differentiation from 3.4.7, it is obtained that along IC_i^0,

$$MRC_{ij} \equiv \left.\frac{dq_i}{dq_j}\right|_{IC_i^0} = \frac{\beta^2 B_i}{C' - \beta B_i} \tag{3.4.8}$$

Therefore, MRC_{ij} is increasing in the discount factor, β, the marginal social cost of GHG, γ_i, and the persistence rate of GHG, δ. Furthermore, it is decreasing in C'. Similarly, MRC_{ji} is

$$MRC_{ji} \equiv \left.\frac{dq_i}{dq_j}\right|_{IC_j^0} = \frac{C' - \beta B_j}{\beta^2 B_j} \tag{3.4.9}$$

Since $B_i = \bar{B}_i$, the reaction function of country i, $C' - \beta B_i = 0$, implies that at $\mathbf{q} = \overline{\mathbf{q}}$, MRC_{ij} is infinite, while MRC_{ji} is zero at this point. Hence $MRC_{ij} = \frac{1}{MRC_{ji}}$, for any $j \neq i$, which implies that at $\mathbf{q} = \overline{\mathbf{q}}$, IC_i^0 is orthogonal to IC_j^0. Furthermore, let us define hyperplane of $q_i = \bar{q}_i$, as $\{\mathbf{q} \mid C' - \beta B_i = 0\}$. Therefore, given the definition of MRC_{ij} in 3.4.8, at $\mathbf{q} = \overline{\mathbf{q}}$, the vector of partial derivative of MRC_{ij} is orthogonal to the hyperplane of $q_i = \bar{q}_i$. In addition, because the reaction function of the BAU problems of all i are orthogonal to each other at $\mathbf{q} = \overline{\mathbf{q}}$, the vector of partial derivative of MRC_{ij} is tangent to the hyperplane of $q_j = \bar{q}_j$ at this point.[45]

[45] As an example, see figure 3.1 for $I = 2$.

It has already been discussed that D is non-empty, because $\overline{\mathbf{q}}$ is the minimum abatement level and always sustains a SPE by threat of BAU reversion. The following proposition shows that for all parameter values of the model, the countries are able to sustain levels of abatement which are strictly larger than the BAU.

Proposition 3. *Set D is non-singleton, for any $\beta > 0$.*

Proof. At $\mathbf{q} = \overline{\mathbf{q}}$, IC_i^0 is orthogonal to IC_j^0 for any $j \neq i$. In addition, because the level sets of IC_i^0 for all i, are strictly convex, there is another unique fixed point, where the symmetric level hypersurfaces IC_i^0 for all i cross each other. Hence, D, as the intersection of strictly convex sets, is itself a convex and non-singleton set. □

Intuitively, orthogonality of IC_i^0 for all i at the BAU level of abatements, implies that at the least incentive-compatible policy level, i.e. at $\mathbf{q} = \overline{\mathbf{q}}$, for any $j \neq i$, when country j increases its abatement level, the amount which country i can increase its abatement and is incentive compatible for i itself is more than the increase in q_i in order to keep country j incentive compatible, i.e. $MRC_{ij} > MRC_{ji}$. This guarantees the existence of some larger levels of abatement which are incentive-compatible for all countries.

I am not restricting the equilibrium of the symmetric game to necessarily be symmetric, but symmetric countries are able to sustain asymmetric levels of abatement in set D.

3.4.4 Equilibrium selection from the set of sustainable SPE under the threat of BAU

Given proposition 3, at two levels of abatement the incentive compatibility constraints of all countries bind. One is the BAU abatement (the minimum sustainable point) and the other one is the maximum sustainable abatement, say $\widehat{\mathbf{q}}$. In fact, beyond some certain level of abatements, the gains and losses of abating according to $\widehat{q}_i$, versus the BAU level, will be equal for all i. To find this point, it is sufficient to solve for $\widehat{\mathbf{q}}$ in

I equations of binding incentive compatibility constraints, for all i,

$$C(\widehat{q}_i) - \beta B_i(\beta \sum_{j \neq i} \widehat{q}_j + \widehat{q}_i) = C(\overline{q}_i) - \beta B_i(\beta \sum_{j \neq i} \overline{q}_j + \overline{q}_i) \tag{3.4.10}$$

The RHS of the equality is a constant, and for the symmetric game a unique non-trivial $\widehat{\mathbf{q}}$, which is strictly greater than the BAU level, solves the system. Again, although I am not imposing any symmetry restriction on the equilibrium abatements, with the assumption of $\gamma_i = \gamma$, $\widehat{\mathbf{q}}$ is symmetric. An explicit solution for $\widehat{\mathbf{q}}$ is derived for the quadratic cost function, in section 3.4.4.

Lemma 1. $\widehat{\mathbf{q}}$ *is finite.*

This is already shown in the proof of proposition 3, and it is a direct result of the strict convexity of private cost, $C(q_i)$ for all i.

Any abatement in set D can be an equilibrium and if the countries agree on it, they will not deviate from it. Among the range of incentive-compatible abatements, the countries choose an equilibrium which minimises their joint long-run loss function. Assuming that for the joint loss function, the countries use the same weights as the social planner, i.e. the Pareto shares, then the countries minimise 3.4.1 over the set D.[46] It is already shown that the minimum of 3.4.1 is $\mathbf{q}^*$. As explained, by varying the Pareto shares, x_i, for all $i \in I$, where $\sum_i x_i = I$, the corresponding Pareto frontier in the abatement space is obtained. Given the fact that the chosen SPE abatement level, $\mathbf{q}^c$, must be incentive compatible for all countries, if the Pareto frontier crosses set D, and $\mathbf{q}^* \in D$, then $\mathbf{q}^c = \mathbf{q}^*$.

However, if for a given Pareto share, $\mathbf{q}^* \notin D$ (where the Pareto frontier may or may not have intersection with D), then the countries choose an abatement level on the boundary of D, where the incentive-compatibility constraint of some countries bind (as a corner solution). Recall that set D is formed by the intersection of strictly convex level sets of IC_i^0, which have two common crossings at $\overline{\mathbf{q}}$ and $\widehat{\mathbf{q}}$. Therefore, if $\mathbf{q}^*$ is not incentive compatible for i, but it is for some $j \neq i$, then $\mathbf{q}^c \in IC_i^0$ while still $\mathbf{q}^c \in D_j$,

[46] Dutta and Randner (2009) refer to this equilibrium as the third-best equilibrium.

such that 3.4.1 is minimised. Let us call such an equilibrium abatement $\mathbf{q}^B$, referring to the boundary solution[47]. Note that $\mathbf{q}^B$ includes $\widehat{\mathbf{q}}$, for example if the Pareto frontier does not have any intersection with set D, and $\mathbf{q}^* > \widehat{\mathbf{q}}$.

Thus, in general, $\mathbf{q}^c \in \{\mathbf{q}^*, \mathbf{q}^B\}$. If the game is symmetric, i.e. if $\gamma_i = \gamma$, and $x_i = 1$ for all i, then $\mathbf{q}^c$ is symmetric as well.

An example of two countries with quadratic private cost function

Assume $C(q_i) = \frac{q_i^2}{2\phi}$, where ϕ is an exogenous parameter affecting the private abatement cost and $0 < \phi \leq 1$. If $I = 2$, and $\gamma_i = \gamma$ for both i, then $q_i^* = \frac{2\beta\gamma\phi}{x_i(1-\beta\delta)}$, $\overline{q}_i = \frac{\beta\gamma\phi}{(1-\beta\delta)}$ and $\widehat{q}_i = \frac{\beta\gamma\phi(2\beta+1)}{(1-\beta\delta)}$. Note that all abatement levels are increasing in the private cost parameter, and in particular $\frac{d\widehat{q}_i}{d\phi} > \frac{d\overline{q}_i}{d\phi}$. In other words, if through the increase of ϕ, the private cost of both countries exogenously increases, then the increase in the maximum sustainable abatement is greater than the increase in the minimum sustainable abatement.

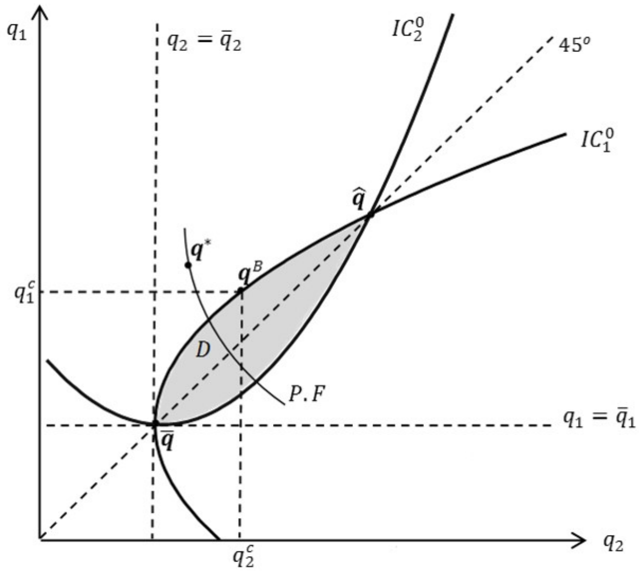
If $x_i = 1$ for both i, then $q_i^* = \frac{2\beta\gamma\phi}{(1-\beta\delta)}$. By replacing this stationary strategy of q_i^* in the condition (3.4.5), it can be verified that the countries are able to sustain the social optimum, if $\beta \geq \frac{1}{2}$. Also this condition can be found by comparison of $\widehat{q}_i$ and q_i^*. Specifically, if $\beta \geq \frac{1}{2}$, then the socially optimal level is uniquely chosen by the countries as a SPE abatement. Although the condition of sustainability of $\mathbf{q}^*$ here is independent of γ, ϕ and δ, the equilibrium abatements are all functions of these parameters. Therefore, a change of the underlying parameters shifts IC_i, so the of set D and the selected equilibrium are affected by them. This is discussed in more detail in the next subsection.

Contrarily, Figure 3.1 illustrates an example for two countries, 1 and 2, where $\mathbf{q}^* \notin D$. Let $x_1 << x_2$. First, note that in the two-dimensional space of abatements, the hypersurfaces of IC^0 are reduced to curves and the hyperplanes of BAU are two

[47] This implies that it may happen that country j should abate more than q_j^*, however as long as it is incentive compatible for j, they agree on an abatement which minimises the joint loss. This is because of the strict quasi-convexity of the optimal loss function of the social optimum problem, defined in the appendix as $V^*(Q_t)$. See Figure 3.1 for an example of this case.

orthogonal lines. The shaded area is set D, formed by the intersection of two sets of D_1 and D_2. Also, it is clear that at $\overline{\mathbf{q}}$, the IC^0 of two countries are tangential to the line of the BAU abatement of the other country, where $MRC_{1,2} \to \infty$ and $MRC_{2,1} = 0$. Thus, strictly convex IC^0 of the two countries have two intersections, $\overline{\mathbf{q}}$ and $\widehat{\mathbf{q}}$. In addition, the Pareto frontier (P.F in the figure), which is different combinations of $\mathbf{q}^*$ as Pareto shares vary, is here a hyperbola above the BAU lines. Because it is assumed that $x_1 << x_2$, $q_1^* >> q_2^*$, and as drawn $q_1^* \notin D_1$. In other words, it is assumed that country 1 cannon sustain the social optimum. Therefore, the chosen equilibrium, $\mathbf{q}^c$, is a boundary policy, i.e. $\mathbf{q}^c = \mathbf{q}^B$, and it belongs to IC_1^0, where here $q_2^c > q_2^*$.

Fig. 3.1 Equilibrium selection of two countries with asymmetric Pareto shares



3.4.5 Comparative statics and dynamics with respect to the cost-ratio parameter

According to the model, levels of abatements depend on the functional form of private cost, the discount factor, the decay rate of GHG, and the marginal social cost of GHG. In fact, all policy levels are increasing in β, δ and γ. Furthermore, as discussed before, MRCs of any two countries depend on these parameters as well. Thus, the set

D, which depends on MRCs in addition to the distance of the minimum and maximum sustainable abatements, is positively related to these parameters.

Among all these factors, in the literature of IEA in climate change, the social cost of carbon or GHG has received most attention. It can be argued that the persistence rate of GHG may have a similar importance for policy implications, but, at least in this model, the marginal effect of γ on abatement levels is larger than δ. Indeed, as stated before, the focus of this chapter is on information and learning about the marginal social cost of GHG.

In this section, first I provide some comparative static results specifically for the marginal social cost of GHG, γ, on the social optimum, and the BAU abatement.

$$\begin{aligned} \frac{dq_i^*}{d\gamma_i} &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B_i^*}{x_i})}.\frac{\beta}{x_i}.\frac{dB_i^*}{d\gamma_i} \\ &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B_i^*}{x_i})}.\frac{\beta}{(1-\beta\delta)} \end{aligned} \tag{3.4.11}$$

which is always positive. In other words, as the marginal cost of GHG increases, the Pareto frontier shifts upward and the countries are required to abate more in order to sustain the socially optimal level. This implies that $\mathbf{q}^*$ after the increase in γ_i is not sustainable as a SPE, if it was not sustainable before the increase in γ_i. Likewise,

$$\begin{aligned} \frac{d\overline{q}_i}{d\gamma_i} &= \frac{\partial C'^{-1}}{\partial(\beta\overline{B}_i)}.\beta.\frac{d\overline{B}_i}{d\gamma_i} \\ &= \frac{\partial C'^{-1}}{\partial(\beta\overline{B}_i)}.\frac{\beta}{1-\beta\delta} \end{aligned} \tag{3.4.12}$$

which is again positive for all parameter values of the model. It can be concluded that $\frac{dq_i^*}{d\gamma_i} > \frac{d\overline{q}_i}{d\gamma_i}$. Indeed, when γ_i is increased, the larger the level of abatement, the larger the increase in abatement is.[48]

[48]For the quadratic example of $C(q_i) = \frac{q_i^2}{2}$, actions are linearly increasing in γ_i.

Finally, here I examine the comparative dynamics of the stock of GHG with respect to the cost-ratio parameter. Recall that the equation of motion of GHG in (3.3.1), leads to $\tilde{Q} = \frac{\Psi - \sum_i^I q_i}{1-\delta}$, as the unique long-run equilibrium (steady state) of GHG, where q_i is the level of abatement in the long run. Therefore, given the assumption of $Q_0 < \tilde{Q}$, the stock of GHG, Q_t, over time increases smoothly and converges to $\tilde{Q}$. To check the comparative dynamics of the GHG with respect to γ, assume that the countries select a level of abatement which is increasing in the marginal social cost of GHG. Because the abatement levels affect the steady state of GHG, after the increase in γ, and therefore the abatement levels, the long-run steady state, $\tilde{Q}(\gamma)$, decreases. Hence, if the current level of stock, Q_t, is above the new steady state, then the stock along a decreasing convergence path converges to its long-run level. Conversely, the stock increases over time, if it is below the new steady state.

3.5 Level uncertainty about the marginal social cost of GHG

Similar to most stochastic IEA literature, I focus on uncertainty about the marginal social cost of GHG, representing the uncertainty about the costs of catastrophic events and global warming consequences.

The analysis begins with the assumption that $\gamma_i = \gamma$ for all i, which is known as level uncertainty in the literature. Later I will relax this assumption by allowing for distributional uncertainty, where the countries may be asymmetric with respect to the marginal social cost of GHG. Under the level uncertainty, assume in period zero, nature draws a random $\gamma \in \Gamma$ for all countries from one commonly-known uniform distribution. Furthermore, Γ is a finite set on $\mathbb{R}_+$. The countries know that the stochastic state variable is constant, but they do not observe its true realisation. The prior belief is common knowledge. Finally, under level uncertainty, the game is not necessarily symmetric, i.e. x_i may be different from one.

3.5.1 Ex-ante uncertainty and no-learning scenarios versus full learning

Before observing the precise public signal, one can compute the ex-ante payoffs of different problems. For example, to find the ex-ante socially optimal abatement level, a possible social planner or a country which internalises the social cost of GHG, would choose a sequence of $\{q_{it}\}_{t=0}^{\infty}$ to minimise

$$\mathbb{E}\{\sum_{t=0}^{\infty}\beta^t\sum_i x_i[C(q_{it})+\gamma Q_t]\} \tag{3.5.1}$$

subject to the equation of motion of (3.3.1). Since the model is linear in the random variable, the objective function can be rewritten as

$$\sum_{t=0}^{\infty}\beta^t\sum_i x_i[C(q_{it})+\mathbb{E}(\gamma)Q_t] \tag{3.5.2}$$

In fact, because of the linearity and the constant γ assumption, certainty equivalence holds. $\mathbb{E}(\gamma)$ is the public prior about γ, which is simply its mean. Hence, the Bellman equation can be written as

$$V^*(Q_t)=\min_{q_{it}}\{\sum_i x_i[C(q_{it})+\mathbb{E}(\gamma)Q_t]+\beta\mathbb{E}\{V^*(\delta Q_t+\Psi-\sum_i q_{it})\} \tag{3.5.3}$$

and it is obtained that for all t,

$$C_i'(q_i^*)=\frac{\beta I\mathbb{E}(\gamma)}{x_i(1-\beta\delta)} \tag{3.5.4}$$

In the same way, it is possible to derive set D, by replacing γ with the common prior belief $\mathbb{E}(\gamma)$, in all previous calculations.

The other possible case would be a situation, where countries never observe the true realisation of the social cost parameter. This is in fact the no-learning scenario in the literature, where all the countries will have a common prior about γ, which is its mean,

$\mathbb{E}(\gamma)$. Again, because of the certainty equivalence, the problem will be similar to what I discussed as the ex-ante uncertainty before full learning, where $\mathbb{E}(V(\gamma)) = V(\mathbb{E}(\gamma))$.

Assume that the countries, by receiving a public signal, can learn about the state variable. By learning, I mean that the countries receive a public signal and update their prior belief according to the Bayes rule. I have already discussed how the set of sustainable equilibria, D, changes as γ varies. The effect of learning can be investigated as the effect of change in the belief about γ on the set D, and therefore, the corresponding selected equilibrium, and indeed the value of $V^*(Q)$. Therefore, the comparison of full-learning and no-learning scenarios is in fact a comparative-static exercise which depends on comparison of $\mathbb{E}(\gamma)$ and γ. Indeed, there will be three possible cases:

First, $\mathbb{E}(\gamma) = \gamma$. Then, there is neither a gain nor a loss from learning. For a γ belonging to a continuum, this situation is a zero-probability event.

Second, $\mathbb{E}(\gamma) < \gamma$. If the countries are more optimistic about the marginal social cost of GHG, then necessarily learning improves the social welfare. This result is independent of whether $\mathbf{q}^*(\gamma)$ belongs to neither $D(\mathbb{E}(\gamma))$ nor $D(\gamma)$. In fact, if $\mathbf{q}^*(\gamma) \in D(\gamma)$, then clearly by learning the countries will be able to sustain the true social optimum. If $\mathbf{q}^*(\gamma) \notin D(\gamma)$, then $D(\gamma)$ is larger than $D(\mathbb{E}(\gamma))$, and includes some high levels of abatement which are incentive compatible under full learning, are not sustainable under the no-signal case, and vice versa for low levels of abatement. In addition, since $\mathbf{q}^*(\gamma) > \mathbf{q}^*(\mathbb{E}(\gamma))$ and $V^*(Q)$ is strictly quasi-convex, learning improves the welfare.

Third, $\mathbb{E}(\gamma) > \gamma$. In this case, if $\mathbf{q}^*(\gamma) \in D(\gamma)$, then necessarily learning improves the social welfare. However, if $\mathbf{q}^*(\gamma) \notin D(\gamma)$, then it depends. For example, if $\mathbf{q}^*(\gamma) > \widehat{\mathbf{q}}(\mathbb{E}(\gamma))$, then no-learning scenario is Pareto-superior.

3.5.2 A binary signal by an informed sender at the beginning of the game

Given the results in the last subsection, if it could be determined whether $\mathbb{E}(\gamma)$ is smaller or greater than γ, then ex-ante it were clear whether learning may benefit the countries. Therefore, a potential information central authority, as an information sender, which privately observes the true state realisation, could rank (and possibly choose between) the two scenarios of full learning and no learning for the countries.

As explained, the literature on stochastic IEAs studies the welfare, and emission or abatement policies under two scenarios of full-learning and no learning. Instead of taking the learning possibility as given and studying the comparative statics or dynamics with respect to that, in the rest of this chapter, I examine signalling games between an informed sender and the countries, where the learning outcome is endogenous, and specially I investigate whether the no-learning can be an equilibrium outcome of the game.

Assume that at the beginning of the game, an information sender privately observes the true social cost of GHG, γ. But the countries do not learn about the true state, in the absence of any information from the sender. In other words, the only source of information is the sender. Furthermore, the sender knows the common prior. The (degenerate) belief of the informed sender is not known by the countries.

Given the focus of literature on the two learning scenarios, I assume the sender is constrained to a certain set of strategies to induce either full learning or no learning. In other words, the sender does not design an information structure, but given a specific information structure, he chooses a signalling strategy[49]. In this subsection, I focus on a binary information strategy, where at the beginning of the game, the informed sender decides whether to reveal the state or not. Let $\alpha(\gamma)$ denote the probability of sending a fully revealing signal, given knowing the true state, γ. So the information strategy of the sender is a map, $\alpha : \Gamma \to \{0, 1\}$, where $\alpha(\gamma) = 1$ refers to revealing the true state, and $\alpha(\gamma) = 0$ denotes being silent (equivalently the sender can send a meaningless signal). The sender, conditional on choosing the strategy of revelation of

[49] In the next chapter, I consider a situation where the information sender, at the stage of communication of the information strategy, does not know the state of the world, and he designs an optimal information structure.

the true state, sends a precise public signal $y = \gamma$. Let $y \in Y$, where the set of public signals, Y, is a finite set, and $Y = \Gamma$. Furthermore, the set of signals is also given to the sender and it is not a choice variable.

The timeline is as follows. At the beginning of period $t = 0$, the sender privately observes the true realisation of the state, and decides whether to reveal the state or not. The countries given the information action of the sender and (possibly) the fully-revealing signal realisation, update their common prior to a posterior, $\mu(\gamma \mid \alpha(\gamma))$, and choose their abatement actions in period zero.

As shown in section 3.4, the abatement solutions of the countries are stationary. Thus, after the update of their beliefs in period zero, the countries work out their constant self-enforceable level of abatements for all future periods. I assume that the information sender tries to affect the beliefs of the countries in order to induce a particular action, i.e. an abatement level which has the minimum distance from the true socially optimal level. Specifically, assume that the flow loss of the sender is $\nu(\mathbf{q}^c(\mathbb{E}(\gamma \mid \alpha(\gamma))), \gamma) = \|\mathbf{q}^c(\mathbb{E}(\gamma \mid \alpha(\gamma))) - \mathbf{q}^*(\gamma)\|$. In fact, $\nu(.)$ indirectly depends on the posterior beliefs of the countries about the state of the world, through their chosen abatement levels. Since the sender observes the true γ, and the beliefs of the sender and the countries do not necessarily coincide, the social optimum as the bliss point of the sender is not a function of the countries' beliefs. Because the abatement levels are constant over time, the objective function of the sender is simply $\sum_{t=0}^{\infty} \beta^t \|\mathbf{q}^c(\mathbb{E}(\gamma \mid \alpha(\gamma))) - \mathbf{q}^*(\gamma)\| = \frac{1}{1-\beta}\|\mathbf{q}^c(\mathbb{E}(\gamma \mid \alpha(\gamma))) - \mathbf{q}^*(\gamma)\|$.

Payoffs of both parts are common-knowledge. In addition, I assume that gathering information and communication are costless for the sender, also once the information is provided publicly, acquiring it is free for the countries.

It can be directly concluded that

Lemma 2. *For any $\gamma \in \Gamma$, if $\mathbf{q}^*(\gamma) \in D(\gamma)$, then full disclosure is the equilibrium strategy of the sender.*

In other words, if the countries, knowing the true state, can sustain the socially optimal payoff, then by full revelation of the state, the sender can obtain his bliss point. I restrict attention to the cases where,

Assumption 3. *For any* $\gamma \in \Gamma$, $\mathbf{q}^*(\mathbb{E}(\gamma)) > \widehat{\mathbf{q}}(\mathbb{E}(\gamma))$, $\mathbf{q}^*(\gamma) > \widehat{\mathbf{q}}(\gamma)$, *and* $\mathbf{q}^*(\gamma) > \widehat{\mathbf{q}}(\mathbb{E}(\gamma))$.

The first two conditions of Assumption 3 imply that under both full-learning and no-learning scenarios, $\mathbf{q}^c = \widehat{\mathbf{q}}$. The last two conditions indicate that under both learning scenarios, the sender strictly prefers the maximum level of abatement, $\widehat{\mathbf{q}}$, over any other abatement.

Therefore, given that the abatement strategies are increasing in the social cost of GHG, if the sender knows that $\mathbb{E}(\gamma) \leq \gamma$, he chooses to reveal the state, and sends the precise public signal $y = \gamma$. Since $\widehat{\mathbf{q}}(\gamma)$ is strictly increasing in γ, there is a one-to-one relationship between the selected-action space and Γ. Therefore, following the information action of $\alpha(\gamma) = 1$, the sender by revealing $y = \gamma$, is recommending an action to the countries. Accordingly, the countries update their prior belief to a common posterior belief, denoted by $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$, which leads to selection of $\widehat{\mathbf{q}}(\gamma)$. While, if the sender was informed that $\mathbb{E}(\gamma) > \gamma$, then he would prefer to completely hide his awareness of the state, and leave the countries with their prior belief. However, if he chooses to be silent, then the countries obtain more information relative to their prior belief. In fact, the countries learn (at least more than the no-learning case), as they know that the sender prefers a higher level of abatement which is closer to the social optimum. So, to the countries, which prefer the fully revealing strategy, the silence of the sender can be strategic. Let us denote the posterior belief of the countries upon the silence of the sender by $\mu(\gamma \mid \alpha(\gamma) = 0)$. In other words, the silence of the sender reveals to the countries that $\mathbb{E}(\gamma) > \gamma$. Hence, the countries truncate the uniform distribution of social cost from above, which gives rise to $\mathbb{E}(\gamma \mid \alpha(\gamma) = 0) < \mathbb{E}(\gamma)$.

Obviously, it is an incomplete information game, and the solution concept that is used here, is perfect Bayes Nash equilibrium (PBNE). I am interested to check whether the game can have any pooling equilibrium, where different types of senders choose the action of being silent and lead to no learning or partial learning by the countries.

The PBNE strategies consist of functions $\mu(\gamma \mid \alpha(\gamma) = 0)$, $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma)$, $\mathbf{q}^c$, and $\alpha(\gamma)$ such that (1) $\mu(\gamma \mid \alpha(\gamma) = 0)$, and $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma)$ are consistent with the Bayes rule, (2) $\mathbf{q}^c \in D$ is the incentive-compatible level of abatement of the countries, and given the corresponding updated beliefs, $\mathbf{q}^c$ is best response to $\alpha(\gamma)$, and minimises the sum of joint expected loss of the countries (with weights of x_i for all i), and (3) $\alpha(\gamma)$ minimises the loss of sender and is best response to $\mathbf{q}^c$.

Characterisation of the equilibrium is provided in the next proposition, and the proof is in the appendix:

Proposition 4. *The posterior belief of* $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$, *and strategies of* $\mathbf{q}^c = \widehat{\mathbf{q}}(\gamma) \in D(\gamma)$ *and* $\alpha(\gamma) = 1$ *constitute the unique PBNE of the game with binary signals.*

Because the difference of expected loss of the sender from the two strategies is monotone in the true social cost of GHG, the equilibrium strategy of the sender has a threshold form with respect to γ, and as stated in the proposition, the threshold is equal to the minimum element of Γ. In other words, if ex-ante an informed sender has two choices, revealing the true state or being silent, in equilibrium he must fully disclose the true state, and this is independent of whether the prior public belief is more optimistic or pessimistic about the true social cost of GHG.

The objectives of the sender and the receivers do not necessarily match, and the countries optimisation problem is constrained to the set of sustainable abatements. Because full revelation exists in the sender's choice set, and it is optimal for the sender under some conditions, he loses the possibility of using the unrevealing information action in other situations. Put differently, if he reveals the state for some values of γ, he has to do so for all other realisations, and the full-revelation of the state is the equilibrium in any case. In the next subsection, I check the robustness of the result to the possibility of using an information strategy where $\alpha(\gamma) \in [0, 1]$.

3.5.3 A noisy signal by an informed sender at the beginning of the game

In this subsection, I examine a similar game, but here I assume that $\alpha(\gamma)$ is not necessarily degenerate, and can admit any value between $[0, 1]$. I adjust the choices of the sender such that he is constrained to sending a signal which is equal to the true value with probability $\alpha(\gamma) \in [0, 1]$. Such an information structure allows me to investigate whether an informed sender can induce imperfect learning (in addition to the no-learning).

After the sender privately observes the true state, he chooses an information strategy which specifies with probability $\alpha(\gamma)$ he reveals the true state of the world, γ, and with probability $1 - \alpha(\gamma)$ the sender sends a random draw from Γ, which is indeed sending a meaningless signal (or noise). In fact, $\alpha(\gamma)$ is the precision of the public signal. I refer to this strategy as the noisy signalling strategy. Then the sender send a signal $y \in Y$, according to the chosen strategy. Given the information strategy, $\alpha(\gamma)$, and the observed signal, y, the countries update their common prior belief. Subsequently, the countries choose an abatement level.

The objective functions of the sender and countries, are the same as in the last subsection. As before, what matters for the countries is the conditional expected value of the social cost parameter, $\mathbb{E}(\gamma \mid \alpha(\gamma), y)$. Hence, the continuation losses of the countries and the resulting abatement levels all depend on the precision of the public signal. Furthermore, let assumption 3 be satisfied here as well.

The sender, chooses an optimal precision which minimises its long-run loss function and is the best response to the strategy of the countries. The PBNE is also the same as was specified in subsection 3.5.2, except the posterior beliefs, and here they are $\mu(\gamma \mid \alpha(\gamma), y)$ for any $\alpha(\gamma) \in [0, 1]$. But the equilibrium outcome is similar to the binary-signal case:

Proposition 5. *The posterior belief of $\mu(\gamma \mid \alpha(\gamma) = 1, y = \gamma) = 1$, and strategies of $\widehat{\mathbf{q}}(\gamma) \in D(\gamma)$ and $\alpha(\gamma) = 1$ constitute the unique PBNE of the game with noisy signals.*

For the proof see appendix. Intuitively, if an informed sender has access to a randomisation device to select between either revealing the true social cost of GHG or sending noise (a meaningless signal) and induce agents to adjust their profile of abatements such that the sum of sender's discounted loss is minimised, in equilibrium, he reduces the noise of public information to zero, and provides the countries with as precise as possible information.

3.5.4 Delay in communicating with the countries

In the last two subsections, it was shown that the informed sender in equilibrium, as soon as he observes the state, announces the fully-revealing information strategy, i.e. $\alpha(\gamma) = 1$, and immediately sends the public signal of the true level of social cost of GHG. In this section, I check whether the sender can postpone sending signal y.

Specifically, in either binary or noisy signalling games, assume the sender, after observing the state γ, sets $\alpha(\gamma) = 1$ in $t = 0$, but has the option of delaying sending signal $y = \gamma$, from period $t = 0$ to $t = T$, where T is a positive integer.

Although the expected loss of countries is a function of the total level of GHG in each period, Q_t, in this linear model, the level of abatements are independent of the stock, and after learning the state, the chosen abatement is independent of Q_t in both scenarios of learning in period 0 and T. As explained, the countries select a level of abatement in the set of incentive-compatible abatements, D, given their belief about the social cost of GHG, such that $V^*(Q_t)$ is minimised. Hence, the countries prefer to immediately update their beliefs and adjust their abatement to $\widehat{\mathbf{q}}(\gamma)$.

From the expected loss of the sender, it is clear that if $\mathbb{E}(\gamma) \leq \gamma$, then the sender prefers to send out the signal in $t = 0$, as well. In other words, if initially the countries are more optimistic about the social cost of GHG, the sooner the countries receive the signal and increase their level of abatements, the better.

Conversely, assume that $\mathbb{E}(\gamma) > \gamma$, where the sender prefers to delay the communication of true social cost of GHG. But the countries, as soon as they experience delay in receiving the signal, will realise that ex-ante they are abating more than necessary. Although the long-run level of GHG is lower under the prior belief, i.e. $\tilde{Q}(\gamma) > \tilde{Q}(\mathbb{E}(\gamma))$, and in each period $t < T$, the lower Q_t under no learning leads to a lower level of loss, $V^*(Q_t)$, delay reveals that $\mathbb{E}(\gamma) > \gamma$, thus for the countries $\widehat{\mathbf{q}}(\mathbb{E}(\gamma))$ is not incentive compatible any more. Therefore, the countries truncate the distribution of beliefs to say γ^*, and as a best response to delay, they decrease their selected abatement to $\widehat{\mathbf{q}}(\frac{\gamma^*}{2})$. Assuming that $\widehat{\mathbf{q}}(\frac{\gamma^*}{2}) < \widehat{\mathbf{q}}(\gamma)$, the sender will send the signal in $t = 0$. The result of the equilibrium time of communication is provided in the next proposition.

Proposition 6. *In equilibrium the informed sender sends the precise public signal at the beginning of the game, immediately after observing the social cost of GHG.*

3.6 Distribution and level uncertainty about the marginal social cost of GHG

In this section, I study a situation, where the countries are not symmetric in terms of their marginal cost of GHG. Distributional uncertainty in the literature of stochastic IEAs refers to a situation where the realised values of state for different countries do not coincide, and each country has a different unknown cost-ratio parameter γ_i drawn from one commonly-known distribution. Distribution and level uncertainty means that there exists a distribution Γ_i for every country i, and the marginal social costs of GHG are random draws from these known independent distributions (the level of cost-ratio parameters of different countries may coincide, though they are from different distributions). For both situations, as long as the signals are publicly observed by all countries and the (expected value of) distribution(s) is (are) known, the analysis of level and distributional uncertainty will be similar to distributional uncertainty. Here I look into the more general case of distribution and level uncertainty, and again I assume that the distributions of the countries are uniform.

In this section I assume $I = 2$.[50] At the beginning of the game, nature draws two independent values for the two countries from the two commonly known distributions of Γ_i for each $i \in \{1, 2\}$.

For the precise public signals, by replacing γ with γ_i, all derivations are generalised to the case of level and distributional uncertainty. Furthermore, the incentive-compatibility constraints for sustaining abatements greater than BAU levels as a SPE by threat of BAU reversion, are the same as (3.4.5). The definitions such as IC_i^0, D, MRC_{ij}, are the same here. Proposition 3 is also applied directly, as its proof is independent of asymmetry of marginal social cost of GHG. In addition, still $\mathbf{q}^c = \{\mathbf{q}^*, \mathbf{q}^B\}$. Note that here $\overline{\mathbf{q}}$ and $\widehat{\mathbf{q}}$ are not necessarily symmetric, although if $x_1 = x_2$, the social optimum, $\mathbf{q}^*$, is symmetric. In addition,

$$\begin{aligned} \frac{dq_1^*}{d\gamma_1} &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B^*}{x_1})} \cdot \frac{\beta}{(1-\beta\delta)} \\ \frac{dq_1^*}{d\gamma_2} &= \frac{\partial C'^{-1}}{\partial(\frac{\beta B^*}{x_1})} \cdot \frac{\beta x_2}{x_1(1-\beta\delta)} \end{aligned} \tag{3.6.1}$$

Thus, if $x_1 < x_2$, then $0 < \frac{dq_2^*}{d\gamma_1} < \frac{dq_2^*}{d\gamma_2} = \frac{dq_1^*}{d\gamma_1} < \frac{dq_1^*}{d\gamma_2}$. In other words, the social-optimal level of abatement of country 1 is relatively more sensitive to the marginal social cost of GHG in country 2, which has a greater weight in the social loss function.

Now let us consider the games between an informed information sender and the countries, with level and distributional uncertainty. Assume that in period $t = 0$, the sender observes the states, and announces the chosen $\alpha_i(\gamma_1, \gamma_2)$ of each country publicly. Therefore, both countries receive $\alpha_1(\gamma_1, \gamma_2)$, and $\alpha_2(\gamma_1, \gamma_2)$, and if specified by the information strategy, afterwards they both observe the two signal realisations of y_1 and y_2. The sender's problem is minimising

$$\|\mathbf{q}^c(\mathbb{E}(\gamma_1 \mid \alpha_1(\gamma_1, \gamma_2), y_1), \mathbb{E}(\gamma_2 \mid \alpha_2(\gamma_1, \gamma_2), y_2)) - \mathbf{q}^*(\gamma_1, \gamma_2)\| \tag{3.6.2}$$

[50] This assumption guarantees the uniqueness of $\widehat{\mathbf{q}}$, and therefore $\mathbf{q}^c$.

where the choice variables are $\alpha_1(\gamma_1, \gamma_2)$, and $\alpha_2(\gamma_1, \gamma_2)$. Also assume that Assumption 3 is generalised to this case. Thus, $\mathbf{q}^c = \widehat{\mathbf{q}}$ under any belief, furthermore, the sender strictly prefers higher levels of abatement. The following proposition is directly generalised from proposition 4, 5 and 6.

Proposition 7. *The posterior beliefs of* $\mu(\gamma_1 \mid \alpha_1(\gamma_1, \gamma_2) = 1, y_1 = \gamma_1) = 1$, *and* $\mu(\gamma_2 \mid \alpha_2(\gamma_1, \gamma_2) = 1, y_2 = \gamma_2) = 1$ *and strategies of* $\widehat{\mathbf{q}}(\gamma_1, \gamma_2) \in D(\gamma_1, \gamma_2)$, $\alpha_1(\gamma_1, \gamma_2) = 1$ *and* $\alpha_2(\gamma_1, \gamma_2) = 1$ *constitute the unique PBNE of the game with either binary or noisy signals. Furthermore, in equilibrium public signals of* y_1 *and* y_2 *are sent in* $t = 0$.

In other words, given the assumed information structures, an informed sender always fully reveals the true state to asymmetric countries. Again the result is independent of whether one or both countries are more optimistic or pessimistic about the true marginal social cost of GHG. Furthermore, it can be deduced that the sender cannot choose the country with which to communicate the information strategy, as any strategy other than the full revelation of the state is off the equilibrium path.

3.7 Conclusion

An IEA model is presented, where in an infinite-horizon climate-change setup, the countries are involved in self-enforcing agreements and decide about their investments in emission abatement technologies. The equilibrium selection of the countries from the set of sustainable abatements is discussed and the sensitivity of this set and the selected abatement to the social cost of GHG is examined.

In another step, the uncertainty about the social cost of GHG is introduced, and the chapter investigates the possibility of affecting the equilibrium behaviour of countries through the public information released by a central authority in the field. In the literature on stochastic IEAs, the conditions under which learning may contribute to increasing or decreasing social welfare are verified, and most literature, by comparison of scenarios of full learning and no learning, suggest that no learning on the social cost of GHG, or delay in the learning process, is Pareto superior.

This chapter introduces an information sender into the stochastic IEA model, who has access to a specific signalling structure, which can lead to full-learning, no-learning or imperfect-learning outcomes. The sender adjusts the likelihood of noise in the given public information structure, and tries to induce Pareto-superior actions by the countries.

It is shown that the equilibrium learning outcome is always full learning and the optimal time of communication of true signal realisation is right at the beginning of the game. In fact, if the countries are ex-ante more optimistic about the social cost, and hence they are abating less than they could do under the full learning of the state, the sender's best response is full revelation. Therefore, in the other case that the countries prior belief is more pessimistic about the social cost of GHG, where the sender's preferred abatement level (which is closer to the true socially-optimal abatement) is no learning, any signalling choice other than full revelation by the informed sender, implies that the countries ex-ante are abating more than is sustainable, and the countries can block the choice of any signalling action which provides less than fully-revealing information.

Therefore, if the research central authorities are supposed to announce results of their research on the social cost of carbon, given the model, the countries are provided with full information. In other words, the no-learning outcome is not on the equilibrium path, and this is independent of whether the public prior belief is more pessimistic or optimistic about the social cost of GHGs.

3.8 Appendix

3.8.1 The socially optimal abatement level- the precise-signal case

The Bellman equation of the social planner problem is

$$V^*(Q_t) = \min_{q_{it}}\{\sum_i x_i[C(q_{it}) + \gamma Q_t] + \beta V^*[Q_{t+1}]\} \tag{3.8.1}$$

where Q_{t+1} is given by equation (3.3.1), and $V^*(Q_t)$ is the optimal loss function of the social-optimal abatements.

Because the flow loss, $\prod_{it}$, is a continuous and strictly convex function, also the set $\{(Q_t, Q_{t+1}) : Q_{t+1} = \delta Q_t + \Psi - \sum_i q_{it}, q_{it} \in \mathrm{I\!R}_+\}$ is convex and compact, $V^*(Q_t)$ is differentiable, strictly increasing and strictly convex. Hence, the set of optimal controls is non-empty and single-valued.

Using the guess and verify method, it can be guessed that the optimal loss function has a form of $V^*(Q_t) = A^*_{it} + B^*_{it}Q_t$.[51] Hence, from the first-order condition of the abatement level, the solution in equation (3.4.2) is obtained. To verify the coefficients, by plugging the guess into the Bellman equation, it turns out to be

$$V^*(Q_t) = \min_{q_{it}}\{\sum_i x_i[C(q_{it}) + \gamma_i Q_t] + \beta A^*_{it} + \beta B^*_{it}Q_{t+1}\} \tag{3.8.2}$$

Verification of the coefficients gives $B^*_i = \frac{\sum_i x_i\gamma_i}{1-\beta\delta}$. Hence the socially optimal abatement is independent of t. By substituting B^*_i in equation (3.8.2), one can verify A^*_{it} as

$$A^*_i = \frac{\sum_i x_i C(q^*_i) + \beta B^*_i(\Psi - \sum_i q^*_i)}{1-\beta} \tag{3.8.3}$$

3.8.2 The BAU abatement level- the precise-signal case

The Bellman equation of the BAU problem of country i is

[51]The guess can be obtained by iteration of the loss function for a few times.

$$\overline{V}_i(Q_t) = \min_{q_{it}}\{[C(q_{it}) + \gamma_i Q_t] + \beta \overline{V}_i[\delta Q_t + \Psi - q_{it} - \sum_{j \neq i} q_{jt}]\} \tag{3.8.4}$$

where $\overline{V}_i(Q_t)$ is the optimal loss function of BAU policy. If the optimal loss function has a form of $\overline{V}_i(Q_t) = \overline{A}_{it} + \overline{B}_{it}Q_t$, from the first-order condition of abatement level, the BAU abatement in equation (3.4.3) is obtained. Again, in order to verify the coefficients, after substituting the guess in the Bellman equation, it turns out to be

$$\overline{V}_i(Q_t) = \min_{q_t}\{[C(q_{it}) + \gamma_i Q_t] + \beta \overline{A}_{it} + \beta \overline{B}_{it}[\delta Q_t + \Psi - q_{it} - \sum_{j \neq i} q_{jt}]\} \tag{3.8.5}$$

Verification of the coefficients gives $\overline{B}_i = \frac{\gamma_i}{1-\beta\delta}$, so the BAU solution of various countries differ only with respect to γ_i. Hence, by substituting $\overline{B}_i$ and $\overline{q}_i$ for all i in equation (3.8.5), one can verify $\overline{A}_{it}$ as

$$\overline{A}_i = \frac{C(\overline{q}_i) + \beta \overline{B}_i(\Psi - \sum_i \overline{q}_i)}{1-\beta} \tag{3.8.6}$$

3.8.3 The incentive-compatibility constraint for following a constant level of abatement in every period under the punishment of BAU reversion- the precise-signal case

The total loss of following the stationary strategy of q_i, for every i, is denoted by $V(Q_t)$. As an optimal loss, q_i is the solution to the following Bellman equation:

$$V_i(Q_t) = \min_{q_{it}}\{[C(q_{it}) + \gamma_i Q_t] + \beta V_i[\delta Q_t + \Psi - q_{it} - \sum_{j \neq i} q_{jt}]\} \tag{3.8.7}$$

The iteration of the loss function shows that it is linear in the level of GHG. In subsection 3.4.3, I denoted it as $V(Q_t) = A_i + B_i Q_t$. It can be verified that $B_i = \frac{\gamma_i}{1-\beta\delta}$ for all i, also

$$A_i = \frac{C(q_i) + \beta B_i(\Psi - \sum_i q_i)}{1-\beta} \tag{3.8.8}$$

Therefore, the sufficient condition of (3.4.4) can be simplified to

$$\begin{aligned} & C(q_i) + \gamma_i Q_t + \beta[A_i + B_i(\delta Q_t + \Psi - \sum_i q_i)] \leq \\ & C(q_i^{BR}) + \gamma_i Q_t + \beta[\overline{A}_i + \overline{B}_i(\delta Q_t + \Psi - q_i^{BR} - \sum_{j \neq i} q_j)] \end{aligned} \tag{3.8.9}$$

Furthermore, q_i^{BR} is the level of abatement which is the best response to $\sum_{j \neq i} q_j$. In order to find q_i^{BR}, it is sufficient to take the derivative with respect to q_i from the right-hand side of the inequality in (3.8.9), which is the short-run and long-run payoff of deviation, and by equating it to zero, it will be obtained that $q_i^{BR} = \overline{q}_i$.

Given this result, the IC constraint in (3.8.9) can be further simplified to

$$C(q_i) + \beta A_i - \beta B_i q_i \leq C(\overline{q}_i) + \beta \overline{A}_i - \beta \overline{B}_i \overline{q}_i \tag{3.8.10}$$

By substituting for A_i, $\overline{A}_i$, and using $B_i = \overline{B}_i$, it can be written as

$$C(q_i) - \beta B_i(\beta \sum_{j \neq i} q_j + q_i) \leq C(\overline{q}_i) - \beta B_i(\beta \sum_{j \neq i} \overline{q}_j + \overline{q}_i) \tag{3.8.11}$$

3.8.4 Proof of proposition 4

Starting from the last subgame of $t = 0$, and given the results of equilibrium selection of the countries in subsection 3.4.4, and assumption 3, the countries choose $\widehat{\mathbf{q}}$ given their updated belief.

By contradiction, assume that by selection of being silent, the sender could block the transmission of information. So, let $\alpha'(\gamma)$ denote such a strategy. Then the sender compares the expected losses of $\alpha'(\gamma) = 1$, and $\alpha'(\gamma) = 0$. Let us denote the difference of expected losses by $Dif(\gamma) \equiv \|\widehat{\mathbf{q}}(\gamma) - \mathbf{q}^*(\gamma)\| - \|\widehat{\mathbf{q}}(\mathbb{E}(\gamma)) - \mathbf{q}^*(\gamma)\|$. Because $\mathbb{E}(\gamma)$ is constant, $Dif(\gamma)$ is strictly monotone in γ. Furthermore, $Dif(\gamma) \leq 0$ iff $\widehat{\mathbf{q}}(\gamma) \geq \widehat{\mathbf{q}}(\mathbb{E}(\gamma))$ iff $\gamma \geq \mathbb{E}(\gamma)$. This leads to the threshold-form strategy of

$$\alpha'(\gamma) = \begin{cases} 1 & \text{if } \gamma \geq \mathbb{E}(\gamma) \\ 0 & \text{if } \gamma < \mathbb{E}(\gamma) \end{cases} \tag{3.8.12}$$

Therefore, if $\alpha'(\gamma) = 1$, then the strategies specified in the proposition are all best response. While if $\alpha'(\gamma) = 0$, the countries realise that $\mathbb{E}(\gamma) > \gamma$, and optimally truncate the distribution of random variable γ to γ^*, and the best response of the countries implies $\mathbb{E}(\gamma \mid \alpha'(\gamma) = 0) < \mathbb{E}(\gamma)$. Indeed, given the uniform assumption, $\mathbb{E}(\gamma \mid \alpha'(\gamma) = 0) = \frac{\gamma^*}{2}$. Thus, the sender's strategy of $\alpha'(\gamma)$ is not a best response to the countries' strategy. The same reasoning applies to a situation where the sender chooses a strategy with threshold $\frac{\gamma^*}{2}$, etc. Therefore, the unique PBNE threshold of the sender coincides with the minimum element of Γ, implying that in equilibrium for all $\gamma \in \Gamma$, the sender chooses $\alpha(\gamma) = 1$. □

3.8.5 Proof of proposition 5

The countries choose $\widehat{\mathbf{q}} \in D$ given their updated belief. By contradiction, assume that the sender can use a noisy signalling strategy, $\alpha''(\gamma) < 1$. Let us assume that it is possible to exactly by probability $1 - \alpha''(\gamma)$ leave the countries with their prior belief to achieve the best outcome as if the sender was not informed about the state. This implies that $\mathbb{E}(\gamma \mid \alpha''(\gamma), y) = \alpha''(\gamma)y + (1 - \alpha''(\gamma))\mathbb{E}(\gamma)$. Hence, the posterior belief of the countries is a convex combination of the true state and the prior expectation. Because the optimal abatements are strictly increasing in beliefs, any induced solution $\widehat{\mathbf{q}}(\mathbb{E}(\gamma \mid \alpha''(\gamma), y))$ is also a convex combination of $\widehat{\mathbf{q}}(\gamma)$ and $\widehat{\mathbf{q}}(\mathbb{E}(\gamma))$. Then the best response of the sender is as follows. If $\mathbb{E}(\gamma) \leq \gamma$, then the separating PBNE specified in the proposition, constitutes best response for all players, as no one has any incentive to deviate. However, if $\mathbb{E}(\gamma) > \gamma$, the sender optimally, chooses $\alpha''(\gamma) = 0$ to minimise his loss function. But this is similar to proposition 4, where the sender has a threshold strategy and knowing that the sender is biased to higher levels of abatement (given assumption 3), if the countries observe $\alpha''(\gamma) = 0$, they truncate the distribution of social cost of GHG from above. So, they will have a posterior expectation which is strictly less than $\mathbb{E}(\gamma \mid \alpha''(\gamma), y) = \mathbb{E}(\gamma)$, and they select an abatement $\widehat{\mathbf{q}}$, which is strictly less than $\widehat{\mathbf{q}}(\mathbb{E}(\gamma))$. Therefore, $\alpha''(\gamma) = 0$ is not a best response to the selected $\widehat{\mathbf{q}}$. Similarly, no other $\alpha(\gamma) < 1$ can be a best response to the countries' strategy. The only best-response abatements and signalling strategy are where the posterior beliefs of the countries lead to $\mathbb{E}(\gamma \mid \alpha''(\gamma), y) = \gamma$. Hence, the sender has no choice other than setting $\alpha(\gamma) = 1$, and countries choose $\widehat{\mathbf{q}}(\gamma) \in D(\gamma)$. $\square$

Chapter 4

Optimal Communication of Climate Change With The Public

Abstract

I examine a setting, where a central authority, as an information sender, conducts research on the true social cost of climate change, and releases information to the countries. The sender, who has commitment power, by designing an information mechanism (a set of signals and a probability distribution over them), maximises his payoff, which depends on the mitigation action of countries and the social cost of green-house gases(GHG). The countries, given the information policy (the probability distribution over signals) and the public signal, update their beliefs about the social cost of GHG and take a mitigation action. I derive the optimal information mechanism from the general set of public information mechanisms, in coalition formation games. I show that the coalition size, as a function of beliefs, is an endogenous variable, induced by the information sender. If the sender maximises the expected payoff of either of non-signatories or signatories of the climate treaty, then full revelation is the optimal information policy, while if the sender attempts to reduce the global level of GHG, then optimal information policy leads to imperfect disclosure of the social cost. Furthermore, given any of the specifications of the sender's payoff, the optimal information policy leads to the socially optimal mitigation and membership outcomes.

Key words: Climate Change; International Environmental Agreements; Coalition Formation; Learning; Information Persuasion

JEL Classification: Q54; D81; D83; C72; D62

4.1 Introduction

The historic climate change agreement, which was adopted in Paris in December 2015, led to the formation of a grand coalition of over 190 countries with the objective of reducing the level of GHG emissions, with the consequent hope to limit the rise in the average global temperature. The success in obtaining full participation in the international environmental agreement (IEA) was undoubtedly indebted to the role of international research institutes on climate change (the IPCC and other partners of the UN), which had conducted research on climate change, and communicated the results to the countries. In this chapter, a theoretical framework is constructed to understand the significance of communication of the research central authorities (information sender) with the countries (receivers) about the information on climate change.

More specifically, I consider a model in which the sender maximises its payoff which depends on the mitigation action undertaken by the countries and a payoff-relevant state variable, which here is the social cost of GHG emissions. Before any decision making by the countries, the sender initiates the research by choosing an optimal information mechanism (a set of signals, as recommended actions, and an information policy, which is a probability distribution over signals) to maximise his expected payoff. Indeed, choosing a research strategy is modelled as choosing a probability distribution over a signal. In contrast to the third chapter, before choosing the information policy, the sender is uninformed about the state. Furthermore, the sender is assumed to have commitment power. So, after conducting the research on the state variable, he commits to the information mechanism and sends a public signal. Payoffs of both sender and receivers are common knowledge.

Finding the optimal information mechanism is studied in the recent but growing literature on information design, introduced by Kamenica and Gentzkow (2011). This chapter applies the information design to a climate change context, and generalises Kamenica and Gentzkow (2011) to coalition formation games, where there are multiple receivers who are either non-signatories or signatories of a climate treaty, and the information sender can achieve formation of a desired environmental coalition by designing an optimal information mechanism.

Indeed, the interaction of the countries is modelled as a coalition game, which has two stages: the membership stage and then the mitigation (abatement or emission) stage. The timeline is as follows. The sender announces an information policy, and sends a public signal to the countries. Given the information mechanism the countries update their (common) prior belief, and in the membership stage, they decide whether to join a coalition or become non-signatories. Finally, the non-signatories and signatories of the coalition choose their mitigation actions.

Subgame perfection implies that given their posterior belief, the countries decide about their mitigation and subsequently their membership strategies. Finally, given the best responses of the countries in the emission and membership subgames, the sender chooses an optimal information mechanism.

The information mechanism leads to a probability distribution over posterior beliefs of the countries, which in turn determines the mitigation and membership outcomes. Kamenica and Gentzkow (2011) use terminology of "persuasion" to refer to affecting the receiver's action by inducing a certain distribution over her posterior beliefs. Here, it reflects the fact that the sender's choice of information policy influences the coalition formation choices of the countries. In other words, the sender can persuade the countries as to what mitigation and membership choices to make.

Therefore, beliefs are endogenous variables, and in contrast to the literature on IEAs, posterior beliefs are not fixed parameters. Indeed, in our analysis, the beliefs about the state variable are the critical variables in determining the profitability and stability (self-enforceability for signatories and non-signatories) of a coalition, and in this chapter, the threshold behaviour of the signatories and non-signatories of a climate treaty are dissected with respect to their beliefs with regard to the social cost of GHG.

It is shown that the number of signatories of a coalition, depends on the beliefs, and therefore, it is an endogenous variable induced by the information sender. I consider a simple and tractable model, where the state space and the mitigation choices are binary.

Therefore, strategies take a threshold form with respect to beliefs about the social cost. Let the state space be either high or low social cost of GHG, and the action space be either emitting or abating. Then, for example, the support of common belief about high social cost of GHG, has three distinct ranges, divided by the stability thresholds of different coalitions. The lowest threshold belief is the threshold of grand coalition, below which all countries choose emitting. The largest threshold is the threshold of singleton coalition structure (coalitions formed by one country only), above which all countries coordinate on abating their emissions. The range of beliefs between the thresholds of grand coalition and coalition of singletons, is where signatories of stable coalitions choose abating, while non-signatories emit. This range itself is divided into sub-partitions, where in each sub-partition of beliefs, a unique coalition of a size, which varies between two to full participation, is stable.

I examine two different payoff specifications for the sender, where either his expected payoff coincides with the expected payoff of a group of countries, or he minimises the global stock of GHG. First, the cases are investigated where the expected payoff of the sender coincides with the expected payoff of signatories, non-signatories, or a combination of both groups, and it is shown that the unique optimal information mechanism takes the form of full learning by the countries. The fact that alignment of the payoffs of the sender and receiver leads to full revelation, is a known result in the literature on information design. But here, the sender faces a problem where the two groups of signatories and non-signatories of the IEA have different threshold behaviours. Moreover, given any of the mentioned expected payoffs of the sender, the induced equilibrium action of the countries, coincides with the socially optimal mitigation outcome, as if the expected payoff of a potential grand coalition were maximised.

In addition, the problem of a sender whose target is reducing the global level of GHG is examined, and the model suggests that the optimal information mechanism is imperfect learning of the social cost of GHG. The analysis provides a simple setup to understand the underlying logic behind the observed behaviour of the countries and the involved research authorities in the Paris communications; the alignment of our results with the adopted information policy of the international research institutes is discussed in more detail in the conclusion section. More interestingly, it is shown that the optimal information persuasion given the objective of minimising the total level of GHG, also leads to the selection of the socially optimal mitigation and membership strategies.

The remainder of the chapter is organised as follows. The related literature is reviewed in the next section, and the general framework is presented in section 4.3. Section 4.4 introduces an example of persuasion of a single country. The persuasion in a coalition game is investigated in section 4.5. Finally, section 4.6 concludes and the appendix contains all proofs.

4.2 Related Literature

The literature on IEAs is reviewed by Toman (1998), Wagner (2002), Kolstad and Toman (2001), Aldy and Stavins (2009) and Benchekroun and Long (2012), among others. This chapter contributes to the literature on non-cooperative coalition formation and self-enforcing IEAs.

In general, self-enforcing coalition formation IEAs are modelled to include two stages. The first stage is the membership stage, where the players decide whether to join a coalition, and the second stage is the emission stage, where non-members and coalition members interact. In some models, both coalition members and non-members act simultaneously, in other models, the coalition is a Stackelburg leader. Seminal papers about coalition formation in IEAs include Carrao and Siniscalco (1993) and Barrett (1994). Most of the literature studies static emission models, and focuses on issues such as asymmetric countries, open and exclusive membership, network formation and R&D, multiplicity of coexisting IEAs, adaptation and mitigation, renegotiation and so on.

Benchekroun and Ray Chaudhuri (2011) assume that the emission stage of a coalition formation is an infinite-horizon game. In the dynamic coalition game of Rubio and Ulph (2002), the countries may revise their membership decisions in any period (variable membership). Therefore there are both stock and membership dynamics. Furthermore, Breton et al. (2010) assume that membership may evolve exogenously over time.

The dominant part of the literature of coalition formation in IEAs examine the largest number of countries under d'Aspremont stability criterion from the cartel literature, i.e. internal and external stability under the assumption that if any member of the coalition deviates, other members will continue to cooperate. This myopic stability criterion has been criticised for the fact that it justifies free riding. Ecchia and Mariotti (1998) and Diamantoudi and Sartzetakis (2006) apply the farsighted stability of Chwe (1994) in the IEAs. So, in their models agents take into account the reaction of others in case of deviation.

A relatively small subset of the literature investigates the role of uncertainty and learning in IEAs. In stochastic IEAs, the uncertainty is basically modelled as uncertainty about an unknown parameter in the payoff function of the involved countries, which is mainly the social cost of GHG (known as the cost-benefit ratio). As mentioned in the third chapter, a seminal paper in this strand of literature, is Na and Shin (1998), which introduces asymmetric uncertainty (distributional uncertainty) in a coalition game of three countries. Ulph (2004) extends the idea of variable membership to stochastic IEAs, and Kolstad (2007) suggests learning after the membership stage and before the emission stage, known as partial learning[52]. Kolstad and Ulph (2011) investigate the case of ex-post asymmetry of social cost of GHG among countries. In addition, Finus and Pintassilgo (2013) assume a continuum choice variable, and by comparing effect of learning in different stages of a coalition game for a symmetric and asymmetric state variable derive more general conclusions. Moreover, Barrett (2013) introduces uncertainty about a catastrophic threshold in a climate change coalition game, where if the threshold is met the countries suffer a catastrophic cost in addition to the conventional social cost of GHG.

[52]Term "partial" learning in the literature, refers to uncertainty with respect to time of learning, where there is no noisy information and learning is perfect.

This chapter considers as a stochastic IEA model, and in order to elaborate with respect to the stochastic dimension, a simple coalition setup is adopted. Ulph (2004), Finus (2008) and Finus and Pintassilgo (2013) have called for models with richer learning structures in IEAs. Here, the coalition game is solved with respect to the beliefs about the social cost of GHG, where information may be noisy and learning can be imperfect. Hence, the full-learning and no-learning cases studied in the literature on stochastic IEAs, are considered as specific cases.

In addition to the literature on stochastic IEAs and coalition formation, the chapter also relates to the literature on information design. The seminal paper in this area is Kamenica and Gentzkow (2011), which introduces information persuasion of one agent by a sender. The literature is growing extensively in various dimensions, such as dynamic information design with public and private signals (Ely, 2015), persuasion of an informed receiver (Kolotilin et al. 2015), private persuasion by the sender (Taneva, 2015), costly persuasion for the sender (Gentzkow and Kamenica, 2014), and multiple senders and one receiver (Gentzkow and Kamenica, 2012).

This chapter contributes to the strand of public persuasion. The existing literature mostly relates to the literature on media communication in a political economy environment. Gehlbach and Sonin (2014) use information design, where they model a government as a strategic player, which controls the media output to a mass of citizens. In a binary model (binary state and binary action choices for the citizens) the sender tries to influence the belief of citizens by sending public signals, and they derive the equilibrium level of media bias.

Shapiro and Gentzkow (2015) have applied the idea of persuasion by multiple senders to climate change. Referring to the fact that media balances both scientific and political views on climate change, and the public does not reach a consensus on global warming, they suggest a political economy model, where the receiver is a voter and has binary choices, and seeks information about a binary state variable. There are a mass of experts, which are divided to two groups of informed and “wrongly” informed experts, who belong to the “opposition party”. The voter receives messages indirectly through a media journalist, who may combine messages of two experts, who can be from both parties. The opposition party is indeed the sender, which is maximising its payoff by allocating its own expert in the media to influence the journalists' report. They examine the effect of cost of opposition party for hiring expert on the informativeness of signals in equilibrium.

As a public persuasion model, instead of the effect of media on voters, this chapter focuses on coalition formation. Furthermore, in contrast to the mentioned papers, there is no cost of information distortion, and the communication strategies of the sender in equilibrium lead to a socially optimal outcome. Moreover, the receivers of the public signal are heterogeneous with respect to being signatories or non-signatories of the coalition.

The current research also contributes to the literature on "nudges", or affecting individuals decision-making by provision of information. This literature, which is inspired by psychology experiments, includes quantitative and empirical studies, which are mainly applied to energy economics. For example, see Ferraro and Price (2013), Costa and Kahn (2013) Galle (2013) and Ayres et al. (2013). However, as they do not model the sender, their focus is not on the optimal information structure, but on evaluating the effect of intervention through information transmission and its comparison with other available policy instruments.

4.3 The Model

A sender releases public information to the countries about an (uncertain) payoff-relevant state variable, in order to induce some specific environmental action. Let I refer to the set of countries. Country $i \in I$ has payoff of $u_i(\mathbf{q}, \gamma)$, where $\mathbf{q} = (q_1, q_2, ..., q_N)$ refers to the vector of mitigation actions chosen by the N countries, and assume that the mitigation action space is binary. Furthermore, $\gamma \in \Gamma$ is the state variable about which the countries receive information, where Γ is also taken to be a binary set. The sender has payoff of $\nu(\mathbf{q}, \gamma)$, which depends on the action chosen by the countries and the state variable. The payoffs of both sides are common knowledge.

Before the countries choose any action, in order to affect their beliefs about the state variable, the sender, who has commitment power, can initiate research about the unknown state variable. Choosing a research strategy is modelled as choosing an information mechanism, which consists of the set of signals, S, and the information policy which is a map from the state, γ, to the probability distribution over signals when the true state is γ, i.e. $\gamma \to \pi(. \mid \gamma) \in \Delta(S)$. In other words, if the observed state by the sender is γ, the information policy specifies that the sender chooses a signal according to the rule of $\pi(. \mid \gamma)$. There is no need to specify the details of research, as it all reduces to the information mechanism. The sender commits to the chosen information policy. Furthermore, it is assumed that the research is costless for the sender.

The sender selects a binary signal space, which implies that there is a one-to-one relationship between the signal space and the countries' action space. Hence, the sender by sending a signal, recommends a certain action, and the countries accordingly take the corresponding action. This is known as "direct" information mechanism, and in fact the sender could not do better than that.

The timeline is as follows. At the beginning of the game, and before observing the true state, the sender announces the information mechanism, and commits to it. By conducting the research, he observes the state[53]. The results of research are presented as a public signal, $s \in S$, according to the information policy. The countries, interpret the information policy and the signal, using Bayes rule. So, given the information policy and the observed signal realisation, the countries update their belief about the state, and choose an action to maximise their payoffs. We refer to this process as "persuasion".

[53]If the sender does not observe the state realisation, he has access to a limited set of policies, for example, the truthful policy is not available. But given that limited set, it is still possible to derive the optimal policy. Hence, observation of the state is not a crucial assumption in the analysis. As I do not restrict the set of public mechanisms, and any probability distribution is available to the sender, it is assumed that he observes the state after setting the information policy.

The countries and the sender share a common prior, $p(\gamma)$. In addition, every piece of information that the countries ever get, comes from the sender. So, sending signal $s \in S$, the information sender knows the countries' updated belief, $\mu_s(\gamma) \in \Delta(\Gamma)$. The solution concept is sender's preferred subgame perfect equilibrium. In other words, if the countries are indifferent between two actions, they choose the sender's preferred action.[54]

Therefore, for any state, each signal realisation, s, induces a posterior belief, $\mu_s(\gamma)$.[55] The probability of a given signal s is $\tau(s) = \sum_{\gamma} p(\gamma)\pi(s \mid \gamma)$, which is the sum of conditional probability distributions of the signal, given all states, weighted by the prior belief. Hence, we can think of any mechanism as inducing a probability distribution over updated beliefs. In other words, an element $\tau \in \Delta(\Delta\Gamma)$ represents a distribution over posteriors. Since the action of the countries depend on their beliefs, all that matters is the probability distributions about beliefs, which is summarised by τ. From this, we can focus on τ; in other words, the problem of finding the optimal information policy reduces to directly choosing the optimal τ.

Here, as the first step, we adapt the single-agent information design model of Kamenica and Gentzkow (2011) to the context of climate change, and we explain the main elements of their analysis. Then we extend the model to the case of multiple countries, where we examine a coalition model from the perspective of induced beliefs and information persuasion, and we derive the optimal information policies given different payoffs of the sender.

[54]The tie-breaking rule is a standard trick, and as the the problem is well-defined and the solution exists, the tie is broken in this way.

[55]Using the Bayes rule, $\mu_s(\gamma) = \frac{p(\gamma)\pi(s|\gamma)}{\sum_{\gamma' \in \Gamma} p(\gamma')\pi(s|\gamma')}$ for all γ and s.

4.4 Introductory example: persuasion of a single country

To explain the model in its simplest context, we first consider the case of a single country. Assume there are binary states and binary choices. Let $\Gamma = \{0, 1\}$, where 0 refers to no catastrophe and 1 refers to catastrophe. The one country can choose between two levels of abatement, $q = \{\underline{q}, \overline{q}\}$, where $\underline{q} < \overline{q}$. If the state of the world is catastrophic, the country wants to choose the higher level of abatement, $\overline{q}$, and vice versa. In other words, $u(\overline{q}, 1) = u(\underline{q}, 0) = 1$. Otherwise, the country receives zero payoff, i.e. $u(\overline{q}, 0) = u(\underline{q}, 1) = 0$. We examine the problem of finding the optimal information mechanism under two different preference specifications for the sender: a biased sender and a benevolent sender. We examine each case in turn.

4.4.1 A biased sender

Suppose the information sender only cares about the high abatement level, and his payoff is

$$\hat{\nu}(q^*) = \begin{cases} 1 & \text{if } q^* = \overline{q} \\ 0 & \text{if } q^* = \underline{q} \end{cases} \tag{4.4.1}$$

where q^* refers to the equilibrium action chosen by the country, which is the best response to its belief, and the sender takes q^* as given. This model is directly equivalent to the jury example of Kamenica and Gentzkow (2011), where a biased prosecutor persuades a judge to convict a suspect, instead of serving justice, which is in favour of the judge.

In this binary model, let us simplify the notation, so μ denote the potential posterior probability of catastrophic state, and p be the prior belief of the state. The information sender can compute the belief at which the country is indifferent between the two actions. Since, $\mathbb{E}_\mu u(\overline{q}, .) = \mu$ and $\mathbb{E}_\mu u(\underline{q}, .) = 1 - \mu$, the country chooses $\overline{q}$ if $\mu \geq \frac{1}{2}$, and $\underline{q}$ if $\mu < \frac{1}{2}$.[56] Upon the fact that the country's belief is μ, the expected value of sender's payoff for a given belief, can be written directly as a function of μ. Let $\nu(\mu) = \mathbb{E}_\mu \hat{\nu}(.)$.[57] Therefore, here the expected payoff of the biased sender, given belief μ, can be rewritten as

$$\nu(\mu) = \begin{cases} 1 & \text{if } \mu \geq \frac{1}{2} \\ 0 & \text{if } \mu < \frac{1}{2} \end{cases} \tag{4.4.2}$$

The basic idea is that the information sender can use a signal space, which is just equal to the set of states, so here $S = \{0, 1\}$. The notation μ_1 refers to the probability that the state is catastrophic conditional on a catastrophic signal. In this binary world, let τ represents the probability of catastrophic signal (the probability of μ_1). Because each belief is associated with a payoff, and as the sender by choosing an information policy is going to choose a distribution τ, every policy yields the expected payoff of $\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0)$ for the sender. So any information policy can be represented by τ and we can write the expected payoff of the sender as a function of τ.

To derive the feasible subset of policies, a necessary condition is that the expected value of the posteriors over τ, must be equal to the prior, i.e. $\mathbb{E}_\tau \mu = p$, which is the law of total probability. Kamenica and Gentzkow (2011) refer to it as the Bayes-plausibility condition, and they show that this is the only restriction. In other words, this canonical subset of policies captures all possibilities. Indeed a distribution τ over posterior beliefs can be generated by an information mechanism if and only if it satisfies the law of total probability. So here the problem of sender will maximise

$$\begin{aligned} &\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) \\ &\text{subject to } \tau\mu_1 + (1-\tau)\mu_0 = p \end{aligned} \tag{4.4.3}$$

[56] Recall that the country chooses the sender's preferred action, when it is indifferent.

[57] In this example, $\hat{\nu}(.)$ is not a function of state variable, but even if it were, because the belief of the countries is μ, the expected payoff of $\nu(.)$ is just a function of μ and the state variable would be irrelevant.

by choice of τ. The solution can be illustrated in $(\mu, \nu)-$space. Let us denote $V(\mu) \equiv \max_\tau[\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) \mid \tau\mu_1 + (1-\tau)\mu_0 = p]$, which given any lottery over beliefs, represents the maximum expected payoff over the beliefs. The function $V(\mu)$ is the supremum of convex hull of the hypergraph of $\nu(\mu)$, or the smallest concave function that is no smaller than $\nu(\mu)$ at every belief. This determines the optimal policy for a given support of the beliefs. In addition, given the constraint of the optimisation, the lottery over beliefs should be on average equal to the prior, p. So, it is possible to read off the optimised value of the information policy as $V(p)$. Panel (a) of Figure 4.1 depicts $\nu(\mu)$ for the biased sender and its concave closure, $V(\mu)$.

Before, deriving the optimal policy, let us consider two other possibilities. Assume that the sender can construct arbitrary research to achieve an ambitious policy, such that a catastrophic signal will always be sent to the country to choose the higher level of abatement, i.e. no matter what the state is, $\pi(1 \mid 0) = 1$ and $\pi(1 \mid 1) = 1$. This is not Bayes-plausible and knowing this the signal is uninformative for the country. Thus, $\mu_1 = p$. In other words, the ambitious policy will be ignored and the country will behave according to its prior.

As another possibility, consider the truthful policy which leads to two possible beliefs for the country; either the country should be certain that the state is catastrophic, i.e. $\mu_1 = 1$, or it should be certain that it is not, i.e. $1 - \mu_0 = 1$. Because this is a Bayes-plausible policy, the country chooses $\underline{q}$ whenever it receives a signal $s = 0$, and chooses $\overline{q}$, whenever a signal $s = 1$ is observed. But, the Bayes-plausible constraint leads to $\tau = p$. In other words, the sender sends the catastrophic signal with probability p, which is the prior probability of catastrophic event, and the biased sender obtains expected payoff of τ. Thus, depending on the prior, the sender might be able to do better.

If $p \geq \frac{1}{2}$, then the country is choosing $\overline{q}$, which is the preferred action of the sender. In fact, in this range, $V(\mu)$ coincides with $\nu(.)$, and the optimal policy is not unique. It either prescribes leaving the country with its prior (sending no signal at all is optimal), or choosing a degenerate lottery which is equal to the prior, p, with probability one.

But suppose $p < \frac{1}{2}$. By setting both μ_1 and μ_0 more than $\frac{1}{2}$, the sender obtains payoff of one, but such posteriors do not satisfy the law of total probability. On the other hand, choosing both μ_1 and μ_0 less than $\frac{1}{2}$, leads to payoff of zero. Hence, one of μ_1 and μ_0 should be above $\frac{1}{2}$ and one below it. If $\mu_1 \geq \frac{1}{2}$ and $\mu_0 < \frac{1}{2}$, then the expected payoff of the sender is increasing in τ. Since, $\mu_1 \geq \frac{1}{2}$, the law of total probability, $\tau = \frac{p-\mu_0}{\mu_1-\mu_0}$, implies the expected payoff is decreasing in both μ_1 and μ_0. Therefore, setting $\mu_1 = \frac{1}{2}$ and $\mu_0 = 0$ maximises the expected payoff of the sender.

As shown in panel (a) of Figure 4.1 in this range, $V(\mu)$ is above $\nu(.)$, and the optimal mechanism is a non-degenerate lottery over beliefs. As explained, the truthful mechanism is not optimal, as when the state is catastrophic the sender is wasting its persuading power by sending signal $s = 1$ too often (or with too high a probability). Knowing the threshold at which the country is indifferent, instead of $\mu_1 = 1$, the biased sender optimally can choose $\mu_1 = \frac{1}{2}$. On the other hand, signal $s = 0$ only happens when the state is not catastrophic. So, it should be that $1 - \mu_0 = 1$ or $\mu_0 = 0$. A Bayes-plausible randomisation over $\mu_1 = \frac{1}{2}$ and $\mu_0 = 0$, means $\tau = 2p$, which is the expected payoff of the sender as well.

Using the Bayes rule, $\mu_1 = \frac{\pi(1|1)p}{\tau}$, implies that on the equilibrium path, the sender should use $\pi(1 \mid 1) = 1$. Similarly, $1 - \mu_1 = \frac{\pi(1|0)(1-p)}{\tau}$ leads to $\pi(1 \mid 0) = \frac{p}{1-p}$.

Hence, despite the fact that the payoffs are common knowledge, and the country knows that the sender is biased, the sender can send a catastrophic signal with probability $\tau = 2p$, and the country chooses the high level of abatement, whenever it receives such a signal.

4.4.2 A benevolent sender

Now assume the payoffs of the country and the information sender coincide. In other words, given the fact that the country holds belief μ about the catastrophic state, the expected payoff of sender for a belief μ is,

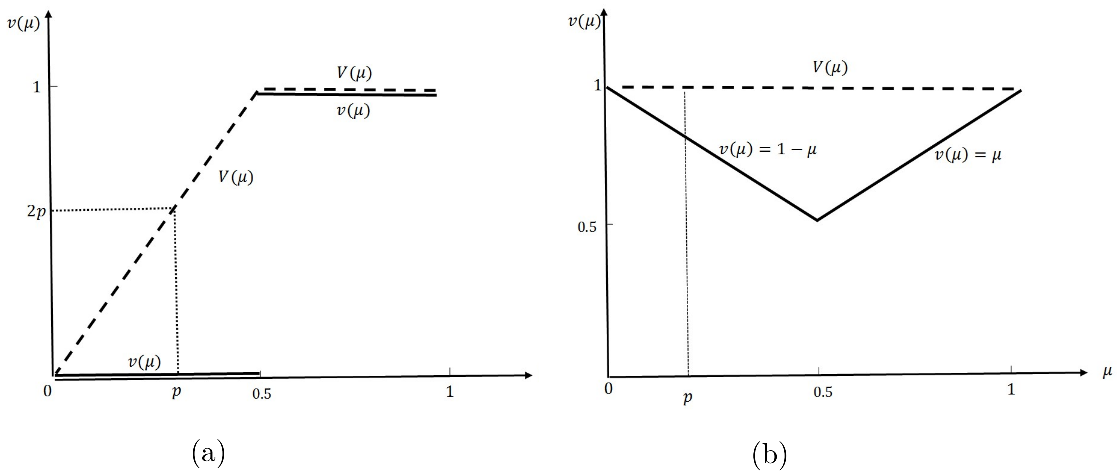


Fig. 4.1 Panel (a) The biased sender. Panel (b) The benevolent sender.

$$\nu(\mu) = \mathbb{E}_\mu u(q^*, \gamma) = \begin{cases} \mu & \text{if } \mu \geq \frac{1}{2} \\ 1 - \mu & \text{if } \mu < \frac{1}{2} \end{cases} \tag{4.4.4}$$

Panel (b) of Figure 4.1 shows $\nu(\mu)$ and $V(\mu)$ for such a sender.

Lemma 1. *The optimal policy of the benevolent sender to a single country is full revelation of the realised state.*

Since, $V(\mu)$ is a straight line over the whole support of beliefs, the optimal policy is a randomisation of $\mu_0 = 0$ and $\mu_1 = 1$. The Bayes-plausibility implies $\tau = p$ for all $p \in [0, 1]$. Clearly, Bayes rule determines that the conditional probabilities of signals should be $\pi(1 \mid 1) = 1$ and $\pi(0 \mid 0) = 1$.

Given the insight from persuasion of a single agent, in the next subsection, we generalise a coalition model to a setting where an information sender can affect decision making of multiple countries, by designing an optimal information policy.

4.5 Persuasion of N countries in a coalition game

Consider a coalition formation model, where every country $i \in I$ decides about joining a coalition. Let the number of countries, N, be a finite Natural number and $N \geq 2$. In addition, let us label the set of coalition members by M, where $M \subseteq I$. The game consists of two stages: the membership stage and the stage of the emission or abatement decision. The membership is open (voluntary), but in contrast to the model in the third chapter, here the membership is fixed (i.e. joining implies ratifying the treaty, which makes compliance compulsory, and signatories cannot leave the agreement). Furthermore, it is a single-coalition game. In other words, it is assumed that along an equilibrium path, only one coalition forms, and we do not study simultaneous formation of more than one coalition. This is of course in addition to the coalition of singletons, which is always a Nash equilibrium, and hence self-enforceable.

We build on the binary model specification of Kolstad (2007). However, here we analyse the model from the perspective of information design, so we are interested in finding the optimal action of the countries for any belief. Indeed, in contrast to the literature on IEAs, where beliefs are given parameters, and the profitability and stability of a coalition are studied with respect to the number of signatories of a treaty, in this chapter, the threshold behaviour of the signatories and non-signatories of the IEA are examined with respect to their beliefs about the social cost of GHG. Hence, the stable number of signatories is a function of the endogenous beliefs.

Furthermore, I extend the model to have an information sender, in order to derive the optimal information mechanism. Assume that before the membership stage, the sender announces the information policy, conducts the research and sends a public signal. The model is solved according to the sender's-preferred subgame perfect equilibrium (SPE). Specifically, given their beliefs, in the emission stage, the countries choose their optimal emission (or abatement) strategies, which construct a vector of Nash equilibrium emission (or abatement) actions. This forms the expected payoff of (potential) signatories of the IEA and non-signatories, which determines the profitability of joining a coalition, and its stability in the membership stage. Conventionally, we check unilateral deviations, so the membership strategies also form a Nash equilibrium. Then upon the optimal behaviour of the countries in emission and membership stages, the sender designs an optimal information mechanism, which results in his most preferred outcome. Recall that even if the countries can predict the optimal information mechanism, the signal is a random draw according to the information policy. The problems of the information receivers and the sender are respectively investigated in the next two subsections.

4.5.1 Coalition formation

Let $u_i(\mathbf{q}, \gamma) = q_i - \gamma Q$ denote the payoff of country $i \in I$. Assume $q_i \in \{0, 1\}$, and we label $q_i = 0$ as abating and $q_i = 1$ as emitting.[58] Furthermore, Q is the aggregate emission, i.e. $Q = \sum_i q_i$. Assume $\gamma \in \Gamma = \{\gamma_l, \gamma_h\}$ is the random state variable which is the marginal social cost of emission, or the cost-ratio parameter. Here, it is either low or high, $\gamma_l < \gamma_h$. At the beginning of the game, nature draws one parameter from set Γ for all countries. This is known as level uncertainty in the literature. Hence, γQ captures the damage from the aggregate emission to country i, and clearly we focus on risk-neutral countries. Let μ refer to the probability of $\gamma = \gamma_h$, which is potentially an updated posterior belief after observation of the signal of sender, also p is the prior belief about such a state. Given the public belief, all signatories will have the same expected payoff, also all non-signatories share their common expected payoff. For simplicity, let us assume $\gamma_l = 0$, which implies that if the social cost of GHG is γ_l, emitting is not harmful. Furthermore, let γ_h be a finite real number, also assume that $\gamma_h > 1$. As it becomes clear in the next two subsections, the latter assumption ensures existence of a possible large social cost of GHG, which leads to structure of singleton coalitions, such that all countries choose abating. This is in contrast to the literature where the focus is on situations where $\gamma_h < 1$, and abstract from the possibility of coordination of all countries on abating. Hence, we do not restrict $\mathbb{E}_\mu(\gamma)$ to be less than one.

[58] The functional form is commonly used in the literature, for example see binary models of Ulph (2004), Kolstad (2007) and Kolstad and Ulph (2011). At the end of this section, robustness of the results with respect to the functional form and the assumption of binary action space is discussed.

Non-signatories' emission decision

Consider a coalition of n members, where $n \leq N$. In the emission stage, a non-signatory takes the number of coalition members, and the action chosen by signatories and other non-signatories as given and individually maximises its expected payoff of $\mathbb{E}_\mu u_i^{fn}(\mathbf{q}, \gamma) = q_i^f - \mathbb{E}_\mu(\gamma)[nq_i^m + (N-n-1)q_{-i}^f + q_i^f]$, where superscript f is for the non-signatories or fringe countries and m for the coalition members, also superscript n shows the dependence of the payoff (or in future, other variables) to the number of coalition members. Thus superscript fn refers to fringe where the number of coalition members is n. Furthermore, subscript $-i$ is the index for the other country in the group (of non-signatories here).

By choosing $q_i^f = 0$, the expected payoff of the fringe country is $-\mathbb{E}_\mu(\gamma)[nq_i^m + (N-n-1)q_{-i}^f]$, and choosing $q_i^f = 1$ leads to expected payoff of $1 - \mathbb{E}_\mu(\gamma)[nq_i^m + (N-n-1)q_{-i}^f + 1]$. Therefore, independent of the decision of coalition and other fringe countries, if a fringe country believes that $\mu \geq \mu^f \equiv \frac{1}{\gamma_h}$, then it chooses $q_i^{*f} = 0$, and if $\mu < \mu^f$, then $q_i^{*f} = 1$ is chosen. Thus, the non-signatories have a dominant strategy which only depends on their belief about the social cost of emission, and not the action undertaken by other countries, or number of coalition members. Hence, in studying the underlying coalition formation game, both assumptions of Stackelberg and Cournot lead to the same result.

The threshold μ^f is positive and strictly less than one, i.e. $0 < \mu^f < 1$. Furthermore, it is clear that the larger is γ_h, the smaller is the threshold belief of a fringe country, which leads to an abatement decision for a larger range of support of μ. Finally, μ^f is independent of the number of coalition members, and given the parameter value of γ_h, it is fixed.

Signatories' emission decision

The coalition members in the emission stage, act as a singleton, given the action chosen by fringe countries. In fact, they compare expected payoff of $-n\mathbb{E}_\mu(\gamma)(N-n)q_i^f$ by choosing $q_i^m = 0$ each, and $n - n\mathbb{E}_\mu(\gamma)[n + (N-n)q_i^f]$ by choosing $q_i^m = 1$. Therefore, independent of the action of non-signatories, they will have a common threshold of belief, $\mu^{mn} \equiv \frac{1}{\gamma_h n}$, above which they abate and below which they choose to emit. Specifically, if $\mu \geq \mu^{mn}$, they abate and if $\mu < \mu^{mn}$, the signatories choose emitting.[59] Their threshold is decreasing in γ_h and the number of coalition members. Furthermore, $0 < \mu^{mn} \leq \mu^f$, where the equality of two thresholds occur if and only if $n = 1$. Hence, the coalition of singletons chooses abating above μ^f, and below it, all individual countries choose emitting. Thus, we may refer to μ^f as the threshold of coalition of singletons.

Socially optimal emission

Before proceeding to the membership stage, let us verify the emission (or abatement) actions corresponding to the social optimum. The social-optimal mitigation is a profile of emission (or abatement) strategies that maximises the sum of countries' expected payoffs. This is a benchmark, and later the equilibrium outcome of the model is compared with the social optimum. The next lemma verifies the social-optimal vector of emissions or abatements, $\mathbf{q}^{so}$, which includes both imperfect (non-degenerate μ) and perfect-learning (degenerate μ) situations.

Lemma 2. *Given a common belief $\mu \in [0, 1]$, the social optimum for all $i \in I$, implies selection of $q_i^{so} = 1$ for all posterior beliefs $0 \leq \mu < \mu^N \equiv \frac{1}{\gamma_h N}$, and selection of $q_i^{so} = 0$ for all beliefs $\mu^N \leq \mu \leq 1$.*

Proof. Examining the sum of expected payoffs under the two actions, implies a country obtains expected payoff of $1 - N\gamma_h\mu$, if all countries choose to emit, and expected payoff of zero, if they all cooperate on abating. This leads to the threshold behaviour specified in the lemma. □

In addition, $0 < \mu^N \leq \mu^{mn}$, where these two thresholds are equal if and only if $n = N$. In fact, the socially optimal mitigation strategies are equivalent to the

[59] In future, we examine different payoffs for the sender, and the equilibrium is always the sender's preferred SPE. Given the expected payoff of the sender, the tie-breaking rule of signatories and non-signatories may be revised, if necessary.

mitigation strategy of a potential grand coalition ($n = N$) at each level of beliefs. In other words, if a grand coalition can be formed for all levels of beliefs, then μ^N is the abating threshold of such a coalition. Furthermore, as the number of countries increases, the socially optimal threshold, μ^N, decreases, implying that achieving the social optimum requires cooperation on abatement for a larger range of beliefs.

Membership stage

In the membership subgame, given the optimal decision and expected payoffs of the two groups of signatories and non-signatories in the emission stage, the countries consider joining an IEA. This analysis consists of examining the profitability and self-enforceability (stability) of a coalition.

A coalition is stable if the strategies in the membership stage construct a Nash equilibrium. Sufficient conditions for stability are the internal and external stability conditions, which are the Nash equilibrium conditions for signatories and non-signatories in the membership subgame. Recall that M is the set of coalition members, also let $n^*(\mu)$ be the expected number of signatories of the stable coalition, which depends on belief. The internal stability condition implies that no signatory has an incentive to leave the coalition, i.e. $\mathbb{E}_\mu u_i^{n^*}(M) \geq \mathbb{E}_\mu u_i^{n^*}(M \backslash \{i\})$, for all $i \in M$. The external stability refers to the condition that no non-signatory has an incentive to join the coalition, i.e. $\mathbb{E}_\mu u_i^{n^*}(M) > \mathbb{E}_\mu u_i^{n^*}(M \cup \{i\})$, for all $i \notin M$. Given the common beliefs, and the fact that all signatories have the same expected payoff, as well as all non-signatories, the internal stability implies that the size of coalition cannot be smaller than $n^*(\mu)$, otherwise the coalition becomes ineffective, i.e. $\mathbb{E}_\mu u_i^{mn^*}(n^*(\mu)) \geq \mathbb{E}_\mu u_i^{fn^*}(n^*(\mu) - 1)$. Furthermore, the external stability is reduced to the condition that the size of coalition cannot be greater than $n^*(\mu)$, otherwise unilateral deviation (free-riding) becomes profitable, i.e. $\mathbb{E}_\mu u_i^{fn^*}(n^*(\mu)) > \mathbb{E}_\mu u_i^{mn^*}(n^*(\mu) + 1)$.

To derive the stable number of countries in the coalition formation subgame, the mitigation strategies, and hence the expected payoffs of signatories and non-signatories for each level of beliefs must be examined. Given the ranking of thresholds of coalition of singletons and the grand coalition, $0 < \mu^N < \mu^f < 1$, the support of belief admits three distinct ranges.

First, if $\mu \geq \mu^f$, then both groups optimally choose to abate, i.e. $q_i^* = 0$ for all $i \in I$, and each country gets expected payoff of zero. So in that range of posterior beliefs, no coalition is as good as full cooperation, or grand coalition, which corresponds to the socially optimal level of abatements[60]. Hence, in this range of beliefs the stable coalition is either the coalition of singletons or the grand coalition.

Second, for any belief $\mu < \mu^N$, signatories of the grand coalition choose to emit, or $q_i^* = 1$ for all $i \in I$. As explained, μ^N is the abating threshold of the grand coalition, and indeed, formation of the grand coalition is a stable membership strategy for this range of beliefs and each country receives expected payoff of $\mathbb{E}_\mu u_i^{mn^*} = 1 - \mu\gamma_h N$. In addition, the coalition of singletons that emits in this range of beliefs is clearly another stable coalition.

The final range of posterior beliefs is $\mu^N \leq \mu < \mu^f$. The threshold of signatories is between these two thresholds, i.e. for any $2 \leq n^*(\mu) \leq N$, the thresholds are $\mu^N \leq \mu^{mn^*} < \mu^f$.[61] Given any $n^*(\mu)$, it may be profitable for the $n^*(\mu)$ members of the stable coalition to sign a treaty which specifies abatement for all members, while the fringe countries can be emitting (if $n^*(\mu) < N$). Hence, the payoffs of signatories and non-signatories are $\mathbb{E}_\mu u_i^{mn^*} = -\mu\gamma_h(N - n^*(\mu))$ and $\mathbb{E}_\mu u_i^{fn^*} = 1 - \mu\gamma_h(N - n^*(\mu))$, respectively. The stability of a coalition with size $n^*(\mu)$ is examined in the appendix, and the results of the membership stage are summarised in the next proposition. First, let us zoom deeper into the range of beliefs where $\mu^N \leq \mu < \mu^f$.

Two facts can be directly verified: (i) the condition $\mu^{mn^*} \leq \mu$ implies that a stable coalition of size $I(\frac{1}{\mu\gamma_h})$ can be formed, where $I(.)$ is the smallest integer which is no smaller than its argument. (ii) for any $2 \leq n^*(\mu) \leq N$, the threshold μ^{mn^*} depends

[60] As mentioned, in the existing binary IEA models, the attention is restricted to $\mathbb{E}(\gamma) < 1$, hence, the threshold behaviour of the non-signatories is not taken into account. However, here it is assumed that $\gamma_h > 1$, so we do not abstract from the possibility of obtaining the social optimum by countries coordination, and necessarily they do not need cooperation.

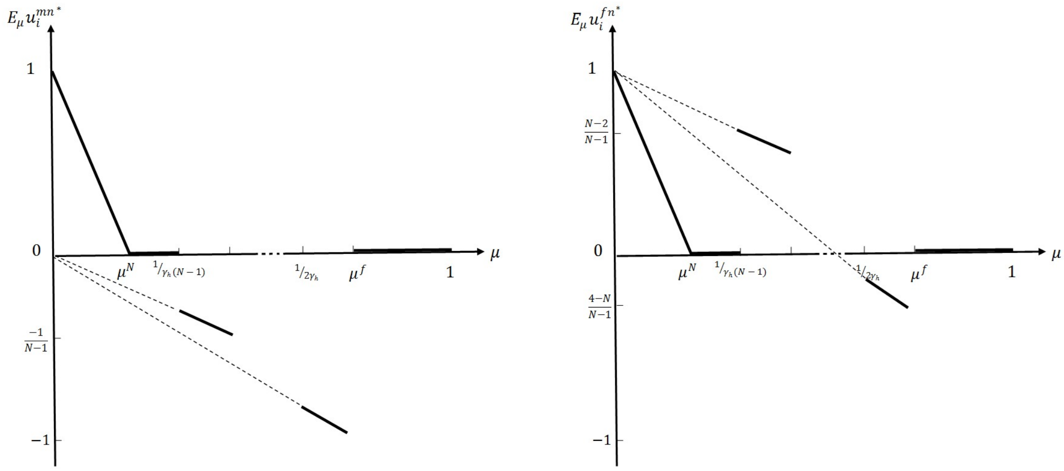
[61] It has already been discussed that if $n^*(\mu) = 1$, then $\mu^{mn^*} = \mu^f$, which implies that the threshold of coalition of singletons is fixed at μ^f.

on $n^*(\mu)$. So, every $n^*(\mu)$ leads to a different threshold for the signatories. Facts (i) and (ii) imply that the coalition formation is endogenous, and there exists a mapping from the beliefs to the set of size of stable coalitions. Given that $n^*(\mu)$ is an integer, it is not a one-to-one mapping, but every range of beliefs between every two successive thresholds corresponds to a unique $n^*(\mu)$. Hence, the size of stable coalition can be uniquely pinned down by choosing the posterior beliefs.

For any belief between the thresholds of grand coalition and coalition of singletons, i.e. $\mu^N \leq \mu < \mu^f$, the model admits (possibly) finitely many thresholds for the signatories of different coalitions. Therefore, the intermediate partition of posterior beliefs is itself partitioned by smaller ranges, say sub-partitions, where in each sub-partition, the stable abating coalition has a unique size. For any generic $2 \leq n^*(\mu) \leq N$, if $\mu^{mn^*} \leq \mu < \frac{1}{\gamma_h(n^*(\mu)-1)}$, the stable coalition has $n^*(\mu)$ members. If $\mu < \mu^{mn^*}$, by the internal stability condition, the coalition of size $n^*(\mu)$ is not stable, and the incentive for cooperation is cancelled out by the incentive to free ride, and the signatories leave such a coalition and make it worthless, i.e. $-\mu\gamma_h(N - n^*(\mu)) < 1 - \mu\gamma_h N$. Similarly, if $n^*(\mu) > 2$, for any belief $\frac{1}{\gamma_h(n^*(\mu)-1)} \leq \mu < \frac{1}{\gamma_h(n^*(\mu)-2)}$, the abating coalition of size $n^*(\mu) - 1$ is stable, and so on.

Accordingly, the minimum threshold of signatories is μ^N, thus if $\mu^N \leq \mu < \frac{1}{\gamma_h(N-1)}$, then the abating grand coalition is stable. Also, the maximum threshold is $\frac{1}{2\gamma_h}$, implying that for any belief $\frac{1}{2\gamma_h} \leq \mu < \mu^f$, abating coalition of size $n^*(\mu) = 2$ is stable. Clearly, for $N = 2$, the minimum and maximum signatories' thresholds coincide, implying that for any $\mu \geq \mu^N$, the coalition with $n^*(\mu) = 2$ is stable, where both countries cooperate on abating.

Hence, in the range of $\mu^N \leq \mu < \mu^f$, the expected number of members of the stable coalition, $n^*(\mu)$, is a (weakly) decreasing function of posterior belief μ. The negative relationship of the social cost of GHG and the number of members of stable coalition is known from Ulph (2004), but in contrast to the literature, where belief is a constant parameter, and a model admits one n^*, here if $\mu^N \leq \mu < \mu^f$, the endogenous size of stable coalitions, $n^*(\mu)$, varies from one sub-partition to the other.



(a) (b)

Fig. 4.2 Panel (a) The membership equilibrium expected payoffs of a representative signatory, $\mathbb{E}_\mu u_i^{mn^*}(\mu)$, for $N > 4$. Panel (b) The membership equilibrium expected payoffs of a representative non-signatory, $\mathbb{E}_\mu u_i^{fn^*}(\mu)$, for $N > 4$.

Figure 4.2 depicts the membership equilibrium expected payoffs of a representative signatory and non-signatory for $N > 4$. The two panels are different only in the range of beliefs $\mu^N \leq \mu < \mu^f$. It can be verified that for each $n^*(\mu)$, the difference of corresponding expected payoff of the two groups, are constant, as they have dominant strategies. The tie-breaking rule in the figure is as specified in this section, and in future depending on the sender's expected payoff, it may be different. Furthermore, note that if $\mu^N \leq \mu < \mu^f$, as belief about high state decreases, and the number of signatories of the stable coalition increases, for each $n^*(\mu)$, the expected payoffs of both signatories and non-signatories increase, as does the total payoff of $n^*(\mu)\mathbb{E}_\mu u_i^{*m} + (N - n^*(\mu))\mathbb{E}_\mu u_i^{*f}$. This property is known as "global efficiency".

The following proposition specifies the equilibrium strategies of the membership subgame.

Proposition 8. *(i) If $\mu < \mu^N$, the grand coalition and coalition of singletons are stable, where $q_i^* = 1$ for $i \in I$.*

(ii) If $\mu^N \leq \mu < \mu^f$, there are $N-1$ thresholds of signatories, μ^{mn^*}, and for any $2 \leq n^*(\mu) \leq N$, the beliefs in between every two successive thresholds, $\mu^{mn^*} \leq \mu < \frac{1}{\gamma_h(n^*(\mu)-1)}$, map to the unique $n^*(\mu)$, where $q_i^{*m} = 0$ and (if $n^*(\mu) < N$) $q_i^{*f} = 1$. In this range of beliefs, emitting coalition of singletons is also stable.
(iii) If $\mu \geq \mu^f$, then grand coalition and coalition of singletons are stable, where $q_i^* = 0$ for all $i \in I$.

For the proof see Appendix 4.7.1.

In terms of comparison of equilibrium outcome of the membership subgames with the socially optimal outcome, as explained in section 4.5.1, the equilibrium outcome of a potential grand coalition corresponds to the social optimum. Therefore, based on proposition 8, if beliefs are $0 \leq \mu \leq \mu^N$, where the grand coalition chooses emitting, and if beliefs are $\mu^N \leq \mu < \frac{1}{\gamma_h(N-1)}$ and $\mu^f \leq \mu \leq 1$, where the grand coalition for abatement is stable, the mitigation outcomes coincide with the social optimum. However, the actions undertaken by the countries do not satisfy the social optimum if $\frac{1}{\gamma_h(N-1)} < \mu < \mu^f$. In fact, in this range of beliefs the grand coalition is not stable, and a group of countries abate, while other(s) free ride. Furthermore, note if $N = 2$, where the minimum and maximum thresholds of signatories coincide, there would not be any difference between the equilibrium mitigation strategies and the socially optimal strategies for any belief.

Finally, the assumptions of binary state variable and binary action space lead to the threshold behaviour of signatories and non-signatories with respect to their beliefs. In terms of robustness of the results to these assumptions and the functional form, it should be noted that although the results depend on the single-crossing property of the expected payoffs, the linearity of the payoff function is for simplicity. In other words, as long as the single-crossing property holds, an alternative functional form, such as a quadratic payoff function, can also be assumed.

Comparison with a perfect-learning model

As mentioned, in the literature on stochastic IEAs, two cases of full learning, i.e. $\mu = 0$ or $\mu = 1$, and no learning $\mu = p$ are studied. According to Kolstad (2007), the stable coalition has a unique size between two and N, depending on the parameter values, and under full learning of the state, it is either $I(\frac{1}{\gamma_l})$ or $I(\frac{1}{\gamma_h})$. Accordingly, in his model, the minimum number of coalition members (two) corresponds to $\mu = 1$, where $n^* = I(\frac{1}{\gamma_h})$. Our model, includes these two cases of full learning. However, the two models are different with respect to the parameter value assumptions. In order to see the similarities, some modification of parameter values are required. For the case of $\mu = 1$, to make the comparison possible, if similar to the literature, in our model, (only in this subsection) we assume $\gamma_h < 1$, as if μ^f is increased to one (and excluded), then the stable coalition with the minimum number signatories (two) forms at supremum of set $[0, \mu^f)$, which is the same as Kolstad (2007). However, abstracting from the possibility of abating grand coalition in the existing literature, i.e. the assumption of $\gamma_h < 1$, implies ruling out the non-monotonic relationship of $n^*(\mu)$ and the belief.

In addition, in Kolstad (2007), the maximum number of members of the stable abating coalition is $I(\frac{1}{\gamma_l})$ which corresponds to $\mu = 0$. In our model, at $\mu = 0$, a grand coalition is stable, where all countries choose emitting, and the minimum belief corresponding to the maximum number of abating coalition members is μ^N, which is non-degenerate. Again the difference of the two models is a result of parameter value assumptions. In order to compare the two models, if (in this subsection) we relax the assumption of $\gamma_l = 0$, then $\mu^N = \frac{1-N\gamma_l}{N(\gamma_h-\gamma_l)}$. So in our model, $\mu^N = 0$ if and only if $1 - N\gamma_l = 0$, which implies $N = I(\frac{1}{\gamma_l})$, and it is the same as Kolstad (2007). However, $\mu^N = 0$ suggests that a model with perfect learning, does not include the range of beliefs $0 \leq \mu < \mu^N$, where $n^*(\mu)$ is constant at N (or one), and all countries choose the emitting strategy.

Therefore, given the assumptions of existing literature about the parameter values, our model will be restricted to the posterior beliefs $\mu^N \leq \mu < \mu^f$, where the lower-bound and the maximum beliefs map into to the maximum and minimum number of stable coalition members, respectively.

4.5.2 Sender's persuasion

The sender, given the best response of the countries in the mitigation and membership stages, chooses a lottery over posterior beliefs such that it results in his most preferred stable coalition sizes and mitigation strategies. To fix ideas, in this section, by "equilibrium", we refer to the sender's-preferred SPE, and "stable" coalition, as explained above, refers to any coalition which satisfies the internal and external stability conditions, and it may or may not be the "equilibrium" outcome.

Before the membership stage, the sender can communicate an information policy and conduct research, which leads to sending a signal, before any decision about the membership is made by the countries. The sender and the countries share a common prior. However, the sender does not know yet which country is going to be a signatory and which one will be a fringe. Hence, we focus on public signals. Since, each group of signatories and non-signatories have different thresholds, the sender faces a problem where the receivers of the public signal (may) have different payoffs, and accordingly different best-response actions.

First, in the next two subsections, we consider cases where the preferences of the sender coincide with the signatories and non-signatories, respectively. However, it is shown that no matter whether the sender has the same preferences as the signatories or non-signatories of the coalition, for any $p \in [0, 1]$, the unique optimal public information policy, is full revelation of the state of the world.

Then, the results are generalised to a case where the expected payoff of sender is a combination of the expected payoffs of the two groups of coalition members and fringe countries, and it is shown that the unique information policy is again perfect learning.

Finally, a case is studied, where the sender's objective is minimising the total level of GHG. If the main concerns of sender are the global consequences of the emission and abatement of countries, for example if the incentives of sender are driven from the affect of increase of GHG on the average temperature of the planet, e.g. meeting the two-degree threshold, or if the preferences of sender reflect the wide difference of social and private discount factors, then it is reasonable to assume that $\hat{\nu}(\mathbf{q}, \gamma) = -Q$. In such a situation, the expected payoff of sender, as a globally benevolent sender, does not coincide with the payoff of the countries, and it is shown that the optimal information policy leads to imperfect learning by the countries.

Optimally, given any of the mentioned payoff specifications for the sender, he chooses a binary signal space, say $S = \{0, 1\}$, where $s = 0$ refers to state γ_l, and $s = 1$ corresponds to state γ_h. Indeed, as before, on the equilibrium path, the sender chooses a mechanism which leads to a one-to-one relationship between the actions space and the signal space. Hence, here for example signal $s = 1$, which refers to state γ_h, leads to action $q_i = 0$. Because of the Bayes-plausibility of the signals, the countries follow the recommendation of the sender. Furthermore, given our payoff structure, this implies that on the equilibrium path, $\mu_0 \leq \mu_1$.

Furthermore, let τ represent the probability of signal $s = 1$. Recall that the law of total probability implies $\tau = \frac{p-\mu_0}{\mu_1-\mu_0}$. Therefore, $\frac{\partial\tau}{\partial\mu_1} = \frac{\mu_0-p}{(\mu_1-\mu_0)^2}$, which is always non-positive, as $\mu_0 \leq p$. In addition, $\frac{\partial\tau}{\partial\mu_0} = \frac{p-\mu_1}{(\mu_1-\mu_0)^2}$, this is also non-positive, as $p \leq \mu_1$. The corner solution, which is found in most of the following problems, relies on these properties.

Sender with the same preference as the signatories

Suppose the expected payoff of sender coincides with the expected payoff of a representative signatory, then upon the fact that the belief of countries about the high state is μ,

$$\nu(\mu) = \mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma) = \begin{cases} 0 & \text{if } \mu^f \leq \mu \leq 1 \\ -\mu\gamma_h(N - n^*(\mu)) & \text{if } \mu^{mn^*} < \mu \leq \frac{1}{(n^*(\mu)-1)\gamma_h} \\ 1 - \mu\gamma_h N & \text{if } 0 \leq \mu \leq \mu^N \end{cases} \tag{4.5.1}$$

where $2 \leq n^*(\mu) \leq N$, and for the case of $n^*(\mu) = 2$, the range of beliefs does not include any thresholds, i.e $\frac{1}{2\gamma_h} < \mu < \mu^f$, to ensure existence of the sender's-preferred equilibrium.

As explained, the sender chooses an optimal distribution of signals, τ, which satisfies the law of total probability and maximises his payoff as described in (4.5.1). This in turn reduces the problem to finding a lottery over the common belief μ. The problem is analysed formally in Appendix 4.7.2.[62] Furthermore, from panel (a) of Figure 4.2, it can be verified that the unique smallest concave function, which is no smaller than $\nu(\mu)$ is a straight line connecting $\mu = 0$ and $\mu = 1$, which implies that for any interior prior, the full revelation is the unique optimal mechanism.[63]

Lemma 3. *If the payoff of sender is* $\nu(\mu) = \mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma)$, *then for any prior belief* $p \in (0, 1)$, *the unique optimal conditional probability of signals are* $\pi(1 \mid \gamma_h) = 1$ *and* $\pi(0 \mid \gamma_l) = 1$.

In addition, the convexity in $\mathbb{E}_\mu u_i^{mn^*}(\mu)$ implies that for any $p \in (0, 1)$, $V(p)$, which is the value of optimal mechanism, is greater than $\nu(p)$, which is the sender's expected payoff in the absence of any persuasion. In other words,

Corollary 1. *If the payoff of sender is* $\nu(\mu) = \mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma)$, *then for any prior belief* $p \in (0, 1)$, *the sender strictly benefits from the persuasion.*

Sender with the same preference as the potential non-signatories

In this section, we check the sensitivity of our results to the preference of sender over non-signatories and signatories. Assume before the membership decision, the sender chooses an information policy to maximise the expected payoff of a potential representative non-signatory, in other words,

[62]The proofs of the following lemmas and propositions are provided for the general case of $N > 3$, where there are at least three sub-partitions between the thresholds of grand coalition and coalition of singletons. Clearly, the proofs for cases of $N = 2$ and $N = 3$ include subsets of the proofs for case $N > 3$.

[63]If the prior is degenerate, i.e $p = 1$, when $\gamma = \gamma_h$, and $p = 0$ when $\gamma = \gamma_l$, then in fact the sender need not do anything. But formally the optimal mechanism is not unique is such cases, as choosing the full-revelation policy is still optimal, although the sender does not benefit from it.

$$\nu(\mu) = \mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma) = \begin{cases} 0 & \text{if } \mu^f \leq \mu \leq 1 \text{ or if } \mu^N < \mu < \frac{1}{(N-1)\gamma_h} \\ 1 - \mu\gamma_h(N - n^*(\mu)) & \text{if } \mu^{mn^*} < \mu \leq \frac{1}{(n^*(\mu)-1)\gamma_h} \\ 1 - \mu\gamma_h N & \text{if } 0 \leq \mu \leq \mu^N \end{cases} \tag{4.5.2}$$

where in this equation by $n^*(\mu)$ we refer to any $2 \leq n^*(\mu) \leq N-1$. Furthermore, the tie-breaking rule is such that for the case of $n^*(\mu) = 2$, the range of beliefs are $\frac{1}{2\gamma_h} < \mu < \mu^f$, and for the case of $n^*(\mu) = N-1$, the range of beliefs are $\frac{1}{(N-1)\gamma_h} \leq \mu \leq \frac{1}{(N-2)\gamma_h}$.

It turns out that the optimal information mechanism is the same as if the expected payoff of signatories was chosen. In fact, the following lemma and corollary are parallel to the results in the previous subsection.

Lemma 4. *If the payoff of sender is* $\nu(\mu) = \mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma)$*, then for any prior belief* $p \in (0,1)$*, the unique optimal conditional probability of signals are* $\pi(1 \mid \gamma_h) = 1$ *and* $\pi(0 \mid \gamma_l) = 1$.

See Appendix 4.7.3 for the proof of lemma 4. Panel(b) of Figure 4.2 also confirms the results. From the figure, it can also be verified that for all parameter values of the model, and all interior posterior beliefs, $\mathbb{E}_\mu u_i^{fn^*}(\mu)$ is below $V(\mu)$. In other words,

Corollary 2. *If the payoff of sender is* $\nu(\mu) = \mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma)$*, then for any prior belief* $p \in (0,1)$*, the sender strictly benefits from the persuasion.*

Given the last two lemmas, for both cases that the sender maximises the expected payoff of signatories or non-signatories, the optimal information mechanism is full revelation of the state of the world. Accordingly, any non-degenerate μ is out of the equilibrium path, and the mitigation equilibrium outcome will be reduced to selection of $q_i = 0$, for all $i \in I$ if $\mu_1 = 1$, also $q_i = 1$, for all $i \in I$, where $\mu_0 = 0$. Thus, the action vectors in the emission stage coincide with the social optimum, defined in lemma 2, even though the sender maximises the expected payoff of one group.

Proposition 9. *If $\nu(\mu) = \mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma)$, or if $\nu(\mu) = \mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma)$, the optimal information mechanism of full revelation leads to the socially optimal mitigation outcome.*

Finally, in both cases, the equilibrium (mitigation strategies, membership strategies, and the information mechanism) is independent of the level of γ_h, and the prior p.

Sender and a combination of preferences of both signatories and non-signatories

Suppose

$$\nu(\mu) = \alpha n^*(\mu)\mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma) + (N - n^*(\mu))\mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma) \tag{4.5.3}$$

where α is a constant and let $\alpha \geq 1$. In other words, assume that the sender maximises the summation of expected payoffs of both groups of signatories and non-signatories, and it may weight signatories' preferences more, knowing that $n^*(\mu)$ varies over different partitions of beliefs.

Proposition 10. *If the expected payoff of sender is $\nu(\mu) = \alpha n^*(\mu)\mathbb{E}_\mu u_i^{mn^*}(\mathbf{q}^*, \gamma) + (N - n^*(\mu))\mathbb{E}_\mu u_i^{fn^*}(\mathbf{q}^*, \gamma)$, then for any $\alpha \geq 1$, and any prior $p \in (0, 1)$, the unique optimal information mechanism is full revelation of the state, and the equilibrium mitigation strategies coincide with the socially optimal outcome.*

Formal proof is in Appendix 4.7.4. Intuitively, if $0 \leq \mu < \frac{1}{(N-1)\gamma_h}$,[64] or if $\mu^f \leq \mu \leq 1$, then $n^*(\mu) = N$, and the sender maximises the summation of expected payoffs of the grand coalition, or equivalently, the expected payoff of a representative country. While, (for the case of $N > 2$) if beliefs belong to, $\frac{1}{(N-1)\gamma_h} \leq \mu < \mu^f$, then the expected payoffs of signatories and non-signatories are different. Indeed, the expected payoff of signatories in range of beliefs $\frac{1}{(N-1)\gamma_h} \leq \mu < \mu^f$, is negative, and the maximum possible expected payoff of non-signatories is $1 - \mu\gamma_h$, where $n^*(\mu) = N - 1$. Given that the posterior beliefs on average should be equal to the prior, in lemma 4, it was shown

[64]The tie-breaking rule is for $N > 2$.

that the maximum value of expected payoff of a representative non-signatory, $1 - p\gamma_h$, is below $1 - p$ for interior prior beliefs, specifically, $1 - p\gamma_h < 1 - p$. In this problem, perfect learning prescribed by the optimal information mechanism, i.e. $\mu_0 = 0$ and $\mu_1 = 1$, suggests that $V(p) = N(1 - p)$. Thus, in the current problem, the summation of maximum value of expected payoffs of non-signatories is clearly below $V(p)$ of the optimal mechanism, i.e. $1 - p\gamma_h < N(1 - p)$. Accordingly, the maximum value of expected payoff of both signatories and non-signatories is below $V(p) = N(1 - p)$, ensuring that for no prior, the sender could benefit from a partially uninformative policy, also, the sender gains from the optimal policy of full revelation for all interior prior beliefs.

Sender and minimising the total level of GHG

In this section, we consider a situation, where the sender's objective is minimising the total level of GHG, or maximising $\hat{\nu}(\mathbf{q}, \gamma) = -Q$. Therefore, given the best-response strategies of the countries in the emission and membership stages, the expected payoff of the sender can be written as

$$\nu(\mu) = \begin{cases} 0 & \text{if } \mu^f \leq \mu \leq 1 \\ n^*(\mu) - N & \text{if } \mu^{mn^*} < \mu \leq \frac{1}{(n^*(\mu)-1)\gamma_h} \\ -N & \text{if } 0 \leq \mu < \mu^N \end{cases} \tag{4.5.4}$$

where in this equation by $n^*(\mu)$ we refer to any $2 \leq n^*(\mu) \leq N$. Furthermore, the tie-breaking rule is such that for the case of $n^*(\mu) = 2$, the range of beliefs are $\frac{1}{2\gamma_h} < \mu < \mu^f$, and for the case of $n^*(\mu) = N$, the range of beliefs are $\mu^N \leq \mu \leq \frac{1}{(N-1)\gamma_h}$. The supremum of convex hull of graph of $\nu(\mu)$ suggests that the optimal information policy is not globally unique, and depending on p, it takes a form of partial learning, either by selection of a non-degenerate lottery over posteriors, or leaving the countries at their prior beliefs.

Proposition 11. *IF $\hat{\nu}(\mathbf{q}, \gamma) = -Q$, the optimal information mechanism prescribes imperfect learning for $p \in (0, 1)$, where*

(i) if $\mu^f \leq p < 1$, or if $\mu^N \leq p \leq \frac{1}{(N-1)\gamma_h}$, then a degenerate lottery over posteriors which is equal to the prior with probability one, i.e. $\mu_1 = p$ and $\tau = 1$, is optimal. This is equivalent to communication of no signal.

(ii) if $0 < \mu < \mu^N$, then the unique optimal policy consists of a Bayes-plausible randomisation over $\mu_0 = 0$ and $\mu_1 = \mu^N$.

(iii) for any $\mu^N \leq p < 1$, the information policy of a Bayes-plausible randomisation over $\mu_0 \in [\mu^N, \frac{1}{(N-1)\gamma_h}]$ and $\mu_1 \in [\mu^f, 1]$, is one of the optimal information policies.

The proof is in Appendix 4.7.5, and it includes all possible optimal information policies for different prior beliefs. In contrast to other expected payoffs of the sender, which were examined, here the optimal information policy leads to imperfect learning. If $\mu^f \leq p < 1$, or if $\mu^N \leq p \leq \frac{1}{(N-1)\gamma_h}$, the countries in the absence of any persuasion, choose the sender's preferred action, which is formation of the abating grand coalition. Hence, in such cases, sending no signal is an optimal information policy. In situations where non-signatorie(s) emit, i.e. if $\frac{1}{(N-1)\gamma_h} < p < \mu^f$, all possible optimal policies include selection of a Bayes-plausible lottery over posteriors corresponding to the formation of the abating grand coalition, i.e. $\mu_0 \in [\mu^N, \frac{1}{(N-1)\gamma_h}]$ and $\mu_1 \in [\mu^f, 1]$. Furthermore, if $0 < p < \mu^N$, by selection of a randomisation over the minimum posterior associated with the abating grand coalition, i.e. μ^N, and the posterior of $\mu_0 = 0$, the sender strictly gains. More specifically,

Corollary 3. *For any $0 < p < \mu^N$ and $\frac{1}{(N-1)\gamma_h} < p < \mu^f$, the sender strictly benefits from the persuasion. Furthermore, for all $p \in [0, 1]$, the sender's-preferred mitigation and membership SPE coincides with the socially optimal outcome.*

Hence, in cases where sending no signal is an optimal information policy, the sender does not benefit from persuasion. While for all other interior prior beliefs, the sender strictly gains from persuasion. In terms of equivalence of the equilibrium outcome with the social optimum, here although the sender's expected payoff does not coincide with the preferences of (any or all of) the countries, and leads to partial learning, minimising the total level of GHG by the sender, results in formation of the grand coalition with the threshold belief of μ^N for all interior prior beliefs, which indeed implies the socially optimal mitigation outcome, as specified in lemma 2.

4.6 Conclusions

The chapter examines a coalition formation and IEA from the perspective of information design. A theoretical model is developed, where a research central authority in climate change, as an information sender, communicates an information policy and signals about a payoff-relevant state variable (social cost of GHG) to the countries, in order to affect their decision about joining a coalition. This information, through the updated beliefs of the countries, determines the mitigation action of signatories and non-signatories of an IEA, which in turn forms a certain stable coalition.

More specifically, in a coalition formation model that the beliefs are not exogenous variables, it is shown that the induced beliefs map to a unique coalition size. Hence, the size of stable coalition, as an endogenous variable, can be uniquely pinned down by choosing the posterior beliefs. Knowing this, the research central authority in climate change designs an information policy to persuade the countries to form the coalition which maximises its expected payoff.

Most literature on the stochastic IEA concludes that the "veil of uncertainty" helps the formation of climate coalitions. Our analysis suggests that if the payoff of the sender and (a group of) countries coincide, the optimal information policy takes the form of perfect learning. On the other hand, if the objective of the research central authority is minimising the global GHG, then optimal information policy results in partial learning of the state by the countries. However, for all of the assumed expected payoffs which were examined for the sender, it turned out that the optimal information mechanisms lead to the formation of grand coalition, which implies that the equilibrium mitigation and membership outcome coincide with the social optimum. This is in fact because in all cases, the assumed expected payoffs of the sender are increasing in the expected number of signatories of the coalition.

According to our model, formation of the grand coalition in Paris, with the focus on minimising the total level of GHG, could be the result of adoption of two communication strategies by the IPCC and other partners of the UN. Given the fact that in contrast to previous meetings, from the beginning of the Paris conference, the leaders of many of participating states were optimistic about achieving an agreement, it can be said that the countries' prior belief about the social cost of GHG had already implied believing in a high (or catastrophic) level of the state[65]. If this was the case, then our simple model suggests that one of the possible optimal information policies is sending no signal. In fact, the strategy of IPCC from months prior to the conference, was not communicating the social cost of GHG, and instead the focus was given to the level of GHG and the average global temperature, although prominent research was carried out by the IPCC on the social cost of carbon.[66] Another possible communication policy could be that the involved international research authorities referring to the wide uncertainty about the state variable, optimally used a randomisation of signals, which correspond to the posterior beliefs which lead to formation of the abating grand coalition.

Finally, in terms of future research, the analysis of optimal communication by central authorities in climate change can be generalised in various ways such as gradual learning by receiving multiple signals over time and deriving the optimal time of communication and delay, private information acquisition by the countries, private persuasion versus public persuasion by the sender, and costly research for the sender.

[65]The high prior belief of the countries could be a result of private pre-communication with many individual countries from months before the conference.

[66] This is according to a public lecture at the University of Edinburgh by professor Ottmar Edenhofer, co-chair of Working Group III of the IPCC, in May 2015.

4.7 Appendix

4.7.1 Proof of proposition 8

First, the coalition of singletons is always stable, as no unilateral deviation can make anyone better off. Accordingly, the resulted equilibrium mitigation outcome of the coalition of singletons is the same as was derived for the fringe countries, i.e. $q_i^* = 1$ for any $\mu < \mu^f$, and $q_i^* = 0$ for any $\mu \geq \mu^f$. Now we continue the proof for $n^*(\mu) \geq 2$ and the three different ranges of beliefs.

I) Consider the case where $\mu^N \leq \mu < \mu^f$. Fix $n^*(\mu)$, also assume $\mu^{mn^*} \leq \mu < \frac{1}{(n^*(\mu)-1)\gamma_h}$. We claim that in this range of beliefs, there is a stable coalition of unique size $n^*(\mu) = I(\frac{1}{\mu\gamma_h})$, where $q_i^{*m} = 0$, and $q_i^{*f} = 1$. Then if $n \geq n^*(\mu)$, $\mathbb{E}_\mu u_i^{mn^*} = -\mu\gamma_h(N-n)$, and $\mathbb{E}_\mu u_i^{fn^*} = 1 - \mu\gamma_h(N-n)$. While if $n < n^*(\mu)$, $\mathbb{E}_\mu u_i^{fn^*} = 1 - \mu\gamma_h N$. As explained in section 4.5.1, the Nash equilibrium condition for the coalition members (the internal stability condition) implies that the equilibrium number of signatories cannot be less than $n^*(\mu)$, i.e.

$$\mathbb{E}_\mu u_i^{mn^*}(n^*(\mu)) \geq \mathbb{E}_\mu u_i^{fn^*}(n^*(\mu)-1) \tag{4.7.1}$$

Condition (4.7.1) is satisfied if and only if $-\mu\gamma_h(N-n^*(\mu)) \geq 1 - \mu\gamma_h N$. This is always satisfied as in this range, $\mu \geq \frac{1}{n^*(\mu)\gamma_h} \equiv \mu^{mn^*}$. Therefore, no coalition member has incentive to leave the coalition of size $n^*(\mu)$.

In addition, the Nash equilibrium condition for the non-signatories (the external stability condition) implies that the equilibrium number of signatories cannot be greater than $n^*(\mu)$, i.e.

$$\mathbb{E}_\mu u_i^{mn^*}(n^*(\mu)+1) < \mathbb{E}_\mu u_i^{fn^*}(n^*(\mu)) \tag{4.7.2}$$

This is satisfied if and only if $-\mu\gamma_h(N-n^*(\mu)-1) < 1 - \mu\gamma_h(N-n^*(\mu))$, which is the case as in this range $\mu < \frac{1}{\gamma_h} \equiv \mu^f$. In other words, it does not pay any non-signatory to change its decision.

If $\mu < \mu^{mn^*}$, then coalition of $n^*(\mu)$ with decision of $q_i^{*m} = 0$ is not internally stable and signatories have incentive to leave the coalition as $-\mu\gamma_h(N - n^*(\mu)) < 1 - \mu\gamma_h N$. Similarly, (in case that $n^*(\mu) > 2$), if $\frac{1}{(n^*(\mu)-1)\gamma_h} \leq \mu < \frac{1}{(n^*(\mu)-2)\gamma_h}$, then abating coalition of size n^*-1 is stable, which results in expected payoff of $\mathbb{E}_\mu u_i^{mn^*} = -\mu\gamma_h(N-n^*(\mu)+1)$ for the signatories of coalition.

Therefore, in the range $\mu^N \leq \mu < \mu^f$, given that the minimum threshold of signatories is μ^N, and (in the case that $N > 2$,) the maximum threshold is $\frac{1}{2\gamma_h}$, there exists $N - 1$ thresholds for signatories, μ^{mn^*}, and accordingly $N - 1$ sub-partitions of beliefs, $\mu^{mn^*} \leq \mu < \frac{1}{(n^*(\mu)-1)\gamma_h}$. Thus, the size of stable coalition varies between two and N, i.e. $2 \leq n^*(\mu) \leq N$.

II) Now suppose $\mu \geq \mu^f$. Given condition (4.7.1), the grand coalition is internally stable, as in this range of beliefs, $1 - \mu\gamma_h N < 0$. External stability cannot be checked for the grand coalition, since there exists no non-signatory country to be considered.

III) Similarly, if $\mu < \mu^N$, no coalition for abatement in this range is profitable, and the emitting grand coalition is stable, where for all countries it is profitable to choose $q_i^* = 1$, and the expected payoff of country i is $\mathbb{E}_\mu u_i^* = 1 - \mu\gamma_h N$. Indeed, no unilateral deviation can make anyone better off, i.e. $1 - \mu\gamma_h N > -\mu\gamma_h(N - 1)$, for any $\mu < \mu^N$, which implies the internal stability of grand coalition.

4.7.2 Proof of lemma 3

Given proposition 8 and the corresponding equilibrium payoff of signatories in (4.5.1), the problem of the sender as specified in (4.4.3) can be written as maximising

$$\tau \begin{cases} 0 & \text{if } \mu^f \leq \mu_1 \leq 1 \\ -\mu_1\gamma_h(N - n^*(\mu_1)) & \text{if } \mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 1 - \mu_1\gamma_h N & \text{if } 0 \leq \mu_1 \leq \mu^N \end{cases}$$
$$+ (1-\tau) \begin{cases} 0 & \text{if } \mu^f \leq \mu_0 \leq 1 \\ -\mu_0\gamma_h(N - n^*(\mu_0)) & \text{if } \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h} \\ 1 - \mu_0\gamma_h N & \text{if } 0 \leq \mu_0 \leq \mu^N \end{cases} \tag{4.7.3}$$

with respect to μ_1 and μ_0, subject to $\tau\mu_1 + (1-\tau)\mu_0 = p$. Also, as mentioned, $2 \leq n^*(\mu) \leq N$, and for the case of $n^*(\mu) = 2$, the range of beliefs is $\frac{1}{2\gamma_h} < \mu < \mu^f$. Moreover, the expected payoff in (4.7.3) can be further decoded to

$$\begin{aligned}
&\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) = [(1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ 0 \leq \mu_0 \leq \mu^N}} \\
&- [(1-\tau)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [0]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^f \leq \mu_0 \leq 1}} + [(1-\tau)(1-\mu_0\gamma_h N) - \tau\mu_1\gamma_h(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 0 \leq \mu_0 \leq \mu^N}} \\
&- [\tau\mu_1\gamma_h(N - n^*(\mu_1)) + (1-\tau)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&- [\tau\mu_1\gamma_h(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^f \leq \mu_0 \leq 1}} \\
&+ [\tau(1-\mu_1\gamma_h N) + (1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ 0 \leq \mu_0 \leq \mu^N}} \\
&+ [\tau(1-\mu_1\gamma_h N) - (1-\tau)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [\tau(1-\mu_1\gamma_h N)]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ \mu^f \leq \mu_0 \leq 1}}
\end{aligned} \tag{4.7.4}$$

In order to prove the lemma, and find the unique optimal mechanism, it is required to compare the maximised expected payoff of all of the above nine partitions of posterior beliefs with each other, and select the policy corresponding to the maximum expected payoff.

Let us label each term of the above expected payoff by ascending numbers, e.g. case 1 refers to the first term where $\mu^f \leq \mu_1 \leq 1$ and $0 \leq \mu_0 \leq \mu^N$.

It is easy to verify that selection of posterior beliefs corresponding to cases 6, 8, and 9, where $\mu_0 > \mu_1$, are dominated as the persuasion would be worthless. For example, in case 9, where $0 \leq \mu_1 \leq \mu^N$ and $\mu^f \leq \mu_0 \leq 1$. The resulted expected payoff of $\tau(1 - \mu_1\gamma_h N)$ is maximised if $\mu_1 = 0$, to obtain expected payoff of τ. Then, the constraint of law of total probability implies $1 - \frac{p}{\mu_0} = \tau$. So the maximum τ is achieved by setting $\mu_0 = 1$. Hence $\pi(1 \mid \gamma_h) = 0$ and $\pi(0 \mid \gamma_l) = 0$, which is absolute lying and such a policy will be ignored by the countries.

In addition, in cases that the corresponding expected payoff depends on $n^*(\mu)$, it is an increasing function of $n^*(\mu)$. Therefore, selection of posteriors which lead to $n^*(\mu) = N$ maximises the sender's payoff. Furthermore, the expected payoffs of cases 2, 3, and 5 are inferior relative to cases 1, 4, and 7, which lead to positive expected payoffs. Now we compare the maximum possible values of these positive candidates.

Case 1: $\mu^f \leq \mu_1 \leq 1$ and $0 \leq \mu_0 < \mu^N$. Then, the expected payoff of $(1 - \tau)(1 - \mu_0\gamma_h N)$ is maximised if $\mu_0 = 0$. Thus, the law of total probability implies $\tau = \frac{p}{\mu_1}$. Therefore, the resulted expected payoff of $(1 - \tau)$ is maximised if τ is minimised, which is achieved by choosing $\mu_1 = 1$. Hence, $V(p) = 1 - p$ is a potential value of the optimal mechanism.

Case 4: $\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h}$ and $0 \leq \mu_0 < \mu^N$. To maximise the associated expected payoff, it should be that $\mu_0 = 0$. Also, ideally, μ_1 should be such that $n^*(\mu_1) = N$. In other words, $\mu^N < \mu_1 \leq \frac{1}{(N-1)\gamma_h}$. Hence, the resulted expected payoff, which is decreasing in τ, so increasing in μ_1, is maximised if $\mu_1 = \frac{1}{(N-1)\gamma_h}$. However, first, it may not be Bayes-plausible if $p > \frac{1}{(N-1)\gamma_h}$. Second, $\mu_1 = \frac{1}{(N-1)\gamma_h}$ leads to an expected payoff which is less than case 1, where $\mu_1 = 1$.

Case 7: $0 \leq \mu_1 \leq \mu^N$ and $0 \leq \mu_0 \leq \mu^N$. Then, the expected payoff of $\tau(1-\mu_1\gamma_h N)+(1 - \tau)(1 - \mu_0\gamma_h N)$ is maximised if $\mu_0 = \mu_1 = 0$, but this is not Bayes-plausible, for an interior p. If we search for a pair of Bayes-plausible (μ_0, μ_1), and let $\mu_0 = 0$, then given the law of total probability, $\tau = \frac{p}{\mu_1}$, and the expected payoff of $\tau(1 - \mu_1\gamma_h N) + (1 - \tau)$, is reduced to $1 - p\gamma_h N$. But for any $p > 0$, this is less than the maximised expected payoff of case 1, which is $1 - p$. Moreover, as the expected payoff is linear in μ_0 and μ_1, any other combination of the two variables in this range leads to an expected payoff which is less than $1 - p$.

Therefore, case 1 has the unique maximum expected payoff of $1 - p$, by choosing the corner solution of $\mu_0 = 0$ and $\mu_1 = 1$. Hence, optimally $\pi(1 \mid \gamma_h) = 1$ and $\pi(0 \mid \gamma_l) = 1$.

4.7.3 Proof of lemma 4

Based on the expected payoff of non-signatories for any belief in equation (4.5.2), the problem of sender can be formalised as maximising

$$
\begin{aligned}
&\tau \begin{cases} 0 & \text{if } \mu^f \leq \mu_1 \leq 1 \text{ or if } \mu^N < \mu_1 < \frac{1}{(N-1)\gamma_h} \\ 1 - \mu_1\gamma_h(N - n^*(\mu_1)) & \text{if } \mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 1 - \mu_1\gamma_h N & \text{if } 0 \leq \mu_1 \leq \mu^N \end{cases} \\
&+ (1-\tau) \begin{cases} 0 & \text{if } \mu^f \leq \mu_0 \leq 1 \text{ or if } \mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h} \\ 1 - \mu_0\gamma_h(N - n^*(\mu_0)) & \text{if } \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h} \\ 1 - \mu_0\gamma_h N & \text{if } 0 \leq \mu_0 \leq \mu^N \end{cases}
\end{aligned}
\tag{4.7.5}
$$

with respect to μ_1 and μ_0, subject to $\tau\mu_1 + (1 - \tau)\mu_0 = p$. Also, as mentioned, in this equation by $n^*(\mu)$ we refer to any $2 \leq n^*(\mu) \leq N - 1$. In addition, for the case of $n^*(\mu) = 2$, the range of beliefs are $\frac{1}{2\gamma_h} < \mu < \mu^f$, and for the case of $n^*(\mu) = N - 1$, the range of beliefs are $\frac{1}{(N-1)\gamma_h} \leq \mu \leq \frac{1}{(N-2)\gamma_h}$. The expected payoff in (4.7.5) can be rewritten as

$$
\begin{aligned}
\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) &= [(1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{\mu^f \le \mu_1 \le 1 \\ 0 \le \mu_0 \le \mu^N}} + [0]\mathbf{1}_{\substack{\mu^f \le \mu_1 \le 1 \\ \mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h}}} \\
&+ [(1-\tau)(1-\mu_0\gamma_h(N-n^*(\mu_0)))]\mathbf{1}_{\substack{\mu^f \le \mu_1 \le 1 \\ \mu^{mn^*} < \mu_0 \le \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} + [0]\mathbf{1}_{\substack{\mu^f \le \mu_1 \le 1 \\ \mu^f \le \mu_0 \le 1}} \\
&+ [(1-\tau)(1-\mu_0\gamma_h N) + \tau(1-\mu_1\gamma_h(N-n^*(\mu_1)))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \le \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 0 \le \mu_0 \le \mu^N}} \\
&+ [\tau(1-\mu_1\gamma_h(N-n^*(\mu_1)))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \le \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h}}} \\
&+ [\tau(1-\mu_1\gamma_h(N-n^*(\mu_1))) + (1-\tau)(1-\mu_0\gamma_h(N-n^*(\mu_0)))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \le \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^{mn^*} < \mu_0 \le \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [\tau(1-\mu_1\gamma_h(N-n^*(\mu_1)))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \le \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^f \le \mu_0 \le 1}} + [(1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{(N-1)\gamma_h} \\ 0 \le \mu_0 \le \mu^N}} \\
&+ [0]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^N < \mu_0 < \frac{1}{\gamma_h(N-1)}}} + [(1-\tau)(1-\mu_0\gamma_h(N-n^*(\mu_0)))]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^{mn^*} < \mu_0 \le \frac{1}{\gamma_h(n^*(\mu_0)-1)}}} \\
&+ [0]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^f \le \mu_0 \le 1}} + [\tau(1-\mu_1\gamma_h N) + (1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{0 \le \mu_1 \le \mu^N \\ 0 \le \mu_0 \le \mu^N}} \\
&+ [\tau(1-\mu_1\gamma_h N)]\mathbf{1}_{\substack{0 \le \mu_1 \le \mu^N \\ \mu^N < \mu_0 < \frac{1}{\gamma_h(N-1)}}} \\
&+ [\tau(1-\mu_1\gamma_h N) + (1-\tau)(1-\mu_0\gamma_h(N-n^*(\mu_0)))]\mathbf{1}_{\substack{0 \le \mu_1 \le \mu^N \\ \mu^{mn^*} < \mu_0 \le \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [\tau(1-\mu_1\gamma_h N)]\mathbf{1}_{\substack{0 \le \mu_1 \le \mu^N \\ \mu^f \le \mu_0 \le 1}}
\end{aligned}
\tag{4.7.6}
$$

Again we label each term of the above expected payoff by ascending numbers, e.g. case 1 refers to the first term where $\mu^f \le \mu_1 \le 1$ and $0 \le \mu_0 \le \mu^N$. So, there are 16 cases, where cases 8, 11, 12, 14, 15, and 16 cannot be equilibrium because in these cases $\mu_0 > \mu_1$.

The cases with potential positive payoffs are as follows:

Case 1: $\mu^f \le \mu_1 \le 1$ and $0 \le \mu_0 \le \mu^N$. This can be a candidate, as by setting $\mu_0 = 0$, the Bayes-plausibility implies $\tau = \frac{p}{\mu_1}$. Hence, the expected payoff of $1-\tau$ is maximised by setting $\mu_1 = 1$. Thus the full-revelation policy leads to the expected payoff of $1 - p$.

Case 3: $\mu^f \leq \mu_1 \leq 1$ and $\mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}$. Ideally, choosing μ_0 in the range that $\frac{1}{(N-1)\gamma_h} < \mu_0 \leq \frac{1}{(N-2)\gamma_h}$, leads to $n^*(\mu_0) = N - 1$, and expected payoff of $(1 - \tau)(1 - \mu_0\gamma_h)$, which is increasing in μ_1, as $\mu_0 \leq p$. Therefore, setting $\mu_1 = 1$ leads to expected payoff of $\frac{1-p}{1-\mu_0}(1 - \mu_0\gamma_h)$, which is strictly less than the maximised expected payoff of case 1, $1 - p$, for any μ_0 in this range.

Case 5: $\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h}$ and $0 \leq \mu_0 \leq \mu^N$. The expected payoff is maximised if $\mu_0 = 0$, and Bayes-plausibility implies $\tau = \frac{p}{\mu_1}$. So, the resulted expected payoff of $\tau(1 - \mu_1\gamma_h(N - n^*(\mu_1))) + (1 - \tau)$ can be simplified to $1 - p\gamma_h(N - n^*(\mu_1))$. Again, to maximise this, μ_1 can be selected such that $\frac{1}{(N-1)\gamma_h} < \mu_1 \leq \frac{1}{(N-2)\gamma_h}$. Thus, $n^*(\mu_1) = N - 1$, and the expected payoff is reduced to $1 - p\gamma_h$, but this is always less than $V(p) = (1 - p)$ in case 1, for any $p > 0$.

Case 6: $\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h}$ and $\mu^N \leq \mu_0 \leq \frac{1}{(N-1)\gamma_h}$. The corresponding expected payoff is maximised by choosing $\frac{1}{(N-1)\gamma_h} < \mu_1 \leq \frac{1}{(N-2)\gamma_h}$ to the expected payoff of $\tau(1 - \mu_1\gamma_h)$. The law of total probability for μ_0 and μ_1, restricts the resulted expected payoff to $\frac{p-\mu_0}{\mu_1-\mu_0}(1 - \mu_1\gamma_h)$, which is decreasing in μ_1. The minimum possible value of μ_1 is p, but it leads to expected payoff of $1 - \mu_1\gamma_h$, which is less than $1 - p$ for any $p > 0$.

Case 7: $\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h}$ and $\mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}$. The associated expected payoff is maximised if $\frac{1}{(N-1)\gamma_h} < \mu_1 \leq \frac{1}{(N-2)\gamma_h}$ and $\frac{1}{(N-1)\gamma_h} < \mu_0 \leq \frac{1}{(N-2)\gamma_h}$. The resulted expected payoff of $\tau(1 - \mu_1\gamma_h) + (1 - \tau)(1 - \mu_0\gamma_h)$, given a pair of Bayes-plausible (μ_0, μ_1), and replacing $\mu_1 = \frac{p}{\tau} - \frac{1-\tau}{\tau}\mu_0$, can be simplified to $1 - p\gamma_h$, which for any $p > 0$, is less than the payoff of case 1.

Case 9: $\mu^N < \mu_1 \leq \frac{1}{(N-1)\gamma_h}$ and $0 \leq \mu_0 \leq \mu^N$. Similar to case 1, it is possible to set $\mu_0 = 0$ and obtain expected payoff of $1 - \tau$. This is increasing in μ_1, but in this range of beliefs, it cannot be as maximised as case 1, where it was possible to select $\mu_1 = 1$.

Case 13: $0 \leq \mu_1 < \mu^N$ and $0 \leq \mu_0 < \mu^N$. This case is ruled out as it is identical to case 7 of the signatories problem in the proof of lemma 3.

Therefore, case 1 provides the unique maximum expected payoff of $V(p) = 1 - p$, and the optimal policy is full revelation of the state.

4.7.4 Proof of proposition 10

Given equations (4.7.3) and (4.7.5), and adjusting the tie-breaking rule (for $N > 2$), the expected payoff of sender specified in (4.5.3) is

$$
\begin{aligned}
&\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) = [\alpha N(1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ 0 \leq \mu_0 \leq \mu^N}} + [0]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h}}} \\
&+ [(1-\tau)(N - n^*(\mu_0))(1 - \mu_0\gamma_h(N - n^*(\mu_0))) \\
&- (1-\tau)\alpha n^*(\mu_0)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [0]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^f \leq \mu_0 \leq 1}} + [\alpha N(1-\tau)(1-\mu_0\gamma_h N) \\
&- \alpha\tau n^*(\mu_1)\mu_1\gamma_h(N - n^*(\mu_1)) + \tau(N - n^*(\mu_1))(1 - \mu_1\gamma_h(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 0 \leq \mu_0 \leq \mu^N}} \\
&+ [\tau(N - n^*(\mu_1))(1 - \mu_1\gamma_h(N - n^*(\mu_1)) - \alpha\tau n^*(\mu_1)\mu_1\gamma_h(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h}}} \\
&+ [(1-\tau)(N - n^*(\mu_0))(1 - \mu_0\gamma_h(N - n^*(\mu_0))) + \tau(N - n^*(\mu_1))(1 - \mu_1\gamma_h(N - n^*(\mu_1))) \\
&- \alpha\tau n^*(\mu_1)\mu_1\gamma_h(N - n^*(\mu_1)) - \alpha(1-\tau)n^*(\mu_0)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [\tau(N - n^*(\mu_1))(1 - \mu_1\gamma_h(N - n^*(\mu_1))) \\
&- \tau\alpha n^*(\mu_1)\mu_1\gamma_h(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^f \leq \mu_0 \leq 1}} \\
&+ [\alpha N(1-\tau)(1-\mu_0\gamma_h N)]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{(N-1)\gamma_h} \\ 0 \leq \mu_0 \leq \mu^N}} + [0]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^N < \mu_0 < \frac{1}{\gamma_h(N-1)}}} \\
&+ [(1-\tau)(N - n^*(\mu_0))(1 - \mu_0\gamma_h(N - n^*(\mu_0))) \\
&- (1-\tau)\alpha n^*(\mu_0)\mu_0\gamma_h(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{\gamma_h(n^*(\mu_0)-1)}}} + [0]\mathbf{1}_{\substack{\mu^N < \mu_1 < \frac{1}{\gamma_h(N-1)} \\ \mu^f \leq \mu_0 \leq 1}} \\
&+ [\alpha N(\tau(1-\mu_1\gamma_h N) + (1-\tau)(1-\mu_0\gamma_h N))]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ 0 \leq \mu_0 \leq \mu^N}} + [\alpha N\tau(1-\mu_1\gamma_h N)]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ \mu^N < \mu_0 < \frac{1}{\gamma_h(N-1)}}} \\
&+ [\alpha N\tau(1-\mu_1\gamma_h N) - \alpha(1-\tau)n^*(\mu_0)\mu_0\gamma_h(N - n^*(\mu_0)) \\
&+ (1-\tau)(N - n^*(\mu_0))(1 - \mu_0\gamma_h(N - n^*(\mu_0)))]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [\alpha N\tau(1-\mu_1\gamma_h N)]\mathbf{1}_{\substack{0 \leq \mu_1 \leq \mu^N \\ \mu^f \leq \mu_0 \leq 1}}
\end{aligned}
\tag{4.7.7}
$$

where in this equation, $n^*(\mu)$ refers to $2 \leq n^*(\mu) \leq N-1$.

Again by labelling each term of the above expected payoff by ascending numbers, (e.g. case 1 refers to the first term where $\mu^f \leq \mu_1 \leq 1$ and $0 \leq \mu_0 \leq \mu^N$) and ruling out cases where $\mu_0 > \mu_1$ from the analysis, i.e., cases 8, 11, 12, 14, 15, and 16, we compare potential positive payoffs:

Case 1: $\mu^f \leq \mu_1 \leq 1$ and $0 \leq \mu_0 < \mu^N$. Selecting $\mu_0 = 0$, and $\mu_1 = 1$, leads to expected payoff of $\alpha N(1-p)$.

Case 3: $\mu^f \leq \mu_1 \leq 1$ and $\mu^{mn^*} \leq \mu_0 < \frac{1}{\gamma_h(n^*(\mu_0)-1)}$. Given that the maximum possible expected payoff in this range is obtained by selecting $n^*(\mu_0) = N-1$. So, the corresponding expected payoff can be written as $(1-\tau)(1-\mu_0\gamma_h)-(1-\tau)(N-1)\alpha\mu_0\gamma_h$. For any $\alpha \geq 1$ and $N > 2$, the last term is non-positive. For any positive μ_0, this is less that the expected payoff of case 1.

Case 5: $\mu^{mn^*} \leq \mu_1 < \frac{1}{\gamma_h(n^*(\mu_1)-1)}$ and $0 \leq \mu_0 < \mu^N$. Undoubtedly, it is optimal to set $\mu_0 = 0$, thus $\tau = \frac{p}{\mu_1}$ implies that the corresponding expected payoff is $N\frac{p}{\mu_1}(1-\mu_1\gamma_h)+\alpha N(1-\frac{p}{\mu_1})+(1-\alpha)(N-1)p\gamma_h$. This expected payoff can be further simplified to $N\alpha - p\gamma_h(\alpha(N-1)+1)+N\frac{p}{\mu_1}(1-\alpha)$, where the last two terms are non-positive for any $\alpha \geq 1$. So, this is always less than the expected payoff of case 1, $N\alpha - N\alpha p$.

Case 6: $\mu^{mn^*} \leq \mu_1 < \frac{1}{\gamma_h(n^*(\mu_1)-1)}$ and $\mu^N < \mu_0 < \frac{1}{(N-1)\gamma_h}$. Selection of μ_1 such that $n^*(\mu_1) = N-1$ leads to expected payoff of $\tau(1-\mu_1\gamma_g[1+\alpha(N-1)])$. It is decreasing in both μ_0 and μ_1, but relative to case 1, the corner solutions where either of these could be zero is not available in this range of beliefs. Also since $\alpha \geq 1$ and $N-1 > 1$, this expected payoff is less than case 1.

Case 7: $\mu^{mn^*} \leq \mu_1 < \frac{1}{\gamma_h(n^*(\mu_1)-1)}$ and $\mu^{mn^*} \leq \mu_0 < \frac{1}{\gamma_h(n^*(\mu_0)-1)}$. The last two terms of the expected payoff are negative. Given the fact that the in this range of beliefs, the expected payoffs of signatories and non-signatories are maximised if $n^*(\mu) = N-1$, the first two terms are identical to case 7 in the proof of lemma 4, where a Bayes-plausible pair of beliefs leads to expected payoff of $1-p\gamma_h$, which is inferior to the case 1, for any $\alpha \geq 1$.

Case 9: $\mu^N < \mu_1 < \frac{1}{(N-1)\gamma_h}$ and $0 \leq \mu_0 < \mu^N$. The corresponding expected payoff is similar to case 1 if $\mu_0 = 0$. However, here it is not possible to set $\mu_1 = 1$ and achieve the maximised value of expected payoff of case 1.

Case 13: $0 \leq \mu_1 \leq \mu^N$ and $0 \leq \mu_0 \leq \mu^N$. This case is also ruled out, as it is similar to case 7 in proof of lemma 3.

Hence, the expected payoff of case 1, given $\mu_0 = 0$ and $\mu_1 = 1$, provides a unique maximum expected payoff. Furthermore, selection of $\mu_0 = 0$ leads to formation of the emitting grand coalition, while selection of $\mu_1 = 1$ implies formation of the abating grand coalition. This in turn coincides with the socially optimal mitigation outcome specified in 2.

4.7.5 Proof of proposition 11

Given the expected payoff of (4.5.4) for any belief, the problem of sender can be formalised as maximising

$$\tau \begin{cases} 0 & \text{if } \mu^f \leq \mu_1 \leq 1 \\ n^*(\mu_1) - N & \text{if } \mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ -N & \text{if } 0 \leq \mu_1 < \mu^N \end{cases} \tag{4.7.8}$$

$$+(1-\tau) \begin{cases} 0 & \text{if } \mu^f \leq \mu_0 \leq 1 \\ n^*(\mu_0) - N & \text{if } \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h} \\ -N & \text{if } 0 \leq \mu_0 < \mu^N \end{cases}$$

with respect to μ_1 and μ_0, such that $\tau\mu_1 + (1-\tau)\mu_0 = p$. In addition, in this equation by $n^*(\mu)$ we refer to any $2 \leq n^*(\mu) \leq N$. Furthermore, the tie-breaking rule is such that for the case of $n^*(\mu) = 2$, the range of beliefs are $\frac{1}{2\gamma_h} < \mu < \mu^f$, and for the case of $n^*(\mu) = N$, the range of beliefs are $\mu^N \leq \mu \leq \frac{1}{(N-1)\gamma_h}$. The expected payoff in (4.7.8) can be rewritten as

$$
\begin{aligned}
\tau\nu(\mu_1) + (1-\tau)\nu(\mu_0) = &-[(1-\tau)N)]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ 0 \leq \mu_0 < \mu^N}} \\
&- [(1-\tau)(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&+ [0]\mathbf{1}_{\substack{\mu^f \leq \mu_1 \leq 1 \\ \mu^f \leq \mu_0 \leq 1}} - [\tau(N - n^*(\mu_1)) + (1-\tau)N)]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ 0 \leq \mu_0 < \mu^N}} \\
&- [\tau(N - n^*(\mu_1)) + (1-\tau)(N - n^*(\mu_0))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} \\
&- [\tau(N - n^*(\mu_1))]\mathbf{1}_{\substack{\mu^{mn^*} < \mu_1 \leq \frac{1}{(n^*(\mu_1)-1)\gamma_h} \\ \mu^f \leq \mu_0 \leq 1}} - [N]\mathbf{1}_{\substack{0 \leq \mu_1 < \mu^N \\ 0 \leq \mu_0 < \mu^N}} \\
&- [\tau N + (1-\tau)(N - n^*(\mu_0))]\mathbf{1}_{\substack{0 \leq \mu_1 < \mu^N \\ \mu^{mn^*} < \mu_0 \leq \frac{1}{(n^*(\mu_0)-1)\gamma_h}}} - [\tau N]\mathbf{1}_{\substack{0 \leq \mu_1 < \mu^N \\ \mu^f \leq \mu_0 \leq 1}}
\end{aligned}
\tag{4.7.9}
$$

Let us first label each term of the above expected payoff by ascending numbers, e.g. case 1 refers to the first term where $\mu^f \leq \mu_1 \leq 1$ and $0 \leq \mu_0 < \mu^N$. Furthermore, note that cases 6, 8, and 9 are ruled out as in these case $\mu_0 > \mu_1$.

In order to prove the proposition, let us fix p, and consider three possibilities for the prior belief.

First, $\mu^f \leq p < 1$. A Bayes-plausible lottery over posteriors should satisfy the order of $\mu_0 \leq p \leq \mu_1$. Thus, the corresponding expected payoffs of cases 1, 2, and 3 must be compared. As in this range of prior beliefs, $\mu^f \leq p \leq 1$, the countries in the absence of any persuasion, take the sender's-preferred action, the optimal policy can be sending no signal at all. This is not a unique optimal information policy, and it is equivalent to a degenerate randomisation of posteriors, which is equal to the prior with probability one, i.e. $\mu_1 = p$ and $\tau = 1$. This can be obtained by a degenerate randomisation in either of cases 1, 2, or 3, leading to the expected payoff of zero. Another optimal policy is available in case 3, by selecting a Bayes-plausible randomisation over $\mu_0 = \mu^f$ and $\mu_1 = 1$.

Second, $\mu^{mn^*} \leq p < \frac{1}{(n^*(\mu)-1)\gamma_h}$. Searching for a maximum payoff should include expected payoffs of cases 2, 4, and 5. The expected payoff of case 2 is maximised if

$\mu_0 = \mu^N$, which implies $n^*(\mu_0) = N$, and expected payoff of zero. Therefore, for any prior belief in $\mu^N \leq p \leq 1$, a Bayes-plausible randomisation of $\mu_0 = \mu^N$ and $\mu_1 = 1$ is optimal. If $\mu^N \leq p \leq \mu^f$, another optimal policy is randomisation of $\mu_0 = \mu^N$ and $\mu_1 = \mu^f$. Similarly if $\frac{1}{(N-1)\gamma_h} \leq p \leq \mu^f$, then a randomisation of $\mu_0 = \frac{1}{(N-1)\gamma_h}$ and $\mu_1 = \mu^f$ (or $\mu_1 = 1$), which satisfies the law of total probability is also optimal. In short, for any $\mu^N \leq p < 1$, a Bayes-plausible randomisation over $\mu_0 \in [\mu^N, \frac{1}{(N-1)\gamma_h}]$ and $\mu_1 \in [\mu^f, 1]$ is an optimal information policy. In case 5, it is possible to obtain $V(p) = 0$, if and only if $\mu^N \leq p \leq \frac{1}{(N-1)\gamma_h}$. In such a case, that the countries choose the sender's preferred action in the absence of any persuasion, the optimal policy is not unique, and there can be no persuasion, or a degenerate lottery of $\mu_1 = p$ and $\tau = 1$, or the policy of selection of a Bayes-plausible randomisation over $\mu_0 = \mu^N$ and $\mu_1 = \frac{1}{(N-1)\gamma_h}$. All of these policies lead to expected payoff of zero for the sender. Finally, in case 4, if and only if $\mu^N \leq p \leq \frac{1}{(N-1)\gamma_h}$, the optimal policy of $\mu_1 = p$ and $\tau = 1$ leads to $V(p) = 0$.

Third, $0 < p < \mu^N$. This implies comparison of expected payoffs of cases 1, 4, and 7. Let us start the analysis with comparison of expected payoffs of cases 1 and 4. In both cases the expected payoffs are increasing in τ, and therefore decreasing in both μ_0 and μ_1. Hence, for case 1, choosing $\mu_0 = 0$ and $\mu_1 = \mu^f$ obtains maximum expected payoff of $\frac{p}{\mu^f}N - N$. While for case 4, choosing the minimum possible posteriors of $\mu_0 = 0$ and $\mu_1 = \mu^N$, leads to maximum expected payoff of $\frac{p}{\mu^N}N - N$. The expected payoff of 4 is more than 1 if $N > 2$, and the two cases lead to the same expected payoff. In addition, for any non-degenerate randomisation over posteriors, case 7 has the least expected payoff. Therefore, the unique optimal information policy is a Bayes-plausible randomisation of $\mu_0 = 0$ and $\mu_1 = \mu^N$.

Chapter 5

Conclusion

5.1 Overview

The previous three chapters explored three topics in transboundary environmental and resource economics from the perspective of game theory and information economics. This chapter reviews the contributions and the main findings of each chapter. Furthermore, the limitations of the study are discussed and some possible pathways for future research are suggested.

5.2 Second Chapter: Panic-Based Overfishing In Transboundary Fisheries

The second chapter of the thesis set out to find a possible reason for over extraction in transboundary fisheries. The chapter explores whether acquisition of private information about the assessment of the resource by the countries can be a possible answer. In fact the private information of the harvesting agents may lead to strategic uncertainty about each other's assessment. The chapter examines a coordination game, where two countries in addition to biological uncertainty face strategic uncertainty and the results of the chapter converge to derive a unique prediction about the harvesting action of the countries.

Although the biological uncertainty is extensively studied in the literature on resource games, there is no study with analytical solutions, where all agents acquire private information about the resource. Similarly, although there are a number of studies with a focus on multiplicity of equilibria in resource games, the equilibrium refinement of resource coordination games has never been examined in the literature.

Given the assumptions on the payoff structure, the size of the stock admits low and high regions, where respectively sustainable fishing and overfishing are dominant harvesting strategies, and the size of this regions is determined by parameters of the model, i.e. the discount factor, the reproduction rate, the share of sustainable yield, and the overfishing cost parameter. Between these two regions, there is an intermediate region of fish population, where there is no dominant harvesting strategy and the resulting coordination game here leads to multiplicity of equilibria. Hence, a researcher or manger of the stock, in the absence of any equilibrium refinement, cannot make any prediction about the harvesting action of the countries.

In terms of equilibrium refinement, in the first step, where the model is analysed under the assumption of precise signals, the risk-dominance equilibrium-selection criterion of Harsanyi and Selten (1988) is suggested. It is shown that the unique equilibrium admits a threshold form with respect to the stock, above which the countries overfish and below which they coordinate on sustainable harvesting as the less risky action.

In the next step, the model with noisy private information is considered and the analysis starts by solving the game for any general uniform noise (out of the limit). From the perspective of information economics, the chapter suggests two possible reasons for overfishing, either the countries' information implies that the fishery's size is in the upper dominance region, where overfishing is the dominant strategy, or it is possible that although a country acquires private information corresponding to the intermediate region, where it is not dominant to overfish, the negative belief about the private information of the other country may lead to a rational choice of over fishing, "panic-based" overfishing.

Finally, the global-game equilibrium refinement of Carlsson and van Damme (1993) and Morris and Shin (1998) is applied, and it is shown that, for all sufficiently small levels of noise of private information, there is a unique threshold-form PBNE. It is also noted that the symmetric equilibrium of the global games is the unique rationalisable strategy of the game.

Furthermore, the coincidence of the global-game threshold and the risk-dominance threshold of the complete information game provides considerable tractability for policy implications. Specifically, as a practice pathway, the study focuses on the overfishing cost and the share of sustainable catch. It is discussed that if the private information is sufficiently precise, given the unique derived equilibrium outcomes, it is possible to write down the unique equilibrium payoffs corresponding to each level of stock and consequently find an optimal level of the policy parameters, which for example maximises the payoff of a representative country.

As a future research direction in the context of policy implications, it is worthwhile investigating the effect of endogenising information acquisition. In the second chapter, the precision of private information is exogenous and identical across the countries. However, in line with the theoretical study on costly information acquisition in global games by Szkup and Trevino (2015), these assumptions can be relaxed. Szkup and Trevino derive the socially efficient amount of private information to be acquired and check whether there are strategic complementarities in information acquisition. Furthermore, in our context, such a study can help to explain how the value of the private information can change the probability of sustainable harvest.

Another limitation of the study is its two-period assumption, but it should be recalled that this simplicity provides tractability, as the study does not only apply equilibrium refinement techniques, but more generally the model is solved and the corresponding distributions are derived for situations where the noise of private information does not necessarily vanish.

5.3 Third Chapter: The Economics of Climate Change and The Role of Public Information

The focus of the third and fourth chapters is communication of public information on climate change by research central authorities with the countries which are involved in abating or emission decisions. A key objective of the third chapter is to explore the effect of public learning about the social cost of carbon on the investment of the countries on emission abatement technologies.

Currently, empirical studies suggest a wide range of uncertainty around the magnitude of the social cost of carbon. Furthermore, the theoretical literature on stochastic International Environmental Agreements (IEAs), mainly converge to pessimism about learning on this cost, which is modelled as a payoff-relevant parameter in various models.

The chapter is built on the deterministic infinite-horizon model of Dutta and Radner (2009), and the chapter examines the properties of the set of self-enforceable abatements, the equilibrium selection, and the sensitivity of the equilibrium abatements to learning about the social cost of green-house gasses (GHG).

It is shown that if the prior public belief is more optimistic about the social cost of GHG, then learning the true value necessarily enhances social welfare. However, if the prior belief is more than the true realisation of the state variable, the conclusion depends on whether the socially optimum level of abatement is achievable through self-enforceable agreements.

In addition to addressing the question of equilibrium selection and welfare under the learning scenario, as another research question, the third chapter investigates, in a strategic communication setting, whether full-learning, no-learning or imperfect learning are equilibrium outcomes. Specifically, instead of taking the learning as given, the chapter examines signalling games between an informed research central authority, as information sender, and the countries as receivers, where the induced learning outcome is endogenously determined by the interaction of the two groups.

It is assumed that the sender, by choosing a signalling strategy, tries to minimise the gap between the socially-optimum and the selected abatement levels. In the binary signalling game, where the sender chooses between two strategies of full revelation and being silent (no learning), it is shown that the unique PBNE learning outcome is full learning by the countries. In order to check whether the sender can induce imperfect learning, the signalling game is generalised to a setting where the sender chooses the precision of his truthful signal from a continuum. The unique fully revealing equilibrium of this game also reinforces the results of the binary-signal game.

The results are also robust in the case of distribution uncertainty, where the countries are not symmetric with respect to the social cost of GHG. In addition, by endogenising the time of communication, it is concluded that in a signalling setup, the countries in equilibrium block the possibility of any delay in revelation of the state by the sender.

As discussed in the chapter, the findings of the study depend on the simplifying linearity assumptions in the payoff functions and equation of motion of GHG. As a future extension, it would be interesting to investigate whether the results are robust to non-linear payoff functions where the abatement strategies may depend on the stock of global GHG.

In summary, the chapter from a signalling-game perspective concludes that, independently of the gap between the public prior belief and the true realisation, the research central authority fully and immediately reveals the information about the social cost of carbon.

5.4 Fourth Chapter: Optimal Communication of Climate Change With The Public

Similarly to the third chapter, the fourth chapter studies the interaction of the research central authorities and the countries in IEAs, where the sender sends information regarding the social cost of carbon. But in contrast to the third chapter, where an implicit agreement in an infinite-horizon model is studied, the fourth chapter models a coalition-formation game with fixed membership. Furthermore, instead of restricting the information sender to specific information strategies, an optimal information structure within the class of public information structures is derived. Lastly, in contrast to the third chapter, the sender has commitment power and at the stage of choosing the information strategies, he is uninformed about the state.

The main research questions of the study are: Is it possible to induce a specific membership outcome in a coalition formation game? In an IEA context, can a sender achieve a specific emission or abatement outcome? Furthermore, if the answer to these questions is positive, then what is the optimal information structure in coalition-formation games?

The question of the possibility of achieving the grand coalition or social optimum has been investigated extensively in the literature on IEAs. This chapter addresses the research questions using the new approach of information design, introduced by Kamenica and Gentzkow (2011), and relative to the strand of public information design, the study generalises the theory to coalition formation, where the receivers of the public information are two groups of signatories and non-signatories, who may have conflicts of interests.

The study develops a model where payoffs of both sender and receivers depend on the social cost of GHG and the emission decision of the countries. Furthermore, the payoffs of both sides are common knowledge. The sender, before observing the state variable, initiates research which is modelled as announcing the information mechanism (a set of signals and the probability distribution over them which is labelled information policy), and commits to it. After conducting the research, the sender sends a public signal according to the committed policy. The countries, after updating their beliefs, decide about membership of the coalition and subsequently about their emission actions.

It is shown that the equilibrium strategies of signatories and non-signatories take a threshold form with respect to their belief about the social cost of GHG, and it results in partitioning of the support of beliefs such that every partition of beliefs maps to a unique coalition size. Hence, in contrast to the literature on stochastic IEAs, where the beliefs about the state variable are exogenously given, here the beliefs and therefore the size of the stable coalition are induced by the information sender.

The optimal information structure is derived under various assumptions regarding the payoff of the sender, and it is verified that, if the payoff of the sender and either or both signatories and non-signatories coincide, the optimal information policy is full revelation of the state. However, if the sender seeks to minimise the global level of GHG, then imperfect learning may be induced as an optimal information policy. It is also shown that in all of these cases, the optimal information structure leads to the formation of a grand coalition, also the induced mitigation outcome coincide with the social optimum.

As a future extension to the model, it is worth examining the model if the information persuasion occurs after the membership stage. Such a question can be important in the practice pathway of the study, and can provide a robustness check of the results. Even if the results would be different, it still would be an interesting investigation.

Furthermore, the current coalition model is simplified in various dimensions, and a possible generalisation could be extension of the model to a dynamic setting, where the coalition formation can incorporate variable membership. Again, this has been proved to be an important issue in practice of IEAs, and has been given attention in the theoretical literature.

As a final remark, one of the most noteworthy contributions of the study is the suggestion of a new perspective affecting the membership decision of agents in coalition formation, which has been a central question in the literature on IEAs.

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