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International Environmental Agreements under Incomplete Contracts

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Abstract

The thesis analyses international environmental agreements (IEAs) in a static game setting expanding on standard modelling practices regarding two components. Firstly, incomplete contracts account for the abundance of multilateral environmental treaties currently in force. Countries may sign binding agreements on investments in clean technology while abatement efforts remain non-contractible. Secondly, abatement efforts are assumed to be strategic complements. Countries reduce their emissions in reaction to unilateral abatement due to international competitive re-enforcement effects. In this framework, second-best investments lie below ex-post efficient levels to induce a higher level of abatement. Building on the property rights literature, the thesis provides a tool for analysing emissions and investments yielding insights into the design of effective IEAs.

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Glossary

CGE - Computatable General Equilibrium

GEG - Global Emission Game

GHG - Green House Gases

IEA - International Environmental Agreement

IPCC - Intergovernmental Panel on Climate Change

NE - Nash Equilibrium

R&D - Research and Development

UNFCCC - United Nations Framework on Climate Change

1 Introduction

The nexus of environmental problems and its uncertain development poses an unprecedented challenge to international cooperative endeavours. Managing global public goods, such as the global climate, biodiversity or the maritime environment, hinges on voluntary contributions of sovereign countries by the means of individual efforts or international environmental agreements (IEAs). In the absence of an institution with the legitimacy to enforce an agreement, countries have an incentive to 'free-ride' by letting others face the costs of environmental protection. Especially when the stakes are high, strategic interactions between countries impede efficient solutions.

The central principles of current international law are grounded in the Westphalian system of the 17^{th} century. Sovereign nations are fundamentally self-determined, legally equal and free to manage their internal affairs without external intervention. While paramount for a peaceful society, the Westphalian sovereignty aggravates the inefficiencies of public good management (Nordhaus [2015]).

In vertical systems of law - the domain of public economics - public goods are sustained by a government with the legitimacy to impose taxes or allocate property rights. In the horizontal system of international law, however, economic incentives imply severe imperfections in the allocation of globally shared environmental resources. While contributors to an environmental agreement face the cost of pollution reduction, transboundary spillover effects may benefit all countries. Moreover, in case an agreement is achieved, compliance remains a critical issue due to the absence of a supranational institution with the authority to sanction defectors.

Economics has approached this dilemma with the instrument of game theoretic modelling, but results have been dire. IEAs have been studied extensively in the economic literature in the past two decades, but little progress has been made to explain the emergence of large-scale, long-term cooperation. The Intergovernmental Panel on Climate Change [2014] supports this observation in its most recent publication by mentioning among the five most pressing gaps in knowledge that “[c]urrent understanding of the factors that affect national decisions to join and form international agreements and how international cooperation can directly influence achievement of various performance criteria is incomplete”.

Recent surveys of the non-cooperative theoretical literature on IEAs can be found in Calvo et al. [2012] who focus of differential games and Finus [2008] who links a wide variety of modelling practices to an empirical model of strategic interaction. The latter publication follows a book-length survey of static and repeated games of IEAs in Finus [2000]. Furthermore, Dutta and Radner [2009] analyse a widely used type of model giving an account of all subgame perfect equilibria.

A striking phenomenon is the abundance of multilateral environmental treaties; Mitchell [2009] shows that there are 1241 agreements in force in 2013, and the number has been growing exponentially. While some of these have been highly effective with near full cooperation (e.g. The Montreal Protocol), the vast majority tends to merely codify already existing efforts as portrayed in Barrett [2005b]. This fact is not reflected in the above mentioned theoretical literature on IEAs. The most common conclusion is rather that international agreements are incentive compatible only if they involve a very small number of countries.

The non-cooperative approach to IEAs has come a long way since one of the first modelling attempts in Barrett [1994]. Recent contributions to the literature have emphasised the importance of incomplete contracts in modelling IEAs such as Battaglini and Harstad [2012] and Beccherle and Tirole [2011]. These models assume that countries have the ability to contract on certain variables such as emission reductions, while others factors remain non-contractible, for instance investments in clean technology. Specifying these two different channels of interactions gives rise to an increased degree of complexity in the models and creates new types of non-cooperative behaviour. As a consequence, Battaglini and Harstad [2012] can explain the emergence of large-scale, long-term cooperative behaviour.

The second development in the economic modelling of IEAs highlighted in this thesis is the assumption of strategic complementarity in emissions. The majority of non-cooperative IEA models predict that unilateral abatement leads to increased emissions in other countries, i.e. pollution is a strategic substitute. This approach may explain 'carbon leakage' whereby abatement efforts of signatory countries are partially offset by increasing production of pollution-intensive goods by non-signatories. However, findings from trade theory as well as other social, political and technological considerations suggest that abatement might in fact be fuelled by international re-enforcement effects.

Although the focus of the thesis is theoretical, and the underlying assumptions fit a wide range of phenomena, the most relevant association will be the issue of climate change mitigation. As greenhouse gas emissions accumulate in the atmosphere with near irreversibility regardless of the location of emission, they represent an excellent example of a global stock pollutant. Climate change mitigation resembles a global public good whereby all countries derive long-run benefits and none can be excluded.

Even if there was no controversy around an environmental issue from a natural scientific point of view – i.e. no uncertainty involving risks, knowledge about all non-linearities, full information about the allocation of damages and an accurate valuation of environmental goods – and if one abstracts from questions of equity, the economic considerations involved in the provision of public goods would still hamper their efficient utilisation.

This thesis explores new approaches in economic theory to understand, model and improve international environmental cooperation. The objective is to apply findings from the literature of incomplete contracts to the theory of IEAs and deduce specific results relevant to the design of effective treaties.

The thesis is structured into two main parts. First, section 2 gives an account of the fundamental results from the property rights literature and, subsequently, section 3 relates these finding to the theory of IEAs. While section 3.1 analyses one of the most general versions of an IEA model under incomplete contracts, section 3.2 provides a specific model and deduces final results.

2 Incomplete Contracts

The following chapter introduces a basic property rights model and illustrates its applications to IEAs. The goal is to deduce core results from a small set of weak assumptions. The sections of this chapter will incrementally generalise the analytic framework building on the extensive literature on incomplete contracts. The chapter is structured as follows.

After briefly sketching the development of the property rights literature and its application to IEAs, this analytical approach will be placed among other frameworks coping with environmental treaties in section 2.1.

Subsequently, section 2.2 will lay out the foundations of a general static property rights model, where agents take non-contractible actions after a property rights allocation has been established. This model does not allow for bargaining after actions have been taken. The upshot will be threefold.

- If there are no harmful externalities, an IEA can establish a first-best property rights allocation that sustains efficient actions in a Nash equilibrium, henceforth NE (Proposition 2.2.1).
- If actions generate positive externalities, equilibrium actions are weakly below those in an efficient outcome (Proposition 2.2.6).
- An IEA can specify a second-best property rights allocation, which is distorted away from what would be efficient ex-post to increase incentives for actions with positive externalities (Proposition 2.2.8).

2.1 Property Rights and Environmental Goods

Negotiating IEAs has proven to be a highly complex process aiming at establishing a politically, ecologically and economically feasible outcome in a dynamic environment while lacking a supranational institution with the power and legitimacy to enforce an agreement. Yet, the well corroborated Coase Theorem predicts a Pareto optimal outcome by distributing property rights given few basic assumptions are met. While the allocation of property rights will be key for the understanding of IEAs, a solution to the problem is not readily available. The Coase Theorem's irrelevance result is dissolved once non-contractible actions are introduced.

Regarding the property rights literature, a multitude of definitions for property rights coexist, ranging from an explicit bundle of rights to a residual understanding of the ownership of assets. Starrett [2003] exemplifies the former to include access, withdrawal, management, exclusion and alienation rights. Whereas Hart [1989] takes the position that ownership is "the right to use the asset in any way not inconsistent with a prior contract, custom, or any law". The latter definition has developed to become the predominant characterisation of property rights in the economic literature as it emphasises the role of ownership as an incomplete contract.

While the property rights framework has been employed to analyse a wide range of economic phenomena ranging from the theory of the firm to trade agreements and prison management; its application to environmental issues has been sparse. Among the few contributions have been Wirl [2013], Beccherle and Tirole [2011] and Harstad [2012]. Nevertheless, the efficient management of international environmental public goods precisely exhibits those properties that are at the core of the incomplete contracts literature, namely non-contractible actions, externalities and bargaining according to Wirl [2013].

The game theoretic literature about IEAs has in the past either pursued a cooperative or non-cooperative approach to modelling; incomplete contracts represent a third strand in this regard. Cooperative game theory builds on the assumption that treaties are binding while its non-cooperative counterpart assumes that they cannot be binding. Barrett [2005b], for example, argues that countries are unable to commit to an agreement essentially because of the lack of an agreement enforcing third party.

Non-cooperativ game theory, however, widely underpredicts the prevalence of IEAs. This can be illustrated by comparing the benchmark model of IEAs, as in Barrett [2005b], with evidence from the IEA Database Project by Mitchell [2014]. The benchmark model fails to account for cooperation of more than three countries while the database currently lists 1241 multilateral environmental agreements in effect in 2013. The real-world contracting environment likely lies between these two framings of the agreement process.

Drawing on findings from the incomplete contracts literature for the effective management of global environmental goods is crucial to fill this research gap. Countries sign environmental agreements and comply. This fact can be interpreted in various ways ranging from the 'warm glow' hypotheses of overcoming free-rider incentives in favour of the greater good, as empirically tested in Kolstad [2011], to assumptions of 'cynical codification'. The latter position is presented in Mitchell [2009] and describes the more dire view that IEAs merely codify behaviours which would have been undertaken in any event. Regardless of the interpretation, it is essential to, firstly, accept the fact that international agreements are currently in force and, secondly, focus the attention on the politically and environmentally important actions beyond a treaty's text.

2.2 General Static Model

2.2.1 Model Preliminaries

In this static one-shot model, observable but nonverifiable actions[1], $a_i \in \mathfrak{A}_i \subset \mathbb{R}$, are chosen by each agent, $i = 1, \dots, N$. These actions are geared towards a previously specified property rights allocation, $p \in \mathfrak{P} \subset \mathbb{R}^N$, which, to fix ideas, can be thought of as negotiated emission rights or less generally as predetermined emission quotas for pollutants. The action profile $a = (a_1, \dots a_N) \in \mathfrak{A} = \prod_i \mathfrak{A}_i$ may represent any quantity which is output relevant, dependent on the property rights specification and most importantly not subject matter of an agreement. The two most illuminating examples might be

[1] While all agents can tell what actions have been taken by other agents – they are observable – a third party, such as an arbitrator, cannot determine if the actions have been taken – thus they are nonverifiable. The instrumental assumption of observable and nonverifiable action has been criticised from an ontological, economic and legal point of point of view as summarised in Lind and Nyström [2007]. The assumption shall, nevertheless, be maintained throughout this thesis due to pragmatic reasons of resemblance to the international negotiation process.

i) substitute pollutants and other adverse side-effects, such as a rise in NO_x emissions and ancillary costs related to a regulation of CO_2 emissions documented inter alia in Holland [2011] and Intergovernmental Panel on Climate Change [2014] and

ii) investments in clean technology and other co-benefits, which will serve as a prime example in section 3.

Both are most likely negatively related to the emission quota but inhibit opposing transnational spill-over effects. The analysis will focus on determining the optimal allocation of property rights taking into account the direct effect on payoffs, but also the induced reactions in terms of non-contractible actions. If not otherwise indicated the models and results in this section are drawn from Segal and Whinston [2012, pp. 12].

Agents have utility of the form $U_i(p, a)$ and the aggregate surplus is notated as $S(p, a) = \sum_i U_i(p, a)$. The first-best outcomes are defined as

$$\mathfrak{O}^* = \underset{p \in \mathfrak{P},\, a \in \mathfrak{A}}{\arg\max}\, S(p, a).$$

Furthermore, given a fixed property rights allocation, the efficient actions are defined as $\mathfrak{A}^*(\tilde{p}) = \arg\max_{a \in \mathfrak{A}} S(\tilde{p}, a)$ and the efficient property rights allocations given fixed actions are $\mathfrak{P}^*(\tilde{a}) = \arg\max_{p \in \mathfrak{P}} S(p, \tilde{a})$. The latter set is interesting for hypothetical analytical grounds as it reflects the property rights allocations arising in the absence of incentive effects on actions. Should there be no feedback between property rights and non-contractible actions, the asset would be simply allocated to those agents who value access to it the most – the simple allocation benchmark. Although incentive effects cannot be neglected in the analysis of IEAs, this hypothetical situation will be used for comparative statics. Lastly, property rights allocations that can arise in a first-best outcome are $\mathfrak{P}^* = \{p \in \mathfrak{P} : (p, a) \in \mathfrak{O}^* \text{ for an } a \in \mathfrak{A}\}$.

The actions are chosen non-cooperatively to maximise the agents' payoff functions resulting in the following NE set of actions

$$\mathfrak{A}^N(\tilde{p}) = \left[a \in \mathfrak{A} : a_i \in \underset{a'_i \in \mathfrak{A}_i}{\arg\max}\, U_i(\tilde{p}, a'_i, a_{-i})\ \forall\, i \right] \tag{2.1}$$

An action profile resulting in a NE is denoted $a^N = (a_1^N, \dots a_N^N) \in \mathfrak{A}^N$.

2.2.2 Absence of Harmful Externalities

To understand the role of property rights on efficiency it is helpful first to abstract from externalities. Although the focus of this thesis lies in decision making under transnational spill-over effects from non-contractible actions, the following benchmark case illustrates under what conditions a first-best outcome may emerge.

It is helpful first to differentiate a type of externalities by restricting their scope.

Definition 2.2.1 (Absence of Harmful Externalities)**.** *Harmful externalities* are absent at $(p,a) \in \mathfrak{P} \times \mathfrak{A}$ if $U_i(p,a) \leq U_i(p,a_i,a'_{-i})$ for all i and all a'_{-i}.

The above model preliminaries and definition 2.2.1 permits the deduction of a first existence statement for equilibria and implications in regard to Pareto efficiency.

Proposition 2.2.1. *If harmful externalities are absent at a first-best outcome $(p^*,a^*) \in \mathfrak{O}^*$, then the action profile a^* is sustained in a NE, $a^* \in \mathfrak{A}^N(p^*)$. Moreover, every NE outcome (p^*,a^N) is efficient given the property rights allocation p^*, i.e. $a^* \in \mathfrak{A}^N(p^*) \subseteq \mathfrak{A}^*(p^*)$, and every NE action profile a^N given property rights p^* elicits the same payoff for each agent individually.*

Proof. Regarding the first part of the proposition, for all j and $a_j \in \mathfrak{A}_j$,

$$\begin{aligned} U_j(p^*,a^*) &= S(p^*,a^*) - \sum_{i \neq j} U_i(p^*,a^*) \\ &\geq S(p^*,a_j,a^*_{-j}) - \sum_{i \neq j} U_i(p^*,a_j,a^*_{-j}) \\ &= U_j(p^*,a_j,a^*_{-j}). \end{aligned}$$

The inequality follows from the fact that the actions are efficient for the given property rights, $a^* \in \mathfrak{A}^*(p^*)$, thus $S(p^*,a^*) \geq S(p^*,a_j,a^*_{-j})$, and from the assumption that harmful externalities are absent. Hence, $a^* \in \mathfrak{A}^N(p^*)$.

The second part can be proven by stating that for any $a^N \in \mathfrak{A}^N(p^*)$

$$U_i(p^*, a^N) \geq U_i(p^*, a_i^*, a_{-i}^N) \geq U_i(p^*, a^*) \; \forall i \tag{2.2}$$

$$\sum_i U_i(p^*, a^N) \geq \sum_i U_i(p^*, a^*) = S(p^*, a^*). \tag{2.3}$$

The first inequality holds due to the property of a NE and the second due to non-harmful externalities at (p^*, a^*). Summing over all agents and observing that the reverse of inequality 2.3 is implied by the first-best characteristic of the outcome, $(p^*, a^*) \in \mathfrak{O}^*$, yields the desired result that every NE outcome is efficient given p^*, so $a^N \in \mathfrak{A}^*(p^*)$. Finally, this implies that also inequality 2.2 has to hold with equality, $U_i(p^*, a^N) = U_i(p^*, a^*) \; \forall i$. □

While the assumption of absence of harmful externalities might appear strong, its results are distinct from the simple allocation benchmark mentioned before. In this type of models, efficiency can be achieved if there are no harmful externalities at a first-best outcome. Normatively, proposition 2.2.1 highlights the importance of picking a first-best allocation of rights which eradicates harmful externalities. Inspired by the traditional example of vertical integration by Williamson [1971], a possible solution might be allocating all property rights to a single agent if this forestalls suboptimal behaviour.

2.2.3 Externalities and Distortions

This thesis focusses on applications where harmful externalities from non-contractible actions are present at all first-best outcomes. In these cases, equilibrium actions are distorted away from Pareto optimality as a result of not internalised spill-over effects.

The majority of results in this section build on the theory of supermodular games which originated in industrial economics and encompasses a wide range of economic applications of non-cooperative game theory. The main characteristics of supermodular games are that each agent's strategy set is partially ordered and that the game exhibits 'strategic complementarity', meaning that the marginal return to increasing one's strategy rises with increases in competitors' strategies[2]. This small set of intuitively appealing

[2]The definition of supermodular games by Milgrom and Roberts [1990, p. 1255] also lists increasing differences in the components of each agent's strategy as a main characteristic if strategies are multi-

assumptions permits for robust existence statements about equilibria and conclusive comparative statics.

After introducing several basic concepts and fundamental theorems, this section aims to show that if actions generate harmful positive externalities at every first-best property rights allocation, equilibrium actions are weakly below those in an efficient outcome.

Externalities, positive or negative, shall be defined as follows.

Definition 2.2.2 (Externalities)**.** Actions generate positive (negative) *externalities* at p if, for all i, all $j \neq i$, and all $a_{-i} \in \mathfrak{A}_{-i}$, $U_j(p,a)$ is non-decreasing (non-increasing) in a_i.

The following definitions of increasing differences and supermodular functions are an integral part of the theory of supermodular games.

Definition 2.2.3 (Increasing Differences)**.** A function $f(x,y)$ has *increasing differences* in (x,y) if

$$f(x',y) - f(x,y) \leq f(x',y') - f(x,y')$$

for all $(x,y) \leq (x',y')$.

Essentially, the function f with increasing differences will represent a utility function that guarantees that the best response is upwards sloping – a cornerstone assumption of supermodular games ensuring well-behaved equilibria.

As an example consider investments in clean technology before an IEA is negotiated as presented in Harstad [2012]. If the burden of emission reductions is allocated to those countries with the lowest marginal abatement costs, it is strategically disadvantageous to invest in mitigation technology before an agreement is struck unless other countries undertake comparable efforts.

The following lemma stating the property of increasing differences for smooth functions is obtained with proof in appendix A.

Lemma 2.2.2. *A twice continuously differentiable function* $f : \mathbb{R}^2 \to \mathbb{R}$ *has increasing*

dimensional. This feature, however, is left out, because multidimensional strategy spaces lie beyond the scope of this thesis.

differences in (x,y) *if and only if* $y' \geq y$ *implies that* $f_x(x,y') \geq f_x(x,y)$ *for all* x*, or alternatively that* $f_{xy}(x,y) \geq 0$ *for all* (x,y)*.*

Most importantly, increasing differences allow for the application of an existence and monotonicity theorem for the set of maximisers of functions with increasing differences. This result has originally been derived in Donald M. Topkis' doctoral thesis in 1968 and later published in Topkis [1979]. This simplified version of the theorem using a subset of $\mathbb{R}$ instead of a lattice[3] can be found in Levin [2003] with proof in appendix A.

Theorem 2.2.3 (Monotonicity Theorem)**.** *Let* $X \subset \mathbb{R}$ *be compact and* Y *a partially ordered set. Suppose* $f : X \times Y \to \mathbb{R}$ *has increasing differences in* (x,y)*, and is upper semi-continuous in* x*. Then*

i) $x(y) = \arg\max_{x \in X} f(x,y)$ *exists for all* y *and has a greatest and least element,* $\overline{x}(y)$ *and* $\underline{x}(y)$ *respectively, and*

ii) if $y' \geq y$*, then* $\overline{x}(y') \geq \overline{x}(y)$ *and* $\underline{x}(y') \geq \underline{x}(y)$*.*

The concept of increasing differences extends to the idea of supermodular functions and subsequently to supermodular games.

Definition 2.2.4 (Supermodular Function)**.** A function $f(x)$ is supermodular in $x \in \mathbb{R}^m$ if it has increasing differences in every pair (x_k, x_l) of variables.

The following class of games was introduced by Topkis [1979]. Later this concept has been further developed and several applications analysed by Milgrom and Roberts [1990].

Definition 2.2.5 (Supermodular Game)**.** The game consisting of the tuple $(N, \mathfrak{A}_i, U_i)$ with $U_i : \mathfrak{A}_1 \times \ldots \times \mathfrak{A}_N \longrightarrow \mathbb{R}$ and $i \in N = \{1, 2, \ldots, n\}$ is a *(smooth) supermodular game* if for all i

A1 $\mathfrak{A}_i$ is a compact subset of $\mathbb{R}$,

A2 U_i is upper semi-continuous in a_i, a_{-i} and

A3 U_i has increasing differences in (a_i, a_{-i}).

[3] A set $\mathfrak{L}$ is a lattice if for each two point set $\{x,y\} \subset \mathfrak{L}$, there exists a supremum and an infimum for $\{x,y\}$ in $\mathfrak{L}$.

The type of supermodular games can be generalised to multidimensional strategy spaces by allowing $\mathfrak{A}_i$ to be a partially ordered compact lattice and adding the assumption that U_i is supermodular in the components of a_i, i.e. has increasing differences in all dimensions of a_i. The latter assumption represents the economic notion of complementary inputs. The main results of this section can be maintained in the multidimensional setting and under the weaker assumptions about ordering but these generalisations go beyond the scope of this thesis. The version presented above stems from Levin [2003, p. 3].

Supermodular games share several important properties which will be utilised for the purpose of incomplete contracts. They have pure strategy NE and the largest and smallest best strategy profiles exist, coinciding among the concepts of rationalisability, iterated strict dominance, correlated equilibria and NE.

A game satisfying assumptions A1, A2 and A3 exhibits *strategic complementarity* which means that the best response functions are upwards sloping. An actor's marginal utility of playing a higher strategy rises with increases in his rivals' strategies. In other words, when one actor increases his control variable, it becomes more profitable for the others to follow suit. The terminology of strategic complements and substitutes has been introduced by Bulow et al. [1985] in the context of oligopoly theory. While conventional complementarity in an oligopolistic market lowers or raises competitors' *total* profits; strategic complementarity, in turn, affect *marginal* profits.

The above-mentioned property of upwards sloping best response functions become immediately apparent by applying theorem 2.2.3 to the supermodular game structure.

Corollary 2.2.1. *Suppose* $(N, \mathfrak{A}_i, U_i)$ *is a supermodular game and that*

$$a_i^{BR}(a_{-i}) = \arg\max_{a_i \in \mathfrak{A}_i} U_i(a_i, a_{-i}).$$

Then

i) $a_i^{BR}(a_{-i})$ *has a greatest and least element,* $\overline{a}_i^{BR}$ *and* $\underline{a}_i^{BR}$ *respectively, and*

ii) if $a'_{-i} \geq a_{-i}$*, then* $\overline{a}_i^{BR}(a'_{-i}) \geq \overline{a}_i^{BR}(a_{-i})$ *and* $\underline{a}_i^{BR}(a'_{-i}) \geq \underline{a}_i^{BR}(a_{-i})$.

After establishing the characteristics of the best response functions, it remains to be shown that pure strategy NE exist. While it is possible to show this by applying Tarski's fixed-point theorem[4] to the correspondence $f(\tilde{a}) = \left(\overline{a}_1^{BR}(\tilde{a}),\, \ldots,\, \overline{a}_n^{BR}(\tilde{a})\right)$ as exemplified by Fudenberg and Tirole [1991, pp. 493]; here, a stronger version of the statement will be proven using iterated strict dominance. The proof can be found in Appendix A.

Theorem 2.2.4. *In a supermodular game, the set of strategies surviving iterated strict dominance has greatest and least elements $\overline{a}$, $\underline{a}$. Moreover, both are pure strategy NE.*

In terms of the property rights analysis, the above theorem translates directly to the following proposition which is satisfied by assumption.

Proposition 2.2.5. *If actions are strategic complements for a given property rights allocation $p \in \mathfrak{P}$ and the total surplus $S(p,a)$ is supermodular in a then the smallest and largest elements of the sets $\mathfrak{A}^N(p)$ and $\mathfrak{A}^*(p)$ exist, $\left(\underline{a}^N, \overline{a}^N\right)$ and $(\underline{a}^*, \overline{a}^*)$ respectively.*

Under the assumptions of proposition 2.2.5, Milgrom and Roberts [1990] show that the set of equilibria exhibits an order property. Namely, in the case of positive externalities the largest equilibrium, $\overline{a}^N$ and $\overline{a}^*$, is Pareto superior while the smallest equilibrium, $\underline{a}^N$ and $\underline{a}^*$, are Pareto inferior. This holds correspondingly for negative externalities. It will be assumed that actors always settle on the welfare maximising equilibrium.

The next step will prepare the formal tools to compare the NE and the efficient action sets for a given property rights allocation. To attain this goal, the notion of indexed supermodular games, due to Milgrom and Roberts [1990], will be used.

Definition 2.2.6 (Indexed Supermodular Game)**.** A supermodular game is *indexed* by λ if each players' payoff function is indexed by $\lambda \in \Lambda$, an ordered set, and for all i, $U_i(a_i, a_{-i}, \lambda)$ has increasing differences in (a_i, λ).

The distribution of property rights will be symmetric across actors in the applications of this thesis. If countries are identical, their emission quotas will be similar in magnitude. The larger the mitigation burden is, which will be represented by the property rights variable p, the higher will be the incentive to invest in clean technologies for each country. The following corollary states this property for supermodular games. Subsequently,

[4]**Tarski's Fixed Point Theorem.** *If T is a complete lattice and $f : T \to T$ is a non-decreasing function, then f has a fixed point. Moreover, the set of fixed points of f has $\sup\{x \in T : f(x) \geq x\}$ as its largest element and $\inf\{x \in T : f(x) \leq x\}$ as its smallest element Milgrom and Roberts [1990].*

proposition 2.2.6 applies this result to the theory of property rights. Both statements are proven in appendix A.

Corollary 2.2.2. *Suppose* $(\mathfrak{A}, U)$ *is a supermodular game indexed by* $\lambda \in \Lambda$*, some ordered set. The largest and smallest NE are increasing in* λ*.* [5]

Proposition 2.2.6. *If actions generate positive (negative) externalities at p, then* $\underline{a}^N \leq \underline{a}^*$ $(\underline{a}^N \geq \underline{a}^*)$

Under the assumption of positive (negative) externalities, proposition 2.2.6 implies that equilibrium actions a^N are weakly below (above) those in any efficient outcome if there is a unique equilibrium action profile at property rights allocation p.

Up to this point, the presented theories support the intuition that externalities, when they are inevitable, skew incentives away from an efficient outcome. Internalising these has the benefit of improving equilibrium actions.

While the above mainly aimed at conveying fundamental game theoretic tools for the analysis of IEAs with limited scope of discretion; the following sections will focus on the importance of property rights allocations to grapple with inefficient incentive structures and to achieve a second best outcome.

2.2.4 Second-Best

After defining second-best outcomes for the static game with property rights as outlined before, this section will proceed to sketch the economic trade-off between the property rights allocation and induced actions. The first result will be a lemma about specific situations where this trade-off is not immediately relevant. Subsequently this first step will be used to prove the central proposition of this section showing that a second-best property rights allocation is distorted away from what would be efficient ex-post and, moreover, this distortion is in the direction that increases (decreases) incentives for actions with positive (negative) externalities.

A second-best outcome is defined as an optimal outcome subject to the constraint that agents choose optimal actions non-cooperatively, i.e.

[5] Proof see Levin [2003] p.6

$$\mathfrak{O}^{**} = \underset{p\in\mathfrak{P},\, a\in\mathfrak{A}^N(p)}{\arg\max}\; S(p,a).$$

Moreover, the property rights allocations linked to second-best outcomes are denoted as $\mathfrak{P}^{**} = \{p \in \mathfrak{P} : (p,a) \in \mathfrak{O}^{**} \text{ for some } a \in \mathfrak{A}\}$.

If a property rights allocation is both directly beneficial, i.e. $S(p', a) \geq S(p, a)$, and induces (stifles) actions with positive (negative) externalities then the outcome is welfare-enhancing.

Lemma 2.2.7. *Let $a \in \mathfrak{A}^N(p)$ and $a' \in \mathfrak{A}^N(p')$ be two NE resulting from the property rights allocations p and p'. If actions generate positive (negative) externalities at p' and $a' \geq (\leq)\ a$ then*

$$S(p',a) \geq S(p,a) \implies S(p',a') \geq S(p,a)$$

Proof.

$$\begin{aligned} S(p',a') - S(p,a) &\geq S(p',a') - S(p',a) = \sum_i \left[U_i\left(p',a'\right) - U_i\left(p',a\right)\right] \\ &\geq \sum_i \left[U_i\left(p',a_i,a'_{-i}\right) - U_i\left(p',a\right)\right] \\ &\geq 0 \end{aligned}$$

where the first inequality is implied by the premise, the second is a result of $a' \in \mathfrak{A}^N(p')$ and the last due to positive (negative) externalities at p' and $a' \geq (\leq)\ a$. □

While lemma 2.2.7 considered property rights changes which both induced surplus-enhancing behavioural changes and lead to an increase in ex-post surplus for fixed actions; the following proposition will also look at cases where a trade-off between direct and indirect effects of changes in the property rights allocation exists.

For the remainder of this section, the property rights allocation shall be single-dimensional for simplicity, $p \in \mathfrak{P} \subset \mathbb{R}$. Besides tractability, this assumption is representative for situations in which all parties agree on a single mitigation goal that is shared equally or in which countries are identical.

Proposition 2.2.8. *Consider actions which are strategic complements for all property rights allocations and suppose that $U_i(p,a_i,a_{-i})$ has increasing differences in (p,a_i) for all i. Take any second-best outcome $(p^{**},a^{**}) \in \mathfrak{O}^{**}$ and any ex-post efficient allocation given actions a^{**}, i.e. $p' \in \mathfrak{P}^*(a^{**})$. Under the assumption that actions generate positive (negative) externalities at p' one finds that $\max\{p',p^{**}\} \in \mathfrak{P}^{**}$ ($\min\{p',p^{**}\} \in \mathfrak{P}^{**}$).*

Proof. Consider the case of positive externalities at p' and let $p' > p^{**}$. For the reverse inequality or equality the proposition is satisfied by assumption because trivially $\max\{p',p^{**}\} = p^{**}$. As established in theorem 2.2.4 the assumptions are sufficient for the existence of the largest NE action profiles $a' = \max \mathfrak{A}^N(p')$ and $a^{**} = \max \mathfrak{A}^N(p^{**})$. Observe that the game is supermodular and indexed by p, thus $p' > p^{**}$ implies $a' \geq a^{**}$. Furthermore, the ex-post optimality of the property rights allocation $p' \in \mathfrak{P}^*(a^{**})$ leads to the inequality $S(p',a^{**}) \geq S(p^{**},a^{**})$. As the premises of Lemma 2.2.7 are satisfied one can conclude that $S(p',a') \geq S(p^{**},a^{**})$, so also $p' \in \mathfrak{P}^{**}$. The proof for negative externalities works by the same token. □

When a unique second-best outcome can be determined and positive externalities are present at all allocations, proposition 2.2.8 implies that p^{**} is weakly higher than any ex-post efficient allocation $p' \in \mathfrak{P}^*(a^{**})$ given actions a^{**}. The converse statement is true for negative externalities. In any respect, the second-best allocation of property rights moves in the direction which generates a positive effect through the induced actions.

For a general set of second-best outcomes, it has been established that $\max\{p',p^{**}\} \in \mathfrak{P}^{**}$. Consequently, a second-best allocation is either larger than an efficient one in term of property rights or, when this is not the case, the efficient and the second-best allocations elicit the same level of aggregate utility. This fact is implied by the result that $S(p',a') \geq S(p^{**},a^{**})$ while the reverse inequality also holds due to the second-best property of (p^{**},a^{**}).

To illustrate the above proposition with an application to IEAs, consider that countries have the possibility to contract on enforceable emission reduction quotas. These negotiated mitigation prescriptions can be represented by the property rights p. It is reasonable to assume that the marginal gain to investments in clean technology rises both with increases of the mitigation quota to substitute for the lost input factor and the investments of other countries if long-term strategic effects are accounted for. Hence, an IEA needs to account for the induced effect from emissions to non-contracted investments in a way that the latter are increased.

3 International Environmental Agreements

After laying out the theoretical foundations for incomplete contracts in game theoretic models, the following chapter explores applications in the area of international environmental agreements. The table below summarises the game designs that are described in the remainder of this thesis.

Table 3.1: Topology of game structures

Game structure	**Benchmark**	**Emissions / Abatement**	**Investment**	**Section**
Global Emission Game	Non-contractible	Non-coop.	Exogenous	3.1.3
	Cooperative	Cooperative	Exogenous	3.1.4
	Incomplete contracts	Non-coop.	Cooperative	3.1.5
Specific model	Non-cooperative	Non-coop.	Exogenous	3.2.2
	First-best	Cooperative	Cooperative	3.2.3
	Incomplete contracts	Non-coop.	Cooperative	3.2.4

3.1 The Global Emission Game

The following model is known as the Global Emission Game (GEG) and is the most general static version of a large class of models in the literature on IEAs. It is contained among others in the original emission game put forward by Barrett [1994] or more recently in Helm and Wirl [2014]. Moreover, it represents a special case of the dynamic model in Harstad [2012].

The model at hand is the basic game theoretic interpretation of a situation where countries control a continuous amount of emissions. These emissions result in local consumption while a global public bad is produced.

This type of model is frequently applied to analyse non-cooperative behaviours in settings where global cooperation would maximise individual payoffs while free-rider incentives forestall an efficient outcome. Besides comparing the cooperative and non-cooperative benchmarks, the model is often framed as a coalition formation game where countries decide in a preceding game stage whether they want to be part of a group of cooperating countries. The latter group are often called signatory states of a treaty or participants in an international environmental agreement as opposed to non-signatories or free-riders.

This game design is well known for its dire results. On the one hand, cooperative behaviour is hardest to achieve when it is needed the most. The larger the externality and the more countries are involved the larger is the incentive to free-ride on other countries mitigation efforts as summarised in Barrett [2005a]. On the other hand, as shown for example by Diamantoudi and Sartzetakis [2006], cooperation of at most three countries can be elicited because of the lack of an enforcement mechanism and as benefits to staying out of an agreement are increasing rapidly with the number of signatories.

An extension to the model very often found in the literature adds a second control variable, namely investment in clean technologies. These R&D investments are modelled in a wide variety of ways, from damage reducing such as in Helm and Wirl [2014] to consumption increasing for example in Benchekroun and Chaudhuri [2011]. Clean technology is nearly exclusively modelled as a type of public good, whereby investment of one country yields positive externalities often via a shared stock of R&D. The game structure used in Harstad [2012] is exceptional in the regard that every single country invests in its independent stock of clean technologies. Only through interaction in a dynamic setting, R&D obtains a public good character.

The aim of the following section is threefold:

- Apply findings from chapter 2 to IEAs with a focus on climate change models.
- Explore the GEG under the assumption of incomplete contracts by expanding on the standard model with an R&D component. Countries will have the possibility to sign binding agreements on the level of R&D.
- Follow novel modelling practices by allowing for strategic complementarity.

While this section works with general functions, a specific example will be given thereafter in section 3.2.

3.1.1 Model Preliminaries

The model at hand is inspired by Heugues [2013] insightful classification of strategic interactions between countries in GEGs. The author draws in her research on recent results from the literature on trade and concludes that trade liberalisation fundamentally modifies countries' interactions over emissions.

While Heugues [2013] specifies the GEG in terms of emissions, the model in this thesis will pursue an abatement modelling approach as for example in Barrett [2005a], Diamantoudi and Sartzetakis [2006], Beccherle and Tirole [2011] or Schmidt and Strausz [2014]. Diamantoudi and Sartzetakis [2006] provide a formal proof that the two types of models are directly comparable when abatement is defined as a reduction in the flow of emissions. The rationale behind focusing on abatement rather than emissions as control variables lies in the interpretation of model components which will be detailed in section 3.1.2.

The model is expressed as a symmetric game of n identical countries, $i \in \{1,...,n\}$. Each country's payoff function is expressed as the difference between benefits linked to global abatement efforts, $B\left(\sum_{i=1}^{n} a_i\right)$, and the costs of abatement and investments in R&D, $C(p,a_i)$ and $K(p)$ respectively. The global level of technology, p, affects pollution mitigation via the cost of abatement[1].

Payoff are, thus, defined as

$$U(p,a_i,a_{-i}) = B(a_i + a_{-i}) - C(p,a_i) - K(p) \quad \text{for all } i \in \{1,...,n\}, \tag{3.1}$$

where $a_i \in [0,K]$ represents country i's abatement efforts and $a_{-i} \in [0,(n-1)K]$ is the sum of all other countries abatement. Abatement has to be limited so that it does not exceed the maximum uncontrolled flow of emissions. Diamantoudi and Sartzetakis [2006] show that limiting the space of abatement efforts is necessary for a meaningful interpretation of abatement as reduction in the flow of emissions and to guarantee that

[1] Level of clean technology and investments in R&D will be used synonymously. The interpretative difference between flow and stock does not alter the results of this thesis as all examined models are static and p will be either exogenous or jointly set throughout.

all results from the GEG in terms of emissions are carried over to this type of model[2].

The functions $B: R^+ \Longrightarrow R^+$ and $K: R^+ \Longrightarrow R^+$, are assumed to be twice continuously differentiable and strictly increasing in their respective arguments. Countries exert positive abatement externalities

$$\frac{\partial U}{\partial a_{-i}} \geq 0 \quad \forall i.$$

Abatement costs $C: R^{+2} \Longrightarrow R^+$ are twice continuously differentiable and are assumed to satisfy the following criteria

$$\frac{\partial C}{\partial a_i} \geq 0, \quad \frac{\partial C}{\partial p} \leq 0, \quad \frac{\partial^2 C}{\partial a_i \partial p} < 0.$$

The assumption that the global level of clean technology has a negative effect on marginal abatement costs is standard in the literature as stated in Schmidt and Strausz [2014].

While countries have control over their individual abatement efforts, a_i, the R&D level p is exogenous in sections 3.1.3 and 3.1.4, and jointly set using an incomplete contract in section 3.1.5. Decisions on abatement are taken simultaneously, and countries maximise their payoff given the level of clean technology. Due to the assumption of symmetric countries, abatement levels coincide at an equilibrium.

The following section turns the attention to basic consequences of unilateral abatement efforts.

3.1.2 Strategic Complementarity

This section first describes the notion of strategic complementarity and substitutability in the context of the GEG. Subsequently, the rationale for focussing on the former concept will be put forward. Although using strategic complementarity is clearly beyond mainstream modelling practices for GEGs, there are strong arguments in favour of using this specification mainly from Copeland and Taylor [2005] and Heugues [2013].

Game theoretic models of IEAs analyse how countries react to unilateral emission re-

[2] The latter argument is crucial for results from coalition formation models.

ductions. Two types of reactions are conceivable. On the one side, some models assume that a reduction in emissions in one country leads to increased pollution in others. Emissions are, thus, substituted by pollution in other countries. On the other side, emissions may also be complementary. In this case, countries face a strategic incentive to reduce pollution if others are doing the same. The latter assumption is termed strategic complementarity.

Strategic interactions in the GEG hinge on the function that captures the externality. In models that are set up with benefits to emissions and cost of pollution, counties influence other countries' behaviour via damages of transboundary pollution. When abatement is the control variable as in the model specified above, strategic decisions are based on the benefit of joint abatement efforts.

The above game structure is characterised by the curvature of the benefit function. Inspecting the change in marginal utility of a unit of abatement when the behaviour of other countries changes, one finds that the cross partial derivative of the payoff function equals

$$\frac{\partial^2 U}{\partial a_i \partial a_{-i}} = \frac{\partial^2 B}{\partial a_i \partial a_{-i}} = B''(a_i + a_{-i}). \tag{3.2}$$

Due to the additive nature of the problem, i.e. only the sum of abatement efforts affects benefits, the cross partial derivative of the benefit function is equivalent to the second derivative with respect to abatement [3].

Hence, the game is coined by strategic complementarity if the benefit function is convex, i.e. if $B'' > 0$. Conversely, if the benefit function is concave, abatement levels are strategic substitutes. In the former case, the best-response function is strictly increasing in its argument and countries have a larger incentive to step up their efforts if other countries are doing the same.

Mainstream modelling practices for GEGs often explicitly reject the assumption of convex benefit functions. Finus [2000], one of the most comprehensive early accounts of game theoretic IEA models, for example, stated that "[...] one has to think hard to find a case where [the assumption of a convex benefit function][4] would hold true". Also Calvo

[3] It is also common to model benefits from abatement as a weighted sum to capture the importance of local abatement on benefits over international efforts as performed in Schmidt and Strausz [2014]. This assumption, however, would not aid the analysis in this thesis.

[4] Finus [2000] expresses this point in terms of a concave damage function rather than a convex benefit

et al. [2012], who provide a survey of dynamic models, list nearly exclusively models with convex benefits to abatement or equivalently concave damages to emissions.

The main argument against strategic complementarity in abatement is carbon leakage, whereby emission reduction are offset by an increase in pollution outside an IEA. According to Barrett [2005a], coordinated emission reductions of a group of countries have an effect on relative prices. Shifting demand leads pollution-intensive industries to evade to non-participating countries, increasing emissions in the target region; partly offsetting the originally intended emission reduction. These effects are particularly prominent in the theoretical literature on coalition formation games mentioned in 3.1, as carbon leakage poses an additional free-rider incentive.

Examining the evidence however, the Intergovernmental Panel on Climate Change [2014] assesses the importance of carbon leakage for climate change mitigation policies as ambivalent:

> ”Scenario studies have shown that such ‘carbon leakage’ rates of energy-related emissions are relatively contained, often below 20% of the emissions reductions. Leakage in land-use emissions could be substantial, though fewer studies have quantified it. While border tax adjustments are seen as enhancing the competitiveness of GHG- and trade-intensive industries within a climate policy regime, they can also entail welfare losses for non-participating, and particularly developing, countries.”

Notwithstanding the scepticism expressed by Finus [2000], a large number of researchers have since *”thought hard”*, and evidence in favour of strategic complementarity is accumulating. This approach is most commonly justified by international spillovers that act as reinforcement effects. These can be results of competitive interactions between governments in terms of technological, political and social factors or trade.

The notion of complementarity in the GEG means that a country has a higher benefit of increasing abatement efforts if other countries are doing the same or, equivalently, it is less inclined to reduce pollution if others are increasing emissions. Reinforcement effects lead to concerted movement in terms of the level of production and consumption

function. These two assumptions are in effect equivalent as they both entail strategic complementarity in emission reduction.

that trigger emissions. This idea relies on the diffusion of consumption and production paths between countries as expressed by Heugues [2013] and resembles what is known in international trade theory as a scale effect.

Recent findings from general equilibrium models corroborate the assumption of strategic complementarity and describe a phenomenon termed *negative leakage*. Copeland and Taylor [2005] analyse a deliberately conventional perfectly competitive general equilibrium trade model of two open economies with two inputs and two outputs. Countries can specialise in producing clean goods or pollution-intensive goods and consume a combination thereof. By endogenising consumption and production factors in an open economy simultaneously, it can be shown that international trade has the potential to harmonise marginal abatement costs across countries. The authors decompose a country's best response to unilateral mitigation policies into free-rider, substitution and income effects. Depending on the elasticities of substitution in production and consumption and the size of the free-rider and income effects, they show that it is conceivable that other countries reduce their emissions in reaction to unilateral abatement efforts. Consumption of environmentally friendly goods will rise because pollution-intensive goods become more expensive. The substitution effect in consumption and the income effect always work against carbon leakage as relative price changes for pollution-intensive and clean goods always affect both production and consumption.

More recently Baylis et al. [2014] specify a CGE model along the lines of Copeland and Taylor [2005]. They coin the term 'abatement resource effect' which essentially captures the price driven and consumption-inducing shift towards clean production. The authors distinguish three necessary assumptions that need to be met to create negative leakage. First, substitution in consumption towards pollution-intensive goods after a mitigation policy is not perfect. Second, inputs to production can be substituted towards clean inputs. Third, the clean input is mobile between countries. Baylis et al. [2014] simulate sizeable negative leakage effects, although they do not argue that leakage must necessarily be negative.

Besides findings from the literature on trade, strategic complementarity has also been addressed from political, social and technological vantage points. Although Wagner [2011] describes complementarity in the timing of treaty ratification, his arguments are relevant to this analysis. Strategic complementarity may arise for a variety of reasons, including social preferences or concerns about reputation held by governments, discreteness of the public good which the treaty seeks to provide, or aspects of the treaty design itself.

Also Heal and Kunreuther [2012] argue that strategic complementarity is present in the ratification of climate change agreements and elaborate on the existence of tipping treaties, a critical mass of countries participating in an agreement to elicit an efficient equilibrium. This approach has been pioneered by Heal [1994]. They attribute complementarity to two factors. First, they mention scale effects in R&D, specifically fixed costs of developing new technologies which may be shared among signatories. Second, they emphasise that committing to reducing emissions has a reciprocal effect on the loss of competitiveness. The larger the number of countries implementing mitigation policies, the less is the risk of carbon leakage occurring. Contrary to models which focus on small coalitions or penalties for non-participants such as Nordhaus [2015], Heal and Kunreuther [2012] emphasise the importance of a broad agreement and its self-enforcing strength.

This thesis builds on the argumentation rendered above. Models allowing for strategic complementarity in abatement capture elements of international trade but also technological, political and social interactions, which are otherwise out of the scope of GEG models.

Another line of critique questions the convexity of abatement benefits directly. The Intergovernmental Panel on Climate Change [2014] provides a comprehensive analysis of potential tipping points and thresholds in the global climate system which can lead to catastrophic consequences. It is assumed that the system's auto-purification capacities are reduced at higher concentrations of greenhouse gases in the atmosphere. Hence, there are evident non-linearities in the damages linked to climate change, which is widely accounted for in the literature. An exception is a recent publication by Dutta and Radner [2009], who justify their assumption of linear damages by the grounds of model tractability and lack of consensus about the form of non-linearity.

Although this criticism remains essentially relevant, specifying the model in terms of abatement rather than emissions might allow more leeway for interpretation. As previously described, abatement efforts and emissions are closely related. A convex damage function is mirrored by concave gains to mitigation. Avoiding the most dangerous consequences of anthropogenic climate change has the largest impact while marginal benfits of emission reduction are decreasing at lower levels of GHG in the atmosphere. When emissions have decreased to a lower level, for example, the 2 degrees Celsius target set by the UNFCCC, benefits from emission reduction might not be as large. The concentration of GHGs in the atmosphere is measured in parts per million (ppm) and damage studies are abundantly available. Abatement, on the other hand, can have a variety of interpretations. This breadth in interpretation is a strength which is utilised in this thesis to explore a wide class of strategic interactions.

After illustrating two benchmark scenarios in the following two sections, this chapter proceeds to analyse incomplete contacts in section 3.1.5.

3.1.3 Non-Contractible Emissions

The following section identifies the GEG as a supermodular game and draws first results about the existence of equilibria.

In the pure non-cooperative benchmark, each country i maximises its payoff given the level of clean technology p and taking other countries' emissions as given. Best responses equate marginal costs and benefits without taking the externality into account.

When the benefit function is strictly convex, the cross partial derivative of $U(p, a_i, a_{-i})$ with respect to a_i and a_{-i} is strictly positive as shown in 3.2. Consequently, lemma 2.2.2 implies that the function $U(p, a_i, a_{-i})$ has increasing differences in (a_i, a_{-i}). As argued in the preceding section, countries will increase their abatement efforts in reaction to higher abatement from others. This property, however, neither remedies the public good character of the game as efforts might still be suboptimally low nor would it eliminate the free-rider incentive in a coalition formation model.

The GEG thereby satisfies criteria A1 to A3 from definition 2.2.5 to be deemed a supermodular game. This characteristic opens the analysis up to a wide variety of readily available game theoretic results and inherits properties of well-behaved equilibria to the structure.

By Topkis' Monotonicity Theorem, cited in 2.2.3 and as shown in Corollary 2.2.1, the best response function a_i^{BR} has a highest and smallest element respectively denoted by

$\overline{a}_i^{BR}$ and $\underline{a}_i^{BR}$ for every level of investments in clean technology p.

When the benefit function is strictly convex, the existence of a Nash Equilibrium, non-empty $\mathfrak{A}^N$, is directly established as a consequence of Theorem 2.2.4[5]. Moreover, one obtains the existence of smallest and largest elements in the set of Nash equilibria with an order property that the largest equilibrium is Pareto superior in the case of positive externalities. The equilibrium point, however, can be unique as will be demonstrated in section 3.2.

The next section will turn to the cooperative benchmark and qualitatively compare the two scenarios.

3.1.4 Cooperative Benchmark

In the full cooperative case, countries maximise their joint payoff given technology level p. As abatement exerts positive externalities via the benefit function, the ensuing total surplus is larger in the cooperative benchmark than in the non-cooperative one,

$$S\Big(p, \sum_{i=0}^{n} a_i\Big) = \sum_{i=1}^{n} \Big[U_i\Big(p, \sum_{i=0}^{n} a\Big)\Big].$$

Aggregate surplus $S(p, \sum a_i)$ exhibits increasing differences in every pair $(a_i,\, a_j)$ for $i \neq j$ following the argumentation in the proof of proposition 2.2.6. Hence, all conditions are satisfied for the application of proposition 2.2.5. This implies that both $\mathfrak{A}^N$ and $\mathfrak{A}^*$ are non-empty and the equilibria have smallest and largest elements. Moreover, the larger equilibria are Pareto superior.

One finds that $\overline{a}^* > \overline{a}^{NE}$ and analogously for the lowest elements following proposition 2.2.6.

[5]Heugues [2013] shows that in the presence of strategic complementarities in $(a_i,\, a_{-i})$, it must be the case that the cost function is also convex, $C''(a_i) > 0$. This is proven by contradiction as the evolution of global and individual equilibrium abatement levels would go in incompatible directions.

3.1.5 Incomplete Contracts

This section first lays out the rationale behind incomplete contracts in IEAs. The assumption that countries can sign binding contracts is strong from a game theoretic perspective; however it portrays the fact that there are numerous IEAs in place that are successful at generating compliance. Moreover, the literature on incomplete contracts in IEAs is scarce, although results may be crucial to the design of an eventual climate mitigation treaty.

This thesis deliberately abstracts from the notions of limited participation in an agreement and non-compliance issues in order to shift the focus to elements of treaty design. The excluded factors are certainly important for effective IEAs. However, they have been treated to a large extent in the economic literature and are in the degree of abstraction often far from empirical evidence. This was highlighted beforehand in section 2.1.

Figure A.1 in the appendix depicts a conceptual map of international institutions involved in climate change mitigation. The Intergovernmental Panel on Climate Change [2014] expresses in the most recent report the importance of the current state of IEAs as follows:

> "[I]n theory and practice, international institutions can help to promote, negotiate, and administer an IEA. They can do so by serving to coordinate and moderate negotiations and implementation, reducing transaction costs of negotiations, and generating trust; changing the interests of actors by providing new information or building capacity; enlisting actors in domestic politics within and across states; and inculcating norms."

Moreover, participation and compliance do not necessarily imply success, as an important criterion for an effective IEA is whether it changes countries' behaviours rather than codifies existing business as usual practices as pointed out by Mitchell [2009]. Among the four categories of compliance, namely treaty-induced compliance, coincidental compliance, good faith non-compliance and intentional non-compliance, only the first one is treated in detail in this thesis.

Countries have the possibility to sign binding agreements on investment in technology. Thus, this thesis abstracts from the difficulties of motivating participation and compliance similar to the models in Battaglini and Harstad [2012]. Also according to Harstad [2012] countries may be able to commit to at least the short term as domestic stakeholders can hold the government accountable if a treaty has been ratified.

Regarding the effect of clean technology on abatement, on can state that country i's payoff is supermodular in (p, a_i) because $\frac{\partial^2 C}{\partial a_i \partial p} < 0$ and hence

$$\frac{\partial^2 U}{\partial a_i \partial p} = -\frac{\partial^2 C}{\partial a_i \partial p}.$$

If countries cooperate in R&D, proposition 2.2.8 ascertains that investments are set such that abatement efforts are encouraged. For any second best level of abatement, the ex-post efficient level of technology lies weakly below the second best level.

The results in this chapter can conceptually be generalised to any public good situation, which exhibits strategic complementarity. Investment in clean technology is one area that has a positive effect on climate change mitigation and is correctly seen as one of the most important factors behind any IEA. An eventual agreement needs to take the pivotal role of R&D into consideration and should provide a framework to trigger investments which lie not only above the business-as-usual scenario, but also above an ideal first-best level.

The next chapter analyses a specific model in detail and expands on the above-presented findings by introducing a simple explicit model and solving it.

3.2 Modelling Incomplete Contracts

The present chapter illustrates the general findings of the previous sections with a specific model. A static game represents the strategic interactions of countries which decide over the amount of emissions of a global transboundary pollutant and investments in clean technology. Comparative static results for the non-cooperative and full cooperative benchmark as well as the case of incomplete contracts will be provided.

3.2.1 Model Preliminaries

Similar to the previous section, the model at hand describes a static game among n identical countries, $i \in \{1,...,n\}$. Countries have discretion over the amount of pollution abatement, a_i. Reducing emissions from a business-as-usual scenario yields positive spill-over effects for all other countries. Payoffs are structured as the difference between benefits from pollution abatement, $B(a_i + a_{-i})$, and costs for mitigation and investment, $C(a_i,p)$ and $K(p)$ respectively.

Unilateral reduction of emissions yields convex benefits for all countries. This represents the abatement of a transboundary pollutant. Marginal benefits are increasing linearly by a factor b. As can be seen in the following equations, the model is consistent with the conditions for strategic complementarity set out in section 3.1.2

$$\begin{aligned} B(a_i + a_{-i}) &= \frac{b}{2}(a_i + a_{-i})^2 \\ \frac{\partial B}{\partial a_i} &= \frac{\partial B}{\partial a_{-i}} = B'(a_i + a_{-i}) = b(a_i + a_{-i}) \\ \frac{\partial^2 B}{\partial a_i \partial a_{-i}} &= B''(a_i + a_{-i}) = b > 0. \end{aligned}$$

While the level of clean technologies, p, is set exogenously in section 3.2.2, countries will be able to jointly determine their R&D policy in the sections thereafter. Costs of emission reduction are growing quadratically, but one unit of clean technologies substitutes one unit of abatement.

$$C(a_i, p) = \frac{c}{2}(a_i - p)^2$$

Marginal costs are increasing in abatement efforts and decreasing in the level of clean technologies as long as $a_i > p$. This condition will be shown to be true for each model setup individually. Moreover, the following equations show that marginal costs are decreasing in p as the cross-partial derivative is negative

$$\frac{\partial C}{\partial a_i} = c(a_i - p) > 0$$
$$\frac{\partial C}{\partial p} = -c(a_i - p) < 0$$
$$\frac{\partial^2 C}{\partial a_i \partial p} = -c < 0.$$

Finally, sustaining a level of clean technology p is linked to quadratic costs $\frac{k}{2}(p-1)^2$. The parameter k represents the slope of each country's marginal costs to investment. Together these elements yield the following expression for a country's utility

$$U(p, a_i, a_{-i}) = \frac{b}{2}(a_i + a_{-i})^2 - \frac{c}{2}(a_i - p)^2 - \frac{k}{2}(p-1)^2.$$

All cost and benefit parameters are assumed to be positive, $b > 0$, $c > 0$ and $k > 0$. A single additional parameter assumption has to be put in place to guarantee positive abatement and R&D levels as well as the existence of maxima across all presented models. This assumption, called assumption A, implies two weaker assumptions that are by themselves sufficient for some of the following results.Their relevance will be highlighted explicitly. Implications are proven in appendix A,

$$ck - (c+k)bn^2 > 0 \tag{A}$$
$$\implies c - b > c - bn^2 > 0 \tag{A.i}$$
$$\implies k(c - bn)^2 - (c-b)bcn^2 > 0. \tag{A.ii}$$

Overall, payoffs are concave in the level of clean technologies p and country i's own abatement by assumption A.i. At the same time, there are increasing differences in terms of (a_i, a_{-i}) and (a_i, p) as stated by the following,

$$\frac{\partial^2 U}{\partial^2 a_i} = b - c < 0, \quad \frac{\partial^2 U}{\partial^2 p} = -c - k < 0, \quad \frac{\partial^2 U}{\partial a_i \partial p} = c > 0, \quad \frac{\partial^2 U}{\partial a_i \partial a_{-i}} = b > 0.$$

3.2.2 Non-Cooperative Benchmark

In a first approach to analysing IEAs, the non-cooperative benchmark will serve as reference point for strategic interaction among countries. This section treats the level of clean technologies p as exogenous and, thus, rules out strategic interactions via investments.

As described earlier, the present game is characterised by strategic complementarity. Unilateral increases of abatement encourage other countries to raise a. Conversely, free-riding incentives are lower than in the standard model as reducing efforts is penalised by lower abatement by all other countries. Several political, technological, social and trade-related competitive elements are assumed to drive this behaviour captured by

$$\frac{\partial^2 U}{\partial a_i \partial a_{-i}} = b > 0.$$

Given other countries' behaviour, a_{-i}, country i chooses to set its abatement efforts to maximise payoffs. This goal is reached by equalising marginal benefits with marginal costs to pollution reduction. In this setting, countries do not internalise the positive effect that abatement has on other countries. One finds that country i's best response is hence determined by the first order condition

$$\begin{aligned} \frac{\partial B}{\partial a_i} &= \frac{\partial C}{\partial a_i} \\ b(a_i + a_{-i}) &= c(a_i - p) \\ \implies a_i^{BR}(p) &= \frac{ba_{-i} + cp}{c - b}, \ \forall p. \end{aligned}$$

The above expression is a global maximum as the second order condition, $b - c < 0$, is satisfied for all a_i by assumption A.i. No unilateral deviation in strategy by any country is profitable in this symmetric game when

$$a^N = \frac{cp}{c - bn}, \ \forall p.$$

Equilibrium actions depend on the relative benefits and costs of additional units of emission reduction. Intuitively, abatement increases in the benefit parameter b and decreases in its costs c.

For $p = 1$, this result is very similar to the original contribution by Barrett [1994].

The biggest difference, however, is the fact that the number of countries does not affect equilibrium abatement levels negatively, but positively. Because of international re-enforcement effects, countries anticipate a higher overall level of abatement than in the case of concave benefits.

This result is also in opposition to models specified in term of emissions with strategic complementarity. While both setups formalise international re-enforcement effects, equilibrium emissions are increasing in the number of countries shown by Heugues [2012].

While this may suggest an optimistic take on international environmental efforts, it is arguably the opposite. As stated earlier, an IEA must improve upon the business-as-usual scenario to be effective. Interpreting the status-quo as the non-cooperative case, an effective IEA needs to improve on the benchmark with re-enforcement effects in mitigation rather than one that assumed an incentive structure of strategic substitution effects between countries.

The next section compares cooperative behaviour in abatement to the non-cooperative benchmark and introduces endogenous clean technology investments.

3.2.3 Cooperative Benchmark

This section assumes that countries jointly set their abatement to maximise global surplus as described by

$$\max_{a,\,p} S(p,a) = \sum_{i=1}^{n} U(p,a) = n\left[\frac{b}{2}(na)^2 - \frac{c}{2}(a-p)^2 - \frac{k}{2}(p-1)^2\right]$$

The first order condition captures the internalised positive effect of abatement by increased marginal benefits, as in

$$\begin{aligned} nB'(a) &= \frac{\partial C(a,p)}{\partial a} \\ bn^2 a &= c(a-p). \end{aligned}$$

First-best abatement levels are, thus,

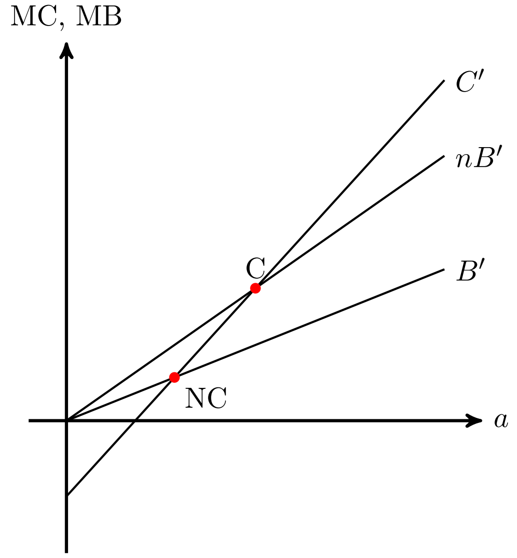
$$a^*(p) = \frac{cp}{c - bn^2} \; \forall p.$$

Comparing first best and non-cooperative abatement levels yields

$$a^* = \frac{cp}{c - bn^2} > \frac{cp}{c - bn} = a^N$$

Evidently, countries in the full cooperative benchmark reduce more emissions than in the non-cooperative case. Figure 3.2.3 compares the first order condition in the non-cooperative benchmark to the cooperative case. In point NC, countries maximise their payoff non-cooperatively. By taking into account the positive spillover effects of abatement, a higher level of emission reduction is sustained in the cooperative benchmark's optimum, shown at point C.

Figure 3.1: Cooperative and non-cooperative benchmarks illustrated comparing first order conditions



Countries do not only jointly set their abatement efforts, but they are also assumed to decide on a globally optimal level of clean technologies, p^*. To solve the system of abatement and investments in R&D, one may observe that the first order condition with respect to investments in clean technology equals

$$\frac{\partial C(a,p)}{\partial p} = K'(p)$$
$$c(a-p) = k(p-1).$$

This implies that the optimal level of clean technology for any given level of abatement is

$$p^*(a) = \frac{ca+k}{c+k}.$$

From the Hessian, one can conclude that the second order conditions are met for any critical point,

$$D^2U = \begin{bmatrix} bn^2 - c & c \\ c & -(c+k) \end{bmatrix} \implies \begin{cases} |D_1| = bn^2 - c < 0 \\ |D_2| = \det(D^2U) = ck - bn^2(c+k) > 0 \end{cases}$$

The negativity of the first leading principal minor is asserted by assumption A.i, while the second leading principal minor is positive directly due to assumption A. Hence, the Hessian is negative definite for any (a^*, p^*) and the second order condition is met for any critical point.

Solving the system of linear equations given by the first order conditions we find that the critical point yields

$$p^* = \frac{k(c-bn^2)}{k(c-bn^2)-cbn^2} \qquad \text{and} \qquad a^* = \frac{ck}{k(c-bn^2)-cbn^2}.$$

Both p^* and a^* are positive as a consequence of assumptions A.i and A. One can again directly observe that $a^* > p^*$.

3.2.4 Incomplete Contracts

This thesis builds on the assumption that countries neither behave fully cooperatively; environmental protection is the prime example of a Tragedy of the Commons. However, evidence suggests that the option to sign binding contracts among countries cannot be neglected. Neither the cooperative, nor the non-cooperative benchmark fully capture the strategic interaction in an IEA. This section attempts to bridge this gap by modelling the possibility to contract on one variable while formalising the inability to contract on another variable. Co-benefits and adverse side-effect of these two control variables play a vital role in determining the outcome and are, thus, relevant for an effective IEA design.

Incomplete contracts are modelled as a two-stage game and solved by backwards induction. In the first stage countries jointly determine optimal investments in clean technology, p^{**}. It is assumed that countries have the option to sign binding agreements as laid out in section 3.1.5.

Second Stage

In the second stage, countries non-cooperatively maximise their payoffs with respect to abatement, taking other countries efforts and the level of clean technologies as given.

$$\max_{a_i} U(p, a_i, a_{-i}) = \frac{b}{2}(a_i + a_{-i})^2 - \frac{c}{2}(a_i - p)^2 - \frac{k}{2}(p-1)^2$$

The result is identical to the solution in the non-cooperative benchmark, i.e.

$$a^{**}(p) = a^N(p) = \frac{cp}{c - bn}.$$

First Stage

In the stage preceding the non-cooperative game of abatement, countries design their R&D policy together. They perfectly anticipate their behaviour in the second stage and, hence, have the ability to steer abatement. Understanding $a^N(p)$ as conditional on clean technology, the maximisation problem is formalised by

$$\max_p U\Big(p, a^N(p)\Big) = \frac{b}{2}\Big(na^N(p)\Big)^2 - \frac{c}{2}\Big(a^N(p) - p\Big)^2 - \frac{k}{2}\Big(p-1\Big)^2.$$

Solving this problem, as shown in appendix A, yields second best investment and abatement levels

$$p^{**} = \frac{k(c-bn)^2}{k(c-bn)^2 - bcn^2(c-b)} \qquad \text{and} \qquad a^{**} = \frac{ck(c-bn)}{k(c-bn)^2 - bcn^2(c-b)}.$$

Making use of assumption A.ii, both p^{**} and a^{**} are positive. Also, the following second order condition is satisfied by the same assumption

$$bcn^2 \frac{c-b}{(c-bn)^2} - k < 0.$$

The final part of section 3.2, examines the ex-post efficient allocation of clean technology and determines crucial design elements for an IEA.

3.2.5 Ex-post Efficient Investment

In negotiating a second best level p^{**} countries take into account that abatement in the second stage will be suboptimally low. This section explores the implications for the design of the incomplete contract by examining the counter-factual of a fixed level of abatement a^{**}. This translates to the following maximisation problem

$$\max_p U(p, a^{**}) = \frac{b}{2}(na^{**})^2 - \frac{c}{2}(a^{**} - p)^2 - \frac{k}{2}(p-1)^2.$$

Derived in appendix A, one finds that the ex-post efficient level p' equals

$$p' = \frac{c^2 k(c-bn) + k\left[k(c-bn)^2 - bcn^2(c-b)\right]}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]}.$$

Making use of assumption A.ii, one can show that the above expression for p' is positive.

Finally, comparing the ex-post efficient allocation, p', for abatement efforts a^{**} with the second best allocation p^{**} shows that the ex-post efficient level of investments always lies above the second best level. The following result is proven in appendix A:

$$p' < p^{**} \tag{3.3}$$

Investments are set suboptimally high to sustain a second best level of abatement. Countries anticipate that because of increasing differences in (a_i, p), larger levels of clean technology induce higher of abatement efforts. Efficiency in the level of R&D is sacrificed to induce larger emission reductions after a contract has been set. This finding is a direct upshot from result portrayed in proposition 2.2.8. If countries have the ability to sign binding contracts on a variable that affects a non-contractible pollutant, the former factor should partly internalise the benefits of emission abatement.

The following and final section of this thesis summarises the presented results in the context of IEAs.

4 Conclusion

This thesis deduces fundamental properties of an incomplete environmental treaty from basic game theoretic assumptions. Starting from the literature on property rights, results are step-by-step carried over and expanded from abstract terms to a specific model of IEAs. The thesis' findings are far-reaching and entail implications for the practice of IEA modelling as well as the design of effective international treaties. The model provided in the last section of this thesis fits well as a benchmark to analyse extensions such as non-cooperative coalition formation or asymmetric game structures.

In conclusion, the analysis uncovers three main factors influencing the design of an effective IEA. The first upshot from the theory of property rights is that an IEA can sustain efficient actions in an equilibrium if there are no harmful externalities at the first-best for a given property rights allocation. Albeit idealised, this result highlights the importance of creating an institution with the legitimacy to enforce an agreement.

Secondly, if actions generate positive externalities at all property right allocations, equilibrium efforts will necessarily be suboptimally low. Widely recognised, this result poses the starting point for most economic research on IEAs. Contrary to the majority of literature on IEAs, the thesis assumes strategic complementarity in emission, i.e. international re-enforcement effects in environmental protection. If a country increases its mitigation efforts, others have an incentive to follow suit. Even under this benign assumption, free-riding incentives persist to be the biggest cause of inefficiencies in the management of global public goods.

Differently to models without international re-enforcement effects, however, equilibrium abatement efforts are increasing in the number of affected countries. As an extension to the models presented in this thesis, this finding might lead to qualitatively different result regarding the breadth of a treaty.

Thirdly, a successful IEA specifies a second-best allocation to increase abatement efforts. The effective allocation is distorted away from an ex-post efficient outcome to induce a more beneficial level of effort among all countries. If countries have the ability to sign binding agreements, contractible factors play a dual role. On one hand, they indirectly induce externalities via their strategic effect on other variables. On the other hand, if the other variables are inherently non-contractible, contractible treaty elements are essential to achieving an efficient outcome outside the agreement domain.

In the case of climate change mitigation, the lack of effective international governance mechanisms has proven to lead to highly inefficient outcomes. The inability to contract on emissions implies that other international treaties should take adverse effects and co-benefits on carbon emissions into account to manage the global public good of environmental protection. The thesis emphasises the importance of focussing on linked issues in existing agreements, such as investments in clean technology or trade agreements, to yield beneficial outcomes for climate change mitigation.

In summary, this thesis demonstrated that the field of incomplete contracts as well as the specification of strategic complementarity yield novel insights into the challenges of international environmental cooperation.

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A Appendix

Proof of lemma 2.2.2. The statement in definition 2.2.3 is equivalent to $f(x',y)-f(x,y)$ being an increasing function of y if $x' \geq x$. This implies

$$\frac{\partial f(x',y)-f(x,y)}{\partial y} \geq 0 \Longleftrightarrow \frac{\partial f(x',y)}{\partial y} \geq \frac{\partial f(x,y)}{\partial y}$$

Which means that $\partial f(x,y)/\partial y$ is increasing in x or $\partial^2 f(x,y)/\partial x \partial y \geq 0$ $\square$

Proof of theorem 2.2.3. This proof will first confirm that the set of arguments maximising the function f is nonempty, bounded and closed which suffices to show that the greatest and least elements of $x(y)$ exist proving point *i)*.

As the function f is upper semicontinuous and X is compact, the Weierstrass Theorem asserts that $x(y)$ is nonempty for all $y \in Y$. Therefore, $x(y) \subset X$ is bounded. Regarding closedness, let $\left\{x^k\right\}$ be a sequence in $x(y)$ which WLOG converges to a limit point $\overline{x}(y)$. This limit point exists as X is compact. It is left to show that $\overline{x}(y)$ is also part of the set of maximisers. As $x^k \in x(y)$ for all k, one obtains

$$f(x^k,y) \geq f(x,y), \quad \forall x \in X.$$

Taking the limit for $k \to \infty$ and using the upper semicontinuity of f, it follows that

$$f(\overline{x},y) \geq \limsup_{k\to\infty} f(x^k,y) \geq f(x,y), \quad \forall x \in X.$$

Hence, $\overline{x}(y)$ belongs to the set of maximisers $x(y)$. The proof for $\underline{x}(y)$ runs analogously using the limit inferior of a series converging to $\underline{x}(y)$, which together proves the closedness of the set of maximisers.

Regarding point *ii)*, suppose y and y' are two elements in Y for which $y' \geq y$ in the partial ordering. Let $x \in x(y)$ and $x' = \overline{x}(y')$. Since x maximises $f(x,y)$, one can state that

$$f(x,y) - f\left(\min(x,x'),y\right) \geq 0.$$

This implies that

$$f\left(\max(x,x'),y\right) - f(x',y) \geq 0,$$

as the statement holds true for both $x \geq x'$ and $x \leq x'$. Using the property of increasing differences yields

$$f\left(\max(x,x'),\, y'\right) - f(x',y') \geq 0.$$

Hence, $\max(x,x')$ maximises f at y', i.e. $\max(x,x') \in x(y')$. Seeing that x' is the greatest element of the set $x(y')$, one can conclude that $\max(x,x') \leq x'$ implies $x \leq x'$. As x is an arbitrary element of $x(y)$, one obtains $\overline{x}(y) \leq \overline{x}(y')$ and analogously for the smallest maximisers [Ozdaglar, 2010]. □

Proof of theorem 2.2.4. The existence of a greatest and least set of strategies will be shown by iterating best response mappings which converge to the sought profiles, $\overline{a}$ and $\underline{a}$. These profiles will then be identified as NE [Levin, 2003, pp. 5].

The proof starts by establishing the existance of $\overline{a}$. Let $\mathfrak{A}^0 = \mathfrak{A}$ be the entire set of possible actions and $a^0 = (a_1^0,\, \ldots,\, a_n^0)$ the largest element of $\mathfrak{A}^0$. The first iteration excludes all strictly dominated strategies by defining the set

$$\mathfrak{A}_i^1 = \left\{ a_i \in \mathfrak{A}_i^0 \;:\; a_i \leq a_i^1 \right\} \text{ for } a_i^1 = \overline{a}_i^{BR}\left(a_{-i}^0\right).$$

Observe that every $a_i \notin \mathfrak{A}_i^1$, i.e. $a_i > a_i^1$, is dominated by a_i^1 because for these elements, a_i, and arbitrary a_{-i} one can deduce

$$U_i\left(a_i,a_{-i}\right) - U_i\left(a_i^1,a_{-i}\right) \leq U_i\left(a_i,a_{-i}^0\right) - U_i\left(a_i^1,a_{-i}^0\right) < 0.$$

The first inequality is due to increasing differences and the second a result of the fact that a_i^1 is the greatest maximizer, implying that any $a_i > a_i^1$ must necessarily yield lower utility.

Continuing, recursively define the iteration step

$$\mathfrak{A}_i^{k+1} = \left\{a_i \in \mathfrak{A}_i^k \,:\, a_i \leq a_i^{k+1}\right\} \text{ for } a_i^{k+1} = \overline{a}_i^{BR}\left(a_{-i}^k\right).$$

If $a_i^k \leq a_i^{k-1}$ for all i (this has been shown to be true for $k=1$) then corollary 2.2.1 implies that also

$$a_i^{k+1} = \overline{a}_i^{BR}\left(a_{-i}^k\right) \leq \overline{a}_i^{BR}\left(a_{-i}^{k-1}\right) = a_i^k.$$

It has been shown by induction that a_i^k is a decreasing sequence for each i. Since a_i^k is bounded from below, the limit of the sequence exists,

$$\lim_{k\to\infty} a_i^k = \overline{a}_i.$$

All strategies $a_i > \overline{a}_i$ are strictly dominated. Analogously, one can define $a^0 = (a_1^0, \ldots, a_n^0)$ as the smallest element in $\mathfrak{A}$ and thus construct $\underline{a}$.

It remains to be shown that $\overline{a}^N = (\overline{a}_1, \ldots \overline{a}_n)$ and $\underline{a}^N = (\underline{a}_1, \ldots \underline{a}_n)$ are NE. By construction, one can state

$$U_i\left(a_i^{k+1},\, a_{-i}^k\right) \geq U_i\left(a_i,\, a_{-i}^k\right) \qquad \forall i,\, a_i \in \mathfrak{A}_i.$$

Taking the limit as $k \to \infty$ using the upper semicontinuity of U_i in a_i and a_{-i} one obtains the desired results that

$$U_i\left(\overline{a}_i^N,\, \overline{a}_{-i}^N\right) \geq U_i\left(a_i,\, \overline{a}_{-i}^N\right) \qquad \forall i,\, a_i \in \mathfrak{A}_i.$$

The same is true for the sequence of least elements.

□

Proof of corollary 2.2.2. Let $\overline{a}^N(a,\lambda) \,:\, \mathfrak{A} \times \Lambda \to \mathfrak{A}$ be the largest best joint response correspondence for the game with parameter λ as defined in the previous proof . By the monotonicity theorem 2.2.3, the individual best response $\overline{a}_i^{BR}(a_{-i},\lambda)$ is nondecreasing in a_{-i} and λ, hence $\overline{a}^N$ is nondecreasing. Every NE satisfies $\overline{a}^N(a,\lambda) \geq a$. Tarski's Fixed Point Theorem, set out in footnote 4, implies that $\overline{a}(\lambda) = \sup\left\{a \,:\, \overline{a}^N(a,\lambda) \geq a\right\}$ is the largest fixed point of $\overline{a}^N(a,\lambda)$. The result follows because the set of fixed points for

$\overline{a}^N(a,\, \lambda)$ is identical to the set of equilibrium points for the game λ as shown in Topkis [1998] lemma 4.2.1 [Milgrom and Roberts, 1990]. □

Proof of proposition 2.2.6. The following proof consists of three parts. First, a new function $\psi_i(p, a_i, a_{-i}, \lambda)$ will be defined. Second, the NE and first-best set of actions are shown to be induced as special cases of functions ψ_i depending on λ. Finally, illustrating that $(\mathfrak{A},\, \psi)$ is a supermodular game indexed by λ as defined in corollary 2.2.2 proves the proposition.

In order to establish this key proposition for positive externalities, a new group of functions is defined making use of corollary 2.2.2

$$\psi_i(p, a_i, a_{-i}, \lambda) \equiv U_i(p, a_i, a_{-i}) + \lambda \sum_{j \neq i} U_j(p, a_i, a_{-i}) = (1-\lambda) U_i(p, a_i, a_{-i}) + \lambda S(p, a)$$

where $\lambda \in \{0, 1\}$. The functions ψ_i are assumed to be supermodular in $(a_i,\, a_{-i})$. Assuming $\lambda = 0$ yields

$$\psi_i(p, a_i, a_{-i}, 0) = U_i(p, a_i, a_{-i}).$$

Theorem 2.2.4 asserts that a NE exists for the game $\left(\mathfrak{A}, \psi_i(p, a_i, a_{-i}, 0)\right)$ with greatest and least elements $\left(\underline{a}^N, \overline{a}^N\right)$. Considering $\lambda = 1$ on the other hand, one obtains

$$\psi_i(p, a_i, a_{-i}, 1) = S(p, a).$$

In proposition 2.2.5 was established that the solution to

$$\mathfrak{A}^*(p) = \arg\max_{\alpha \in \mathfrak{A}} S(p, a) = \arg\max_{\alpha \in \mathfrak{A}} \psi_i(p, a, 1)$$

exists with greatest and least elements $(\underline{a}^*, \overline{a}^*)$ if $S(p, a)$ is supermodular in a. Thus, for $\lambda = 1$ the function ψ elicits first-best actions as a NE. Hence, both the NE and first-best set of actions arise as special cases of the game $(\mathfrak{A},\, \psi_i)$.

The functions ψ_i are supermodular in (a_i, a_{-i}) by assumption. Moreover, positive externalities imply that ψ_i has increasing differences in $(a_i,\, \lambda)$. Hence, this proof established a group of functions ψ_i which induce the NE and first-best set of actions as special cases and satisfy the conditions for the application of corollary 2.2.2. This implies that the smallest Nash equilibrium action profile when $\lambda = 1$ is larger than the smallest Nash equilibrium action profile when $\lambda = 0$. The game is indexed by λ and thus $\underline{a}^N \leq \underline{a}^*$.

The proof for negative externalities can be established analogously. □

Proof A implies A.i. Assumption A grants that

$$ck - (c+k)bn^2 > 0 \implies \frac{ck}{c+k} - bn^2 > 0.$$

Using this result, one can show that assumption A is stronger than assumption A.i

$$c - \frac{ck}{c+k} = \frac{c(c+k-k)}{c+k} = \frac{c^2}{c+k} > 0.$$

□

Proof A implies A.ii. Assumption A together with $c - b > 0$ from assumption A.i yields

$$ck - (c+k)bn^2 = k(c-bn^2) - bcn^2 > 0 \implies k(c-bn^2)(c-b) - bcn^2(c-b) > 0.$$

Using this result, one can show that assumption A is stronger than assumption A.ii

$$\begin{aligned}
k(c-bn)^2 - bcn^2(c-b) - \Big[k(c-bn^2)(c-b) - bcn^2(c-b)\Big] = \\
&= k(c-bn)^2 - k(c-bn^2)(c-b) \\
&= k\left[c^2 - 2bcn + b^2n^2 - c^2 + bc + bcn^2 - b^2n^2\right] \\
&= k\left[bc - 2bcn + bcn^2\right] \\
&= bck(1-n)^2 > 0.
\end{aligned}$$

□

Determining second best investment level p^{**}.

$$\begin{aligned}
\max_p U\Big(p, a^N(p)\Big) =& \frac{b}{2}\Big(na^N(p)\Big)^2 - \frac{c}{2}\Big(a^N(p) - p\Big)^2 - \frac{k}{2}\Big(p-1\Big)^2 \\
&\Longrightarrow b\left(\frac{cn}{c-bn}\right)^2 p - c\left(\frac{bn}{c-bn}\right)^2 p = k(p-1) \\
&\Longleftrightarrow p\left[k + bcn^2\left(\frac{b-c}{(c-bn)^2}\right)\right] = k \\
&\Longrightarrow p^{**} = \frac{k(c-bn)^2}{k(c-bn)^2 - bcn^2(c-b)}
\end{aligned}$$

□

Deriving the solution for p'.

$$\max_p S(p, a^{**}) = \sum_{i=1}^{n} U(p, a^{**}) = n\left[\frac{b}{2}(na^{**})^2 - \frac{c}{2}(a^{**} - p)^2 - \frac{k}{2}(p-1)^2\right]$$

The first order condition is then

$$\frac{\partial U}{\partial p} = c(a^{**} - p) - k(p-1) = 0$$

which further implies

$$p' = \frac{ca^{**} + k}{c+k}.$$

Substituting for a^{**} yields

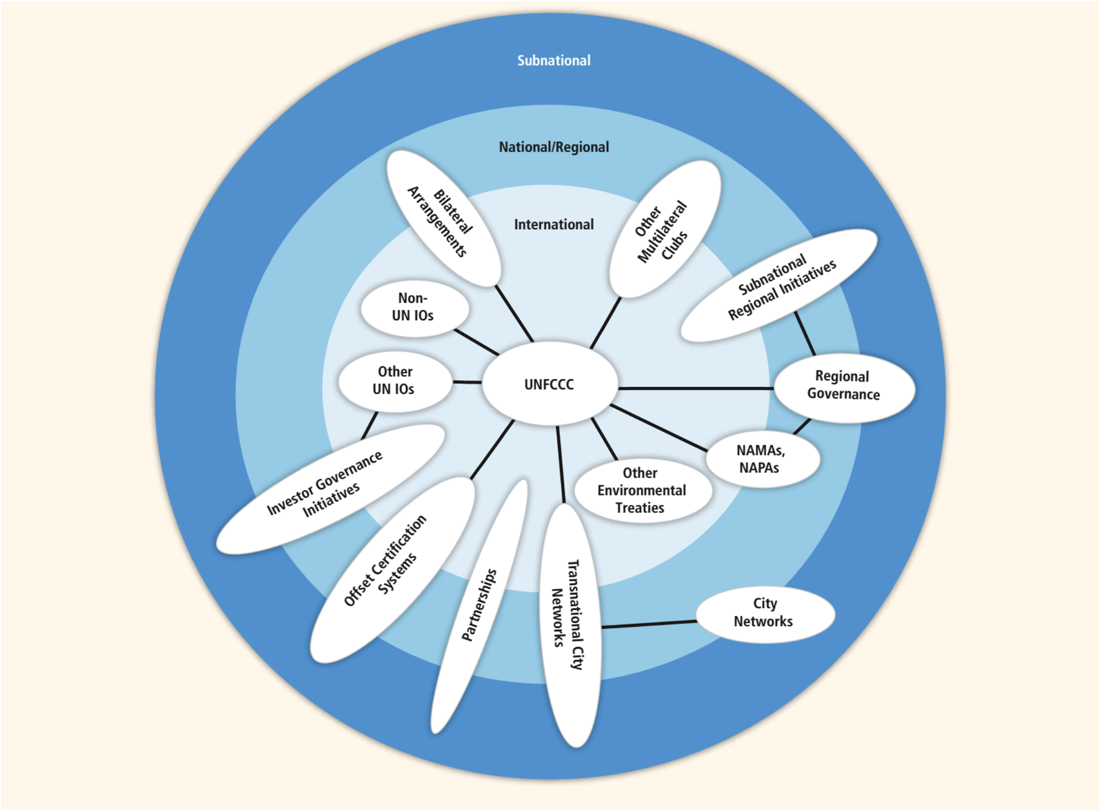
$$\begin{aligned}
p' &= \frac{k}{c+k} + \frac{c^2k(c-bn)}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]} \\
&= \frac{k\left[k(c-bn)^2 - bcn^2(c-b)\right] + c^2k(c-bn)}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]}.
\end{aligned}$$

□

Proof of the result in line 3.3.

$$\begin{aligned} p^{**} - p' &= \frac{k(c-bn)^2(c+k) - c^2k(c-bn) - k\left[k(c-bn)^2 - bcn^2(c-b)\right]}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]} \\ &= \frac{bckn^2(c-b) - cbkn(c-bn)}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]} \\ &= \frac{bc^2kn(n-1)}{(c+k)\left[k(c-bn)^2 - bcn^2(c-b)\right]} > 0 \quad \text{following assumption A.ii} \end{aligned}$$

□



UNFCCC	Kyoto Protocol, Clean Development Mechanism, International Emissions Trading
Other UN Intergovernmental organizations	Intergovernmental Panel on Climate Change, UN Development Programme, UN Environment Programme, UN Global Compact, International Civil Aviation Organization, International Maritime Organization, UN Fund for International Partnerships
Non-UN IOs	World Bank, World Trade Organization
Other environmental treaties	Montreal Protocol, UN Conference on the Law of the Sea, Environmental Modification Treaty, Convention on Biological Diversity
Other multilateral 'clubs'	Major Economies Forum on Energy and Climate, G20, REDD+ Partnerships
Bilateral arrangements	e.g., US-India, Norway-Indonesia
Partnerships	Global Methane Initiative, Renewable Energy and Energy Efficiency Partnership, Climate Group
Offset certification systems	e.g., Gold Standard, Voluntary Carbon Standard
Investor governance initiatives	Carbon Disclosure Project, Investor Network on Climate Risk
Regional governance	e.g., EU climate change policy
Subnational regional initiatives	Regional Greenhouse Gas Initiative, California emissions-trading system
City networks	US Mayors' Agreement, Transition Towns

Figure A.1: The landscape of agreements and institutions on climate change found in Intergovernmental Panel on Climate Change [2014]

Zusammenfassung / German Abstract

Diese Masterarbeit analysiert internationale Umweltabkommen als statisches Spiel. Die Methodik unterscheidet sich von Standardmodellen in zweierlei Hinsicht. Erstens wird die Annahme unvollständiger Verträge der Tatsache getreu, dass eine vielzahl multilateraler Abkommen in Kraft sind. Länder haben die Möglichkeit bindende Verträge über Investitionen in grüne Technologien zu unterzeichnen, Emissionen können jedoch nicht Vertragsbestandteil sein. Zweitens wird angenommen, dass Emissionen für Länder strategisch komplementär sind. Auf einseitige Emissionsreduktionen reagieren andere Länder ebenfalls mit weniger Verschmutzung, da internationaler Wettbewerb Verstärkungseffekte auflöst. In diesem Modell liegt das zweitbeste Investitionsniveau unter einem ex-post optimalen Level, um mehr Emissionsreduktionen zu induzieren. Aufbauend auf der Literatur zu Eigentumsrechten stellt das Modell der Masterarbeit ein Instrument dar, um Emissionen und Investitionen zu analysieren und Schlüsse für die Gestaltung eines effektiven Umweltabkommens zu deduzieren.

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curriculum vitae

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Education

2011 – 2015 **MSc Economics**
University of Vienna
Including two semesters of the PhD programme in Economics at the University of Melbourne

2006 – 2011 **BSc Business and Economics**
Vienna University of Economics and Business
Including an exchange semester at the Free University Berlin (Mathematics) and Humboldt University (Economics), as well as an exchange semester at Babson College, Boston (Entrepreneurship)

Professional Experience

2013 – ongoing **Parkville Global Advisory**
Data Manager / Research Associate
Research in the economics of education, evaluation of an Australian funding programme for schools using regression discontinuity and other advanced panel methods, assessment of the effect of school leaders using non-linear least squares

2011 – 2012 and 2013 – 2014 **Austrian National Bank – Economic Studies Division**
Research Assistant
Assistance in the development of an international survey (10,000 observations per year), independent data analysis using Stata and generating data used for spatial econometric models

2012 **The University of Melbourne – Department of Economics**
Research Assistant
Assistance in the compilation of teaching material, transcription of a lecture script in latex, editing and designing of graphs

2011 – 2012 **SERI - Sustainable Europe Research Institute**
Research Assistant
Co-authoring of a macroeconomic report for the European Commission, assistance in the organisation of conferences, other research activities in the fields of environmental economics and ecology

Other Experience

2012	**ACE 2012 - Australian Conference of Economists** *Volunteer* Volunteering at the largest annual Australian economics conference, assistance in the organisation of the event, support for speakers
2006 – 2010	**Südwind – Association for Educational and Advocacy Activities Related to Development Policy** *Event Manager* Organisation of an annual event with more than 50 participating advocacy organisations and over 5,000 visitors

Publications

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Grants

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Other Information

Languages	German (native), English (IELTS 8.5), French (intermediate)
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Other interests	Data visualisation and information aesthetics, Ultimate Frisbee, travelling