Game Theory and Climate Change

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For Bayla and Anura

With the hope that this work will lead to more effective policies and climate change will be under control as Bayla and Anura grow up

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Preface

Climate change is an international environmental issue that has gained importance and public attention in recent years. From a theoretical perspective, tackling this issue is equivalent to solving the problem of providing a global public good that has some special characteristics. I address this issue in the book and pursue two complementary objectives. On the one hand, I propose a unified conceptual framework within which to think about climate change and other similar international issues, and, on the other hand, I present this framework in terms that lead to policies and applications.

The text is quite focused, and by no means encyclopedic. It presents the material in a unified analytical framework, combining the economic, the ecological, and the game-theoretic components of the problem and thereby permitting the readers to see their respective roles in a focused but comprehensive study. As is well known, the market mechanism, in the context of international environmental issues, has to be replaced by some other allocation mechanism – negotiations and voluntary agreements, for example. Thus, the book introduces many new concepts and results that have not been reported previously.

As to the target readership, the text is meant for both academic researchers and practitioners and policy makers. It attempts to offer to the researchers a rigorous and complete exposition of what game theory can bring to this field. It offers an analytical framework for understanding why the Paris Agreement on climate change may succeed whereas the Kyoto Protocol failed. It begins with an introduction written for someone with little knowledge of the disciplines involved and leads to the state of the art in advanced game theory designed for an expert in game theory. It is a steep road to traverse but the book, I believe, does it ably. For practitioners and policy makers the book includes two chapters that focus mainly on policy.

The material in the book can be used for a full one-semester course for graduate students specializing in environmental economics and economics of climate change and/or in applied game theory. To be specific, chapters 2,3,5, and 9 can be useful for teaching environmental economics at an undergraduate level and chapters 4 to 8 may be used for PhD level courses. Thus, some readers may want to skip chapters 4 to 8 while others may want to skip chapters 2 and 3. Chapters 4 to 7 can also be used to supplement a public economics course at the upper undergraduate level. They were indeed used by me as part of a fourth-year undergraduate course in public economics at the National University of Singapore (NUS). Chapters 9 and 11 focus mainly on climate change policy and are written in such a way that they can be read even with minimal knowledge of the preceding chapters in the book. Chapter 10 is also concerned with an important policy question in that it examines whether combining negotiations on climate change and free trade can lead to greater world welfare.

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Chapter 1
Purpose and Scope

Serious problems require serious policy responses, and no problem is more threatening to the human future than climate change or global warming caused by emissions of greenhouse gases (GHGs). Our understanding of the physical science of climate change has been growing steadily,[1] but there has been no meaningful progress towards fixing the economic and strategic forces that are causing it, except perhaps the Paris Agreement adopted by 196 countries in 2015 at Paris, France. This is often attributed to a failure of political will, but, as will be made clear in this book, it is the result of a particularly challenging economic and strategic setup. Accordingly, the book proposes game-theoretic solutions to the problem which are efficient and immune to strategic behavior by sovereign nations in the hope that it will lead to a better understanding of the economic and strategic forces behind climate change in general and of the Paris Agreement and its predecessor – the Kyoto Protocol – in particular.[2] It discusses why and how the Paris Agreement may succeed in controlling climate change whereas the Kyoto Protocol failed. However, applications of the theory developed in this book are not restricted to climate change

[1] For a thorough account of the scientific evidence on the state of the problem, the reader is referred to the assessment reports issued by the Intergovernmental Panel on Climate Change (referenced in the bibliography as IPCC 1990, 1995, 2001, 2007, 2013. The negotiations themselves have been taking place under a body that was created by the General Assembly of the United Nations in 1992 and established in Geneva as the United Nations Framework Convention on Climate Change (UNFCCC) and established in Geneva.

[2] See Barrett (2003) for a comprehensive study of a variety of actual international agreements.

alone. It is applicable also to other similar problems of global environmental externalities such as ozone layer depletion, acid rain, and sea and ocean pollution, to name a few.

1.1 The Multidisciplinary Nature of Climate Change

Climate change, which is caused mainly by emissions of GHGs, is a global environmental externality. It is an externality because it is a form of interaction between agents that takes place outside the market for exchange of goods and services, it is global because the externality extends beyond boundaries of any kind, and it is environmental because it affects people through the environment in which they live. Each one of these three characteristics of climate change puts it outside the scope of standard social sciences, especially standard economics. As a result, some basic concepts have to be modified and some new ones have to be invented to enable these sciences to cope with the issues involved.

1.1.1 *The Three Disciplines*

The choice of the title of the book puts game theory in the forefront because this discipline provides key intellectual tools to handle the problem. But more generally, three different disciplines are involved: ecological science, economics, and game theory. This section summarizes what the book has to offer regarding each one of them.

Ecological science

Because the book deals with an ecological phenomenon, the reason for the involvement of this discipline should be obvious. Without pretense of contributing much new to this discipline, the book borrows from it whatever ideas are useful or relevant for the analysis. In particular, the main idea that is imported from this discipline is the concept of a *transfer function*, which is a tool whereby ecological science describes the effect of exogenous interventions on the measurable characteristics of the environment. How this tool operates is illustrated by an example of air pollution in Chapter 2. In the rest of the book only a simple linear form of the transfer function is used so that the complexity in this respect does not divert our attention away from the more important complexity of strategic interactions among the agents, which is the main focus.

Another idea that is borrowed from ecological science is the notion of a *stock* externality as distinct from a *flow* externality. Economics started to take note of this distinction only in the late eighties when it could no longer ignore the ecological phenomena such as buildup of acidic depositions in soil due to acid rains or of accumulation of GHGs in the atmosphere due to their continual emissions on Earth. Before that time, externalities were treated just in terms of more or less bucolic examples of externalities such as the celebrated bees and orchard fable and the locomotives that emit sparks and set fire to farmers' fields.

The treatment of GHGs as a stock externality in the economic analysis forces introduction of time in the formulation of the climate change problem. One implication of this is that the emitters and recipients of the externality may be separated in time in such a way that they cannot meet or interact (e.g. they may belong to different non-overlapping generations),[3] making it impossible for them to engage in Coasian bargaining. Involvement of the government of each country, which can act on behalf of its future generations, is thus essential if climate change is indeed to be treated as a stock externality. Furthermore, ecological science also teaches us that phenomena such as climate change extend over a very long period. This has deep consequences for the choice of a discount rate that is appropriate for payoffs occurring only in a very distant future. Keeping these facts in view, chapters 7 and 8 treat climate change as a stock externality in contrast to its treatment as a flow externality in chapters 5 and 6.

At a more general level, introduction of economic reasoning in environmental matters definitely gives ecological science an anthropocentric perspective. That is so when economic analysis, whether positive or normative, is introduced in models in which human behavior affects a natural phenomenon. Indeed, a central concept in positive economics is that of an equilibrium, which is typically the outcome of utility or payoff maximization by agents representing the humans. This puts the natural phenomenon described by ecology as an object that is subject to human behavior and gives it essentially a human perspective. This is a fortiori so with normative economics, in which human behavior with respect to nature is advocated on the basis of criteria chosen and formulated by humans or agents representing them.

[3] If elapse of time is substituted for river flow and distance, this is analogous to upstream pollution that affects people downstream.

Moving one step higher in this philosophical discussion makes one realize that the anthropocentric view is the source, and the only source, of attributing value to environment.[4] Indeed, the notion of value itself is void if not supported by humans. As a natural corollary, the notion of pollution rights may be interpreted as an export from economics to ecological science. Because natural resources have value, they must have prices that are meaningful in a market economy. Moreover, prices mean exchange, and exchange presupposes property rights. In this way, the notion of pollution rights appears to be an export from economics to ecological science.

The theory developed in this book eventually leads to a fairly fundamental rethinking of the notion of value of environment which is a matter of debate between "environmental economics" and "ecological economics".[5] Chapter 8 revisits this issue. It proposes a value that is free from the typical notion of scarcity in economics and from the exclusively physical thermodynamic theory of energy relied upon in ecological economics. It is derived from a dynamic model in which each country is assumed to have developed so much that the capacity to produce consumption goods, whose production results in GHG emissions and climate change, is no

[4] This fact has been also recognized by the famous Brundtland Report (UN, 1987). To quote, "The environment does not exist as a sphere separate from human actions, ambitions, and needs, and attempts to defend it in isolation from human concerns have given the very word 'environment' a connotation of naivety in some political circles." Similarly, Karp (2017) argues that an anthropocentric view, putting humans at the center of the narrative, can lead to more effective remedies, though the environment may have intrinsic value apart from any effect, however, indirect, it has on current or future welfare.

[5] For a summary presentation, see, for example, Kolstad (2000), especially chapters 1 and 3. Common and Stagl (2005) offer a comprehensive exposition.

longer a binding constraint. Instead, the environment is the only limiting factor, and all countries have equal opportunity to exploit it. The countries differ, if at all, only in terms of how they are affected by their own emissions and climate change. Consideration and analysis of such an idealized world model leads to a reconciliation of the two different views regarding the value of environment, as then it is optimal to minimize the polluting energy content of delivered goods and services. The analysis also leads to a proposal that can serve as a reference in the negotiations on climate change. Roughly speaking, the proposal means that a country affected relatively more by its own emissions and climate change should have fewer rights to emit GHGs that cause local pollution and climate change.[6] Such a proposal is free from any normative considerations such as equal per capita emission rights or grandfathering of current national emissions, but, as discussed in Chapter 9, it may be considered unfair by some countries, especially by the low-lying island states and least developed small countries, which are severely affected by climate change but contribute little to it.

Economics

As to economics, known to be the science of resource allocation, the first extensions and novelties, introduced in Chapter 2, are at the basic level of making precise whether and how the environment can be treated as an economic good. Connections are established between the standard notions of externalities, private goods, and public goods. In fact, all three are involved,

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[6] Combustion of fossil fuels often causes local pollution (e.g., smog) as well as climate change. A country is said to be more seriously affected by both its own emissions and climate change if marginal damage from both its own emissions and climate change are uniformly higher.

and disentangling their respective roles in the climate change problem is a necessary starting point.

With this in mind, the basic framework for this work is presented in Chapter 3 in terms of the two main classical strands of economic theory: namely, general equilibrium, a positive one, and welfare economics, a normative one. In both cases the fact that the agents are sovereign nation-states is kept in mind as this is the single most important fact underlying the climate change problem that distinguishes it from a standard externality problem. The proposed framework is also in the spirit of public economics, which recognizes the role of government in a market economy when widespread externalities are involved.

In 1960, Ronald Coase introduced a very powerful idea of great importance, and this idea has had arguably the single most important influence on policy for the problem of externalities in the past five decades. He argued that in the absence of any transaction costs, assignment of arbitrary but well-defined pollution rights and bargaining among the parties involved can internalize any externality and ensure efficiency. This was later dubbed the "Coase theorem". However, Coase took for granted the existence of a government or authority that can allocate and enforce pollution rights between the parties involved. He did not foresee the global problem of climate change where there is no such authority at the supranational level. Thus, the Coase theorem as such cannot be applied to the externality problem of climate change.[7] Furthermore, Coase did not

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[7] This limitation of the Coase Theorem is not restricted to climate change alone. First, there are many other similar global externalities (e.g., depletion of the ozone layer). Second, in many parts of the world even today, as in the Middle

consider stock externalities, which as noted above, can make Coasian bargaining impossible among the current and future affected parties.

Chapters 5 and 8 propose suitable generalizations of the Coase theorem which are applicable in such instances of externalities that were originally ignored by Coase (1960). Chapter 5 treats greenhouse gases as a flow externality and shows that in the absence of a supranational authority, the nation-states will themselves assign rights to each other that are self-enforcing in the sense that none of them will have incentive to violate them. Furthermore, as the original Coase theorem predicts, such self-enforcing rights can lead to efficiency if they can be traded on a competitive market. However, unlike the assertion of the original Coase theorem, not every arbitrary assignment of rights can lead to efficiency, as every assignment of rights is not self-enforcing. Similarly, in the dynamic model in Chapter 8 which, unlike Chapter 5, treats GHGs as a stock externality, the steady-state Nash equilibrium emissions are interpreted as self-enforcing pollution rights that can lead to efficiency.

For the same reason for which the Coase theorem does not apply to climate change, the Pigouvian argument (Pigou, 1920) that appropriate taxes and subsidies can internalize externalities cannot be applied either. Thus, in the absence of a supranational authority, only voluntary negotiations and agreements among the sovereign countries can ensure efficiency, if at

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Ages, authorities who could allocate and enforce pollution rights are missing. One may wonder whether efficiency can be achieved at all in such instances.

all. What should be those negotiations and agreements and what should they bear on? That is broadly the theme pursued in this book.

Climate change has the characteristics of a global public good (or rather a bad). However, it does not fit the conventional notion of a public good. That is because reduction of greenhouse gas emissions by a country can be more than offset by another country, which may respond by increasing its own emissions. By contrast, in the conventional model of a public good, contributions to the public good by an agent cannot be neutralized by other agents. An agent can *at most* not contribute anything to the public good; it cannot reduce the public good provision made by others. Thus, the incentive to free ride in the case of climate change is much stronger than in a conventional public good model.[8] Dealing with it requires concepts and solutions that are more appropriate for tackling climate change, which, as noted above, provides stronger incentives to free ride. These are discussed in the subsection on game theory later in the chapter.

Disentangling the private and public good aspects of climate change is an important step in understanding the virtues of the "cap-and-trade" mechanism which was proposed in the Kyoto Protocol and has been retained in the Paris Agreement. In summary, the argument presented in chapters 5 and 9 is as follows: Decisions pertaining to "caps" are, in the aggregate, decisions on the provision of a public good, which explains and justifies that they be decided and agreed upon by the governments of the nation-states when negotiating an aggregate emission target. By

[8] See, for example, Groves and Ledyard (1977) and Chander (1993) for solutions to the problem of incentives in a conventional public good model.

contrast, decisions to "trade" in emissions are pertaining to private goods, namely, the pollution permits, and this explains and justifies that they be left to markets. The economic analysis in chapters 5 and 9 shows that these two types of decision- making processes are complementary to each other and together form a mechanism that can lead to a solution of the climate change problem.

Besides the negotiations on climate change, the countries are also presently engaged in negotiations on trade liberalization through the World Trade Organization (WTO). Though the negotiations on these two international problems have been conducted independently of each other, it is often claimed that increased free trade in goods will aggravate the climate change problem. That is because the scale of economic activities then will be higher and production of pollution-intensive goods will shift from countries with stricter pollution control to those with lax ones. Chapter 10 considers this issue and explores in a model with trade in consumption goods and pollution permits to determine whether or not merging negotiations on climate change and free trade could have led to a "better" agreement on climate change and improved world welfare. It derives sufficient conditions under which merging the negotiations would not have led to additional gains in welfare.[9] It also shows that the claim that free international trade in goods and services will aggravate climate change and shift the production of the "carbon intensive" goods from countries with strict environmental regulations towards those with lax ones is questionable.

[9] Indeed, the Paris Agreement on climate change was concluded on December 12, 2015 without waiting for the outcome of the WTO Ministerial Conference which started soon thereafter on December 16, 2015.

Game theory

Then, whither game theory? Games are essentially mathematical objects, to which it has become apparently fashionable in economics to have recourse.[10] The use of game theory in this book, however, finds its roots less in fashion than in realizing that economics per se does not offer conceptual tools that are rich enough for dealing with the two most essential aspects of climate change: namely, (i) the absence of a supranational authority that can enforce its policy decisions on the nation-states, and (ii) the externality has public good characteristics – though it does not fit the *classic* notion of a public good.

Thus, the decision-making processes involved in tackling climate change and other global environmental externalities are neither of the same nature as those operating in designing the usual domestic macroeconomic policies (where an institution empowered by the nation state makes decisions and can use its authority to implement them), nor are they akin to international trade negotiations on tariffs or opening of markets (where only private goods are involved). What is required is the optimal control of a global externality with public good characteristics. Thus, incentive mechanisms for optimal provision of a public good – Clarke (1971), Groves and Ledyard (1977), and others – may seem appropriate for tackling the problem. But these mechanisms begin by assuming that the power to design and implement the mechanism has been

[10] My basic references on game theory are Osborne and Rubinstein (1994), Myerson (1991) and Mas-Colell, Whinston and Green (1995).

handed over to an independent authority, presumably with the agreement of all agents. They do not consider that the agents may not have incentives to hand over such power to an independent authority. Thus, the incentive mechanisms for public goods, though extremely important and of an independent interest, are not consistent with voluntary negotiations among sovereign countries.

Newer concepts are needed to understand the nature of interactions that may take place between sovereign countries, each pursuing its own interests, and the kind of outcomes those interactions may lead to. Classical economics does not provide enough of them,[11] whereas game theory offers many ways to describe and understand a wide variety of interactions among independent agents. This book makes no encyclopedic review of game theory. Instead, it innovates as well as selectively uses those existing concepts that are appropriate for the game formulations of climate change studied in this book. They are dealt with in full detail with the aim of showing how deeply and rigorously they can solve the problem, and those that are not directly relevant are left aside deliberately and without apology.

Games can be analyzed in two ways: noncooperative analysis of games focuses on the strategies that each player would undertake to maximize his own payoff and the subsequent equilibrium that would be reached when all players do so, while cooperative analysis of games focuses on

[11] That is due to several reasons, but mainly because resource scarcity is at the root of the discipline (there is no economic, i.e. resource allocation, problem if there is no scarcity) whereas the object of game theory is of wider scope, namely, all forms of interactive decision making. Though, resource scarcity may also be a concern of game theory.

how incentives can be designed such that the players will adopt the strategies to achieve the outcome with the maximum total payoff.

In the case of the climate change problem there is definite room for applying cooperative game analysis as the sum of benefits (i.e., damages prevented) from controlling climate change outweighs the total costs of controlling climate change. However, though the total benefits exceed the total costs, the benefits and costs may not be spread out evenly among the countries in that the costs may be higher than the benefits for some countries unless the countries are identical. Because in reality the countries are indeed not identical, not every country would be willing to engage in controlling climate change.

To incentivize every country to engage in controlling climate change, a solution offered by cooperative game theory is that of side payments. If the premise that the sum of benefits from controlling climate change exceeds the costs of controlling climate change is indeed correct, then it might be possible to distribute the social surplus that will be generated such that after the side payments, every country is better-off. Designing such side payments is a trying task and this is where the book becomes fairly technical.

Both types of game analysis are involved in this work. A general strategic game provides a natural primitive framework for analyzing an interactive decision problems like climate change in which decisions of the agents (nation-states) affect each other. Accordingly, a central concept that is used throughout the book is that of the core of a strategic game which, as will be shown, can be interpreted both as a cooperative and a noncooperative game theory solution concept.

More specifically, the standard approach in classical cooperative game theory is to convert a strategic game into a coalitional game, and analyze the core of the game so defined. The core of a strategic game in this book, called the γ-core, is defined in the same way except that the conversion is not standard. More specifically, the *worth* of a coalition is defined as equal to its Nash equilibrium payoff in an induced game in which the coalition acts as one single player and all other players act individually as in a Nash equilibrium of the original game. In other words, the worth of a coalition is the payoff that the coalition can obtain without cooperation *from* and *among* the rest of players.

Chapter 4 presents the γ-core and related concepts in the primitive framework of a *general* strategic game, and these concepts are then applied to different game formulations of climate change in the rest of the book. More specifically, Chapter 5 introduces a strategic game formulation of climate change, called the environmental game, which corresponds to the short-run model that treats greenhouse gases as a flow externality. Chapter 7 introduces a dynamic game formulation of climate change in discrete time, called the dynamic environmental game. This dynamic game consists of a sequence of linked strategic games. Chapter 8 introduces a dynamic game formulation of climate change in continuous time. Chapter 10 introduces a trade and climate change model and interprets and analyses it as a game.

The motivation for the γ-core concept comes from the fact that the classical α- and β- cores are not suitable solution concepts for the environmental game. They result in too large a set of outcomes: in fact, the entire set of efficient outcomes. This is because under these core concepts, the players outside a deviating coalition can more than offset the pollution abatement carried out by the coalition. Thus, there is no minimum payoff that a coalition can ensure for itself by reducing its own pollution. In contrast, the γ- core concept is based on a more plausible assumption concerning the behavior of the players outside a deviating coalition and results in a smaller set of outcomes.

More specifically, the γ-coalitional function is such that $w^{\alpha}(S) \leq w^{\beta}(S) \leq w^{\gamma}(S)$ for all $S \subset N$, where w^{α}, w^{β}, and w^{γ} are the coalitional functions derived from a general strategic game under the behavioral assumptions implicit in the α-, β-, and γ- core concepts, respectively. Thus, the γ-core is a stronger concept than the conventional α- and β- cores. Furthermore, for the class of strategic games that admit a *unique* strong Nash equilibrium, the γ-core consists of the *unique* imputation in which the payoffs of the players are equal to their strong Nash equilibrium payoffs. However, the γ-core may be nonempty even if the game admits no strong Nash equilibrium. Thus, for a class of strategic games the γ-core is a weaker concept than that of a strong Nash equilibrium.

Chapter 4 also proposes, but does not pursue, an alternative γ-core concept. More specifically, the alternative γ-core is defined analogously except that the players in deviating coalitions are not capable of writing binding agreements, as in the concept of a coalition-proof Nash equilibrium. This alternative concept is based entirely on the noncooperative approach to game theory. But it is a weaker concept in the sense that the payoffs that deviating coalitions can achieve if they cannot write binding agreements are generally lower. For this reason, the alternative formulation of the concept is introduced and contrasted, but not applied or pursued further.

A growing branch of literature seeks to unify cooperative and noncooperative approaches to game theory through underpinning cooperative game-theoretic solutions with noncooperative equilibria, the "Nash program" for cooperative games, initiated by Nash (1953).[12] In the same vein, I show that the γ-core payoff vectors (a cooperative solution concept) of a general strategic game can be supported as equilibrium payoff vectors of a noncooperative game and the grand coalition is the unique equilibrium outcome if the γ-core is nonempty and the game is "partially superadditive". In this way, the book also contributes to the Nash program by rationalizing the γ-core as an equilibrium outcome of a noncooperative game. In fact, the book makes significant progress in reconciling cooperative and noncooperative game theory and, therefore, it might be of interest to noncooperative game theorists as well – even though its contribution may seem to be primarily in the realm of cooperative game theory. To be specific, the book includes applications and contextual characterizations of the Nash equilibrium, the strong Nash equilibrium, the coalition-proof Nash equilibrium, the subgame-perfect Nash equilibrium, the closed-loop and open-loop Nash equilibria, and subgame-perfect stationary strategy equilibria of an infinitely repeated game. It also introduces a newer concept called a subgame-perfect agreement that combines the two concepts of the γ-core (a cooperative solution concept) and the subgame-perfect Nash equilibrium (a noncooperative solution concept).

[12] Analogous to the micro-foundations of macroeconomics, which aim at bridging the gap between the two branches of economic theory, the Nash program seeks to unify the cooperative and noncooperative approaches to game theory. Numerous papers have contributed to this program including Rubinstein (1982), Perry and Reny (1994), Pérez-Castrillo (1994), and Lehrer and Scarsini (2013), for example.

The noncooperative game in which the γ-core payoff vectors are equilibrium outcomes is intuitive and explicitly models the process by which the players may agree to form a partition when they know in advance what their payoffs will be in each partition. It consists of infinitely repeated two-stages.[13] In the first stage of the two-stages, which begins with the finest partition as the status quo, each player announces whether it wishes to stay alone or form a nontrivial partition. In the second stage of the two-stages, the players form a partition as per their announcements. The two-stages are repeated if the outcome of the second stage of the two-stages is the finest partition as in the status quo from which the game began in the first place. It is shown that if the partition function representation of the strategic game is "partially superadditive", then breaking apart into singletons upon deviation by a coalition, as the γ-core concept requires, is a subgame-perfect equilibrium strategy of the remaining players.

The cooperative game theory is largely devoted to understanding how a group of agents may share the benefit of forming the grand coalition. However, there is another more recent strand of literature that aims at understanding whether agents will have incentives to form the grand coalition at all (i.e., whether they will *actually* decide to form the grand coalition). In the presence of externalities, a player can derive benefits from the activities of a coalition without joining it (i.e., free ride. Therefore, the grand coalition may not form. Several coalition formation games have been proposed in the recent literature, (see, e.g., Ray and Vohra,1997 among others). The economic applications of these games, however, have focused primarily on strategic or

[13] If the game is limited to a single play of the two-stages, then, as shown by Ray and Vohra (1997) and Yi (1997), the grand coalition is not an equilibrium outcome.

partition function games with *identical* players. Though closely related to the approach in this book and extremely important and of independent interest, the results from this strand of literature cannot be applied to study climate change. To be applicable, a theory must necessarily deal with heterogeneous players – developed versus developing or low-lying small island states versus large countries. Furthermore, coalition formation theory has not been so far extended to dynamic games. The theory developed in this book applies to both strategic and dynamic games with heterogeneous players.

Chapter 7, as mentioned earlier, treats greenhouse gases as a stock externality and formulates the problem of climate change as a dynamic game of finite or infinite time horizon, called the dynamic environmental game. An important new issue that arises in the context of the dynamic game formulation of climate change is that of subgame perfection of an agreement. To be precise, an agreement is subgame perfect if no coalition of countries has incentive to withdraw from it in *any* subgame.[14] I prove existence and comprehensively characterize a subgame-perfect agreement. From a methodological point of view, the concept of a subgame perfect agreement brings together two of the most important solution concepts in game theory, namely, the subgame-perfect Nash equilibrium of a noncooperative game and the core of a cooperative game – a link between the two is apparently missing in the extant literature.

[14] See Chander (2017a) for motivating the requirement of subgame-perfection of an agreement. Becker and Chakrabarti (1995) show that the need for subgame-perfection of an agreement can also arise in dynamic games without externalities and, thus, propose the recursive core as the set of allocations such that no coalition can improve upon its consumption stream in any subgame.

Chapter 9 interprets the cap-and-trade mechanism that was proposed in the Kyoto Protocol and has been retained in the Paris Agreement as a blend of economics and game theory. In addition to what was said earlier about the disentangling of the public and private good aspects of climate change, and about the extensions of the Coase theorem to global flow and stock externalities, it is shown that as far as emissions under a cap-and-trade scheme are concerned, the market equilibrium of pollution permits, when it is competitive, belongs to the core of an appropriately formulated market game. Thus, the two disciplines of economics and game theory when put together contribute, each in its own way, to the understanding of the cap-and-trade mechanism proposed in the Kyoto Protocol and retained in the Paris Agreement.

1.1.2 *The Common Methodology and Climate Policy*

The common language of mathematical modeling is prevalent throughout the book. The main justification for it lies in the fact that this methodology allows us to make direct connections between the three disciplines involved, which is a necessary condition if the aim is to contribute new results rather than to only describe problems and known solutions.

There can be at least two kinds of mathematical models: those used to derive theoretical results – (these are abstract models), and those used for computing actual policy – (these are simulation models). The book deals mostly with the former, because the current state of the field requires that an elaborate theoretical background be made available to provide a solid foundation to the highly desirable computational work for the problem of climate change. Allusions to the latter are indeed made throughout the book, to serve as illustrations.

Policy considerations may be seen as the ultimate goal of a work of applied theory like this book. The book indeed approaches policy considerations to the extent that an actual policy can be enlightened by theory or a policy recommendation can be derived from theory. This is done specifically in chapters 8 and 9, which study the two international agreements on climate change: the 2015 Paris Agreement and the failed 1997 Kyoto Protocol. In these chapters, I discuss why the Paris Agreement may succeed whereas the Kyoto Protocol failed. More specifically, Chapter 8 interprets the Paris Agreement in terms of a differential game model and demonstrates how the theory can be applied to assess and propose a road map for its successful implementation. It shows that development and adoption of cleaner technologies is the key to the success of the Paris Agreement and recommends that development of cleaner technologies should not be left to market forces alone. In parallel to the Paris Agreement and the International Solar Alliance of 121 countries initiated by the proactive Prime Minister Narendra Modi of India, a global agreement to fund research for development of cleaner technologies is needed. Such a fund to which governments of all countries as well as private individuals and entities may contribute can boost the efforts to develop and adopt cleaner technologies and overcome intellectual property rights barriers.

One broad conclusion concerning climate policy that follows from this work is that financial transfers to balance the costs and benefits of controlling climate change are a necessity and not a matter of approach or choice. In the absence of transfers, sovereign and peaceful countries, unless they are identical, cannot be induced to take actions that are necessary for controlling climate change.[15]

A conclusion is drawn in the final final chapter of this book. It summarizes both the theory and the policy implications of this work. It also discusses problems that have been left open and that may be addressed in future work. Some readers may find it useful to go through the concluding chapter before proceeding to read the rest of the text.

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[15]However, many preceding studies, for reasons of tractability, get around the necessity of transfers by assuming identical countries such that the costs and benefits of controlling climate change can be balanced without transfers. In contrast, transfers are implicit in Coase's (1960) classical solution for tackling externalities, which requires direct transfers between the parties involved for reducing an externality. As shown in Ellerman and Decaux (1998) and Chander (2003), transfers were also implicit in the Kyoto Protocol via the Clean Development Mechanism and the assignment of emission quotas that could be traded on an international market. The Montreal Protocol, which has been hailed as an example of successful international cooperation, explicitly requires transfers, though not in as large amounts as those implicit in the Kyoto Protocol.

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