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PROSPECTS OF TOOLS FROM DIFFERENTIAL GAMES IN THE STUDY OF MACROECONOMICS OF CLIMATE CHANGE

By

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Prospects of Tools from Differential Games in the study of macroeconomics of climate change*

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Abstract In this note we sketch a dynamic framework within which the discussion on the macro economic effects of climate change take place. The problem setting is characterized by scientific uncertainties about the development of climate, potential large economic losses and human beings having their specific features. Some considerations about climate change, macroeconomics and their relationship are given. A characteristic feature of the problem setting is that there are multiple decision makers interacting in a dynamic world with large uncertainties. Problems of this type have been studied extensively by (dynamic) game theory. A rough literature review is provided and some items open for future research are indicated.

Keywords: Climate change, environmental change, macro-economic effects, dynamic games

JEL-codes: C7,D6,D8,E6,F,I3,O44,Q

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1 Introduction

Writing a chapter for this Handbook is quite a challenging task. According the guidelines this chapter should make on the one hand new and original arguments and on the other hand survey what are the essential issues and questions in the field of research I am supposed to address. Further, though I should aim to present the theories and opinions of all sides fairly and accurately, my coverage may and should advocate my specific opinion and standpoint. As a mathematician, who is trained to think in terms of definitions and resulting theorems, this is a hard job. After some lengthy thoughts I decided to sketch a framework within which the discussion on the macro economic effects of climate change take place. In section two I argue that the problem setting is characterized by scientific uncertainties about the development of climate, potential large losses and human beings having their specific features. The section provides some considerations about climate change, macroeconomics and their relationship. A characteristic feature of the problem setting is that there are multiple decision makers interacting in a dynamic world with large uncertainties. Problems of this type have been studied extensively by (dynamic) game theory. Section three starts with an introductory section on what (dynamic) game theory is about, followed by an overview of tools which have been developed in this area and which (may) play a role in the analysis of macroeconomics of climate change. An important aspect in this analysis is whether and when countries will engage in "green energy" and its technology. Section four illustrates some issues that occur when one likes to tackle this question. Using some simple well-known game theoretic modeling tools, it is illustrated how coordination problems occur which may lead to suboptimal policies. A literature review suggests that, though there has been done already quite some work to better understand and solve the resulting problems, the current game theoretic tools can only partially address these problems. An extensive list of "to do" items concludes this section. The chapter concludes with some general observations.

At this point I already want to stress that this chapter is based on an extensive literature and it is impossible to list all adequate references. For that reason a number of survey articles and books are referenced where one can find extensive lists of relevant literature.

2 Some private considerations

2.1 Considerations about climate change

The main reason to include this section is twofold. First we hope to give the reader, not too familiar with the subject, some basic insights into the complex material. Second, we hope that this (far from complete) outline may help to better understand some issues dealt with in the next sections.

Going through the literature to find an explanation of which factors basically determine the climate (average weather conditions and the distribution of events around that average) one gets puzzled. Below we give some considerations that can be traced in literature about climate change. They are mainly based on the Intergovernmental Panel on Climate Change report 2007 [67], where one can find many references to scientific studies that lead to these considerations. Unfortunately, however, there are also studies that question the accuracy or even conclusions of this report, see e.g. [20], [65], [37]. As a scientist, and lay-man in this field, the overall impression is that we start of to see some global contours and factors impacting each other, but that an in-depth understanding of the material is far from complete.

Studies on deep sea sediments, continental deposits of flora, fauna and loess, and ice cores show

that during the last one million years series of large glacial-interglacial changes occurred with cycles of about 100.000 years (see e.g. [38], [73]). This implies that climate in the past was not fixed.
From a physics point of view temperature changes are due to changes in the global energy balance on earth. At this moment there is no reasonable doubt to believe that the main source of energy is the sun and that energy is lost to space. If either the input from the sun and/or the output to space changes and these changes do not outweigh each other the total energy that is available on earth changes. Energy is distributed around the globe by winds, ocean currents, and other mechanisms and determines the climate of different regions. So, if there is a change in the amount of energy to be distributed, climate will change in at least some regions.

Looking for an explanation for these large glacial-interglacial changes Milankovith [47] came up with the idea to relate local changes in solar radiation to long-term variations in earth's orbital variations. Slight variations in Earth's orbit lead to changes in the seasonal distribution of sunlight reaching the Earth's surface and how it is distributed across the globe. Milankovith [47] and later on Berger [10] show that there is a high correlation between the earth's orbital variations and the occurrence of glacial and interglacial periods. A model of future climate solely based on the observed orbital-climate relationships predicts that the long-term trend over the next seven thousand years is toward extensive Northern Hemisphere glaciation (see [35]).

Other factors that impact climate on a long term basis are, e.g., mountain building and continental drift.

A factor that one expects to affect the energy balance on a more short term basis is the amount of solar radiation produced by the sun. Sunspots, indicating lower sun temperatures, are an indicator for a change in the solar radiation. They have a cycle of approximately 11 years and they are reported already in ancient times. Also studies of rock layers and layering show repeating peaks in layer thickness, with a pattern approximately repeating every 11 layers. This suggests that solar cycles have been active for hundreds of millions of years. From 1978 on there are measurements on the total solar irradiation obtained by satellites. Since the observed changes in solar radiation over the last decades are quite small the common conclusion of a wide range of studies (see, e.g., the third assessment report of IPCC) is that the changes in solar irradiance are not the major cause of the temperature changes in the second half of the 20th century unless those changes can induce unknown large feedbacks in the climate system. This reservation is made because the exact relationships between solar irradiance and long-term climatological changes, such as global warming, are not well understood yet.

Statistics show that in the last 100 years, earth's average surface temperature increased by about $0.8°C$ $(1.4°F)$ with about two thirds of the increase occurring over just the last three decades. Physicists have produced a model that relates the incoming sun radiation to the Earth temperature. An important point in this model is that thermal radiation that is reflected by the Earth into space is partially reflected to Earth again due to, so-called, greenhouse gases in the atmosphere. One of these gases is carbon dioxide (CO_2). An important property of CO_2 is that once it is in the atmosphere, it stays there for a long time (estimates range from 30-95 years). Since due to fossil burning and deforestation CO_2 concentrations have increased exponentially over the last 150 years (and as such have a strong correlation with the increase of temperature during these years), and given the above mentioned greenhouse effect of CO_2, it seems at least plausible that this increase in CO_2 has caused part of the increases in global average temperatures. However, the above temperature model is just an approximation of reality and there are, separate from a complete understanding of the relationship between more CO_2 concentration in the atmosphere and its impact on the amount

of thermal reflection, also other factors that (might) affect the transfer of solar energy into the temperature on earth.
An important factor are the feedbacks induced by a change in temperature. In case temperature increases, e.g., the composition and formation of clouds will change too. This has both negative (e.g. sun blocking) and positive effects (increase of greenhouse effect) on the thermal radiation. The balance of it is unclear. An extensive list of potential feedbacks can be found in the IPCC reports. An important point is that quite a number of these feedbacks induce transitions that last for long time horizons and as such cannot be redirected within a short time span.

From the above considerations it will be clear that, with no spare Earth with which to experiment, the question whether a climate change occurs that can be attributed to human behavior is far from easy. Models have to be used to make projections of possible future changes over time scales of many decades and for which there are no precise past analogues. To deal with this issue the IPCC working group I pursued as follows: (a) detect whether the climate has changed; (b) demonstrate that the detected change is consistent with computer model simulations of the climate change signal that is calculated to occur in response to human behavior; and (c) demonstrate that the detected change is not consistent with alternative, physically plausible explanations of recent climate change that exclude important human behavior.
Using this set up the fourth IPCC reports that the global mean equilibrium warming for doubling (relative to the year 2000) CO_2 is likely (probability larger than 66%) to lie in the range $2°C$ to $4.5°C$, with a most likely value of about $3°C$. With a probability of 90% the impact of such a doubling will be at least $1.5°C$.

So, in short, there is a trend that average surface temperature rises on Earth, and if we extrapolate this trend the temperature will rise considerably in the nearby future. Furthermore, if indeed the CO_2 concentration is responsible for this increase (as expected by the IPCC reports), this effect will impact for a long period of time.

2.2 Considerations about macroeconomics

2.2.1 Growth prospects

The last decades have shown a large increase of international economic integration (i.e. international trade, finance, investment and migration). As a consequence countries/people have become increasingly interdependent on issues like, e.g., employment, production of goods and income spent abroad. As a consequence economic growth in a single country has become much more vulnerable to developments of growth in other parts of the world. Examples illustrating this are the Asian financial crisis in 1997-1998 that arose due to weaknesses in financial and monetary systems in Asian countries and, more recently, the collapse of the US subprime mortgages and the Eurozone crisis. Asia's recovery from its financial crisis was supported by healthy growth and demand conditions in the developed world. The financial crisis originating in the US, however, had an impact on loans of banks worldwide. In Europe, e.g., generous bank rescue operations were implemented to counteract the serious threat of a negative spiral of an increasing number of banks having solvability problems. Since banks had solvability problems they were very reluctant to provide new loans for any risky investment (which included lending to each other). For that reason governments also engaged in recovery programs. The Eurozone crisis has its roots back in the 90's of the previous century. In that time the deregulation of financial markets (enhancing too much and/or bad private and government loans) was initiated and, together with a bad monitoring of government debt by the European Union, this led to an increase of government debt in, e.g., Greece. Since there was a distrust in financial markets whether Greece would be able to meet its future obligations in 2009 and the European Central Bank (ECB) was forbidden by the Lisbon treaty to buy bonds of its member states, the Greek could not refinance their debts and the Eurozone crisis occurred. Not completely accidently, this happened at the time Europe was just recovering from the US induced financial crisis. Due to the solvency problems of private banks[1], the ECB regulations and the fact that debts in the northern EU countries were also beyond the limits set by the EMU treaty, particularly, in Greece, Italy, Portugal, Spain and Ireland a period of hard budget constraints and belt-tightening has set in, which reverses the growth patterns of the past. The experience of the great depression in the 1930's shows that it is questionable whether in this way the debt ratio of these countries will improve and that the social consequences of such policies can be quite severe. For that reason Article 103 of the Maastricht Treaty that explicitly rules out member state liability for the debts of other EMU member countries is now under revision. The European Union that has intervened from mid 2010 onwards with sometimes rather hastily constructed rescue packages is bracing now for a major reform of the European economic governance system, attempting to blend solidarity with market discipline. This should also become visible in the ECB's regulations concerning the buying/selling of member states's bonds. European banks used to finance a large part of economic activities worldwide. From a world wide economic growth perspective it is therefore important to find a solution for their solvency problems so that European banks can take on this job again.

For the nearby future another problem is the structural trade deficit of the US versus the trade surplus of China, together with the increasing US deficit. In the long end this situation is not sustainable. The standard way out of this would be for the US either to devaluate the dollar and/or to decrease the rate of consumption, whereas China should increase the value of the yuan and/or increase its rate of consumption. Given these conditions and (a further expected) increase of the debt ratio in the US may, however, result in investors to demand higher interest rates since they anticipate a dollar depreciation. Paying these higher interest rates may slow-down domestic U.S. growth again.

So, the general perception is that the main economic growth stimulus in the nearby future is to come from the new developing countries like China and Brazil.

2.2.2 GDP versus Quality of Life

A confusion that frequently occurs in people's mind is that maximization of economic growth is synonymous with maximization of quality of life (QOL).
In fact, economic growth (standard of living/economic wealth/GDP) is just one entry of QOL. QOL has many more entries like, e.g., the built environment, physical and mental health, education, recreation and leisure time, and social belonging ([29]). Probably confusion arises since, often, by using additional money the value of an entry of QOL can be increased. This additional amount of money is then aligned with the additional value of the entry. But, clearly, every entry of QOL has its own dimension and scale of measurement. So, in fact, the above statement of maximizing QOL does not make any sense. Looking for solutions that cannot be improved simultaneously by a better use of the inputs (like e.g. money) is then all one can do. Usually there is more than one QOL vector satisfying this property. It remains then to the decision maker to choose somehow one

[1] In the Netherlands these solvency problems are even increased by the fact that pension funds must value their assets at the current interest rate. This implies that at the current low interest rates they are underfunded and cannot invest too.

solution from this set. This was already formalized by the Italian economist/sociologist Pareto at the end of the 19th century ([56]). Notice that increasing the value of one entry of QOL may sometimes have a positive effect on some other entries (positive externalities) too but also, on the contrary, sometimes have a negative effect on some other entries (negative externalities). For instance, if unemployment decreases probably not only GDP increases but also social belonging may increase; in case unemployment decreases the recreation and leisure time decreases too.

In particular one should keep in mind that improving the standard of living may sometimes have quite a large negative impact on other entries of QOL, like environment, recreation and leisure time. A fact which often is under exposed, particularly in those situations where the standard of living is already high. So, using additional money/input just to improve the standard of living probably does not lead in those cases to a better (let alone optimal) Pareto solution. Or, stated differently, a complete fixation on increasing the standard of living will, usually, not yield a Pareto efficient point within the set of QOL vectors.

Since thinking in more dimensional terms is difficult there have been formulated functions of QOL like, e.g., the Human Development Index (HDI), to compare living standards in different countries.

To be able to shrink, or even make a specific choice within, the set of Pareto efficient points additional preference information of the involved person is required. This, however, presumes that QOL variables can somehow be quantified. To measure QOL variables and compare them is not a trivial job. Most of them are measured in different units. To make them comparable one can normalize these numbers by, e.g., division by the goal target value of the corresponding objective (hence turning all deviations into percentages) or division by the range of the corresponding objective (between the best and the worst possible values, hence mapping all deviations onto a zero-one range). But notice that the effect of this normalization is just that to each variable a real number is attached. How to value the distance between these numbers for variables relative to each other is then still another issue that has to be tackled. Provided with a measure of QOL variables would probably better inform a decision maker about the choices and the directions where to go.

2.2.3 (Socio) economic factors affecting (macro) economic behavior

Every human being has one certainty, namely that he will die (at least physically). Time and what happens after that are uncertain. To cope with this uncertainty is not an easy job. Probably this, together with his instinct to survive, is a drive which makes that (see also [66]) humans look for new challenges (which maybe could lead to at least a partial answer to the uncertainties); they look for (at least some) rest points during their life time; they act according to their own individual preferences, without regard for the consequences of this for the group as a whole; their willingness to repay kindness with kindness and betray with revenge; and they show short run behavior. This might clarify, e.g., the constant drive to change things; herding behavior by people and the current level of international economic integration. Herding behavior is explained from this by the observation that joining a group is a relatively mentally easy job, furthermore it makes the chance that you are doing things wrong small, and if things are wrong, you have the certainty that you are not the only one who went the wrong way. In economics this herding behavior is cleverly manipulated by, e.g., the fashion industry.

Seabright explains the current level of international economic integration in [66] from the optimizing human behavior's point of view. To clarify his point of view we first recall some other basic facts of life, i.e., in order to live one has to eat. In order to eat one has to grow food. To grow food one has to seed, work on the crop and harvest. This can be done either in isolation or in cooperation with others. Seabright points out three fundamental advantages (and their mutual accumulating effects) that may occur due to cooperation. That is, 1) higher levels of specialization (and as a result production levels); 2) reduction of individual risks and uncertainty from unpredictable adverse outcomes; and 3) an increase in the speed of accumulation of knowledge and technological change. According Seabright (see also [9]) the current setting of international economic integration might be explained by human beings' optimization drive to exploit these advantages and could be established due to humans' exceptional capacity to engage in abstract reasoning. This enabled them to design social and economic institutions based on trust that effectively enable total strangers to behave routinely in a cooperative manner despite their instinctive fears of exploitation and personal harm.

2.2.4 Considerations about some growth factors

A number of QOL variables, like environment, cannot be changed instantaneously. They are determined by what happened "long" ago, where the phrase "long" can be either years (litter), decades (CO_2 emissions), centuries or even millennia (nuclear waste). Clearly we cannot judge whether and how these QOL variables will be valued by future generations, or whether future generations will be able to affect these variables at short notice. The short run and optimizing behavior makes that there is a constant pressure not to worry too much about these variables in the future.

Another consequence of optimizing behavior is that if people have a longer-term view of life this longer time perspective enhances investment, innovation, and learning, as all of these activities require some form of short-run sacrifice in exchange for potential future gains.

From an economic point of view, the opportunity cost of global poverty are high due to missed potential contribution to the economic process, migration cost, cost from (prevention of) terrorism and potential destabilization cost of social networks in developed countries. So an important issue is how to improve on this situation. Probably most of human beings would like to assist (everyone in his own way) to help people out of their misery if they cannot be blamed they got into it. The past sad African experience where on a regular basis aid has been provided followed by civil wars again, however, gives people the impression they contribute to a bad vicious circle. Maybe a way out of this circle is to make aid conditional on progress that has been made on previous projects aimed at welfare improvement ("stepped lending"). Furthermore it may be wise to let countries come up with proposals themselves. This, because they can better judge the local situation. Furthermore, in this way it makes them better accountable for the projects and it makes it possible to better coordinate the help among potential providers. Some main starting points to improve QOL variables in developing countries are clean water supply, sanitation, basic health care, education and building an infrastructure (including a formal and informal (like a stepped lending microfinancing) economic infrastructure).

Free trade is the perfect solution in a perfect world, since everybody can specialize on those issues at which he is best. This creates dependency amongst people and people must therefore be able to trust each other. Particularly in stress situations. However, most people want to be able to take their own decisions, to control their own life, and have the natural reaction to choose for their own interest first in stress situations. Consequently, in a non-perfect world with many stress situations, for aggregations of people grouped into countries free trade is probably not optimal from their welfare point of view (for simplicity we identify welfare here with the set of QOL variables). Particularly concerning some basic living conditions (agricultural, energy, security) point of view, the situation where they are up to (at least) some level self supporting seems to be more comfortable and welfare improving.

As already mentioned before, reducing the level of unemployment usually not only positively affects GDP but impacts other entries of QOL too. In case there is large unemployment due to a saturated economy, there are two possibilities to deal with this. One way is to divide the work more equal between everyone. This implies that the employed people would have to substitute income for leisure time. In case this option is not feasible/disliked this option seems to be not welfare improving and there is clearly a need for new employment initiatives. In those situations it seems good to look for initiatives which could improve QOL on other than GDP variables as well. Within the current context of a potential drastic climate change, one could think, e.g., of initiatives that make a better use of/find substitutes for current energy or to invest in new infrastructure to deal with changed weather conditions.
Ideally this should be financed from saved budgets when economic times are fine. This requires a strict execution of policy rules in economic good times. Unfortunately, as the Euro crises illustrates, this is not always as easy as it looks like. Particularly if there are no strict sanctioned policy rules there are always people/countries who want to have their dinner paid by their neighbor. Moreover in most of the cases politicians are driven by election scores that depend on public opinion. Again, since many people like to have their dinner paid by their neighbor, and the government is presumed to be one of them, there is a constant pressure on politicians to spend at least all of the government budget. Given all these considerations it seems good to reflect on the establishment of funds like, e.g., a recession unemployment fund, governed by some independent institution, that is fed by a fixed percentage of economic growth of government income during good times and that conducts the afore mentioned unemployment policy during recession times. Given such a fixed policy rule there is maybe some automatism to reintegrate unemployed people into the economic process again mitigating the negative effects of large unemployment.

Debt in one country are assets for an other party. In case those parties doubt whether the country will meet its future obligations and the central bank of the country doesn't want to provide the government with additional money too to finance the debt the government has to find other political unpopular ways (like raising taxes, cutting social security funds, privatizing publicly owned undertaking). If a country has large foreign debts and a large number of privatized undertaking are owned by foreign companies it will be difficult for a government to conduct a private economic policy. The economy of the country is out of its government control, which usually is disliked by the people for reasons mentioned earlier. This may lead to stress between countries, usually, resulting in a worse realization of welfare in both countries.

2.3 Considerations about macroeconomics of climate change

An increase in global temperature will cause sea levels to rise and will change the amount and pattern of precipitation. Warming is expected to be strongest in the Arctic and implies a continuing retreat of glaciers, permafrost and sea ice. Other likely effects of the warming include more frequent occurrence of extreme weather events including heatwaves, droughts and heavy rainfall events, expansion of subtropical deserts, changes in flora and fauna and changes in agricultural yields. Warming and related changes will vary from region to region around the globe, with projections being more robust in some areas than others (see IPCC reports). The IPCC reports show that not all countries are hit in the same way. In fact some countries may incur better environmental living conditions. According the reports in particular the northern hemisphere will incur the largest rises in temperatures.

So there are large changes to be expected in important QOL variables if temperature increases by some degrees. As mentioned in subsection 1 according the IPCC reports an increase of $1.5°C$ will occur with a probability of 90% if a doubling (compared to its value in the year 2000) or more of CO_2 concentration occurs.

Going through the scientific literature it is striking to see that there are relatively few papers dealing with the impact of climate change on economics. Tol provides in [71] a literature review. Based on a partial assessment of some important variables (agriculture and forestry, water resources, coastal zones, energy consumption, health) his main findings are that, although climate change has both positive and negative effects, the negative effects dominate. In particular when temperature rises by more than $1°C$. He reports, e.g., that an increase of temperature by $2.5°C$ will have an estimated negative impact on global GDP of -1%. The corresponding 95% confidence interval is, however, ranging from $+4\%$ to -11%. In his overview Tol also mentions a number of variables that have not been considered in the analysis and a number of other shortcomings/points that need additional research. However, his impression is that all these points will not reverse the direction of the line of outcome. A second conclusion is that climate change primarily impacts poorer countries, and poverty is one of the main causes for this vulnerability.

Since the risks world-wide associated with the option to do nothing can be quite large, whereas the costs involved with an "overly ambitious" policy are moderate (one can always reverse these policies, if needed) it seems from a risk management point of view for the developed countries best to try to reduce greenhouse gas emissions substantially within a not too long time span. Since, also due to an increasing population's demand, fossils are getting more and more scarce, it seems also from a long-term energy supply point of view good for them to look for greenhouse gas friendly energy. The perspective that they might be self-supporting w.r.t. the supply of energy to a certain extent will probably also have a positive effect on the engagement in "green energy" (and technology). Furthermore the potential smaller loss in value of a number of QOL variables might outweigh the potential drop in increase of GDP. Clearly, the more self-supporting a developed country is projected to be w.r.t. its supply of energy, the less risks it experiences.

It is expected that developing countries will be hit the hardest if temperature increases. This, since they are more exposed to the most additional dangerous consequences of changes in precipitation patterns, rising sea levels, and more frequent weather-related disastersposed risks for agriculture, food, water supplies and health. This assessment is confirmed by Tol's review, where one of his conclusions is that climate change primarily impacts poorer countries, and poverty is one of the main causes for this vulnerability. So poorer countries seem to be trapped. A climate policy that negatively affects economic development may harm them most, whereas a development policy aiming to improve living standards using conventional production technologies may drastically increase CO_2 emissions leading to a probably additional increase of temperature. From the developing aid providing countries' point of view it is to be expected that they will condition economic aid on whether poor countries pursue CO_2 emission friendly policies. This is illustrated, e.g., by the request in 2005 of the industrialized G-8 countries who asked the World Bank to develop a plan for more investments in clean energy in the developing world, in cooperation with other international financial institutions. According the 2010 edition of the World Development Report of the World Bank [74] there is now a focus on development in a changing climate. Climate change adaptation considerations are being integrated into Country Assistance Strategies. The bank is also piloting innovative climate risk insurance possibilities to help countries integrate disaster planning into their development strategies. An increasing interest in trying to improve the identification, quantification, pricing and mitigation of the risks involved is also shown by large insurance companies (see e.g. [1]).

A number of the new industrializing countries like Russia and Brazil are projected to be major providers of fossil fuel energy over the coming decades ([75]). So they may expect a substantial increase in GDP which potentially can lever a substantial increase of various other QOL variables too.

So, we may conclude that different types of countries have different perceptions about the need to engage in "green energy/technology".

3 What is (dynamic) game theory about[2]

Game theory studies the interactive decision making process between persons (or more abstract: decision making entities) with (at least partial) conflicting interests in situations where decisions by one person affect the decision made by another person. This decision making can be done in either a cooperative setting or a non-cooperative setting. It is used to describe, predict, explain and enforce desired behavior.

Most research in game theory has been done on, so-called, static games (see e.g. [54] or [55] for an elementary introduction). In static games one concentrates on the normal form of a game. In this form all possible sequences of decisions of each player are set out against each other. So, e.g., for a two-player game this results in a matrix structure. The information agents have about the game is crucial for the outcome of the decision making. A distinction is made between complete and incomplete information games. In a complete information game, agents know not only their own payoffs, but also the payoffs and strategies of all the other agents. Characteristic for a static game is that it takes place in one moment of time: all players make their choice once and simultaneous and, dependent on the choices made, each player receives his payoff.
In such a formulation important issues like the order of play in the decision process, information available to the players at the time of their decisions, and the evolution of the game are suppressed, and this is the reason why this branch of game theory is usually classified as "static".

To capture information aspects in a static game one uses the so-called extensive form of the game. Basically this involves a tree structure with several nodes and branches, providing an explicit description of the order of play and the information available to each agent at the time of his decision. In case at least one of the agents has an infinite number of actions to choose from it is impossible to use the tree structure to describe the game. In those cases the extensive form involves the description of the evolution of the underlying decision process using a set of difference or differential equations.

Games where a noncooperative static game is played repeatedly are known as repeated games. [3] studies repeated games with incomplete information. Formally the basic model here is a finite family of games with an initial probability that determines which one of these games will be played. In this set-up, after each stage, the players receive information on their opponents moves and/or on the game chosen.

In case the agent's act in a dynamic environment strategic behavior and interdependencies over time play a crucial role and need to be properly specified before one can infer what the outcome of the game will be. This is typically the case in macroeconomic modeling. Games dealing with these aspects are called dynamic games. Dynamic game theory brings together four features that are key to many situations in economy, ecology, and elsewhere: optimizing behavior, presence of multiple agents/players, enduring consequences of decisions and robustness with respect to variability in the environment.

[2] Parts of this section were presented in [24].

To deal with problems bearing these four features the dynamic game theory methodology splits the modeling of the problem into three parts.
One part is the modeling of the environment in which the agents act. To obtain a mathematical model of the agents' environment, usually, a set of differential or difference equations is specified describing the change over time of the set of variables of interest (usually represented in one vector the, so-called, state vector of the considered system). These equations are assumed to capture the main (dynamical) features of the environment. A characteristic property of this specification is that these dynamic equations mostly contain a set of so-called "input" functions. These input functions model the effect of the actions taken by the agents on the environment during the course of the game. In particular by viewing "nature" as a separate player in the game who can choose an input functional that works against the other player(s) one can model worst case scenario's and, consequently, analyze robustness of the "undisturbed" game solution.
A second part is the modeling of the agents' objectives. Usually the agents' objectives are formalized as cost/utility functionals which have to be minimized. Since this minimization has to be performed subject to the specified dynamic model of the environment, techniques developed in optimal control theory play an important role in solving dynamic games.
The third part is then the formalization of the the order of play in the decision process and information available to the players at the time of their decisions (so, in particular, will learning take place over time).

A branch of dynamic games that is frequently analyzed in literature is where the system dynamics are modeled by a set of differential equations, the so-called differential games. But many other mathematical models to describe systems which change over time (or sequentially) like, e.g., difference equations, partial differential equations, differential and algebraic equations, time-delay equations where either stochastic uncertainty is added or not, are considered too. All of these give rise to different classes of dynamic games that have their own specific model features.

To realize his objective an agent can either cooperate with one or more agents in the game or not. In case all agents cooperate we speak about a cooperative game. In case none of the agents cooperates with someone else the game is called a noncooperative game. The intermediate case that groups of agents cooperate in coalitions against each other in a noncooperative way is called a coalitional game.

In some situations where agents cooperate it is possible that agents can transfer (part of) their revenues/cost to another agent. If this is the case the game is called a transferable utility (TU) game. Otherwise it is called a non-transferable utility (NTU) game.

An important issue that affects the outcome of the game is the organization of the decision making process. In case there is one agent who has a leading position in the decision making process the game is called a Hierarchical or Stackelberg game (after H. von Stackelberg [68]). So in this case there is a vertical structure in the decision making process. In case there does not exist such a dependency we talk about a horizontal decision making structure.

Two popular decision rules in dynamic games are the so-called open-loop and feedback strategy. In the open-loop strategy players determine their plans for the entire planning horizon of the game at the start of the game. Next they submit these plans to some authority, who then enforces these plans as binding commitments for the whole planning period. If feedback strategies are used it is assumed that players determine their actions at any point in time as a function of the state of the system at that time. This strategy sets out of course that players can actually implement this strategy at every point in time.

3.1 Choice of Actions

From the previous section it will be clear that the actions played by the agents in a dynamic game depend on the coordination structure, organizational structure, information structure and decision rule (or strategy) followed by the agents. Assuming that every agent likes to minimize his cost the problem as stated so far, however, is not well defined yet. Depending on the coordination structure and organizational structure different solution concepts can be considered.

If a static noncooperative game is played repeatedly, the notion of mixed strategies is often used. In a mixed strategy the agents choose their actions based on a probability distribution. The probability distribution chosen by the agents might be such that, e.g., their average value of the game is optimized.

In a Stackelberg game (see e.g. [36] for a review of its use in supply chain and marketing models) it is assumed that the leader announces his decision u_L, which is subsequently made known to the other player, the follower. With this knowledge, the follower chooses his decision u_F by minimizing his cost for this choice of u_L. So, the optimal reaction of the follower u_F is a function of u_L. The leader takes this optimal reaction function of the follower into account to determine his action as the argument that minimizes his cost $J_L(u_L, u_F(u_L))$. Notice that in this solution concept it is assumed that the leader has a complete knowledge about the follower's preferences and strategy. Other solution concepts have been studied too, like e.g. the so-called inverse Stackelberg equilibrium, where the leader does not announce his action u_L, but his reaction function $\gamma_L(u_F)$. This concept can be used to enforce a by the leader desired behavior of the follower (see [52],[53]). Closely related to this are games of mechanism design for, so-called, Bayesian games (i.e. games in which information about the other players payoffs is incomplete see e.g. [49]). Within this kind of games there is a leader who chooses the payoff structure of the game. The idea is that this leader sets the rules such as to motivate followers to disclose private information (see also [63]). Consistent conjectural variations equilibria are equilibria which can be viewed as "double sided Stackelberg" equilibria. Here it is assumed that both players conjecture a reaction function $\gamma_i(u_j)$ of their opponent in function of their own decision. If the resulting best responses u_i^* and conjectured reactions coincide these responses are called a consistent conjectural variations equilibrium (see [7] or [25]).

In a noncooperative game one of the most frequent used solutions is the *Nash equilibrium*. As the name suggest this is an equilibrium concept. It is assumed that ultimately those actions will be played by the agents that have the property that none of the agents can unilaterally improve by playing a different action. One of the main references that documents the theoretical developments on this issue in dynamic games is the seminal book [7]. Furthermore uncertainty can be dealt within this framework by assuming that the player "nature" always selects a worst-case scenario (see e.g. [6], [45], [14], [23] and [4]). Another minimax approach to model uncertainty which has been used in finance are so-called interval models ([11]). Here it is assumed that a compact set is known that contains the new state vector. Furthermore, in case one views uncertainty as some separate vector entering the system, approaches to isolate this "disturbance" in a multi-player context have been formulated in, e.g., [13].

Since the Nash equilibrium is an equilibrium concept in many applications an important issue is how this equilibrium is attained. Two of the approaches that try to answer this question, particularly in the context with large number of agents, are evolutionary game theory and coordination games. Using, e.g., learning models they try to predict the road towards the equilibrium (see, e.g., [27], [32], [64], [19]).

In a cooperative setting it seems reasonable to look for those combinations of control actions that

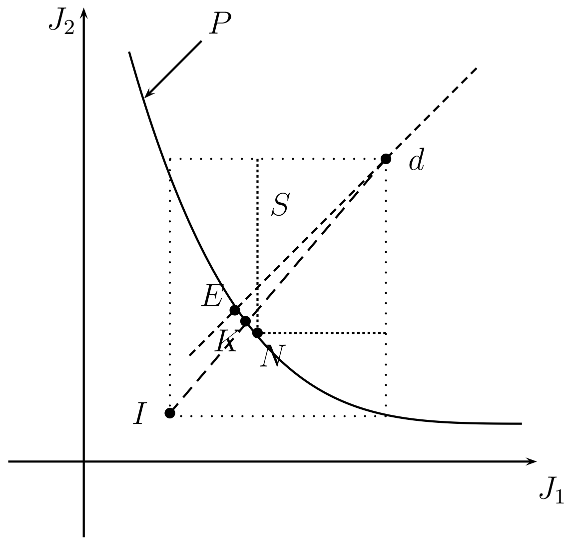

Figure 1: The bargaining game.

have the property that the resulting cost incurred by the different players cannot be improved for all players simultaneously by choosing a different set of control actions. Formally, a set of control actions $\hat{u}$ is called *Pareto efficient* if the set of inequalities $J_i(u) \leq J_i(\hat{u}),\ i = 1, \cdots, N$, where at least one of the inequalities is strict, does not allow for any solution $u \in \mathcal{U}$. The corresponding point $(J_1(\hat{u}), \cdots, J_N(\hat{u}))$ is called a *Pareto solution*. Usually there is more than one Pareto solution. The set of all Pareto solutions is called the *Pareto frontier*. In particular this implies that this Pareto efficiency concept in general does not suffice to conclude which action is optimal for an agent in a cooperative setting.

In a NTU game the cost of the agents are fixed once the actions of the agents are fixed. So, the question is then which point is reasonable to select on the Pareto frontier. Bargaining theory may help then to select a point on the Pareto frontier.

Bargaining theory has its origin in two papers by Nash [50] and [51]. In these papers a bargaining problem is defined as a situation in which two (or more) individuals or organizations have to agree on the choice of one specific alternative from a set of alternatives available to them, while having conflicting interests over this set of alternatives. Nash proposes in [51] two different approaches to the bargaining problem, namely the *axiomatic* and the *strategic* approach. The axiomatic approach lists a number of desirable properties the solution must have, called the *axioms*. The strategic approach on the other hand, sets out a particular bargaining procedure and asks what outcomes would result from rational behavior by the individual players.

So, bargaining theory deals with the situation in which players can realize -through cooperation- other (and better) outcomes than the one which becomes effective when they do not cooperate. This non-cooperative outcome is called the *threatpoint*. The question is to which outcome the players may possibly agree.

In Figure 1 a typical bargaining game is sketched. The ellipse marks out the set of possible outcomes, the *feasible set* S, of the game. The point d is the threatpoint. The edge P is the Pareto frontier.

Three well-known solutions are the Nash bargaining solution, N, the Kalai-Smorodinsky solution, K, and the Egalitarian solution, E. The *Nash bargaining solution*, selects the point of S at which the product of utility gains from d is maximal. The Kalai-Smorodinsky solution divides utility gains from the threatpoint proportional to the player's most optimistic expectations, I. For each agent, the most optimistic expectation is defined as the lowest cost he can attain in the feasible set subject to the constraint that no agent incurs a cost higher than his coordinate of the threatpoint. Finally, the *Egalitarian solution*, represents the idea that gains should be equal divided between the players. For more background and other axiomatic bargaining solutions we refer to Thomson [69].

In transferable utility games it may happen that it is less clear-cut how the gains of cooperation should be divided. Consider, e.g., the case that agents are involved in a joint project and the joint benefits of this cooperation have to be shared. In those cases an agreement in the cooperative dynamic game, or *solution* of the cooperative dynamic game, involves both an agreement on the allocation rule and an agreement on the set of strategies/controls. Again, in this case the allocation rule is required to be individually rational in the sense that no agent should be worse of than before his decision to cooperate.
In differential games an important issue is then at what point in time the "payments" occur. Is this at the beginning of the planning horizon of the game, at the end of the planning horizon of the game, at some a priori determined fixed points in time of the game or is every agent paid continuously during the length of the game. Particularly in the last case it seems reasonable to demand from the allocation rule that it is consistent over time. That is, the allocation rule is such that the allocation at any point in time is optimal for the remaining part of the game along the optimal state trajectory. So in particular at any point in time the payment should be individually rational for every player. An allocation rule that has this property is called subgame-consistent. Of course in a dynamic cooperative game not only the payment allocation rule is important but, like for all dynamic games, also the time-consistency of the strategies is important from a robustness point of view. A solution is called *subgame-consistent* if the allocation rule is subgame-consistent and the cooperative strategies are strongly time consistent. Yeung and Petrosyan [76] give a rigorous framework for the study of subgame-consistent solutions in cooperative stochastic differential games (see also [77] for an extension of this theory).

3.2 Coalitional Games

The bargaining approach presented in the previous section does not consider the formation of coalitions. In the presence of non binding agreements, even if the players agree upon a cooperative outcome, situations arise where the grand coalition could break down. Classical coalitional games are casted in characteristic function form. When the utilities are transferable a *characteristic function* $v(.)$ assigns to every coalition a real number (*worth*), representing the total payoff of this coalition of players when they cooperate. Stated differently, it denotes the power structure of the game i.e., the players in a coalition collectively demand a payoff $v(S)$ to stay in the grand coalition. In the bargaining problem the coordinates of the threat point d_i represent the payoff each player receives by acting on their own. Similarly $v(S)$ represents the collective payoff that a coalition $S \subset N$ can receive when the left out players in the coalition $N \backslash S$ act against S. In a non-transferable utility setting, however, two distinct set valued characteristic functions have been proposed, see [2], as the α and β characteristic functions. The main difference originates from the functional rules used in deriving them from the normal form game.

Under α notion, the characteristic function indicates those payoffs that coalition S can secure for its members even if the left out players in $N \backslash S$ strive to act against S. Here, players in S first announce their joint correlated strategy before the joint correlated strategy of the players in $N \backslash S$ is chosen. So, this is an assurable representation. Under β notion, the characteristic function indicates those payoffs that the left out players in $N\backslash S$ cannot prevent S from getting. Here, players in S choose their joint correlated strategy after the joint correlated strategy of the players in $N\backslash S$ is announced. So, this is an unpreventable representation.

An *imputation* is a set of allocations which are individually rational, i.e., every allocation is such that it guarantees the involved player a payoff more than what he could achieve on his own. A set of allocations is in the *core* when it is coalitionally rational. That is, the core consists of those imputations for which no coalition would be better off if it would separate itself and get its coalitional worth. Or, stated differently, a set of allocations belongs to the core if there is no incentive to any coalition to break off from the grand coalition. Clearly, the core is a subset of the Pareto frontier. The core is obtained by solving a linear programming problem. It can be empty. There are other solution concepts based on axioms such as Shapley value and nucleolus.

(Endogenous) coalition formation theory studies rules (like coalition membership, voting, structure of the negotiation process) of coalition formation. These rules can be interpreted as different institutional designs where the negotiations take place. Different rules will generally lead to different equilibrium coalition structures. The phrase equilibrium within this context means, e.g., that no player can increase his payoff unilaterally by joining a different coalition. In particular the effect of the rules on the efficiency of the resulting equilibrium coalition structure is analyzed (see e.g. [12], [16], [26], [59], [60]).

The cooperative solutions mentioned above are static concepts. Introducing dynamics in a coalitional setting raises new conceptual questions. It is not straightforward as to how one can extend the classical definition of core in a dynamic setting since there exist many notions of a profitable deviation. As a result, an unifying theory of dynamic coalitional games, at present, seems too ambitious. However, intuitively, in this context one expects the definition of core should capture those situations in which at each stage the grand coalition is formed no coalition has a profitable deviation, i.e., dynamic stability, taking into account the possibility of future profitable deviations of sub-coalitions. In an environment with non binding agreements only self-enforcing allocations are deemed to be stable. The main difference between static and dynamic setting is the credibility [60] of a deviation. A deviation of a coalition S is *credible*, if there is no incentive for a sub-coalition $T \subset S$ to deviate from S. The set of deviations and credible deviations coincide for a static game but differ in a dynamic setting. Kranich et al. [44] suggest new formulations of the core in dynamic cooperative games using credible deviations. For instance, if one makes an assumption that once a coalition deviates players cannot return to cooperation later, results in a core concept called strong sequential core. This allows for further splitting of the deviating coalition in the future. They also introduce a notion of weak sequential core which is a set of allocations for the grand coalition from which no coalition has ever a credible deviation. See, [30] for more details.

We review some work done towards extending the idea of a core in a differential game setting. Haurie [33] constructs an α characteristic function assuming the behavior of left out players is modeled as unknown bounded disturbances. Using this construction he introduces in [34] collectively rational Pareto optimal trajectories with an intent to extend the concept of core to dynamic multi stage games. Analogously, a Pareto equilibrium is called collectively optimal (C-optimal) when, at any stage, no coalition of a subset of the decision-makers can assure each of its members a higher gain than what he can get by full cooperation with all the other decision-makers. It is shown that if the game evolves on these trajectories any coalition does not have an incentive to deviate from the grand coalition in the later stages.

Time consistency, as introduced by Petrosjan et al. [58], in a dynamic cooperative game means that when the game evolves along the cooperative trajectory generated by a solution concept (which can be any solution concept such as core, Shapley value and nucleolus) then no player has an incentive to deviate from the actions prescribed by that solution. The notion of strong sequential core introduced in Kranich et. al [44] is the same as time consistency. Zaccour [78] studies the computational aspects of characteristic functions for linear state differential games. Evaluation of the characteristic function involves $2^N - 2$ equilibrium problems and one optimization problem (for the grand coalition) which is computationally expensive with large number of players. Therefore, instead, they propose an approach by optimizing the joint strategies of the coalition players while the left out players use their Nash equilibrium strategies. This modification involves solving one equilibrium problem and $2^N - 2$ optimization problems. Further, they characterize a class of games where this modified approach provides the same characteristic function values.

Assuming that players at each period/instant of time consider alternatives 'cooperate' and 'do not cooperate', Klompstra [42] studies a linear quadratic differential game. It is shown that for a 3 player game, there exists time dependent switching between different modes namely the grand coalition, formation of sub-coalitions and total non cooperation. Assuming similar behavior of players, i.e., to 'cooperate' or 'do not cooperate' at each time instant, Germain et. al [28] introduce a rational expectations core concept. They use γ characteristic function [18] where the left out players act individually against the coalition instead of forming a counter coalition. They show, using an environmental pollution game, that if each period of time players show interest in continued cooperation then, based on the rational expectations criterion, there exists a transfer scheme that induces core-theoretic cooperation at each period of time. Recently, Jørgensen [39] studies a differential game of waste management and proposes a transfer scheme that sustains inter-temporal core-theoretic cooperation.

3.3 Decentralization

In a cooperative setting, agents coordinate their strategies and it is not always feasible to maintain communication to implement their coordinated actions. Further, problems can arise due to lack of stability in the cooperative agreement. Threats and deterrence are some of the common stability inducing mechanisms used to enforce cooperation like, for instance, trigger strategies where a player using a trigger strategy initially cooperates but punishes the opponent if a certain level of defection (i.e., the trigger) is observed. In the context of differential games, see section 6.2 of [21] for more details on such strategies. In his seminal paper, Rosen [61] introduces a concept of normalized equilibrium that deals with a class of noncooperative games in which the constraints as well as the payoffs may depend on the strategies of all players. Using this approach Tidball et.al [70] show in a static game that a cooperative solution can be attained by a suitable choice of the normalized equilibrium. Further, they show, in a dynamic context, that only by introducing a tax mechanism it is possible to attain cooperation in a decentralized manner. Rosenthal [62] introduced a class of games which admit pure strategy Nash equilibria, which were later studied in a more general setting by Monderer et al. [48] as potential games. A strategic game is a potential game if it admits a potential function. A potential function is a real valued function, defined globally on the strategies of the players, such that its local optimizers are precisely the equilibria of the game. So, these games enable the use of optimization methods to find equilibria in a game instead of fixed point techniques. If, the social objective of the game coincides with the potential function then we see that the social optimum can be implemented in a noncooperative manner. Dragone et al. [22] present some preliminary work towards the extension of potential games in a differential game setting and study games that arise in advertising.

4 Differential games and macroeconomics of climate change

4.1 An Illustration

In the previous Chapter we flashed some major concepts used in game theory to model situations with players that have different interests. In this section we will indicate how these concepts can be/have been used in modeling impacts of climate change on macroeconomic developments. As a first simple illustration of a static single-act matrix game consider the conflict of interest of the developed countries versus the new industrialized countries on the implementation speed of green energy production. Table 1 provides some fictive numbers representing a measure of realized QOL variables using either a laissez faire (LF) (mainly use of fossil fuel) or a green orientated (GO) (more use of "green energy") strategy on a short (S, 5 years), medium (M, 15 years) and longer (L, 30 years) horizon

S	NDC	
DC	GO	LF
GO	100,50	95,60
LF	105,55	110,65

M	NDC	
DC	GO	LF
GO	110,70	105,75
LF	115,60	115,78

M/L	NDC	
DC	GO	LF
GO	120,95	115,83
LF	123,70	116,82

L	NDC	
DC	GO	LF
GO	130,100	120,87
LF	125,75	117,85

Table 1: Gains of LF versus Go strategy. First entries denote gains DC countries, second entries denote gains NDC countries

First consider the short horizon case. From the S table we see that if the policy of the DC is GO, the best strategy for the NDC is LF. If the DC choose for LF, LF is also the best strategy for the NDC. So the NDC will always choose for LF irrespective of the DC's choice. Therefore the equilibrium outcome will be LF for both the NDC and DC countries. This equilibrium is enforced by the NDC's choice. For the long horizon case things are reversed. Here the equilibrium GO is chosen by both the NDC and DC countries and is enforced by the DC countries because irrespective of the choice of the NDC's choice the DC countries choose for the GO option. In the intermediate horizon case both the DC and NDC choose the LF strategy.
We also included a situation M/L that might occur in between the medium and long horizon case. In that case we see that the DC countries always choose for LF, with as a consequence that the NDC will choose for that option too. This solution is, however, suboptimal. If both the DC and NDC countries choose for GO they both can achieve a better outcome. The reason why this does not occur is the lack of coordination (see also [59], where policy cooperation as a prisoners' dilemma is described). This example describes a case of pure discretionary coordination. The DC and NDC countries decide on a case-by-case basis to internalize the economic externalities resulting from macroeconomic interdependence and each country may gain without giving up anything of its sovereignty.
In the above example it was assumed that both DC and NDC countries could choose from just two strategies, i.e. GO or LF. A more realistic assumption is that they can opt for any mix of both

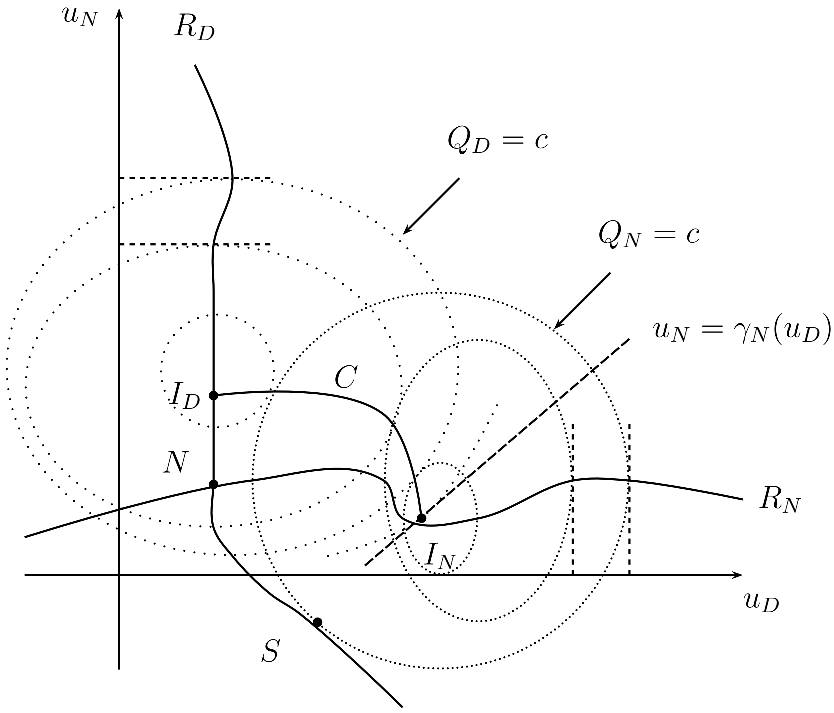

Figure 2: Hamada's diagram. N: Nash; S: Stackelberg (leader NDC); C: Cooperative solutions; I_i: Ideal point player i; R_i: Reaction curve player i; $\gamma_N(u_D)$: Optimal reaction function Stackelberg leader NDC; $Q_i = c$: indifference curves.

strategies too. In that case, assuming some fixed strategy is played by the NDC countries, the DC can determine their optimal strategy (response) given that choice. By considering all potential strategies from the NDC countries the DC countries obtain then an optimal response set (reaction curve). In a similar way the NDC countries arrive at their reaction curve. Figure 2 visualizes this case. On the axis the policies, u_D and u_N, of the DC and NDC countries are displaced. Each combination of policies yields a realization (Q_D, Q_N) of the measure of QOL variables for both countries, like in Table 2. Indifference curves for policies yielding the same value for the DC and NDC countries are drawn, respectively. I_D (I_N) represents the point at which the Q_D (Q_N) value for the DC (NDC) countries is maximal. So, a curve further away from I_D (I_N) indicates a lower value for Q_D (Q_N). The non-cooperative equilibrium of the game is given by point N, where both reaction curves intersect. Clearly in N both the DC and NDC countries have no incentive to deviate from their policy. From the plot we see that by moving north-east it is possible to increase for both DC and NDC countries their Q_i value. Pareto-efficient equilibria, like point C, are represented by the contract curve $I_D - I_N$. All points on this curve can be implemented as the result of a cooperative agreement. Of course, any of these agreement should be binding since points as C are not located on the reaction curves. So they imply an ex-post incentive for both the DC and NDC countries to deviate from them.
We also indicated the Stackelberg solution S if the NDC countries are the leader. Clearly for the NDC countries S is a better outcome than the N solution. Finally we illustrated a reaction function for the NDC countries which would provide them with their maximum Q_N value at the point I_N.

As noticed above cooperation will become non-sustainable if countries do not stick to their commitment and cheat by deviating in their policies from the agreed policy stance. The cooperation problem is closely related to the reputation issue and the international institutional design like e.g. the existence of a supranational authority that enforces international cooperation agreements (see

[59]). If countries face the same international coordination problem in the future, i.e. the game is repeated each period, it must be possible to achieve efficient outcomes by a reputation mechanism. If a country comes to a decision node where there is an incentive to renege on the cooperative outcome, such a cooperative agreement will clearly lack credibility and rational policymakers will not enter into such an agreement and, by symmetry, no cooperation is the outcome. The folk theorem of repeated games stresses that even if countries have an incentive to renege they will not do so because they fear to lose payoffs when other countries can punish them in the subsequent periods. The reason why trigger strategies can support repeated games, consistent with efficient policies, is that for each country the value of deviating from the efficient policy in each period is outweighed by the discounted value of having efficient policies played in the future. Therefore, for trigger strategies to work, payoffs in the future must not be discounted too heavily. As suggested by the example, within the current context of taking a decision whether and when to engage in more "green" (energy) production this may be an issue. If future realizations of QOL variables are discounted a lot the future gains of engaging in an early "green" strategy might be undervalued.

Another way to restore sustainability is to develop an incentive mechanism through sanctions against reneging. If there are supranational institutions that can legally enforce the coordinated solution, then policies will be credible. Such an institution will reduce the likelihood that countries renege upon their commitments. The supranational enforcement implies a loss of sovereignty (see [15]) in comparison with a sovereign policymaking process (with countries coordinating on an agreed outcome and employing a trigger mechanism to enforce it). Other pros and cons of institutionalized rule-based cooperation can be found, e.g., in [59][p.10].

More recently, the idea of issue linkage has been introduced as a device supporting cooperation. This is basically an agreement designed where participants do not negotiate on only one issue, but on two or more issues. The intuition is that by adopting cooperative behavior, some agents gain in a given issue, whereas other agents gain in another. By linking the two issues, the agreement in which agents decide to cooperate on both issues may become profitable to all of them. Issue linkage is a way to increase cooperation on issues where the incentives to free-ride are particularly strong. The goal is to determine under which conditions players actually prefer to link the negotiations on two different issues rather than negotiating on the two issues separately in the context of endogenous coalition formation [17].

4.2 Literature review and open ends

Recently two review papers have been published which give a good impression of what has been achieved the last few decades in modeling environmental and optimal resource extraction problems within a (macro) economic setting using game theoretic tools. We briefly indicate the subjects dealt with in these papers below. The reader can consult himself then either one of both papers for references concerning his favorite subject. We conclude this section with listing a number of subjects which need additional attention.

Jørgensen et al. [40] provides a survey of the literature which utilizes dynamic state-space games to formulate and analyze intertemporal, many decision-maker problems in the economics and management of pollution. In particular [40] surveys the literature devoted to the analysis of various macroeconomic problems using a dynamic game framework. Studies about the interaction between growth and environmental problems, economic-environmental problems of climate change, the effect of population growth and mitigation on macroeconomic policies, the use of income transfers as a mechanism to improve environmental quality and sustainable development are reviewed.

Van Long [46] provides a survey of the use of dynamic games in the exploitation of renewable and exhaustible resources. It includes dynamic games at the industry level (oligopoly, cartel versus fringe, tragedy of the commons) and at the international level (tariffs on exhaustible resources, fish wars, entry deterrence). Amongst other things, international strategic issues involving the link between resource uses and transboundary pollution, the design of taxation to ensure efficient outcomes under symmetric and asymmetric information and the rivalry among factions in countries where property rights on natural resources are not well established are discussed. Outcomes under Nash equilibria and Stackelberg equilibria are compared.

The general impression from the literature is that a lot of work has been done predominantly using an analytic approach. This has improved the understanding of macroeconomic relationships in a strategic and dynamic setting. However, these results are obtained under rather simplifying assumptions. This is an inherent property of dealing with analytic models. Only models having a simple structure are tractable (see [72] for a discussion on the use of small macromodels). To present dynamic games as a relevant decision support tool to better understand macroeconomic processes and more in particular the consequences of climate change on it requires still a lot of work. Extensions as well in the development of more analytic models, numerical simulation models and dynamic game theory is required. In particular it seems that not much progress has been made in developing numerical multi-country dynamic macro economic simulation models that contain strategic elements to analyze potential effects of climate change on key macro economic variables (like have been developed for studying macro economic policy problems elsewhere (see e.g. [8], [59])). Some important topics that need further attention are to model more general environments of interaction, the integration of learning dynamics, including intertemporal budget constraints, the endogeneization of (energy) prices and including demographic structures (in particular modeling population growth and migration). Further issues concern the use of different information structures by different players (e.g. different time horizons with different discounting, different philosophies about common property resources) and the use of different solution concepts. An important point is also to achieve a better understanding on how uncertainty affects human response on, e.g., their engagement in innovation strategies. Finally there is a need to develop within this context further models of dynamic decision making, enforcement rules and satisficing strategies [5].

5 Concluding remarks

Modeling climate change is an intricate job that involves the modeling of many complex processes that affect each other. Since quite a number of these processes are not completely understood this brings on uncertainty if one uses models of these processes to predict the future development of climate. The IPCC reports have been produced to reflect the current knowledge on this. Through its assessment reports, the IPCC has gained enormous respect. However, as noticed in the IAC 2010 report [37], the reports can be improved in particular w.r.t. the presentation of (uncertainty in) results. Expecting that these key recommendations by the IAC will be taken into account one just can hope that the next 2013 IPCC report will provide a better insight into the various involved uncertainties.

The historical development of human beings behavior (with optimizing behavior w.r.t. a relatively short-time horizon), the potential long-term effects of CO_2 increases on temperature and the increase of a large number of people asking for energy will (at some point in time) lead to an increase of demand for "green energy" by many countries. This due to the increase of (taxed) prices of fossil fuels and the desire to be more independent w.r.t. its energy supply. This adaptation will most likely first be carried out by the developed countries. This, since quite a number of the new developing countries possess large amounts of fossil fuels, and therefore have a preference to use old fossil fuel consuming production strategies, and the developing countries cannot pay this investment. A positive aspect of such an adaptation is that it may give a boost to the development of new technology. Since for the (new) developing countries the (much less taxed) prices of fossil fuels are much lower they will continue using them, leading to a boost of CO_2 emissions due to the large number of population involved. Given the expected extension of life expectancy the population growth will maybe stop. However such a scenario will take quite some years before it takes its end and by that time a huge increase of CO_2 emissions has occurred. One way out of this trap seems to make the developing countries use the "green energy" production technology too. Given the vulnerability of poor countries for temperature rises and the help provided by the developed countries the implementation of such production technologies is probably feasible in those countries. In particular there is a large potential for developing countries to cooperate with the developed countries in the realization of, e.g., more solar energy. However, the political instability of developing countries is a serious obstacle here. So, from this perspective, the major problem seems whether the developed countries and the newly industrialized countries can engage in a binding settlement to switch towards societies which depend to a large extent on green energy production. Two major questions here are, first, how countries can be supported in their vast increasing demand for energy. Or, stated differently, how fast can the production of green energy be increased. Second, countries like Russia and Brazil are projected to be a major provider of energy over the coming decades ([75]) and will probably experience growth rates in GDP that exceed those of the developed countries. The question is how to compensate them for the involved short-term opportunity cost.

Can dynamic game theory contribute to the solution of these problems? We illustrated, using a fictive example, how dynamic game theory helps to better understand the arising conflict situations. In particular the example illustrated that without any form of international binding agreements it is hard to expect that Pareto efficient solutions will be obtained.

Further, we showed in this chapter that there are many facets and kinds of risk involved in modeling the effect of climate change on QOL variables and in particular GDP. In the previous section we already mentioned that using mainly analytic models insights have been obtained in various directions and we indicated a number of issues that need further exploration. On the other hand it should be clear from the sketched framework that a basic deterministic mathematical modeling of reality is not possible. Uncertainties are present at all levels and (dynamic) game theory cannot solve these uncertainties. What it is capable to do, or at least tries to do, is to provide a better understanding of interacting systems (where systems should be interpreted in a broad sense) and to provide mechanisms which after implementation imply a more smooth behavior of the complete system.

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