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Games in the Arctic: applying game theory insights to Arctic challenges

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Abstract

We illustrate the benefits of game theoretic analysis for assisting decision-makers in resolving conflicts and other challenges in a rapidly evolving region. We review a series of salient Arctic issues with global implications—managing open-access fisheries, opening Arctic areas for resource extraction and ensuring effective environmental regulation for natural resource extraction—and provide insights to help reach socially preferred outcomes. We provide an overview of game theoretic analysis in layman's terms, explaining how game theory can help researchers and decision-makers to better understand conflicts, and how to identify the need for, and improve the design of, policy interventions. We believe that game theoretic tools are particularly useful in a region with a diverse set of players ranging from countries to firms to individuals. We argue that the Arctic Council should take a more active governing role in the region by, for example, dispersing information to "players" in order to alleviate conflicts regarding the management of common-pool resources such as open-access fisheries and natural resource extraction. We also identify side payments—that is, monetary or in-kind compensation from one party of a conflict to another—as a key mechanism for reaching a more biologically, culturally and economically sustainable Arctic future. By emphasizing the practical insights generated from an academic discipline, we present game theory as an influential tool in shaping the future of the Arctic—for individual researchers, for inter-disciplinary research and for policy-makers themselves.

The Arctic region is undergoing rapid transformation fuelled by economic growth, ever-increasing demand for natural resources and environmental changes. The future of the Arctic is in the hands of a diverse group of decision-makers: individual citizens, politicians, countries, companies, industries, environmental organizations, indigenous people, the scientific community and many others. With the vast array of stakeholders, often with diverging interests, there are many potential conflicts that need to be resolved to promote prosperity and sustainable development in the region.

The purpose of this paper is to demonstrate the usefulness and effectiveness of game theory analysis for improving decision-making in the Arctic. We re-cast well-known Arctic challenges into a game theoretic structure and demonstrate how to draw policy-relevant insights. Further, we promote game theory as an analytic tool for interdisciplinary Arctic research projects (see, e.g., Arctic Institute of North America 2014; Enveco 2014). The insights presented and summarized in this paper are particularly valuable for key players and organizations in the Arctic, including the Arctic Council. In the same way that game theory analysis helps anti-trust authorities fight cartels and reach more socially desirable outcomes (see below), we believe it can also assist Arctic governing institutions, which are ultimately responsible for making decisions on behalf of domestic constituents or global citizens.

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The use of game theory language and formal structure helps penetrate to the core of complex decision-making challenges, for example, how to successfully manage a fish stock, whether to open an area for oil extraction or how to prevent environmental catastrophes such as oil spills. To demonstrate the usefulness of game theory, we start by explaining a classic game theoretic story, which we will return to throughout the paper: the Prisoners' Dilemma:

> Two suspects have committed a crime and have been caught. The prosecutor tells each suspect that if he confesses and testifies against the other, only a light punishment will follow and there will be no punishment at all if at the same time the other suspect does not cooperate with the prosecutor. *Each suspect has to choose between testifying and refusing to do so*. If both testify, then each will receive three years in prison. If both stay quiet, the prosecutor does not have much evidence, and each will receive only a year in prison. If, however, only one testifies, he/she will walk free, while the other will receive a term of five years.

What shall the suspects do? Game theory provides a formal language for describing a conflict or decision-making challenge, as well as a set of tools for analysing or solving it. The suspects are called *players*, their actions *strategies* and their *payoffs* are prison sentences depending on the chosen strategies. A game theoretic analysis of the Prisoners' Dilemma leads to a clear—if perhaps counter-intuitive—prediction: both players will choose to testify against each other. Indeed, from each suspect's perspective no matter what he thinks the other is going to do, testifying is the best choice: if the other testifies, then testifying reduces his prison term from five to three years; if the other does not testify, then testifying reduces his prison term from one to zero years.

The formal structure of game theory comes with many benefits. Conclusions from one game may be transferred to other games that exhibit similar characteristics. For example, anti-trust regulators benefit from game theory-derived lessons of the Prisoners' Dilemma to design regulatory schemes to fight anti-competitive collusive practices by firms. An example is the leniency policy that the European Commission offers to companies that hand over evidence of illegal collusive practices (ECN 2012). Game theory has been applied with useful results in a variety of areas, for example, assessing the threat of nuclear war, analysing and reducing traffic congestion, and explaining animal behaviour. The matching models developed by Lloyd Shapley and Alvin Roth have led to improved functioning of labour markets, better allocation of students to schools and more lives saved by matching kidney donors to patients. These applications earned them what is commonly referred to as the Nobel Prize in Economics in 2012.

Given its adaptability, game theory analysis is particularly useful in addressing existing and resolving emerging challenges in the Arctic. In the paper, we focus on three categories of Arctic decision-making challenges that are amenable to game theory models.

The first of these is the tragedy of the commons. This type of conflict concerns the management of a common pool resource, such as regulating open-access fisheries in the Arctic. Players' incentives are such that each fisherman ignores the fact that his actions make fishing harder for others (i.e., trying to catch as much fish as possible increases costs of other fisherman by reducing the stock), which in general leads to overfishing. The key challenge is to avoid degradation of the common stock and mitigate the conflict between fishermen.

The second category is bargaining and contests. Another decision-making challenge arises when two or more players with diverse interests must reach an agreement. Allowing local access for resource extraction is a relevant Arctic example given that the region contains an estimated 30 and 13% of undiscovered reserves of natural gas and oil, respectively (Gautier et al. 2009; Anonymous 2012). A key question is whether there is room for agreement between players in the question of extraction versus preservation. Petroleum and transport companies are seeking access while other industries (fishing and tourism) and the resource-using public are concerned about future environmental impacts.

The third category comprises principal–agent models and the problem of moral hazard. If a player takes a risk without bearing the full cost of that risk, it may encourage socially costly behaviour. Oil spill risk in the Arctic presents a game theory scenario where actions of a decision-making *agent* (e.g., petroleum or maritime transport company) affect the risk of a spill to another player referred to as the *principal* (e.g., the general public represented by the state). The challenge is that the principal—who wishes to develop effective regulatory oversight—cannot observe the agent's behaviour, which creates an incentive for him to under-invest in risk-reducing measures.

The following section provides background into game theory using a minimal amount of technical language. We then summarize game theory insights from the literature and discuss their relevance in the Arctic, including how game theory has supported existing Arctic decision-making and how it may prove useful for future Arctic challenges. Our conclusions are presented in the final section.

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Background: game theory

People, organizations and countries make decisions. Game theory is the formal analysis of how and why people make decisions in strategic interactions. Its strength is that it distils complex scenarios into a few core components. Further, it provides answers to relevant analytical questions: What choices are available to a player and what are the consequences of these choices? What influences a player's choice? What outcomes are likely and are the likely outcomes desirable?

The study of choice is complicated by the fact that several decision-makers often interact simultaneously. One person's action may affect others' possible actions, which implies that the final outcome is shaped by the actions of multiple actors. An individual decision-maker seeking his best outcome in a conflict must without observing other players' choices (and sometimes even without knowing past choices) figure out what other players will do or have done while selecting his own course of action. The interested reader may wish to consult Kreps (1990) and Osborne (2003) for a formal introduction to game theory, and Poundstone (1993) for a non-technical discussion of common game theoretical problems.

Like most disciplines, game theory has its own vocabulary to describe important concepts. The term *game* refers to any strategic interaction between decision-makers, who are called *players*. Players may act at different times during the game and they may or may not have access to information about players' previous actions. A *strategy* is an explicit plan of action for an entire game. For instance, a "first mover's strategy" in Tic-Tac-Toe may be: put "X" in the centre; if the opponent puts "O" in a corner, put "X" in the opposite corner, otherwise, put "X" in the corner clock-wise to the right; and so on. A *profile of strategies* is a collection of strategies for all the players in the game. Once a profile of strategies is defined, the game can be played and an outcome is reached. For each outcome, there is an associated *payoff* to each player. A payoff may be measured in different ways such as money, years in prison or, more generally, as a level of well-being or utility. Finally, a game's *solution* is a prediction of what strategies the players are going to use, and the corresponding payoffs.

In order to formalize a conflict as a game, an analyst must: (1) identify the players; (2) identify what the players can do to affect the outcome, that is, their strategies; and (3) identify the payoffs to each player for the different outcomes. Once the conflict is formalized as a game using the steps above, the game can be solved.

To solve a game implies finding an *equilibrium* to the game. Given the assumption that players strive to maximize their own payoff—where payoff can be defined broadly and may include altruistic intentions—an equilibrium occurs when no player can improve upon his own payoff by unilaterally changing his strategy. This solution is called Nash equilibrium (or simply equilibrium), after John Nash, who was awarded the Nobel Prize in Economics in 1994 for this key contribution to game theory. He proved that for any game with a finite number of players and a finite number of strategies, at least one equilibrium always exists (Nash 1950, 1951). Equilibrium is a key concept in game theory as it is a prediction of how the game will be played. With the help of game theoretic analysis, a decision-maker can change the game with the aim of steering its equilibrium towards a socially desirable outcome.

A few issues are worth pointing out regarding the equilibrium concept. First, as illustrated in the Prisoners' Dilemma example, an equilibrium does not imply that each players' individual or joint payoff is maximized, that is, there may be other outcomes where players are better off compared to the equilibrium. Second, an equilibrium is not necessarily unique, that is, many equilibria can exist for a given game. Third, an equilibrium may involve randomizing over several strategies. An example of a game with an equilibrium in randomized (mixed) strategies is Rock–Paper–Scissors: if a player's choice of playing *rock* has a probability of one, the other player's optimal response would be to play *paper* with a probability of one. But then the first player would want to play *scissors* with probability of one, etc. The unique equilibrium in Rock–Paper–Scissors is for both players to play *rock*, *paper* and *scissors* with a probability of 1/3, respectively.

We return to the Prisoners' Dilemma to illustrate how to formalize a conflict as a game and find equilibria. In the Prisoners' Dilemma, the players are the two suspects with two possible strategies: to *tell* or *not tell*. The payoffs are the years in prison for each profile of strategies, as presented in matrix form in Table 1.

A general way to find equilibria is to look for the *best responses* of a player to any strategy of the other player. In the Prisoners' Dilemma, *tell* is a best response for both players, regardless of the opponent's strategy choice:

Table 1 A payoff matrix for the Prisoners' Dilemma. Each cell summarizes the payoff to each player from a particular profile of strategies as a pair (payoff to player 1, payoff to player 2). The payoffs are the negative of years in prison, so a higher value indicates a better payoff.

		Player 2	
		Tell	Not tell
Player 1	Tell	−3, −3	0, −5
	Not tell	−5, 0	−1, −1

if player 2 chooses *tell,* player 1 will choose *tell* since it yields a payoff of -3, which is better than -5 which is what player 1 obtains from choosing *not tell* instead. In the same way, playing *tell* is also a best response for player 1 if player 2 plays *not tell*, as 0 is better than -1. The exact same line of reasoning applies for player 2. Therefore, the pair *tell–tell* is a pair of strategies that are best responses to each other, and no player can unilaterally improve upon this outcome. In game theory parlance, *tell–tell* is the unique equilibrium of the game.

Although *players*, *strategies* and *payoffs* are the building blocks of game-theoretic analysis, the discipline offers additional and complementary tools that allow us to study scenarios that are more complex than the Prisoners' Dilemma. For example, some decision-making challenges require a more nuanced picture of reality such as games (1) with more than two players, (2) with asymmetric characteristics, such as strategies or information, (3) with uncertainty over game histories or (4) that repeat over time.

A particularly relevant nuance in the Arctic is the fact that players may not have equal access to relevant or correct information when selecting a strategy. Incomplete information not only influences a player's chosen strategy and therefore the outcome of a game—imagine, for example, the consequences if you accidently observe your opponent's hand in a game of poker—but it also makes it challenging for analysts to predict outcomes or to re-design a game to achieve a particular (or preferable) outcome. Throughout this paper, we emphasize the importance of information and how this may influence conflicts in the Arctic. For example, information about the status of fish stocks affects the choices of both fishermen and regulators, information about the value a nature conservationist or an oil developer places on outcomes related to resource access affects the possibilities for agreement, and information about an oil company's risk-reducing effort has implications for how the state chooses to regulate.

Games in the Arctic

This section illustrates how game theory can provide useful policy recommendations for Arctic decision-making challenges. For each of the categories—tragedy of the commons, bargaining and contests, and moral hazard problems—we describe their relevance to the Arctic and summarize game theory insights.

Tragedy of the commons

A quintessential conflict in the Arctic is the tragedy of the commons, which refers to the overexploitation of a common resource, such as fisheries, public commons such as parks, livestock grazing and transportation routes (see Ostrom [1990] for a thorough discussion of the tragedy of open-access resources). We describe the problem below using a fishery as an example, but also identify other Arctic decision-making challenges where the same game structure applies.

In an economic model of a fishery, one can find the optimal level of a fish stock, depending on market conditions and the biological dynamics of the stock (see, e.g., Clark 1990). Fishermen, keeping the stock at this level, can then harvest the resulting annual growth rate. However, this outcome may not be a game theoretic equilibrium due to the incentives facing each individual fisherman. In the most simplistic model, the decision problem of a single fisherman is straight-forward: spend resources on fishing—time, bait, equipment, and so on—as long as the private benefits (profits) outweigh the private costs. However, when solving this problem a fisherman fails to acknowledge the negative effects of his own fishing on the rest of the community of fishermen. Since a single fisherman does not own any of the fish in the sea, he has no incentives to leave the fish there for future harvests because someone else might catch them instead. Failing to leave fish for regeneration is actually a social cost in the harvesting decision. By not accounting for this extra cost, each fisherman catches more fish than is socially optimal, increasing the risk of resource collapse and the subsequent closure of the commons. This simple model can be used to explain (partly) fish stock collapses such as the Icelandic herring fishery in the late 1960s (Matthíasson 2003) or the collapse of the north-west Atlantic cod fishery in the 1990s (Myers et al. 1997).

The game is referred to as a tragedy because its outcome is bad for all players. However, the game can be changed so it has a new equilibrium that is biologically sustainable. Ostrom (1990) suggests that promoting cooperation among fishermen will address the problem. Together, fishermen can take into account the negative effects of individual harvesting decisions, decide on a jointly optimal harvesting scheme, and then monitor and enforce the agreement. However, certain mechanisms are needed to induce cooperation and thereby reach a sustainable and, arguably, more socially desirable management of the commons. These include, for example, restrictions on fishing activity (quotas), access (licenses) or gear (prohibition of large nets); changing payoffs (taxing the catch); or punishing those who renege on agreements (public disgrace, social obstruction, fines or restrictions on fishing in the future). Governing institutions are especially important in helping to resolve the tragedy of the commons problem. Local governments can work as facilitators of cooperation and work as monitors and enforcers of agreements. Central governments can address multiple problems simultaneously by passing laws and regulations that resolve the problem, promote cooperation and, importantly, educate fishermen about the problem they are facing and the benefits of collective decisions.

Today, there are multiple examples of successful management achieved with the help of carefully designed mechanisms to limit the total catch and provide proper incentives to fishermen, specifically by individual transferrable quota systems. Still, illegal fishing, poor management and implementation of regulations, and other issues underscore the continued importance of the tragedy of the commons game and relevance of game theoretic analysis for its resolution (see, e.g., Beddington et al. 2007).

One important game theory contribution is in identifying the impact on a game of *incomplete information*, that is, when different players have different perceptions about some relevant aspects of the problem. A generic example of incomplete information is *private* information: when a player knows something that others do not. A fisherman, for instance, may (privately) know how much effort he put into fishing and how much he caught. Incomplete information makes it hard for players (even if they work together) to assess the risk of a collapse or recognize when the collective harvest exceeds the biological equilibrium. For example, if individual catches are small, it is difficult to know if it is due to bad luck or a small fish stock. But even if catches are reduced over several years due to a diminishing fish stock, the incentives are such that fishermen may be unwilling to restrict effort due to their need for income. One way to address this potential for resource collapse is for the regulator to provide better and more credible information on the status of fish stocks, which in turn will convince fishermen to engage in cooperation in order to reach a better joint outcome.

Crépin et al. (2012) studied the role of information and risk in a laboratory setting where participants in the experiment were divided in small groups to play a common resource game repeatedly. The participants chose how much of a renewable resource to harvest in a specific period, given knowledge about the level of the resource that generated the maximal yield for the next period. The researchers wanted to see whether information about threshold levels for collapse of the stock affected the players' harvesting decision. The researchers compared two groups: in the first, control group, stock regeneration followed a smooth, so-called logistic growth function, but in the second treatment group, the stock declined abruptly after dropping below a threshold level. The results showed that in the treatment group, where players were informed that they faced a greater risk of experiencing resource collapse, the incentives for cooperation were strengthened, which significantly reduced the likelihood of the tragedy of the commons outcome relative to the control group.

Independently, Howe & Murphy (2010) arrived at to a similar conclusion. Also in a laboratory experiment, they asked subjects to divide an initial endowment into either a common pool resource (fisheries were used as an example) or a private investment (the labour market with a fixed wage). Information from the game's moderator (representing an independent third party) described the probability of a good, average or bad outcome in the fishery, that is, the risk of investing in the common pool resource. The authors came to a similar conclusion as Crépin et al., as they found that with full information, greater risk leads to more cooperation, reducing the likelihood of resource collapse typically connected to the tragedy of the commons.

The experiments conducted by Crépin et al. and Howe & Murphy not only demonstrate the empirical relevance of game theoretic analysis but also provide valuable insight for policy-makers looking to better understand the implications of alternative regulatory strategies. In this case, game theory suggests that the government (including the researchers it employs or depends upon) has an important role to play in describing the current status and expected dynamics (risk) of the fish population so that fishermen are fully informed about the state of the resource. Such information improves the outcome of the game and helps to prevent resource collapse.

The discussion so far has considered the strategic interaction in the tragedy of the commons on a micro-level. Fisheries issues are also dealt with in games on a macro-level where players are states that manage transboundary fish stocks (see Eide et al. [2013] for an example involving Norway and Russia). One key implication follows: in contrast to the micro-level scenario where governments can influence the game, no supra-government exists on the macro-level to change the rules of the game. Instead, players must rely on voluntary agreements or create some type of governing institution or intergovernmental forum. In fact, the purpose of the Arctic Council is to "provide a means for promoting cooperation, coordination and interaction among the Arctic states" (Arctic Council 2014). Note also that the International Maritime Organization (IMO) plays a supra-government role in the case of oil spill prevention and response on the global level, which makes it a key player in games between the regulatory and regulated community. We discuss the IMO further in the next section.

A few considerations are important when designating a state as a player. For example, a state is unlikely to be homogeneous: certain groups may pursue conflicting strategies. Further, the state's decisions are taken by individuals or agencies whose incentives may change over time. The result, which can be accounted for in a game theory analysis, is that an agreement between states may not be reached, or may be delayed, if different factions in a parliament cannot reach a decision. An example is a negotiated agreement between the US and the Soviet Union in 1990 on maritime delimitation in the Bering Sea, which has not yet been ratified because the Russian Duma has not approved it (Norwegian Ministry of Foreign Affairs 2012).

Hannesson (2011) reviews the literature on game theory and fisheries. Players (countries) must agree on the management of the marine resources while fish stocks move across borders, fish population estimates are uncertain and regulators may not be able to observe fish landings in other countries. A key policy question is how international fisheries should be managed and how agreements should be established. The insight of these games is that, in absence of a central policy-maker, the desired solution to the problem is to encourage cooperation between players. But how can this be done in practice?

A key game theory contribution is to study the determinants of cooperative equilibria when games repeat over time (e.g., fishing quotas that are set annually). In many types of games—for example, repeated Prisoners' Dilemma, where players know that they will interact again in the future—this repeated interaction may open opportunities for equilibria that would not have been supported if the players were to interact only once. The key intuition is that due to the repeated interaction, the players can agree to play strategies that are jointly beneficial in the long run, even though a single player can improve on his short run payoff by deviating. For these so called *cooperative equilibria* to be supported, players must be given incentives to honour their agreement and not deviate.

A necessary condition for a "better for all" cooperative equilibrium to emerge in a repeated game is the presence of some single-stage strategies that give a jointly higher payoff than in a non-cooperative equilibrium, which exists in the Prisoner's Dilemma. A useful mechanism to promote cooperation is to punish players for breaking an agreement and leaving the coalition. Examples of punishments may include: not cooperating with such players in the future, limiting access to markets or asking consumers to abstain from buying products from deviant players. For more on the emergence of cooperation in games see Axelrod (2006).

Another useful tool to support cooperation is side payments, that is, monetary or in-kind payment from one player to another. These are particularly useful if payoffs differ between players. Kennedy (2003) uses game theory to study the stability of coalitions in the north-east Atlantic mackerel market and finds that the levels of the total allowable quotas during the 1990s were set too high, which resulted in too much fishing relative to the optimal harvest. Kennedy's game-theoretic analysis provided recommendations on how to improve sustainability: that is, reduce quotas and use side payments to give players incentives to remain in the coalition, making it more stable.

Arnasson et al. (2010) provide an example where side payments play a major role in maintaining the stability of a coalition between states in the North Atlantic herring fishery (Norway, Russia, EU, Faeroe Islands and Iceland). The authors compare the cooperative equilibrium with the alternative: that players (states) deviate, or leave, the coalition. The authors demonstrate that the stability of the coalition can be improved by allowing side payments between countries. In this case, the spatial movements and spawning of the herring give Norway a favourable position such that it is the only country that could increase their profit outside the coalition. The model suggests that side payments to Norway—either monetary payments or allowing Norwegian vessels to fish temporarily in other countries' exclusive economic zones—would entice it to remain in the coalition and ensure stability. Without this game-theoretic insight on the importance of side payments, the countries may not succeed in reaching and acting in agreement, which may result in suboptimal (inefficient) use of resources.

Hassler (2008) describes an Arctic-relevant example of side payments whereby Sweden induces disinterested states to improve oil spill regulation in the Baltic Sea. Sweden is considered a "pro-active" player in addressing risks from maritime transportation because it is likely to incur a disproportionate amount of the costs from a future oil spill (e.g., ecological injuries, impacts to recreation, property values and commercial fishing) relative to the benefits from shipping (e.g., oil revenues). To prevent the so-called "lowest-common-denominator" effect, whereby disinterested actors establish the regulatory ambition (e.g., Russia, Estonia and Latvia), Sweden financed so-called "supporting initiatives": targeted side payments to enhance the disinterested countries' capacity to prevent or respond to oil spills. These include technical assistance to develop regulations that fulfil EU

Directives, to implement international conventions, to update hydrological data and marine charts, and to raise environmental awareness of the Baltic's ecological sensitivity. Sweden's targeted financial and technical support to these countries steered the game toward their socially preferred environmental outcome: reduced oil spill risk. In addition to side payments, Sweden's other strategy to address oil spill risk was to lead and promote regional initiatives related to: (1) monitoring of maritime activities (contributes to more effective compliance); (2) oil spill response training (reduces impacts when spills occur); (3) designation of the Baltic Sea as a Particularly Sensitive Sea Area (PSSA; requires incremental risk-reducing measures by the shipping industry); and (4) development of the HELCOM Automatic Information System (assists regulators in monitoring ship traffic, ensuring safe navigation). Predictably, driven by its own interests as an oil-producing nation, Russia did not agree to the Baltic's PSSA designation (Hassler 2008).

The main conclusions from applying game theory insights to the tragedy of the commons scenario are the relevance of information for players, the need for incentives to induce cooperation, and the importance of governing institutions. These conclusions apply also to other Arctic conflicts over common pool resources. For example, this may include competition over land use between tourism, fisheries and/or petroleum companies (Norwegian Ministry of the Environment 2011), global warming (Desombre 2004) or reindeer herding (Marin 2006).

Bargaining and contests

The rapidly changing Arctic environment presents opportunities and challenges due to the increasing accessibility of resources and transportation routes. With these new outlooks, conflicts naturally arise, for example, over how to distribute the surplus from resource extraction, how to make land use decisions, including the marine environment. Solving these types of disagreements is challenging because these conflicts tend to lack a well-defined structure: there are no clear rules, no clear understanding of the choices and options available to players. A special field of game theory called *bargaining* can be used to study how to efficiently resolve conflicts and reach agreements.

Bargaining deals with decision-making challenges where multiple parties must redistribute an object (e.g., fish or land) or value (e.g., resource or mineral wealth or ecosystem service values), or agree on how to organize a joint activity. Key questions are: what agreements are feasible? What outcome is likely to be reached? Bargaining models also address normative questions, for example, about fairness of possible outcomes, and policy-relevant questions such as how to structure the negotiation so that mutually beneficial agreements are reached, how to support agreements over time and how to design laws, regulations and governing institutions to facilitate agreements and conflict resolution?

A classic example of a bargaining problem is the conflict between an upstream paper mill and a downstream fishery on a river where pollution by the paper mill adversely affects the fishery. Parallels abound in the Arctic. For example, there are concerns related to how aluminium smelters affect air quality in Iceland (Kaetzel et al. 2009) and how sonar and seismic exploration of sea beds by the petroleum industry can impact fisheries (Norwegian Ministry of the Environment 2011). Consider, for instance, aluminium producers and farmers, who may choose their production levels independently, each maximizing own profits. The outcome is likely to be suboptimal since the negative effect of pollution on farmers' operations does not enter aluminium producer's profits, and so it is not internalized in their strategic choice of production. If instead, firms cooperate by coordinating their production decisions, they can account for the negative effect and obtain higher combined profits.

We can use game theory to address two practical questions in this context: (1) will the bargaining parties reach agreement in the absence of intervention? If not, (2) what intervention may encourage agreement? A celebrated conjecture by the Nobel Prize winner Ronald Coase states that the participating parties will reach an efficient agreement if: (1) players have sufficient knowledge about the game (strategies and payoffs) to find the jointly optimal production plan; (2) property rights are well defined (i.e., either the aluminium producers have the right to pollute or the farmers have the right to a non-polluted environment); and (3) the costs of negotiation are negligible (Coase 1960). A particular implication of the Coase theorem is that in either scenario—that is, when the aluminium producers have the property right and can pollute freely or when the farmers have the property right and can prevent pollution—the outcome in terms of level of production and pollution would be the same: that is, the level that maximizes joint profits. The only difference is in the direction of the compensating transfer.

The Coase theorem hints at the possibility that players may be able to agree among themselves without institutions (e.g., organizations and governing bodies) assisting or arbitrating disputes. Such agreements are particularly welcome in the Arctic as they can strengthen local communities' control of their own future. But regulations, institutions and governments are still important in bargaining contexts because the Coase conditions are seldom fulfilled in practice: property rights are rarely defined clearly, individual players rarely have perfect information, and the agreements themselves (contracts) are costly to develop. The Arctic is no exception. Therefore, governing institutions that may affect negotiations and facilitate agreements have a particularly powerful role to play in the region. See Ostrom (2009) for a discussion of self-organization of local communities and the factors that may affect the likelihood of it occurring.

While the property rights can be assigned by laws or privatization, for example, and the negotiation costs can be estimated so their effect is understood, private information or any other differences in the perception of key parameters such as economic values has the potential to have profound effects on the possibility of reaching an agreement and on possible agreements themselves.

Taking into account private information in bargaining problems leads to a key game theory lesson that is in stark contrast to the predictions of the Coase theorem: if both parties have private information about what they are bargaining for, then no matter how clever the design of the negotiations, the jointly optimal agreement is not always reached (see Myerson & Satterthwaite [1983] or, for a more accessible treatment, Krishna [2009]). Players have an incentive to use their private information to their own advantage and, often, failures of negotiations in settings with private information can be directly attributed to the unwillingness of parties to reveal important information. In the Arctic, due to its remoteness and limited industrial development, incomplete information and even significantly different perceptions among participating parties characterize many existing conflicts and so raise new challenges for Arctic decision-makers.

Game theory analysis suggests a possible solution: a central authority (or mediator) may change the information environment by collecting and disclosing information and thus facilitate a mutually beneficial agreement or decision. In the Arctic context the need for strong governing institutions is underscored by the extensive and complicated list of players entering the Arctic arena, all of whom have a bargaining interest in the region. For example, the Arctic Council recently admitted six new states (China, Japan, S. Korea, Singapore, Italy and India) as "Non-Arctic State Observers" (Myers 2013). China and other non-Arctic entities like the EU, Japan and South Korea consider themselves legitimate players as export-dependent countries that have a lot to earn (payoffs) from Arctic shipping routes that save time and money. The strategy by China has been to invest in local infrastructure and development projects to garner good will from locals, increasing their chance of valuable payoffs (e.g., access to resources and transportation routes). Another key player in this game is Greenland, which has resources on offer, but wants to extract sustainable ecological and financial payoffs for their small and vulnerable population that recently earned limited independence from Denmark (it has been reported that there is only one working mine in Greenland, but over 100 on the drawing board [Rosenthal 2012]). With these developments in mind, strong governing and intergovernmental institutions such as the Arctic Council are crucial for a sustainable future as they collect and distribute information, facilitate agreements, monitor and enforce regulations and even establish rules of the game among Arctic players.

The way in which players interact in an institution such as the Arctic Council can itself be considered a game. Resources need to be collected to fund the institution. One problem is that members have an incentive to free ride on other members' contributions to this public good since they will reap the benefits of a well-managed Arctic even without contributing to it. The challenges of setting up such an institution are not unique to the Arctic, but we nonetheless underscore the benefits of developing this type of institutional capacity in the region.

Contest models in game theory consider scenarios in which players fight for control of a resource or situation—a prize—rather than reaching an agreement. Examples may include obtaining the rights to a piece of land, winning a litigation procedure, or successfully lobbying the government for a favourable decision. Game theorists have studied contests extensively including how players act within contests and how to shape contests to reach certain outcomes (see Corchón [2007] for a literature review). A typical contest is a game in which players' strategies are amounts of effort or resources they spend increasing their probability to win (or receiving a favourable decision). In many contests efforts themselves may be unproductive and wasteful. One activity that is sometimes referred to as wasteful is lobbying, for example, when an oil company spends money to influence a parliament in order to obtain exploration permits. Lobbying is seen as socially costly because players spend resources on activities that do not add to the value of any outcome and may increase the probability of a suboptimal outcome.

Incomplete information affects both the strategies chosen by players and the outcome of contests. For example, the following might be unknown to some or all of the players in a contest: players' valuations of the different outcomes (i.e., winning or losing the contest); their marginal benefits of exerting effort to influence an outcome or the costs of doing so. Incomplete information

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makes possible a new strategic element referred to as *signalling*: revealing information for tactical reasons, for example, to win a contest or to avoid it altogether. The information itself may be accurate or purposefully misleading.

When signals misrepresent players' true characteristics, then intervention by an external actor may be beneficial from a social perspective. Ansink (2011) relies on a contest form of a bargaining model to study a litigation procedure. Players claim parts of a contested resource (Arctic land and sea) and defend their claim by investing in "ammunition" such as financing underwater expedition to prove the validity of the claims. The paper provides a major contribution as it shows that when a central authority evaluates land/resource claims—as the UN is currently doing through the Convention on the Law of the Sea, an international framework that divides the sea into legal zones for each coastal state—it lessens the severity of conflicts, reduces the cost to the participants and increases the likelihood of an agreement. This finding underscores the importance of strong governing institutions, as mentioned above.

Avango et al. (2013) note the tactical role of research funding. A government may choose to fund (or not to fund) specific types of research in order to influence the outcome of Arctic negotiations. The authors suggest that the seemingly objective conclusions arising from such research may be seen as "powerful assets" (p. 4) in the negotiations. Their suggestion could be re-interpreted in the game theory framework as "ammunition" in the form of research assets: "icebreakers, research stations, instruments, scientists, assistants and technical personnel" (p. 4).

A typical Arctic contest involves lobbying between stake-holders over use of land and sea. For example, the Norwegian parliament is considering whether to allow offshore oil and gas extraction in Lofoten, where the traditional fishing industry feels threatened by the growing presence of the oil industry. Both sides lobby the parliament to gain a favourable decision. Sjöberg (2013) develops a game theory model to analyse the contest between the fishing and oil industries in influencing the parliament's decision. The model incorporates incomplete information related to the value of the oil production (to the oil industry) and the loss of fishing areas and fish stock quality due to oil spill risk (to the fishermen). That is, this information may not be known or the players may have different perceptions of the values associated with alternative outcomes.

The key contribution of Sjöberg is to study the possibility of avoiding the contest altogether by agreeing to a mutually beneficial decision supported by the use of side payments (analogous to settling out of court). A parallel Arctic example involving mining instead of oil exploration is currently taking place in Kiruna, Sweden. A mining company is providing on-going cash payments to compensate the more than 3000 land-owners that are expropriated from their homes to accommodate the expansion of an iron-ore mine (Miller 2011). Some households have expressed dissatisfaction with this approach, which may be due to the uncertainty associated with pricing one's home (including the memories attached to it). In other cases, the use of side payments as a strategy suffers from the stigma that some associate with receiving financial payment in exchange for allowing environmental impacts with seemingly negative social welfare consequences.

Sjöberg stresses how incomplete information about the players' valuation of alternative outcomes affects the feasibility of an agreement, that is, the larger the differences in player's perceptions, the less likely they are to agree. In the Lofoten case, the value associated with the projected ecosystem service injuries from an oil spill—and the subsequent economic impact on the fishing industry—are uncertain, due in part to the challenges of conducting risk assessment and non-market valuation of ecosystem services. The paper suggests that a successful agreement using side payments is more likely between the fishermen and the petroleum industry when the uncertainty over the players' incongruent valuations is reduced, for example, through credible ecosystem service valuation estimates. (Note that there is also an ancillary benefit of this information provision to a third party of this game: the general public. They benefit in terms of improved awareness of the importance of these ecosystem service values to human welfare and how these values are reduced from an oil spill.)

Principal–agent models and the problem of moral hazard

Although current oil drilling and maritime transport activities in the Arctic are minor in absolute terms, they are expected to increase dramatically in the coming years. There were four transits on the Northern Sea Route in 2009, five in 2010, 33 in 2011, and 46 in 2012 (Mikkelsen & Sander 2012; Pettersen 2012). These trends suggest an increasing risk of accidents and subsequent impact on sensitive Arctic ecosystems, which raises several questions: what is the acceptable level of risk associated with shipping or oil drilling accidents? What types of regulations or international conventions should be implemented (e.g., preventative measures, improved response capabilities)? And can regulations and conventions be developed that create incentives for firms to innovate and adopt more stringent (or technologically-advanced) safety standards?

The problem is that profit-maximizing firms disregard the full economic and social costs of their activities—such as the increased risk of an accident from shipping or petroleum extraction—on the rest of the players involved (citizens or other businesses) and on the ecosystem in general. Yet, completely prohibiting such activities also comes with a substantial cost of missed opportunities. Efficient regulatory approaches should include the relevant players from the regulatory community (e.g., local/regional governments and supra-national institutions like the IMO and the Arctic Council) and should provide firms with the proper incentives to undertake risk-reducing measures, that is, account for the external effects of their activities on society. Game theory provides insights about how to design, implement, and enforce such regulations and international conventions (see, e.g., Hanley et al. 1997).

A relevant game theory model for the case of regulatory oversight is the principal–agent model, where the *principal* is the regulator and the *agent* is the regulated firm. Because the principal cannot perfectly and without cost monitor the risk-reducing efforts of the agent, he must create incentives for the agent to internalize risks.

The principal–agent framework highlights the importance of *moral hazard*. The petroleum companies choose the level of risk reduction at their facilities but the regulator cannot observe their risk-reducing measures. In short, the companies will do what is best for them, not for the society. How can the regulator change the game so that petroleum companies choose strategies that lead to a socially desirable outcome? The tools available to the regulator are the regulatory policy, the enforcement methods and the monitoring strategy—all of which affect the firm's chosen risk-reducing strategy (e.g., technology adaptation and risk-taking behaviour). Thus, the regulator himself ultimately determines the socially-relevant outcome of the game: risk levels and response capacities.

In an influential paper, Cohen (1987) uses a principal–agent model with moral hazard to study optimal enforcement policies for preventing and cleaning up oil-spills. Cohen discusses two regulation standards: *strict liability* (the firm is liable regardless of risk-reducing measures undertaken) and a *negligence standard* (the risk-reducing measures, or the lack thereof, forms the basis of liability). Cohen assumes a benevolent government that is interested in minimizing the cost of environmental damage and clean-up, while the firm is profit-maximizing. The government has to spend resources on both monitoring firms and detecting oil spills. The government uses fines and inspections as incentives for the firm to adhere to environmental standards. Cohen's game theoretic analysis provides several insights into the design of oil spill regulation: (1) fines should not be set too high since this may deter firms from operating under a strict liability regime (e.g., some accidents might happen that are outside the firm's control); (2) a strict liability standard nonetheless provides some incentives for firms to invest in new safer technology because the firm is liable for *any* accident that may occur; (3) negligence standards are more costly for the regulator since they have to invest more time in monitoring the firms' actual compliance with risk-reducing measures; (4) the optimal fine should be increasing in environmental damages and clean up-costs, decreasing in probability of detection and independent of any direct cost the firm suffers from the accident; (5) to decrease monitoring costs and increase incentives for reporting accidents, there should be a significant discrepancy in fines between self-reported accidents and discovered accidents.

The advantages of a strict liability standard are that the regulator does not need to spend resources monitoring the firms' behaviour, only detecting oil spills. It also gives firms incentives to develop safer technologies since they are responsible for any spills. A negligence standard does not provide the same incentive to produce new technologies since once the required level of effort is met, the firm faces no threat of fine. The possible downside with strict liability standards is that fines may become overly expensive and firms may use bankruptcy as an option instead of spending resources on risk-reducing efforts. Also, the vast distances of the Arctic imply that monitoring cost are high, making strict liability standards particularly costly to support and the trade-off between the two approaches even more difficult.

Cohen et al. (2011) study policies in the aftermath of the Deepwater Horizon accident and find that optimal regulation should complement strict liability with mandatory insurance for companies. This prevents scenarios where companies file for bankruptcy and are unable to fund clean-up and compensation. Viscusi & Zeckhauser (2011) also consider the Deepwater Horizon spill and propose a new liability system to address catastrophic environmental risk. Based on a better understanding of the incentives facing such industries, the authors propose a two-tiered liability system: an expansion of current limited liability schemes in the US coupled with a tax to provide incentives for risks beyond the liability limit. The results have implications for the regulation of activities in the Arctic where extraction firms might file for bankruptcy in case of an accident because of the potentially catastrophic (hence, costly) environmental impacts due to two additional oil spill response challenges in the region: (1) the difficulty of recovering oil in cold-water environments and (2) the logistical challenge of remote-area oil spill response (World Wildlife Fund 2009). As a response, game theory suggests that Arctic regulatory bodies should require sufficient insurance coverage for prospecting firms in the region to avoid the extra costs imposed on governments when firms file for bankruptcy after an accident. Although the Arctic regulatory environment implies a more complicated governing structure of national jurisdictions and international conventions (i.e., several relevant players), we nonetheless demonstrate that game theory can provide insights on optimal regulatory approaches.

Given the increased risk from maritime shipping and oil exploration, the Swedish Chairmanship of the Arctic Council has emphasized the need for improved preparedness and prevention of oil spills (Swedish Ministry of Foreign Affairs 2011) and the Arctic Council established the Task Force on Arctic Marine Oil Pollution Preparedness and Response. We argue that principal–agent models provide a framework to study the incentives for firms to take sufficient precautionary measures and to develop optimal regulation, monitoring and enforcement policies. Just as in bargaining and contests, uncertainty plays a role with respect to the risks of Arctic oil extraction practices, un-tested shipping routes and the sensitivity of Arctic ecosystems to oil damage. For example, the social costs of oil spills may be significant but little is known about the economic value of the ecosystem service values at stake. The values estimated by Hasselström et al. (2012) may help to reduce uncertainty associated with determining pay-offs in a game theoretic analysis and thus support improved Arctic decision-making.

Conclusions

We discuss how game theory has been and can be applied to help shape the future of the Arctic. Given that interactions among players on multiple levels are likely to increase in this rapidly developing region, we believe that decision-making challenges related to sustainability can be fruitfully modelled using game theory. We stress the importance of cooperation and effective governance in resolving conflicts and for sustainable development of the region. We demonstrate how policy-makers can rely on game theory insights to change games, affecting the nature of conflicts and ultimately steering conflicts toward preferred outcomes.

Game theory analysis excels at distilling complex scenarios into a few core components that can be analysed in a mathematical model. However, simplification comes at a price, as models may not incorporate certain nuances (e.g., local political variables or values). Interdisciplinary development of game theory models may address this limitation somewhat, as inputs from social and natural scientists can improve model specificity and provide decision-makers with more applicable insights. Two ongoing research projects aim to integrate disciplines to improve game theory application in Arctic decision-making contexts (Arctic Institute of North America 2014; Enveco 2014). Importantly, while game theory provides a powerful tool for identifying policy options in the Arctic, value judgments regarding a policy's social desirability are inevitable. These judgments—by the general public, politicians and/or other decision-makers—are outside the domain of game theory.

A key theme is the importance of information in analysing Arctic conflicts. The fact that different players may have access to different information provides an explanation to many games' undesirable outcomes, that is, reduced probability of reaching agreement, delays in making decisions or decisions that turn out to be poor from a social perspective. These outcomes underscore the importance of strong governing institutions in providing and distributing credible information, for example, about the size of fish stocks, the consequences of oil spill or, more generally, the value of ecosystem services. Some of the relevant information may be non-market or measured in non-monetary terms. Governing institutions can facilitate agreements by fulfilling an important research-supporting role through the funding of, for example, economic valuation studies. Governing institutions with broad public acceptance are also critical for upholding, monitoring and enforcing agreements; in establishing the rules of the game; and, as a game's outcome diverges from a preferable outcome, act as a credible vehicle for adjusting these rules. The Arctic Council is an international forum with the potential to take a more active role in meeting these challenges. A further insight is the potential role of side payments, or compensating transfers, as an effective tool to mitigate or prevent conflicts, which has real and practical relevance for states, companies, fishermen, tourist operators and other Arctic players.

There are plenty of challenges in the Arctic that can benefit from a game theoretic analysis: resolving possible cross-border disputes, assessing alternative futures driven by melting ice, developing agreements between parties that are competing for the same sea, or analysing the effect of new Arctic players. As noted by Rosenthal (2012), there is likely to be a mix of competition and cooperation among Arctic players. Analysing such scenarios will be important for decision-makers and game theory provides a useful framework for the study of both types of behaviour.

The abstract ideas that gave birth to game theory analysis have now led to meaningful empirical applications that improve decision-making in the real world, as exemplified by the 2012 Nobel Prize in Economics. We believe that further refinement of game theory models will continue to produce profound insights that can be effectively used to shape the future of the Arctic—an area with a diverse set of players, strategies and payoffs that have global implications on social, environmental and cultural levels.

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