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Commentary

Modeling international climate change negotiations more responsibly: Can highly simplified game theory models provide reliable policy insights?

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ABSTRACT

In a recent article in this journal entitled "Game Theory and Climate Diplomacy", DeCanio and Fremstad (2013) provide an interesting treatment of a range of simple game theoretic characterizations of international climate negotiations. The authors use the Nash and Maxi-min stability definitions to analyze 25 two-by-two ordinal games, which they recognize as "possible game-theoretic characterizations of climate negotiations between two players (e.g., Great Powers or coalitions of states)". The authors' main conclusion that the Prisoner's Dilemma might not be the best description of climate negotiations game is consistent with the findings of others who have studied two-by-two conflicts over natural commons (Bardhan, 1993; Madani, 2010; Sandler, 1992; Taylor, 1987). Nevertheless, given the importance of the climate change issue, as well as the potential effects of our actions on the state of the environment and the well-being of future generations, I would like to address some gaps in their analysis, which result in it having limited usefulness for policy purposes. Of course, all models are simplified representations of reality, full of limitations. "Essentially, all models are wrong, but some are useful" (Box and Draper, 1987). So, "the practical question is how wrong do they have to be to not be useful" (Box and Draper, 1987). Models' limitations need to be carefully considered when interpreting them or applying their results to policy but some models are too simple to provide useful policy advice.

1. Introduction: Reliability of Simple Game Theory

As an analytical tool, game theory can enhance our understanding of real-world conflicts and provide valuable suggestions for policy development processes (Dietz and Zhao, 2011; Dinar et al., 2008; Finus, 2008; Heitzig et al., 2011; Howard, 2006; Madani, 2011; Wood, 2011). However, considerable simplifying assumptions can limit the applicability of game theory models to real world applications, which must be considered when modeling results are used to develop policies (Madani and Hipel, 2011; Wood, 2011). In my opinion, prescribing policy actions that can affect the state of nature and the well-being of billions of people around the globe must not rely on simple game models that ignore some essential characteristics of the problem. While simplifications are integral to modeling complex conflicts, the effects of simplifying assumptions on the modeling outputs should not be overlooked when interpreting the results.

DeCanio and Fremstad (2013) (DF hereafter) use highly simplistic models to analyze climate change negotiations. While their analysis provides some useful insights, in my opinion the models they consider are too simple to be used in policy advice. This is despite the fact that the literature on "climate change and game theory" (Aldy et al., 2010; Asheim et al., 2006; Camerer and Thaler, 2003; Dutta and Radner, 2004, 2009; Finus, 2008; Froyn and Hovi, 2008; Heitzig et al., 2011; Levy et al., 2009; Pittel and Rübbelke, 2008; Rübbelke, 2011; Rubio and Ulph, 2006; Walker et al., 2007; Weikard et al., 2010; Wood, 2011) is fairly rich and has improved significantly over the last decade due to the importance of the climate change topic. Researchers have adopted game theory approaches that better reflect the reality of climate change negotiations and can suggest practical resolutions.

In this commentary, I raise some fundamental questions about the key assumptions of DF's analysis, and briefly discuss alternative assumptions and solution methods that could lead to more reliable and realistic policy insights. While my comments are specifically addressed to DF's article, they can be generalized to other game theory models of climate change and natural resources conflicts. Given the limited length of commentaries, the supporting analysis has been provided as an appendix. Readers interested in the background game theory science and methods may consult the provided references.

2. Question 1. Are Nash and Maxi-min Solution Concepts Appropriate for Climate Games?

DF mainly rely on the Nash and Maxi-min solution concepts (stability definitions) for determining the equilibria (possible outcomes) of

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climate games, and for determining the dominant strategies of the players. However, these stability definitions may not be appropriate for modeling real-world conflicts, due to their highly restricted assumptions (Selbirak, 1994). Essentially, based on these stability definitions, players' decisions are independent from each other. Players, who make decisions based on these simplistic solution concepts, completely ignore the chance of counteractions by other players when judging the potential benefits of changing strategies (Madani and Hipel, 2011). That is why, for example, Nash stability fails to predict the obvious equilibrium in generic games like Prisoner's Dilemma and Chicken when the players are not myopic and countermovements are credible, i.e. “the breakdown of rationality” (Howard, 1971). Restrictive individual-rationality-based solution concepts have been found inappropriate for predicting the outcomes of real-world common resource games, in which players' decisions are not solely based on individual rationality (Finus, 2008; Madani and Dinar, 2012; Ostrom, 1990, 1998; Ostrom et al., 1994; Wood, 2011). Therefore, it can be argued that the Nash and Maxi-min stability definitions fail to reliably predict the outcomes of international climate games, involving smart negotiators, who are not myopic, do not make decisions independently, and do not ignore the possible counteractions by other negotiators.

Less-restrictive stability definitions such as General Metarationality (Howard, 1971), Symmetric etarationality (Howard, 1971), Sequential Stability (Fraser and Hipel, 1979, 1984), Limited-Move Stability (Fang et al., 1993; Kilgour et al., 1987; Zagare, 1984), and Non-Myopic Stability (Brams and Wittman, 1981) could be applied to improve the ordinal finite-strategy strategic climate game models, and facilitate obtaining reliable policy insights. These stability definitions have been proposed to better reflect the behavior of players in strategic decision making environments, and have been found reliable in finding the equilibria of many interactive real-world games (Fraser and Hipel, 1983; Fraser and Kilgour, 1986; Hamouda et al., 2006; Hipel et al., 1997; Li et al., 2004; Ma et al., 2005; Madani and Lund, 2011; Noakes et al., 2003; Shupe et al., 1980; Wright et al., 1980; Zagare, 1981, 1983). Table 1 summarizes the main characteristics of these solution concepts and compare them with the ones used by DF, namely Nash and Maxi-min.

While I am not suggesting that 2×2 games provide the best framework for analyzing international climate negotiations, the suggested equilibrium concepts can be applied to the games suggested by DF to show how the choice of stability definition can affect the results of game models. Appendix A presents the results of the stability analysis of the 25 climate relevant 2×2 games considered by DF, based on the aforementioned stability definitions. Each table in Appendix A shows the stability analysis details for one of the 25 studied games. In essence, these tables show whether the possible outcomes of each game are stable to the players based on the different stability definitions. Fig. 1 compares the results of the analysis by DF with the findings of this commentary. This figure shows that Nash and Maxi-min stability concepts fail to identify some of the possible equilibria of strategic games in which players are not myopic, do not act independently, and may consider the possible counteractions of the other players when making decisions. Consideration of the stability definitions which better reflect the players' behavioral characteristics in interactive strategic games, results in identifying 17 more possible equilibria in the analyzed games. Given that an equilibrium of the game is essentially a possible resolution of a conflict (or negotiation), the figure shows that some possible outcomes of the “possible” climate negotiation games remain hidden in 16 of the analyzed games, when only Nash and Maxi-min solution concepts are considered. Therefore, one can argue that the provided policy insights are not reliable. For example, while the authors do not recognize (Abate, Abate) as an equilibrium in the Prisoner's Dilemma game (game 111), the stability analysis results (Table A.1) show that this outcome can be a likely resolution of interactive strategic Prisoner's Dilemma games with real decision makers. This finding is consistent with the “breakdown of rationality” discussion by Howard (1971), and extensive lab and field experiments with real agents, suggesting that many commons have been protected and “tragedy of the commons” has been prevented in practice through cooperation among the parties within the Prisoner's Dilemma game structure (Dietz et al., 2003; Ostrom, 1990, 1998; Ostrom et al., 1994).

It should be noted that while the suggested stability definitions do a better job in simulating the behavior of decision makers in interactive games, it is never possible to capture all behavioral characteristics of different decision makers. Therefore, stability definitions are associated with simplifications and limitations. In the absence of information about the actual behavior of human agents in interactive environments, the literature suggests analyzing the game with a range of solution concepts. The states that are identified as equilibria under a larger number of solution concepts have a higher chance of being the final outcome of the game (Kilgour and Eden, 2010; Kilgour et al., 2001; Madani and Hipel, 2011). In this analysis only a few non-cooperative stability definitions which better reflect human behavior in interactive games (Fang et al., 2003; Madani and Hipel, 2011) were applied to highlight the importance of consideration of different stability definitions and to indicate the sensitivity of the results to the stability definitions considered. Future studies of climate change negotiations can consider additional stability definitions to strengthen their models after making sure the selected stability definitions are applicable to the type of the game being analyzed.

Table 1
Summary of the players' behavioral characteristics under different non-cooperative solution concepts.

Stability definition	Stability description	Characteristics		
		Foresight	Disimprovemen	Knowledge of preferences
Nash	Player cannot unilaterally move to a more preferred state.	Low (1 move)	Never	Own
Maxi-min	Player selects a strategy for which the worst possible outcome is at least as good as the worst outcome from any other strategy.	Low (1 move)	Yes (conservatively)	Own
General meta-rationality (GMR)	All unilateral *improvements* are blocked by subsequent unilateral *moves* by other players.	Medium (2 moves)	By opponent	Own
Symmetric meta-rationality (SMR)	All unilateral *improvements* are still blocked by other players even after possible responses by the original player.	Medium (3 moves)	By opponents	Own
Sequential stability (SEQ)	All unilateral *improvements* are blocked by subsequent unilateral *improvements* by other players.	Medium (2 moves)	Never	All
Limited (h)-move	All players are assumed to act optimally and maximum number of state transitions is specified.	Variable (h moves)	Strategically	All
Non-myopic	Limiting case of limited move stability as the maximum number of state transitions increase to infinity.	Unlimited	Strategically	All

111	Abate (A)	Pollute (P)
Abate (A)	3, 3	1, 4
Pollute (P)	4, 1	2, 2 $^{*,+}$

112	Abate (A)	Pollute (P)
Abate (A)	3, 3	1, 4
Pollute (P)	4, 2 $^{*,+}$	2, 1

121	Abate (A)	Pollute (P)
Abate (A)	3, 3	2, 4 $^{*,+}$
Pollute (P)	4, 1	1, 2

Chicken: 122	Abate (A)	Pollute (P)
Abate (A)	3, 3 $^{+}$	2, 4 *
Pollute (P)	4, 2 *	1, 1

211	Abate (A)	Pollute (P)
Abate (A)	4, 3	2, 4 $^{*,+}$
Pollute (P)	3, 1	1, 2

212	Abate (A)	Pollute (P)
Abate (A)	4, 3 $^{+}$	2, 4 *
Pollute (P)	3, 2	1, 1

Alibi: 221	Abate (A)	Pollute (P)
Abate (A)	4, 3	1, 4
Pollute (P)	3, 1	2, 2 $^{*,+}$

Cycle: 222	Abate (A)	Pollute (P)
Abate (A)	4, 3	1, 4
Pollute (P)	3, 2 $^{+}$	2, 1

261	Abate (A)	Pollute (P)
Abate (A)	4, 3	3, 4 $^{*,+}$
Pollute (P)	2, 1	1, 2

262	Abate (A)	Pollute (P)
Abate (A)	4, 3 $^{+}$	3, 4 *
Pollute (P)	2, 2	1, 1

No Conflict: 311	Abate (A)	Pollute (P)
Abate (A)	4, 4 $^{*,+}$	2, 3
Pollute (P)	3, 2	1, 1

312	Abate (A)	Pollute (P)
Abate (A)	4, 4 *	2, 3 $^{+}$
Pollute (P)	3, 1	1, 2

Pure Common Interest: 316	Abate (A)	Pollute (P)
Abate (A)	4, 4 $^{*,+}$	2, 2
Pollute (P)	3, 3	1, 1

321	Abate (A)	Pollute (P)
Abate (A)	4, 4 *	1, 3
Pollute (P)	3, 2 $^{+}$	2, 1

Coordination: 322	Abate (A)	Pollute (P)
Abate (A)	4, 4 *	1, 3
Pollute (P)	3, 1	2, 2 $^{*,+}$

326	Abate (A)	Pollute (P)
Abate (A)	4, 4 *	1, 2
Pollute (P)	3, 3 $^{+}$	2, 1

Pure Common Interest: 361	Abate (A)	Pollute (P)
Abate (A)	4, 4 $^{*,+}$	3, 3
Pollute (P)	2, 2	1, 1

362	Abate (A)	Pollute (P)
Abate (A)	4, 4 *	3, 3 $^{+}$
Pollute (P)	2, 1	1, 2

Harmony: 366	Abate (A)	Pollute (P)
Abate (A)	4, 4 $^{*,+}$	3, 2
Pollute (P)	2, 3	1, 1

411	Abate (A)	Pollute (P)
Abate (A)	3, 4	1, 3
Pollute (P)	4, 2 $^{*,+}$	2, 1

Alibi: 412	Abate (A)	Pollute (P)
Abate (A)	3, 4	1, 3
Pollute (P)	4, 1	2, 2 $^{*,+}$

416	Abate (A)	Pollute (P)
Abate (A)	3, 4	1, 2
Pollute (P)	4, 3 $^{*,+}$	2, 1

421	Abate (A)	Pollute (P)
Abate (A)	3, 4 $^{+}$	2, 3
Pollute (P)	4, 2 *	1, 1

Cycle: 422	Abate (A)	Pollute (P)
Abate (A)	3, 4	2, 3 $^{+}$
Pollute (P)	4, 1	1, 2

426	Abate (A)	Pollute (P)
Abate (A)	3, 4 $^{+}$	2, 2
Pollute (P)	4, 3 *	1, 1

Fig. 1. The 2 × 2 climate change negotiations games suggested by DF in normal form. * and $^{+}$, respectively, indicate the Nash equilibrium and Maxi-min equilibrium, identified by DF. Shaded cells represent the outcomes which found as equilibria in this study based on the considered stability definitions.

3. Question 2. Can Climate Games be Considered as One-Shot Games?

DF treat climate games as one-shot games in which the countries can choose between polluting and abating only once. Consequently, the parties do not have a chance of switching strategies, regardless of what the other parties do. In a one-shot (one move) game counter-action is not possible and the game does not pass any state in transition from the status quo to the final outcome. In contrast, in a continuous (multi-shot) game, players can make multiple moves and counter-moves during the course of the game in transition from the status quo to the final outcome. The international climate game is, in fact, a continuous game in which parties can select pure or mixed strategies (in case of repetitive negotiations).

Based on the one-shot assumption, DF conclude that "game-theoretic examples do demonstrate … that a unilateral approach to emissions reduction may not be the best strategy for a country like the United States." They further discuss that "in the Chicken family of games, prior commitment to Abate by the nation whose dominant strategy is Abate guarantees that the other will Pollute." In fact, the one-shot assumption leads to developing game models which do not reflect the reality of international climate games in which players can change decisions numerous times during the course of the game, adopt mixed strategies (Pittel and Rübbelke, 2008), respond to actions of other players, and benefit from "cheap talks" (Camerer and Thaler, 2003; Sally, 1995). It is noteworthy that in international climate change negotiations parties also have the opportunity to pursue issue linkages (Pittel and Rübbelke, 2008), which is very likely in the international relations context. Linking of games expands the feasible solution set (Buchner et al., 2005; Carraro and Siniscalco, 1998; Kemfert, 2004) and may provide a "strategic loss" (Madani, 2011) opportunity, encouraging players to strategically lose in some games to win in the overall linked game. Climate change games can be linked to other international games to provide cooperation incentives to the non-cooperative parties. DF correctly recognize the importance of issue linkage and providing cooperation incentives.

Relying on one-shot climate negotiation games and isolating them from the other international games result in developing misleading and perhaps selfish solutions to climate change games that are mainly based on individual-rationality. I am highly concerned about the concluding statements of DF that I see as discouraging unilateral action by major players such as the U.S., potentially resulting in a "tragedy of the commons" (Gordon, 1954; Hardin, 1968) and continuation of business-as-usual polluting actions by the so-called "great powers" whose economic development has been argued to be one of the major drivers of global warming (Rübbelke, 2011). The authors' suggestions may lead to continued perception of the climate game as a "Wall Street" or competitive game as opposed to a "community" game (Camerer and Thaler, 2003), in which fairness equilibrium (Camerer, 1997) may not be developed only because the same game has been presented differently to the players.

The analysis of these games could benefit from the aforementioned as well as other stability definitions, which are suitable for multi-shot games and can handle multiple moves and counter- moves during the game. These definitions can help identifying the fairness equilibria and coalitional solutions, which may not be predictable based on Nash and Maxi-min stability definitions, due to their restrictive nature, making them inappropriate for analyzing continuous games. Indeed, analyses that are based on less-restrictive stability definitions can help better present the game to the players and increase the chance of obtaining socially optimal outcomes. In the context of community games where players do not make decisions independently (as opposed to what suggested by Nash and Maxi-min stability definitions), a nice action by one player can trigger reciprocal niceness by other players and provide incentives for sacrificing to repay other players' kindnesses (Camerer, 1997). Therefore, voluntary emission reducing actions may be adopted by countries like the U.S. to develop trust and increase the chance of reaching a socially optimal resolution. Since changing strategies is possible, the cost of failure of such voluntary actions is considerably lower than the case in which the game is considered to be a one-shot game with irreversible moves. Furthermore, since in practice abatement occurs gradually, reversing the decision can occur at any time the volunteer nation feels a credible free- ride threat.

It is noteworthy that given the number of countries involved, developing a global collaborative solution for climate change is very challenging as acknowledged by DF. Nevertheless, the global community can benefit from partial cooperation (Carraro and Siniscalco, 1993; Rotillon and Tazdaït, 1996) and formation of coalitions including countries with high GHG emissions that are willing to abate. In that case, gains from partial cooperation can provide incentives for other parties to join and expand the cooperative coalitions (Carraro and Siniscalco, 1993). A comprehensive analysis of climate negotiation games should go beyond two-by-two one-shot games with homogenous agents as these games do not allow for analyzing the effectiveness of partial coalitions in addressing global warming. While simple categorization of the climate change negotiators into two groups might be a good starting point, climate change negotiations are much more complex. DF correctly conclude that a critical number of countries are needed to enforce a cooperative resolution in Coordination games with multiple players. Under their suggested framework, reaching a cooperative solution in Prisoner's Dilemma is not possible through partial coalitions without an external rewarding or punishment measures for changing the payoff orders (e.g., trade incentives, sanctions). Their analysis does not discuss if partial coalitions can be successful in establishing a cooperative solution under other types of games, most importantly under Chicken.

Considering the continuous nature of the game, as well as the possibility of changing strategies and abatement levels, Heitzig et al. (2011) have designed a promising mechanism to move the global community past the current political impasse in which national climate policies are only concerned about the other nations' possible free-ride opportunities (Dietz and Zhao, 2011). Perhaps, the same concern has persuaded DF to suggest that the “great powers” should not make prior commitments to Abate. Such a conclusion is rooted in consideration of the game as a one- shot normal game. However, as Wood (2011) argues “normal form games … help us to understand the free-rider problem, but do not tell us about the sequential nature of strategic behavior.” This is the reason why climate change games have been considered by many as dynamic multi-shot and repeated games (Asheim et al., 2006; Finus, 2008; Froyn and Hovi, 2008; Wood, 2011).

As indicated in Appendix A, consideration of stability definitions which reflect the behavior of players in continuous (multi-shot) games results in finding some new equilibria for the considered 25 ordinal games. Identification of 17 new equilibria in this study (Fig. 1) proves the unreliability of Nash and Maxi-min solution methods for predicting all possible resolutions of the interactive strategic climate negotiation games. Therefore, the strategic policy insights provided based on simplistic stability definition methods, which do not match the real characteristics of the players, cannot be trusted. When players have a chance to react and change their strategies the equilibria of the game might be different and the policy implications will change accordingly. For example, the (Abate, Abate) outcome has been found as a possible equilibrium of all considered 25 games. Therefore, if we agree with DF that these 25 game models cover “every possible” climate negotiation games at the international level, we see that cooperation is always a feasible (not necessarily always likely) outcome and the global climate change game can be also viewed as a “community game” when agents do not act independently in a one-shot game. If the game is a community game, sticking to the “abate if everyone else abate” policy could result in the tragedy of the commons.

4. Question 3. Are Climate Games Evolving?

DF analyze 25 games that they identify as possible climate relevant 2 × 2 games and suggest that the actual game structure depends on the severity of risk associated with catastrophic climate change and perceptions of the negotiating parties. While I agree that the game structure is sensitive to players' perceptions, there remains a major gap in the analysis due to a “semi-static” game structure assumption. The climate game is an evolving game. Hence, its actual structure depends not only on the available information about climate change effects and the risk of a catastrophe, but also on time and the stock of emitted GHGs remaining in the atmosphere. Consideration of the evolving nature of the game due to an accumulating public ‘bad’ can result in policy implications that are considerably different from that found simply through examining all possible ranking orders and game structures.

Madani (2010) advises great caution with modeling evolving (dynamic) games and identification of the games' changing conditions. Through a simple 2 × 2 game example, he discusses how ignoring time and the changing conditions of a common pool resource can result in decisions which are rational in a specific time-frame, but will eventually entail undesirable game structures. He concludes that early knowledge of an evolving game structure may lead to different behaviors by the players in order to reduce the risk of future losses (lower payoffs). In another study, Rotillon and Tazdaït (1996) discuss that an international environmental game's structure can change over time due to changes in the rules of the games as parties try to coordinate their action and change behavior. They suggest that considering the crossover structure for the Prisoner's Dilemma game, i.e. the Chicken game can help ensure the players' decisions are effective and significant. Madani and Lund (2012) also discuss how ignoring the changing conditions of a hydro-environmental system has resulted in changing the game's structure from Prisoner's Dilemma to Chicken, in which one party may need to “chicken out” (lose instead of “die proudly” (Madani, 2010)) to avoid higher costs due to defection by both parties. Based on these studies and other relevant research (Pittel and Rübbelke, 2008; Rübbelke, 2011), it is reasonable to suggest that no matter what the current climate game structure is (out of the 25 suggested game structures), Chicken may be the future of the international climate game, should all parties keep defecting. Thus, neglecting the evolving nature of the game and the risk of development of Chicken characteristics can have detrimental effects on the state of nature in the future.

Fig. 2, which is based on Madani's (2010) “Evolution of Game Structure” concept, shows how the payoff of a given player in a simple symmetric 2 × 2 climate negotiation game may change over time. With continuous development and associated increase in GHGs, the cost of global warming increases over time. So, let us assume that the cost of climate change to a player at any time (C_i where $i \in$ {*row player, column player*}) is a function of the cost of reducing greenhouse gases (through limiting unsustainable energy-exhaustive development and technological changes, among others) and the level of GHGs in the atmosphere at that time. If none of the players deviates from the Pollute (P) policy, GHGs increase over time, resulting in a higher cost of climate change to the players as shown by the C_i (P, P) curve in Fig. 2. Based on this figure at the beginning of the game (Period 1), increasing the level of

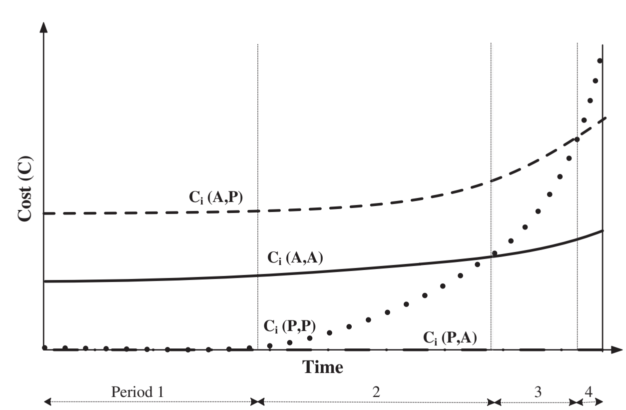

Fig. 2. The climate change game's evolution path.

GHGs has no cost to the players (C_i (P, P) = 0) as the atmosphere has enough capacity to carry the GHGs with no negative feedback. However, C_i (P, P) increases non-linearly over time due to the limited carrying capacity of the atmosphere. The C_i (P, A) curve represents the cost of free riding to player *i* who pollutes when the other party abates and tries to address the problem single-handedly. The cost of a free ride is zero at any time during the game. C_i (A, P) shows the cost of the opposite case, in which player *i* abates and reduces the GHG emissions on his own with no contribution by the other player. C_i (A, P) increases over time, showing that starting abatements later in the game costs more, due to the increased level of GHGs as a result of development by both players. C_i (A, A) indicates the cost of the cooperative outcome in which both players share the burden and abate. In general, C_i (A, A) is less than C_i (A, P) at any time during the game as under cooperation cost of a given level of GHG reduction is shared by the parties (in a symmetric game C_i (A, A) is half of C_i (A, P) at any time).

Given the changing cost of different outcomes during the game, the game structure evolves over time. Madani (2010) identifies 6 game structures during the course of the game represented by Fig. 2 and discusses how dominant strategies and equilibria of the game change with the game's evolution. Players who act independently might stick to the dominant strategy in the game at the earlier time periods, resulting in pushing the game into the last period (Period 4) when the game transforms from a Prisoner's Dilemma (game 111 occurring in Period 3) to a Chicken game (game 122). Based on the same concept it can be argued that, no matter which of the 25 games suggested by DF represents today's state of the game, sticking to the "no abate unless everyone else abates" policy pushes the game to its terminal structure, the risky Chicken game in which the party who has been affected more by climate change (higher costs), has a lower risk tolerance, or has a better ability to resolve the problem (due to higher emission levels, capital cost, and infrastructure) may be forced to solve the problem on its own at a higher cost.

In the climate game, defection simply results in more greenhouse gas emissions, which put the environment as well as today's and future generations in graverdanger. The evolution of the game is the outcome of our decisions and depends on time. While we can wait for our climate change knowledge to change our perception about the game structure, we should be aware of the fact that nature is not waiting for us. So, the increasing level of GHG emissions exacerbates the situation and may result in changing the structure of the game to a Chicken game that may have winners and losers. Therefore, rather than defection as a tactical climate policy to serve national self interest, "great powers" might be better off reducing emissions and developing collaborative resolutions to prevent the Chicken game, if we are not there already. Fortunately, as indicated in Appendix A, cooperative outcomes can be stable for both parties in all "possible" game structure before occurrence of the Chicken game and during this game. However, as discussed, the later the cooperative outcome develops in the game's evolution path, the higher is the cost of cooperation to both parties.

5. Final Remarks

The purpose of this commentary was to complement DF's study by explaining its limitations and providing some alternative methods to improve their suggested models. Some solution concepts, which better reflect decision makers' behavior in interactive environments, were applied to the suggested simple games of DF to show how the results can change if more realistic solution methods are applied. Nevertheless, these solution methods are not the only applicable or the best ones necessarily. More comprehensive analysis of climate change negotiations should: 1) take the analysis out of the 2 × 2 framework; 2) pay more attention to essential characteristics of climate change negotiations and negotiators; 3) consider the heterogeneity of players' payoff functions and powers; and 4) include the possibility of forming coalitions, issue linkage, strategic loss, counteraction, reward and punishment, cheap talks, and playing "community" games.

Game theory is a powerful tool for analyzing climate negotiations. The field of game theory has developed rapidly as have our computational and analytical capacities for analyzing more complex games, which are not simple one-shot games with independent actors. Overly simplistic game theory models can only provide unrealistic and grim conclusions (Dietz and Zhao, 2011). While I agree with most of the general findings and conclusions of DF, some of the policy implications of their study for national climate diplomacy might not be valid due to the limitations of their assumptions and approach.

DF claim that they "have covered every possibility for describing the strategic interactions that might characterize the international climate negotiations." However, even if we assume their game models have covered every possible game structure, it is difficult to believe that their claim is valid for two reasons. First, they have not characterized the players correctly by assuming that the climate change negotiators are Nash and Maxi-min players who act independently with no interaction with other players. Second, they have assumed the climate change games are one- shot, there is no counteraction, and players cannot change their strategies during the course of the games. So, although in their simplest form, climate negotiation game structures can be represented correctly by a two-by-two game, DF's games have not been characterized comprehensively, resulting in failure in developing highly reliable policy conclusions in some cases, as discussed above.

If we view the global climate change game as a one-shot competitive game, a "unilateral approach to emissions reduction" may not appear to be the best national climate policy for the United States. But if all other rational players follow the same tactic this will only result in a tragic future (Gordon, 1954; Hardin, 1968). Instead, voluntary emission reductions ("strategic loss" (Madani, 2011) in the short-run) have the potential for turning the game from "a competition" to "a cooperation" and establishing fair and efficient reward/penalty social mechanisms (such as the one suggested by Heitzig et al. (2011)) that can make the world a better place for all in the long-run.

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Appendix A. Stability Analysis of the Climate Change Negotiations Games Suggested by DF

Tables A.1–A.25 indicate the stability analysis results for the 25 ordinal games considered as "possible" climate negotiations games by DF. These games are shown in Fig. 1. These tables show if the four possible outcomes of each game are stable for the two players based on different stability definitions. When both players find an outcome to be stable under the same stability definition, this outcome is an equilibrium or a likely resolution of the conflict. Fang et al. (1993) and Madani and Hipel (2011) provide detailed instructions on how to examine the stability of each outcome under the different stability definitions considered here.

Table A.1
Stability analysis results for game 111.

Stability definition	(A, A)		(A, P)	(P, A)	(P, P)	
	Stable for					
	Row	Column	Row column	Row column	Row	Column
Nash (L_1)			✓	✓	✓	✓
GMR	✓	✓	✓	✓	✓	✓
SMR	✓	✓	✓	✓	✓	✓
SEQ	✓	✓	✓	✓	✓	✓
L_2	✓	✓	✓	✓	✓	✓
L_3	✓	✓	✓	✓	✓	✓
Non-myopic (L_4)	✓	✓	✓	✓	✓	✓

Table A.2
Stability analysis results for game 112.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)				✓	✓	✓	✓	
GMR	✓	✓		✓	✓	✓	✓	
SMR	✓	✓		✓	✓	✓	✓	
SEQ		✓		✓	✓	✓	✓	
L_2		✓		✓	✓	✓	✓	
L_3		✓		✓	✓	✓	✓	
Non-myopic (L_4)	✓	✓		✓	✓	✓	✓	

Table A.3
Stability analysis results for game 121.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)			✓	✓	✓			✓
GMR	✓	✓	✓	✓	✓			✓
SMR	✓	✓	✓	✓	✓			✓
SEQ	✓		✓	✓	✓			✓
L_2	✓		✓	✓	✓			✓
L_3	✓		✓	✓	✓			✓
Non-myopic (L_4)	✓		✓	✓	✓			✓

Table A.4
Stability analysis results for game 122.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)			✓	✓	✓	✓		
GMR	✓	✓	✓	✓	✓	✓		
SMR	✓	✓	✓	✓	✓	✓		
SEQ			✓	✓	✓	✓		
L_2				✓	✓			
L_3	✓	✓		✓	✓			
Non-myopic (L_4)	✓	✓		✓	✓			

Table A.5
Stability analysis results for game 211.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓		✓	✓				✓
GMR	✓	✓	✓	✓	✓			✓
SMR	✓	✓	✓	✓	✓			✓
SEQ	✓		✓	✓	✓			✓
L_2	✓		✓	✓	✓			
L_3	✓			✓	✓			✓
Non-myopic (L_4)	✓	✓	✓	✓	✓			✓

Table A.6
Stability analysis results for game 212.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓		✓	✓		✓		
GMR	✓	✓	✓	✓	✓	✓		
SMR	✓	✓	✓	✓	✓	✓		
SEQ	✓		✓	✓	✓	✓		
L_2	✓			✓	✓			
L_3	✓	✓		✓	✓			
Non-myopic (L_4)	✓	✓		✓	✓			

Table A.7
Stability analysis results for game 221.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓			✓			✓	✓
GMR	✓	✓		✓	✓		✓	✓
SMR	✓	✓		✓	✓		✓	✓
SEQ	✓	✓		✓	✓		✓	✓
L_2	✓	✓		✓	✓		✓	
L_3	✓	✓		✓			✓	✓
Non-myopic (L_4)	✓	✓		✓			✓	

Table A.8
Stability analysis results for game 222.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓			✓		✓	✓	
GMR	✓	✓		✓	✓	✓	✓	
SMR	✓	✓		✓	✓	✓	✓	
SEQ	✓	✓		✓	✓	✓	✓	
L_2	✓	✓		✓	✓	✓	✓	
L_3	✓	✓		✓		✓	✓	
Non-myopic (L_4)	✓	✓		✓		✓	✓	

Table A.9
Stability analysis results for game 261.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓		✓	✓				✓
GMR	✓	✓	✓	✓				✓
SMR	✓	✓	✓	✓				✓
SEQ	✓		✓	✓				✓
L_2	✓		✓	✓				
L_3	✓			✓				
Non-myopic (L_4)	✓	✓	✓	✓				

Table A.10
Stability analysis results for game 262.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓		✓	✓		✓		
GMR	✓	✓	✓	✓		✓		
SMR	✓	✓	✓	✓		✓		
SEQ	✓		✓	✓		✓		
L_2	✓		✓	✓				
L_3	✓			✓				
Non-myopic (L_4)	✓	✓	✓	✓				

Table A.11
Stability analysis results for game 311.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓			✓		
GMR	✓	✓	✓	✓	✓	✓		
SMR	✓	✓	✓	✓	✓	✓		
SEQ	✓	✓	✓			✓		
L_2	✓	✓						
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.12
Stability analysis results for game 312.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓					✓
GMR	✓	✓	✓	✓	✓			✓
SMR	✓	✓	✓	✓	✓			✓
SEQ	✓	✓	✓					✓
L_2	✓	✓	✓					
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.13
Stability analysis results for game 316.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓			✓		
GMR	✓	✓	✓		✓	✓		
SMR	✓	✓	✓		✓	✓		
SEQ	✓	✓	✓			✓		
L_2	✓	✓				✓		
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.14
Stability analysis results for game 321.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓				✓	✓	
GMR	✓	✓		✓	✓	✓	✓	
SMR	✓	✓		✓	✓	✓	✓	
SEQ	✓	✓				✓	✓	
L_2	✓	✓				✓		
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.15
Stability analysis results for game 322.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓					✓	✓
GMR	✓	✓		✓	✓		✓	✓
SMR	✓	✓		✓	✓		✓	✓
SEQ	✓	✓					✓	✓
L_2	✓	✓						
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.16
Stability analysis results for game 326.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓				✓	✓	
GMR	✓	✓			✓	✓	✓	
SMR	✓	✓			✓	✓	✓	
SEQ	✓	✓				✓	✓	
L_2	✓	✓				✓		
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.17
Stability analysis results for game 361.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓			✓		
GMR	✓	✓	✓	✓		✓		
SMR	✓	✓	✓	✓		✓		
SEQ	✓	✓	✓			✓		
L_2	✓	✓	✓					
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.18
Stability analysis results for game 362.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓					✓
GMR	✓	✓	✓	✓				✓
SMR	✓	✓	✓	✓				✓
SEQ	✓	✓	✓					✓
L_2	✓	✓	✓					
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.19
Stability analysis results for game 366.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)	✓	✓	✓			✓		
GMR	✓	✓	✓			✓		
SMR	✓	✓	✓			✓		
SEQ	✓	✓	✓			✓		
L_2	✓	✓	✓			✓		
L_3	✓	✓						
Non-myopic (L_4)	✓	✓						

Table A.20
Stability analysis results for game 411.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓			✓	✓	✓	
GMR	✓	✓		✓	✓	✓	✓	
SMR	✓	✓		✓	✓	✓	✓	
SEQ		✓		✓	✓	✓	✓	
L_2		✓		✓	✓	✓		
L_3		✓		✓	✓		✓	
Non-myopic (L_4)	✓	✓		✓	✓	✓	✓	

Table A.21
Stability analysis results for game 412.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓			✓		✓	✓
GMR	✓	✓		✓	✓		✓	✓
SMR	✓	✓		✓	✓		✓	✓
SEQ	✓	✓		✓	✓		✓	✓
L_2	✓	✓		✓	✓			✓
L_3	✓	✓			✓		✓	✓
Non-myopic (L_4)	✓	✓			✓			✓

Table A.22
Stability analysis results for game 416.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓			✓	✓	✓	
GMR	✓	✓			✓	✓	✓	
SMR	✓	✓			✓	✓	✓	
SEQ		✓			✓	✓	✓	
L_2		✓			✓	✓		
L_3		✓			✓			
Non-myopic (L_4)	✓	✓			✓	✓		

Table A.23
Stability analysis results for game 421.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓	✓		✓	✓		
GMR	✓	✓	✓	✓	✓	✓		
SMR	✓	✓	✓	✓	✓	✓		
SEQ		✓	✓	✓	✓	✓		
L_2		✓		✓	✓			
L_3	✓	✓		✓	✓			
Non-myopic (L_4)	✓	✓			✓			

Table A.24
Stability analysis results for game 422.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓	✓		✓			✓
GMR	✓	✓	✓	✓	✓			✓
SMR	✓	✓	✓	✓	✓			✓
SEQ	✓	✓	✓	✓	✓			✓
L_2	✓	✓	✓	✓	✓			✓
L_3	✓	✓	✓		✓			✓
Non-myopic (L_4)	✓	✓	✓		✓			✓

Table A.25
Stability analysis results for game 426.

Stability definition	(A, A)		(A, P)		(P, A)		(P, P)	
	Stable for							
	Row	Column	Row	Column	Row	Column	Row	Column
Nash (L_1)		✓	✓		✓	✓		
GMR	✓	✓	✓		✓	✓		
SMR	✓	✓	✓		✓	✓		
SEQ		✓	✓		✓	✓		
L_2		✓			✓	✓		
L_3		✓			✓			
Non-myopic (L_4)	✓	✓			✓	✓		

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