ECONOMIC STUDIES

DEPARTMENT OF ECONOMICS
SCHOOL OF BUSINESS, ECONOMICS AND LAW
UNIVERSITY OF GOTHENBURG
218

Cooperation and Paradoxes in Climate Economics

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ISBN 978-91-85169-91-7 (printed)
ISBN 978-91-85169-92-4 (pdf)
ISSN 1651-4289 print
ISSN 1651-4297 online

Printed in Sweden,
Kompendiet 2015

To my family

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Acknowledgements

Pursuing my PhD here in Gothenburg has been a memorable journey. Now this journey is close to the end. I know that this would never have been possible without the support of so many people who were always with me. The courage and wisdom that they gave to me will benefit me all my life, no matter where I am and what I do. Now is the time to express my sincere gratitude to all of them.

I am profoundly thankful to my family. I want to thank my parents for bringing me into this colorful world and for their love, nurturing and support since then. I would like to give my special thanks to my wife, Yuandong Liang, who has sacrificed so much to accompany me to Sweden. Without her support, I might have never accomplished so much. My lovely daughter, Jiaxuan (Rosie) Zhang, joined us in 2013 and has brought so much happiness to our family. Thanks for your company and being so cute, little Rosie. But you should know that it is not a good idea to sit on me when I am writing in front of the computer.

My deepest gratitude goes to my supervisors: Thomas Sterner and Jessica Coria. They have been not only my thesis advisors, but also great mentors in my academic career by sharing their experiences and philosophy for doing research. Whenever I needed help, they always showed up and gave me a hand, no matter how busy they were. Thomas, thanks for your kind instructions and always-nice smiles. I still remember that you helped me improve my slides word by word, even on weekends. Your comments on my papers were insightful and detailed beyond my imagination. I know you have spent a lot of time on me and I am really grateful for this. From you, I have learnt a lot of wisdom, from the skills of responding to reviewers' comments, to the philosophy of doing research in economics. It has been a fantastic experience to be your student.

Jessica Coria deserves my special gratitude. As one of the most brilliant young researchers in the department, she has been acting as the coordinator of this supervision process. She is so nice and always so kind to her students. She is like the spring season, always giving me the hope, courage, and direction to overcome challenges. I still remember that long time ago she helped me apply for the data from a Chinese survey and we knocked Fredrik's office door together for guidance.

Without Jessica's help, I might never have obtained that data. She was always so fast at providing feedback and comments on each of the drafts. She showed me point by point how to make nice slides and have a good presentation. As my coauthor, she impressed me a lot with her insightful thoughts, inspiring ideas, and excellent calculating and writing abilities, from which I have learnt a lot. Jessica has been more than a thesis supervisor and coauthor. She also has been a mentor who gave me very important guidance and all kinds of support to help me have a better career. It was she who told me to be more patient and more focused in order to write good, solid papers. It was she who taught me how to write proposals for grant applications. It was she who showed me what a good researcher should look like. Thanks for being so kind and nice, Jessica. It is impossible to express in words how much I have benefited from you. I am so lucky to have been one of your students.

I also want to express my appreciation to my coauthor, Magnus Hennlock, who helped a lot in the thesis writing by sharing his great knowledge and insights in economic modeling. He also shared his experience of doing research in academia, which benefited me a lot. Sied Hessen also worked with me on an empirical paper about China's household energy consumption and I would like to thank him for his insightful discussions and nice collaboration. As one of my best friends, Sied gave me a lot of valuable advice for daily life and I have learnt a lot from him.

I would like to thank my opponent during my final seminar before defense, Professor Per Krusell, for his insightful and helpful comments to improve the papers. I also want to thank the participants at my seminars in the department and Andre Grimaud, Carolyn Fischer, Amrish Partel, Efthymia Kyriakopoulou and Xiangping Liu for their valuable comments and suggestions.

I am very grateful to my teachers for sharing their knowledge and wisdom with me during my coursework: Olof Johansson-Stenman, Andreea Mitrut, Amrish Patel, Johan Stennek, Conny Wollbrant, Eyerusalem Siba, Lennart Hjalmarsson, Arne Bigsten, Oleg Shchetinin, Lennart Flood, Ola Olsson, Måns Söderbom, Yonas Alem, Dick Durevall, Joakim Westerlund, Michele Valsecchi, Thomas Sterner, Håkan Eggert, Efthymia Kyriakopoulou, Elizabeth Robinson, Gunnar Köhlin, Fredrik Carlsson, Elina Lampi, Vic Adamowicz, Mitesh Kataria, Francisco Alpizar, Dale Whittington, Peter Martinsson, Katarina Nordblom, Christian Azar, Daniel Johansson, Martin Persson, Jessica Coria, Stefan Ambec, Xiangping Liu, Magnus Hennlock, Daniel Slunge, and Olof Drakenberg. I also want to thank the researchers at the Beijer Institute of Ecological Economics for their hospitality in spring 2012.

I also would like to thank my classmates and friends for accompanying me during this journey: Simona Bejenariu, Oana Borcan, Anja Tolonen, Marcela Jaime, Hang Yin, Sied Hassen, Remidius Ruhinduka, Emil Persson, and Joakim Ruist. The parties, BBQs and laughter we had together have made this journey so much more colorful.

I wish to thank Elizabeth Földi, Eva-Lena Neth-Johansson, Selma Oliveira, Po-Ts'an Goh, Katarina Nordblom, Åsa Adin, Jeanette Saldjoughi, Ann-Christin Räätäri Nyström, Mona Jönefors and Marita Taïb for their great administrative support. Their kind help made life much easier. I am particularly thankful to Elizabeth Földi for her kind hospitality and smart solutions to the problems that I encountered. I also would like to thank Cyndi Berck for her excellent language and editorial support.

Last but not least, I am grateful to my Chinese friends. Ping Qin and Xiangping Liu gave me valuable advice and important help in career planning. Qian Weng and Xiaojun Yang served as my mentors about life in Gothenburg. Yuanyuan Yi and Hang Yin were so kind in helping organize many social events, which made life in Gothenburg more enjoyable. Thanks to you all.

Xiao-Bing Zhang
February 2015
Gothenburg, Sweden

Summary of the thesis

As one of the most important global issues of our time, climate change is expected to affect all aspects of society. With a growing consensus that climate change is caused by anthropogenic emissions of greenhouse gasses (GHGs), the international community is gradually accepting the need to take action in order to limit the effects of climate change. However, this is easier said than done. In reality, there are many obstacles to climate policy at various levels. At the local level, there is a contradiction (or at least a perceived contradiction) between encouraging development and limiting emissions. At higher levels of aggregation, there are many difficult issues relating to the optimal extent and timing of abatement, as well as the distribution of costs and benefits of climate policy. Although in principle most countries would benefit from global climate stabilization, there are many issues of incentive compatibility in the design of international cooperation. All kinds of strategic behavior and paradoxes may affect the implementation of climate policy and the establishment of international cooperation on climate change.

Some climate policies, although designed to abate carbon emissions, might actually have the opposite effect (at least in the short run). For instance, the owners of carbon resources can pre-empt future regulation for fossil fuel demand and respond by accelerating the production of fossil energy while they can. This is the so-called "green paradox" identified by Sinn (2008). A rapidly increasing carbon tax, or the anticipation of a cheap and clean backstop technology, can act as a trigger for the green paradox.

Environmental policies and regulations are only useful if firms comply with them (Heyes, 1998). Compliance is generally achieved by the deterrent effects of punishments, which depend on the probability of inspection and the penalty for being caught in non-compliance. Empirical data shows that firms' compliance with environmental regulations is generally high, even though inspections occur infrequently and fines are rare and small in reality. This seemingly contradictory fact

is referred to in the literature as the “Harrington paradox”.

There is also some paradoxical behavior regarding cooperation on climate change. For instance, some countries such as the United States mention the uncertainties surrounding climate change as a reason for the lack of international cooperation. However, the welfare gains from international cooperation might actually be higher, i.e., cooperation might be even more important, when climate uncertainty is present.

This thesis consists of three self-contained essays on issues related to cooperation and policy making in the area of climate change. The first paper is related to the “green paradox”, the second paper contributes to the “Harrington paradox” literature, and the third paper is about paradoxical behavior in cooperation.

Paper I can be described as a contribution to the “green paradox” literature. It investigates the effect of uncertain innovation in a cheap, carbon-free technology, using a dynamic game to take into account the potential strategic interactions between the fossil resource producers’ energy pricing strategy and the resource consumers’ carbon taxation. There are two players in the game: a consumers’ coalition (such as an empowered International Energy Agency) and an energy producers’ cartel (which we can nick-name “OPEC”). The coalition of resource-importing countries coordinates carbon taxation and uses the taxes for both environmental and strategic purposes, thereby affecting the pricing strategy of energy producers. This means that, in addition to correcting for climate externalities, a carbon tax may also reap part of the producing cartel’s profits. The energy producer side can, however, also react strategically and preempt carbon taxes by raising the producer price (Wirl, 1995). In this strategic interaction, the consumer side that is coordinating taxation understands the effect of carbon taxes on energy prices, and the producer side that is coordinating sales understands the effect of sales on taxation (Liski and Tahvonen, 2004).

The innovation of carbon-free technologies can have an effect on the strategic interactions between carbon taxation and energy pricing. With the expectation that a carbon-free technology (which is a perfect substitute for fossil fuels) can be invented or discovered at some time in the future, both the energy producers and the consumers need to take this into account and may need to change their pricing/taxation strategies, given that the new technology will affect fossil energy demand and carbon emissions. There are many aspects that are uncertain in the processes we sketch here. In our model, we focus on uncertainty concerning the *time* at which the innovation will materialize. Consequently, each player solves a stochastic dynamic optimization problem in the game: the consumers' coalition maximizes the expected net present value of consumers' welfare by choosing carbon taxes, and the energy producers' cartel maximizes the expected net present value of profits by choosing producer prices.

The results show that the possible innovation in cheap non-polluting resources will reduce both the initial carbon tax and the (wellhead) energy price, thereby stimulating higher initial demand for fossil fuels, and thus higher initial emissions, which is a form of the "green paradox" effect in our context of strategic interaction. Though this innovation-triggered effect will also appear in the cooperative case (i.e., no strategic interactions), the presence of strategic interactions between resource producers and consumers can somewhat restrain such an effect. Moreover, if innovation can be stimulated through R&D effort, the optimal R&D should be an increasing function of the initial CO2 concentration. However, the resource consumers can over-invest in R&D relative to the investment level that a global planner would choose.

Paper II is related to the "Harrington paradox" mentioned above. There are many possible explanations for this paradox. Among others, Harrington (1988) shows that state-dependent enforcement based on past compliance records can be one of them. More specifically, Harrington considers two groups of firms: the non-target group, which faces less stringent enforcement and less frequent inspection, and the target group, where scrutiny is high and inspection more frequent. Firms can move from one group to another according to transition probabilities that depend on the current state of the system and compliance with the emission standard. Harrington shows such a scheme generates what he refers to as "enforcement leverage." Because non-compliance triggers greater future scrutiny, the expected costs of non-compliance are beyond the avoidance of immediate fines; as a result, compliance increases.

We propose here an improved transition structure for the audit framework where targeting is based not only on firms' past compliance record but also on adoption of environmentally superior technologies. Specifically, we have sub-groups of adopters (non-adopters) who adopt (do not adopt) a new technology and have lower (higher) abatement cost in the respective non-target and target groups considered by Harrington (1988). Furthermore, compared with non-adopters, the adopters face a lower probability of being transferred to the target group once found violating and a higher probability of moving back to the non-target group if complying.

We show that this transition structure would not only foster the adoption of new technology but also increase deterrence by changing the composition of firms in the industry toward an increased fraction of cleaner firms that pollute less and violate less. That is, with this improved transition structure, it is possible to reduce the aggregate emissions of the industry and decrease the enforcement cost at the same time.

While the first two papers focus on two paradoxes in regulation, **Paper III** focuses on a topic that many find also paradoxical (at least in an everyday sense of the word): the state of international cooperation on climate change. Current cooperation is generally not considered very effective (Finus and Pintassilgo, 2013) and there are a number of possible reasons for this. One important problem that precludes effective cooperation is free-riding. Unless there is international binding law which forces countries to participate in an agreement to reduce GHG emissions, each country can choose to stay outside the agreement and enjoy (almost) the same benefits of reduced GHG emissions as if it participated in the agreement, while it doesn't bear any of the costs of reducing emissions (Hoel, 1993). In addition to the free-riding problem, it has been argued that the huge uncertainties surrounding climate change can also be one of the reasons for the lack of cooperation (Kolstad, 2007; Barrett and Dannenberg, 2012; Finus and Pintassilgo, 2013).

If climate uncertainty could reshape the abatement strategies of individual countries, this may also have an effect on their expected welfare. However, these effects might be different depending on whether they cooperate with each other. This implies that uncertainty could have an impact on the potential welfare gains from cooperation for individual countries, thereby affecting the incentives for cooperation among countries. Therefore, it is important to investigate whether this would be true in a normative perspective and to see precisely in what way, dealing with uncertainty could reshape climate policies and change the incentives for international cooperation on climate change. This paper extends the deterministic dynamic game for international pollution control in Dockner and Long (1993) to study the welfare gain from international cooperation under climate uncertainty. Our analysis shows that, even though greater climate uncertainty will reduce the expected welfare of players in both the non-cooperative and cooperative cases, it is always beneficial to cooperate, and the expected welfare gain from international cooperation is larger with greater climate uncertainty. That is, the greater the uncertainty about climate warming, the more important it is to have international cooperation on emission regulation, even though it seems that, in reality, countries tend not to cooperate under uncertainty. At the same time, however, more transfers will be needed to ensure stable cooperation among asymmetric players.

To sum up, this thesis attempts to investigate issues related to cooperation and paradoxes in climate economics. The findings are expected to contribute to the discussion of climate policy design and climate change cooperation. For instance, being aware of the different magnitudes of the innovation-triggered green paradox effect, it might be a good idea to design different supply-side solutions for mitigating this effect under different market structures. Also, our proposed transition structure for compliance auditing can help increase the efficiency of monitoring and enforcement (M&E) activities to regulate carbon emissions, with the outcome of less emissions with lower M&E costs. Furthermore, we have learnt that international cooperation is more important when facing larger climate uncertainty and we can always induce countries to cooperate through appropriately-designed side payments.

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Paper I

Strategic Carbon Taxation and Energy Pricing: The Role of Innovation*

Xiao-Bing Zhang†

Abstract

This paper uses a dynamic game to investigate the strategic interactions between carbon taxation by a coalition of resource consumers and (wellhead) energy pricing by a producers' cartel under the possibility of innovation in a cheap carbon-free technology. The timing of innovation is uncertain, but can be affected by the amount spent on R&D. The results show that the expectation of possible innovation decreases both the initial carbon tax and producer price, resulting in higher initial resource extraction and carbon emissions. Though this 'green paradox' effect triggered by possible innovation also will appear in the cooperative case (without strategic interactions), the presence of strategic interactions between resource producers and consumers can somewhat restrain such an effect. For both the resource consumers and a global planner, the optimal R&D to stimulate innovation is an increasing function of the initial CO2 concentration. However, the resource consumers can over-invest in R&D relative to the investment level that a global planner would choose.

Keywords: Carbon taxation, innovation, uncertainty, dynamic game
JEL Classification: C73, Q23, H21, Q54

*The author would like to thank Jessica Coria, Thomas Sterner, Magnus Hennlock, Andre Grimaud, Carolyn Fischer, Amrish Partel, Xiangping Liu, Efthymia Kyriakopoulou and participants at the EAERE 2013 conference for their helpful discussions and comments on this paper. All errors and omissions remain the sole responsibility of the author. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7-2007-2013) under grant agreement n [266992] and the Swedish International Development Cooperation Agency (Sida).

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1 Introduction

Climate change has been considered as one of the most important environmental issues at our time and the accumulated greenhouse gases (GHGs) in the atmosphere are believed to be the main cause of this. Mitigating climate change would require policy instruments, e.g., carbon taxes, to take into account the externalities caused by GHGs emissions, which mainly come from fossil fuel consumption. However, the optimal design of climate policy is subject to many issues in reality, e.g., oligopoly in fossil energy markets, strategic behavior of agents, and uncertainty in the innovation of green technologies.

The strategic interactions between the (cartelized) resource producers and consumers can complicate the design of climate policy. Specifically, an energy producer such as OPEC can behave strategically and preempt carbon taxes by raising the producer price (Wirl, 1995). Meanwhile, a coalition of resource-importing countries such as the International Energy Agency (IEA) could coordinate their carbon taxation and thereby affect the pricing strategy of energy producers. That is, in addition to serving its purpose of correcting for externalities associated with carbon emissions, a carbon tax may also assist resource consumers in reaping part of the cartel's profits (Wirl, 1995). Therefore, when investigating climate policy issues, it is important to take into account the strategic behavior of the agents, where the consumer side that is coordinating taxation understands the effect of carbon taxes on energy prices, and the producer side that is coordinating sales understands the effect of sales on taxation (Liski and Tahvonen, 2004).

In addition to the strategic interaction issues, the possible innovation of low-carbon or carbon-free technologies can also have important implications for climate policy design and may affect the strategic interactions between carbon taxation and energy pricing. Imagine now that there is a possibility that a carbon-free technology (which is a perfect substitute for fossil fuels) can be invented or discovered at some time in the future and can be supplied at a lower cost than that of fossil fuels. Given that the new technology will affect fossil energy demand and carbon emissions, both the energy producers and the consumers need to take this into account. Then a natural question is, how would the producers and consumers change their strategies of energy pricing and carbon taxation with the expectation of possible innovation? How would the effect of a possible innovation differ with/without the strategic interactions between the producers' energy pricing and the consumers' carbon taxation? Moreover, if the speed and success of innovation can be affected by the consumers' strategic R&D effort, how would the consumers make their R&D decisions? How does the optimal R&D investment by the consumer side compare with the global efficient level? To investigate these questions, this paper integrates the possible innovation of a carbon-free technology into the strategic interactions on energy pricing and carbon taxation between the energy seller side and the buyer side within a dynamic game framework to study the role of possible innovation and R&D investment in this strategic interaction context.

While the role that technological innovation (and its uncertainty) plays in natural resource extraction or climate policy design has been investigated by numerous studies, e.g., Dasgupta and Stiglitz (1981), Harris and Vickers (1995), Golombek et al. (2010), Fischer and Sterner (2012), and Henriet (2012), the strategic interactions between climate policy design and resource extraction were generally not addressed in these studies. On the other hand, even though the strategic interactions between (fossil fuel) producers' energy pricing strategies and consumers' carbon taxation have been extensively examined in the literature (for instance, Wirl, 1994, 1995; Wirl and Dockner, 1995; Tahvonen, 1994, 1996, 1997; Rubio and Escriche, 2001; Liski and Tahvonen, 2004; Wei et al., 2012), none of the previous studies (to the best of our knowledge) has incorporated the possible innovation of carbon-free technologies, the uncertain arrival time of innovation, and the endogenous R&D investment, into the investigation of the strategic interactions on carbon taxation and energy pricing. This paper fills these gaps in the literature and investigates the effect of innovation on both producers' energy pricing strategy and consumers' carbon taxation strategy (which differs from previous studies in the literature, where the focus is on the effect of innovation on energy consumption alone). Moreover, by comparing the cooperative and non-cooperative solutions of the game, one can see how the effect of innovation differs with/without the existence of strategic interactions between resource producers and consumers.

Another concept that is related to this paper is the so-called 'green paradox', which stems from Sinn (2008) and describes the situations in which some climate policies designed to abate carbon emissions might actually increase carbon emissions, at least in the short run (Hoel, 2012). For instance, a rapidly increasing carbon tax (Sinn, 2008), or the anticipation of a cheap and clean backstop technology (Henriet, 2012), can be the possible causes of a green paradox. In line with the ′green paradox′ argument, this study finds that the expectation of possible innovation in a cheap carbon-free technology decreases both the initial carbon tax and initial producer price, which implies lower initial consumer prices and thus higher initial resource extractions and carbon emissions. Though this ′green paradox′ effect triggered by possible innovation also can be found in the case without strategic interactions, the decrease in initial consumer price, and thus the increase in initial carbon emissions, can be less dramatic in the presence of the strategic interactions of carbon taxation and energy pricing between the energy producer side and the consumer side. This result indicates that the ′green paradox′ effect of possible innovation can be somewhat restrained by the strategic interactions between resource producers and consumers. Moreover, if the consumer side can affect the arrival time of innovation through R&D, it might exert an R&D effort that is higher than the global efficient level.

The rest of this paper is organized as follows. Section 2 describes the dynamic game and derives the non-cooperative and cooperative strategies, respectively. The effect of possible innovation on players' strategies is analyzed in Section 3. In Section 4, the hazard rate of innovation is endogenized and optimal R&D for innovation is investigated. Concluding remarks and their policy implications are summarized in the final section.

2 The dynamic game

2.1 Model setup

As in Wirl (1995), Tahvonen (1994, 1996, 1997), Rubio and Escriche (2001) and Liski and Tahvonen (2004), there are two players in the dynamic game of strategic interactions: a consumers' coalition (such as an empowered International Energy Agency), which maximizes the net present value of consumers' welfare by choosing a carbon tax, $\tau(t)$; and an energy producers' cartel (such as OPEC), which maximizes the net present value of profits by setting the wellhead energy price (i.e., producer price),

$p(t)$.[1] Consequently, the consumer price at time t would be $\pi(t) = p(t) + \tau(t)$, which will determine the (non-negative) consumption of fossil energy (measured in emissions) $D(t) = a - b\pi(t)$, where $a > 0$ and $b > 0$ are constants.[2]

The concentration of CO_2 in the atmosphere depends on the consumption of fossil fuels. As in many other studies, such as Hoel (1993), Wirl (1994), Wirl and Dockner (1995), Tahvonen (1996, 1997), and Rubio and Escriche (2001), this paper assumes that the natural depreciation rate of CO_2 in the atmosphere is zero, so that emissions are irreversible (in this respect, the cumulative resource extraction is used as a proxy of CO_2 concentration):[3]

$$\dot{S}(t) = \underbrace{a - b(\underbrace{p(t) + \tau(t)}_{\pi(t)})}_{D(t)}, S(0) = S_0 \geq 0. \quad (1)$$

As one can see, the dynamics of CO_2 concentration will be affected by both the carbon taxation from the consumer side and the (wellhead) energy pricing from the producer side.

Now let us consider the possibility that a carbon-free energy technology which is a perfect substitute for fossil fuels can be invented or discovered at some time in the future. After the innovation or discovery, the new technology can be accessed easily at a constant marginal cost p_N. As in Harris and Vickers (1995), it is assumed that the cost (price) of the new technology is lower than that of the fossil energy such that

[1]Oil is more important today but coal is much more abundant and hence constitutes a larger potential threat to the climate (Hassler and Krusell, 2012). However, compared with the oil market, there is probably less market power in the coal market. More specifically, coal can be produced in ample quantities in 50 different countries (Banks, 2000), but the major coal exporters are Australia, Indonesia and Russia (in total, these account for more than 60% of the total coal exports (EIA, 2012)). This implies that there is still probably some market power in the coal market, though it is not as strong as that in the oil market.

[2]As in Wirl (1995, 2007), and Rubio and Escriche (2001), we use a linear demand function which will result in a quadratic expression for consumers' welfare, thereby setting up the game in a linear-quadratic form which can be solved analytically.

[3]As in Hoel (1993), Wirl (1994), Wirl and Dockner (1995), Tahvonen (1996, 1997), and Rubio and Escriche (2001), this assumption will simplify the the analysis and make it analytically tractable by reducing two state variables (cumulative resource extractions and CO_2 stock) to one state variable. With a positive decay, the decision rules would depend on both CO2 stock and cumulative resource extraction in a nontrivial way. See Wirl (1995) and Tahvonen (1996) for discussions on the case if two state variables are considered.

there will be no demand for (or production of) fossil fuels as soon as the innovation in this new technology is made. However, the time of innovation (denoted as t_I) is uncertain. Denote the probability that the new technology has been invented by time t as $Prob(t_I < t) = H(t)$. Assume for the moment that the hazard rate of the stochastic process leading to the discovery or innovation of the technology is exogenous:

$$\frac{\dot{H}(t)}{1 - H(t)} = \theta, H(0) = 0. \tag{2}$$

The hazard rate θ can be thought of as the (conditional) probability that the new technology will be innovated at time t, given that this has not happened before time t. Of course, we have $\theta \geq 0$, and $\theta = 0$ would represent the case in which no innovation can happen, i.e., the possibility of innovation is zero. The c.d.f. (cumulative distribution function) and p.d.f (probability density function) of the random variable t_I can be obtained from (2) as $H(t) = 1 - e^{-\theta t}$ and $h(t) = \theta e^{-\theta t}$, respectively. As can be seen, parameter θ affects the probability distribution of the time of innovation. This specification for uncertain arrival time of innovation has been employed widely in previous studies, e.g., Harris and Vickers (1995). After the innovation of the carbon-free technology, there would be no further emissions, thereby making the CO_2 concentration constant. That is, we have:

$$\dot{S}(t) = \begin{cases} a - b(\underbrace{p(t) + \tau(t)}_{\pi(t)}) & if\, t < t_I \\ 0 & if\, t \geq t_I \end{cases}. \tag{3}$$

Taking account of the possible innovation of the new technology, the consumers' coalition wants to maximize the present value of the net consumers' welfare, which consists of consumers' surplus plus carbon tax revenues minus the damage cost of climate change. That is, the consumers' coalition seeks to maximize:

$$\mathbb{E}\left\{ \int_0^{t_I} e^{-rt}[u(p(t) + \tau(t)) + \tau(t)D(p(t) + \tau(t)) - \Omega(S(t))]dt \right. \\ \left. + \int_{t_I}^{\infty} e^{-rt}[u(p_N) - \Omega(S(t))]dt \right\}, \tag{4}$$

subject to (3). r is the discount rate, $u(p(t) + \tau(t)) = u(\pi(t)) = \int_{\pi(t)}^{\pi^c} D(x)dx$ is the consumers' surplus, where π^c is the choke price which makes $D(\pi^c) = 0$. With linear demand, we have $\pi^c = \frac{a}{b}$ and thus $u(p(t)+\tau(t)) = \frac{1}{2}a\pi^c + \frac{1}{2}b[p(t)+\tau(t)]^2 - a[p(t)+\tau(t)]$. The term $\tau D(p(t)+\tau(t))$ in (4) represents the tax revenues, which are reimbursed to the consumers. Since these tax revenues are not taken into account by the consumers' surplus $u(\cdot)$, they are added explicitly in (4). Following previous studies, e.g., Wirl (1995, 2007), and Rubio and Escriche (2001), the external cost of climate change is represented by a quadratic damage function $\Omega(S(t)) = \varepsilon[S(t)]^2$, where $\varepsilon > 0$. The expectation operator $\mathbb{E}\{\cdot\}$ appears in (4) due to uncertainty about the time when the innovation of the new technology will occur (i.e., t_I). As mentioned above, the new technology can be accessed easily at a constant marginal cost p_N (which is lower than that of the fossil fuels) after the occurrence of innovation, which implies that the consumers' surplus at time $t \geq t_I$ would be a constant $\bar{u} = u(p_N) = \frac{1}{2}a\pi^c + \frac{1}{2}b(p_N)^2 - ap_N$. There would be no further fossil energy consumption and no emissions with the new technology, and thus the CO_2 concentration will keep constant after the innovation is made, as indicated in (3). But there will still be environmental damages coming from the previous emission accumulations due to the irreversibility of emissions, as shown in (4).[4]

As in Wirl (1995, 2007) and Rubio and Escriche (2001), we assume that, just as the producers' surplus is neglected by the consumers' coalition, the external cost of climate change is ignored by the energy producer's cartel, which concentrates on maximizing the (expected) present value of its net profits:

$$\mathbb{E}\left\{\int_0^{t_I} e^{-rt}[(p(t) - cS(t))D(p(t)+\tau(t))]dt\right\}, \tag{5}$$

where $c > 0$ is the ratio of marginal extraction cost to cumulative extraction (the marginal extraction cost will increase linearly with the cumulative extraction).[5] Since

[4]As can be seen in (4), we assume that there is no tax on the new (green) technology. However, it should be acknowledged that, in reality, it is also possible to tax green energy in reality. For instance, in Sweden, basically all fuels are taxed based on their energy content. Since this study focuses on carbon emission taxation, i.e., what motivates the tax here is the externality, we simply assume that there would be no tax for green (carbon free) energy since it brings no externality. This will simplify the already quite cumbersome dynamic game.

[5]The increasing marginal extraction cost attempts to capture the fact that, in reality, producers tend to extract the resource fields with lower extraction cost first and then move to the ones with higher cost. The same specification of extraction cost has been extensively used in the literature; see e.g., Ulph and Ulph (1994), Wirl (1995), Farzin (1996), Farzin and Tahvonen (1996), Hoel and Kverndokk (1996), and Rubio and Escriche (2001).

there will be no further demand for fossil fuels after the innovation is made, the producers' cartel will receive zero profit after the innovation time t_I. Again, due to the uncertainty of innovation time, (5) comes with the expectation operator $\mathbb{E}\{\cdot\}$.

As in many other related studies (e.g., Wirl, 1994; Tahvonen, 1994, 1996, 1997; Rubio and Escriche, 2001; Liski and Tahvonen, 2004), the natural resource constraints are ignored, which implies that the cumulative extractions (emissions) are not constrained by the resource in the ground.[6] The strategic interactions between a consumers' coalition and a producers' cartel with possible innovation in a carbon-free technology is thus modeled by a stochastic dynamic game where the time of innovation is uncertain. Since there will be no more fossil energy consumption and carbon taxation after the innovation, the game is essentially ended at a stochastic time t_I when the innovation of the new technology occurs.

2.2 Markov-perfect Nash equilibrium

The stochastic dynamic game developed in Section 2.1 is essentially a piecewise deterministic differential game with two modes (regimes): mode $k = 0$ is active before the innovation of the new technology and mode $k = 1$ becomes active after the new technology is invented (or discovered). After the innovation, the game will stay in mode 1; therefore, there can be at most one switch of mode in the game. The hazard rate of switching is assumed to be exogenous at the moment (i.e., θ is considered as an exogenous parameter in this section and the one that follows) and it will be made endogenous in Section 4.

Compared with an open-loop Nash equilibrium, a Markov-perfect Nash equilibrium would be more interesting in the context of strategic interactions because it provides a subgame perfect equilibrium that is dynamically consistent (Rubio and Escriche, 2001). Moreover, we consider linear Markov strategies to ensure the existence of equilibrium independently of the stock level.[7] Define $W(k, S)$ and $V(k, S)$ as the

[6]As highlighted by Wirl (2007), this assumption emphasizes that the atmosphere as sink instead of the resources in the ground constrains fossil energy use. If fossil fuels were insufficient to raise global temperature significantly, then global warming would not be a serious problem.

[7]As highlighted by Liski and Tahvonen (2004), while there is no reason to rule out nonlinear strategies, the linear strategies are know to be global: their domain of definition extends (or can be extended) to the entire state space. Nonlinear strategies were considered by Wirl (1994) and Wirl and Dockner (1995) in a similar game of strategic interactions but were found less efficient in a Pareto sense.

current value functions for the consumers' coalition and the producers' cartel (respectively) in system mode $k = 0, 1$. The players' Markovian strategies $\tau(k, S)$ and $p(k, S)$ need to satisfy the following Hamilton-Jacobi-Bellman (HJB) equations:

$$
\begin{aligned}
rW(0,S) &= \max_{\{\tau\}} \big\{ u(p(0,S)+\tau) + \tau D(p(0,S)+\tau) - \varepsilon S^2 \\
&\qquad + D(p(0,S)+\tau) W_S(0,S) + \theta[W(1,S) - W(0,S)] \big\}, && (6.1)\\
rW(1,S) &= \bar{u} - \varepsilon S^2, && (6.2)\\
rV(0,S) &= \max_{\{p\}} \{ (p - cS) D(p + \tau(0,S)) \\
&\qquad + D(p+\tau(0,S)) V_S(0,S) + \theta[V(1,S) - V(0,S)] \}, && (6.3)\\
rV(1,S) &= 0, && (6.4)
\end{aligned}
$$

where $W_S(0, S)$ and $V_S(0, S)$ are the first-order derivatives of respective value functions $W(0, S)$ and $V(0, S)$ with respect to the CO_2 concentration level S. HJB equations (6.1) and (6.3) suggest that both players need to take into account the possibility of innovation in the new technology for decision-making if the innovation has not happened yet (system is in mode 0). Equation (6.2) says that the consumers' coalition will receive constant consumers' surplus and suffer from (constant) instantaneous environmental damage after the occurrence of innovation. Since there are no more profits from resource extraction after the innovation, equation (6.4) holds. It should be noticed that the carbon taxation and (wellhead) energy pricing decisions need to be made in mode $k = 0$ only, i.e., before the innovation. Therefore, players' Markovian strategies can be denoted as $\tau(0, S)$ and $p(0, S)$, where 0 indicates that the innovation has not yet happened, i.e., the model system is in mode 0.

From the first-order conditions for the maximization of the right-hand sides of the HJB equations (6.1) and (6.3), one can get the consumers and producers' optimal strategies:

$$\tau(0,S) = -W_S(0,S), \tag{7.1}$$

$$p(0,S) = \frac{1}{2}\left[\pi^c + cS + [W_S(0,S) - V_S(0,S)]\right]. \tag{7.2}$$

Consequently one can obtain the equilibrium consumer price by summing up the carbon tax and energy price:

$$\pi(0, S) = \frac{1}{2}\left[\pi^c + cS - [W_S(0, S) + V_S(0, S)]\right]. \tag{7.3}$$

By incorporating the optimal strategies into the HJB equations, one can then obtain a pair of differential equations for the value functions. More specifically, substitute the optimal strategies (7.1) and (7.2) together with the value functions $W(1, S)$ from (6.2) and $V(1, S)$ from (6.4) into the HJB equations (6.1) and (6.3) and eliminate the maximization. After some calculations, one can obtain the following differential equations:

$$(r + \theta)W(0, S) = \frac{1}{8}b[\pi^c - cS + W_S(0, S) + V_S(0, S)]^2 - (1 + \frac{\theta}{r})\varepsilon S^2 + \theta\frac{\bar{u}}{r}, \tag{8.1}$$

$$(r + \theta)V(0, S) = \frac{1}{4}b[\pi^c - cS + W_S(0, S) + V_S(0, S)]^2. \tag{8.2}$$

Due to the linear-quadratic structure of the game, let us conjecture quadratic forms for the value functions $W(0, S)$ and $V(0, S)$. That is:

$$W(0, S) = w_0 + w_1 S + \frac{1}{2}w_2 S^2,\ V(0, S) = v_0 + v_1 S + \frac{1}{2}v_2 S^2, \tag{9}$$

where w_0, w_1, w_2, v_0, v_1, and v_2 are coefficients to be determined. Substituting (9) into (8.1) and (8.2) and collecting terms, we have:

$$\begin{aligned}(r + \theta)[w_0 + w_1 S + \frac{1}{2}w_2 S^2] = \frac{1}{8}b[\pi^c + w_1 + v_1 + (w_2 + v_2 - c)S]^2 \\ - (1 + \frac{\theta}{r})\varepsilon S^2 + \theta\frac{\bar{u}}{r},\end{aligned} \tag{10.1}$$

$$(r + \theta)[v_0 + v_1 S + \frac{1}{2}v_2 S^2] = \frac{1}{4}b[\pi^c + w_1 + v_1 + (w_2 + v_2 - c)S]^2. \tag{10.2}$$

Equating the coefficients of 1, S and S^2 on the two sides of (10.1) and (10.2) leads to a system of 6 equations. Solving the equation system for w_i and v_i, $i = 0, 1, 2$ (one trick is to define new variables $z = w_2 + v_2$, $x = w_1 + v_1$), one can obtain the coefficients for the value functions $W(0,S)$ and $V(0,S)$, as shown in Table 1, where

$$z = w_2 + v_2 = c + \frac{2}{3b}\left(r+\theta - \sqrt{(r+\theta)^2 + 3(r+\theta)bc + 6b\varepsilon(1+\tfrac{\theta}{r})}\right), \tag{11.1}$$

$$x = w_1 + v_1 = \frac{4(r+\theta)\pi^c}{4(r+\theta)+3b(c-z)} - \pi^c, \tag{11.2}$$

and one can verify that $c - z > 0$ and $x < 0$.[8]

Based on the value functions (9) and their coefficients in Table 1, one can obtain the equilibrium strategies of the consumers' coalition and the producers' cartel as functions of model parameters and CO_2 concentration level by substituting the value functions (9) into the equilibrium strategies (7.1) and (7.2):

$$\tau(0,S) = -w_1 - w_2 S, \tag{12.1}$$

$$p(0,S) = \frac{1}{2}\left[\pi^c + (w_1 - v_1) + [c + (w_2 - v_2)]S\right], \tag{12.2}$$

where w_1, w_2, v_1 and v_2 are the coefficients of the value functions as in Table 1. The equilibrium consumer price can be obtained by summing up (12.1) and (12.2):

$$\pi(0,S) = \tau(0,S) + p(0,S) = \frac{1}{2}\left[\pi^c - (w_1 + v_1) + [c - (w_2 + v_2)]S\right]. \tag{12.3}$$

Table 1. Coefficients for value functions $W(0,S)$ and $V(0,S)$

$w_0 = \frac{b}{8(r+\theta)}\left[\frac{4(r+\theta)\pi^c}{4(r+\theta)+3b(c-z)}\right]^2 + \frac{\theta\bar{u}}{r(r+\theta)}$	$v_0 = \frac{b}{4(r+\theta)}\left[\frac{4(r+\theta)\pi^c}{4(r+\theta)+3b(c-z)}\right]^2$
$w_1 = \frac{1}{3}\left[\frac{4(r+\theta)\pi^c}{4(r+\theta)+3b(c-z)} - \pi^c\right] = \frac{1}{3}x$	$v_1 = \frac{2}{3}\left[\frac{4(r+\theta)\pi^c}{4(r+\theta)+3b(c-z)} - \pi^c\right] = \frac{2}{3}x$
$w_2 = \frac{1}{3}\left[z - \frac{4\varepsilon}{r}\right]$	$v_2 = \frac{2}{3}\left[z + \frac{2\varepsilon}{r}\right]$

Plugging (12.3) into the differential equation (1) and solving the equation, one can

[8]The procedure for calculating the coefficients is similar to the one that is used by Wirl and Dockner (1995) and Rubio and Escriche (2001). Therefore, the detailed procedure is omitted. Complete computation is available upon request.

find the temporal trajectory for CO_2 concentration before the innovation:

$$S(t) = S_\infty + (S_0 - S_\infty) \exp\left\{-\frac{1}{2}b(c-z)t\right\} \quad if\, t < t_I, \tag{13}$$

where S_0 is the initial CO_2 concentration (cumulative emissions) and S_∞ is the long-run CO_2 concentration equilibrium or steady state for system mode 0, (i.e., before the innovation), which can be further calculated as:

$$S_\infty = \frac{x + \pi^c}{c - z} = \frac{r\pi^c}{rc + 2\varepsilon}, \tag{14}$$

where (11.1) and (11.2) are used for the last equality in (14). It can be seen that the long-run CO_2 concentration equilibrium S_∞ is independent of θ, which implies that the CO_2 concentration with the possibility of technological innovation (which has not happened yet) would tend to approach the same long-run equilibrium CO_2 concentration as in the case where no innovation can happen (i.e., $\theta = 0$).[9] Due to the assumption of irreversible emissions, it is reasonable to have $S_0 < S_\infty$. Therefore, it can be seen from (13) that the CO_2 concentration (cumulative emissions) before the occurrence of innovation (in mode 0) will increase monotonically toward the long-run equilibrium level S_∞ (recall $c - z > 0$).

Plugging (13) into the equilibrium strategies (12.1)-(12.3), one can obtain the temporal trajectories of carbon tax, producer price and consumer price (before the occurrence of innovation, i.e., in mode 0) after some calculations[10]:

$$\tau(0,t) = \frac{2\pi^c\varepsilon}{rc + 2\varepsilon} - w_2(S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}, \tag{15.1}$$

$$p(0,t) = \frac{c\pi^c r}{rc + 2\varepsilon} + \frac{1}{2}(c + w_2 - v_2)(S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}, \tag{15.2}$$

$$\pi(0,t) = \pi^c + \frac{1}{2}(c - z)(S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}. \tag{15.3}$$

It can be observed from these equations that, if the innovation has not yet happened, the equilibrium strategies of carbon taxation and (wellhead) energy pricing would follow the paths toward long-run equilibria that are characterized by $\tau_\infty =$

[9] This is due to the fact that, as time goes to infinity, the uncertainty of innovation tends to vanish.

[10] The calculations are omitted here to save space. Complete computation is available upon request.

$\dfrac{2\pi^c\varepsilon}{rc+2\varepsilon}$ and $p_\infty = \dfrac{c\pi^c r}{rc+2\varepsilon}$, respectively. The equilibrium consumer price will approach the choke price π^c in the long run, i.e., $\pi_\infty = \pi^c$. Moreover, it is noticeable that the long-run equilibria τ_∞, p_∞, and π_∞ are independent of the hazard rate of innovation θ. This implies that, with the possibility of technological innovation (that has not happened yet), the long-run equilibrium carbon tax, (producer) energy price, and consumer price would be the same as those in the case without the possibility of innovation ($\theta = 0$). It can also be observed from (15.3) that the equilibrium consumer price would increase monotonically over time (recall $c - z > 0$ and $S_0 < S_\infty$). However, how the carbon tax and producer price would evolve over time is still ambiguous. To see this, recall $w_2 = \frac{1}{3}[z - \frac{4\varepsilon}{r}]$ and $v_2 = \frac{2}{3}[z + \frac{2\varepsilon}{r}]$, where we have $z = c + \frac{2}{3b}\big(r + \theta - \sqrt{(r+\theta)^2 + 3bc(r+\theta) + 6b\varepsilon(1+\frac{\theta}{r})}\big)$ (see (11.1)). By varying values of c and ε, we could make w_2 either negative or positive. Similarly, the sign of $c + w_2 - v_2$ will also depend on the relative magnitude of c and ε (keeping other parameters constant). This implies that the slopes of temporal trajectories of carbon tax and producer price are ambiguous. However, since the consumer price is increasing, we know that at least one of the two (carbon tax or producer price) needs to be increasing over time. That is, only three cases are possible: (i) increasing carbon tax and decreasing producer price; (ii) decreasing carbon tax and increasing producer price; (iii) both the carbon tax and producer price are increasing. An economic interpretation can be stated in terms of whether the increase in extraction cost dominates the increase in environmental damages, or the other way around (Wirl 1995; Rubio and Escriche, 2001). For instance, if the environmental damage is high enough, we will have increasing carbon tax and decreasing producer/wellhead price (it can be verified that $w_2 \to -\infty$ and $c + w_2 - v_2 \to -\infty$ if $\varepsilon \to +\infty$, where it should be kept in mind that the order of infinity will be lowered by a square root).

2.3 Cooperative strategies

The Markov-perfect Nash equilibrium obtained above is based on the assumption that the two players have conflicting objectives: the consumers' coalition cares about the consumers' welfare and damage from climate change, while the producers' cartel cares only about the profits from resource extraction. In this section, the cooperative solution for the dynamic game, i.e., the global efficient strategy, will be calculated and investigated. As stated by Wirl (1995), this efficient strategy can serve as the benchmark and provide more insights into the strategic interaction issues by comparing the global efficient solution with the non-cooperative solution (Markov-perfect Nash equilibrium).

It should be noticed that, in the cooperative case, the consumers' welfare and the producers' profits need to be added together to account for global welfare. That is:

$$\mathbb{E}\left\{\int_0^{t_I} e^{-rt}[u(p(t)+\tau(t))+(p(t)+\tau(t)-cS(t))D(p(t)+\tau(t))-\Omega(S(t))]dt \right. \\ \left. + \int_{t_I}^{\infty} e^{-rt}[u(p_N)-\Omega(S(t))]dt\right\}. \tag{16}$$

In the cooperative case, the maximization of global welfare (16) is by definition the same for the consumers' coalition and the producers' cartel, so that the split of the consumer price π into a producer price p and the carbon tax τ is indefinite, with the result that the final consumer price π become the only decision variable in the maximization of (16) (i.e., $p(t)+\tau(t)$ can be replaced by $\pi(t)$ in (16)). That is, the cooperative case degenerates to a maximization problem and the global planner seeks to maximize:

$$\mathbb{E}\left\{\int_0^{t_I} e^{-rt}[u(\pi(t))+(\pi(t)-cS(t))D(\pi(t))-\Omega(S(t))]dt \right. \\ \left. + \int_{t_I}^{\infty} e^{-rt}[u(p_N)-\Omega(S(t))]dt\right\}. \tag{17}$$

Similar to the non-cooperative case in Section 2.2, define $M(k,S)$ as the current value functions for the global planner in system mode k. Then the global efficient/optimal strategy needs to satisfy the following HJB equations:

$$rM(0,S) = \max_{\{\pi\}}\left\{u(\pi)+(\pi-cS)D(\pi)-\varepsilon S^2+D(\pi)M_S(0,S) \right. \\ \left. +\theta[M(1,S)-M(0,S)]\right\}, \tag{18.1}$$

$$rM(1,S) = \bar{u}-\varepsilon S^2, \tag{18.2}$$

where $M_S(0,S)$ is the first-order derivative of value function $M(0,S)$ with respect to the CO_2 concentration S.

The first-order condition for the maximization of the right-hand sides of the HJB equations (18.1) gives the global efficient strategy:

$$\pi^G(0,S) = -M_S(0,S) + cS. \tag{19}$$

Substitute the optimal strategy (19) and the value functions $M(1,S)$ from (18.2) into the HJB equations (18.1), eliminate the maximization, and, after some calculations, we have

$$(r+\theta)M(0,S) = \frac{1}{2}b[\pi^c - cS + M_S(0,S)]^2 - (1+\frac{\theta}{r})\varepsilon S^2 + \theta\frac{\bar{u}}{r}. \tag{20}$$

Again, let us conjecture a quadratic form for the value function

$$M(0,S) = m_0 + m_1 S + \frac{1}{2}m_2 S^2, \tag{21}$$

where m_0, m_1, and m_2 are coefficients that need to be determined. Substituting (21) into (20) and collecting terms, we have:

$$(r+\theta)[m_0 + m_1 S + \frac{1}{2}m_2 S^2] = \frac{1}{2}b\left[\pi^c + m_1 + (m_2 - c)S\right]^2 - (1+\frac{\theta}{r})\varepsilon S^2 + \theta\frac{\bar{u}}{r}. \tag{22}$$

Equating the coefficients of 1, S, and S^2 on the two sides of (22) and solving for m_0, m_1, and m_2, one can obtain the coefficients for the value function $M(0,S)$, as shown in Table 2.[11] It can be verified that $c - m_2 > 0$.

Substituting the value functions (21) with the calculated coefficients, one can obtain the global efficient strategy as a function of model parameters and CO_2 concentration level:

$$\pi^G(0,S) = (c - m_2)S - m_1, \tag{23}$$

where m_1 and m_2 are the coefficients of the value functions, as in Table 2. Plugging (23) into the differential equation (1) and solving the equation, one can get the explicit solution:

$$S^G(t) = S^G_\infty + (S_0 - S^G_\infty)\exp\{-b(c-m_2)t\} \quad if\, t < t_I, \tag{24}$$

where S_0 is the initial CO_2 concentration (cumulative emissions) and $S^G_\infty = \dfrac{\pi^c + m_1}{c - m_2} =$

[11] We have omitted the detailed calculations. They are available from the author upon request.

$\dfrac{r\pi^c}{rc+2\varepsilon}$ is the long-run CO_2 concentration equilibrium or steady state for system mode 0, i.e., before the innovation.

Table 2. Coefficients for value function $M(0,S)$

$$m_0 = \frac{b}{2(r+\theta)}\left[\frac{(r+\theta)\pi^c}{(r+\theta)+b(c-m_2)}\right]^2 + \frac{\theta\bar{u}}{r(r+\theta)}$$
$$m_1 = \frac{(r+\theta)\pi^c}{(r+\theta)+b(c-m_2)} - \pi^c$$
$$m_2 = c + \frac{1}{2b}\left(r+\theta-\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\tfrac{\theta}{r})}\right)$$

It can be noticed that the long-run CO_2 concentration equilibrium in the cooperative case is the same as that in the non-cooperative case, i.e., $S_\infty^G = S_\infty$. Similar to the non-cooperative case, the long-run CO_2 concentration S_∞^G is also independent of θ, the hazard rate of innovation. Besides, one can see from (24) that the CO_2 concentration under the global efficient strategy will also increase monotonically before the occurrence of innovation (in mode 0) toward the long-run equilibrium level S_∞^G (recall $c - m_2 > 0$).

Plugging (24) into (23), one can obtain the temporal trajectory of the global efficient strategy (before the occurrence of innovation, i.e., in mode 0) after some calculations:

$$\pi^G(0,t) = \pi^c + (c-m_2)(S_0 - S_\infty^G)\exp\{-b(c-m_2)t\}. \tag{25}$$

It can also be observed from (25) that the equilibrium consumer price in the cooperative case would also increase monotonically over time (because $c - m_2 > 0$ and $S_0 < S_\infty^G$).

2.4 Comparison of the cooperative and non-cooperative solutions

While the global efficient strategy serves as a benchmark or first-best solution for the global warming problem, the non-cooperative solution reflects the effect of strategic interactions between the consumers' coalition and the producers' cartel. Therefore, it would be of interest to compare the cooperative and non-cooperative solutions. Specifically, by comparing the consumer price in the cooperative case with that in the non-cooperative case, one can find the result summarized in Proposition 1

Proposition 1 *The consumer price in the global efficient solution has a lower initial value than that in the Markov-perfect Nash equilibrium.*

Proof. Recall from (15.3) and (25) that the temporal trajectories of consumer prices in the cooperative and non-cooperative cases are, respectively:

$$\pi^G(0,t) = \pi^c + (c - m_2)(S_0 - S_\infty^G)\exp\{-b(c-m_2)t\},$$
$$\pi(0,t) = \pi^c + \frac{1}{2}(c-z)(S_0 - S_\infty)\exp\{-\frac{1}{2}b(c-z)t\}.$$

Note that the initial consumer prices in the two cases are, respectively:

$$\pi^G(0,0) = \pi^c + (c - m_2)(S_0 - S_\infty^G),$$
$$\pi(0,0) = \pi^c + \frac{1}{2}(c-z)(S_0 - S_\infty),$$

where we have (from (11.1) and Table 2)

$$\frac{1}{2}(c-z) = -\frac{1}{3b}\left(r + \theta - \sqrt{(r+\theta)^2 + 3bc(r+\theta) + 6b\varepsilon(1+\tfrac{\theta}{r})}\right),$$
$$c - m_2 = -\frac{1}{2b}\left(r + \theta - \sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1+\tfrac{\theta}{r})}\right).$$

As mentioned before, both $\frac{1}{2}(c-z)$ and $c - m_2$ are positive. If we can know the sign of $(c-m_2) - \frac{1}{2}(c-z)$, we can say something about the comparison of initial consumer prices in the cooperative and non-cooperative cases. Since we have

$$(c-m_2) - \frac{1}{2}(c-z) = -\frac{1}{6b}(r+\theta) + \frac{1}{2b}\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1+\tfrac{\theta}{r})}$$
$$- \frac{1}{3b}\sqrt{(r+\theta)^2 + 3bc(r+\theta) + 6b\varepsilon(1+\tfrac{\theta}{r})}$$

and we know $\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1+\frac{\theta}{r})} > \sqrt{(r+\theta)^2 + 3bc(r+\theta) + 6b\varepsilon(1+\frac{\theta}{r})}$, this implies $(c-m_2) - \frac{1}{2}(c-z) > -\frac{1}{6b}(r+\theta) + \frac{1}{6b}\sqrt{(r+\theta)^2 + 3bc(r+\theta) + 6b\varepsilon(1+\frac{\theta}{r})} > 0$. Therefore, we have: $\pi^G(0,0) < \pi(0,0)$, i.e., the initial consumer price is lower for the cooperative case. ■

This implies that the strategic interaction or rent contest between the consumers' coalition and the producers' cartel will decrease the initial fossil fuel consumption, compared with the case when they are cooperating with each other. This is consistent with the numerical results in Wirl (1995). As Wirl (1995) highlighted, this confirms the usual property that the monopolist is the conservationist's best friend. This result implies that, if we had a social planner, we would be emitting more than markets would do in the short term. However, it should be noticed that consumer prices in both the competitive and cooperative cases will approach the same steady level π^c in system mode $k = 0$, as indicated by (15.3) and (25).

3 The effect of possible innovation

Based on the game's cooperative and non-cooperative solutions obtained above, one can analyze the effect of possible innovation on both solutions by comparing the case with a positive θ (with possible innovation) and the case of $\theta = 0$ (with no innovation). It should be noticed that, because the dynamic game is essentially ended after the innovation, the analysis will concentrate on the effect of possible innovation in system mode $k = 0$, in which the innovation has not yet happened but the players expect that it can happen sometime in the future.

3.1 Effect of possible innovation on the Markov-perfect Nash equilibrium

To see the effect of possible innovation on the non-cooperative strategies, let us take the derivatives of (15.1)-(15.3) with respect to the hazard rate of innovation θ. After some calculations, one can obtain:

$$\frac{\partial \tau(0,t)}{\partial \theta} = -\frac{1}{6}\frac{\partial z}{\partial \theta}(2 + 3bw_2 t)(S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}, \tag{26.1}$$

$$\frac{\partial p(0,t)}{\partial \theta} = -\frac{1}{12}\frac{\partial z}{\partial \theta}\left[2 - 3b(c + w_2 - v_2)t\right](S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}, \tag{26.2}$$

$$\frac{\partial \pi(0,t)}{\partial \theta} = -\frac{1}{4}\frac{\partial z}{\partial \theta}[2 - b(c-z)t](S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}. \tag{26.3}$$

First, let us find out how the possible innovation will affect the initial carbon tax, producer price and consumer price. The results are summarized in the following proposition.

Proposition 2 *The possible innovation of the new technology will lead to both a lower initial carbon tax and a lower initial producer price.*

Proof. By substituting $t = 0$ into (26.1)-(26.3), one can obtain the marginal effect of innovation hazard rate on the initial values of carbon tax, fuel price, and consumer price:

$$\frac{\partial \tau(0,0)}{\partial \theta} = -\frac{1}{3}\frac{\partial z}{\partial \theta}(S_0 - S_\infty), \tag{27.1}$$

$$\frac{\partial p(0,0)}{\partial \theta} = -\frac{1}{6}\frac{\partial z}{\partial \theta}(S_0 - S_\infty), \tag{27.2}$$

$$\frac{\partial \pi(0,0)}{\partial \theta} = -\frac{1}{2}\frac{\partial z}{\partial \theta}(S_0 - S_\infty). \tag{27.3}$$

Since $S_0 < S_\infty$, one can identify the signs of (27.1)-(27.3) if the sign of $\frac{\partial z}{\partial \theta}$ is known. We show in Appendix A1 that $\frac{\partial z}{\partial \theta} < 0$ for all $\theta \geq 0$. Thus, we have $\frac{\partial \tau(0,0)}{\partial \theta} < 0$, $\frac{\partial p(0,0)}{\partial \theta} < 0$, and $\frac{\partial \pi(0,0)}{\partial \theta} < 0$, which implies $\tau(0,0)|_{\theta>0} < \tau(0,0)|_{\theta=0}$, $p(0,0)|_{\theta>0} < p(0,0)|_{\theta=0}$ and $\pi(0,0)|_{\theta>0} < \pi(0,0)|_{\theta=0}$. That is, the anticipation of possible innovation will lower the initial carbon taxation, fuel price, and consumer price. ■

This result suggests that the possibility of innovation will stimulate a higher initial demand for fossil fuels, and thus higher initial emissions. With the expectation that the innovation of a carbon-free technology can happen and will relieve the concerns about environmental damage, the consumers' coalition lowers the initial carbon tax. Being aware that innovation would lead to zero demand for fossil energy, the producers' cartel also would like to lower the initial (wellhead) energy price to stimulate the consumption of fossil fuels. Consequently, the initial consumer price is lower as a result of the reduced carbon tax and producer price, and this leads to a higher initial demand for fossil fuels and higher initial CO_2 emissions.

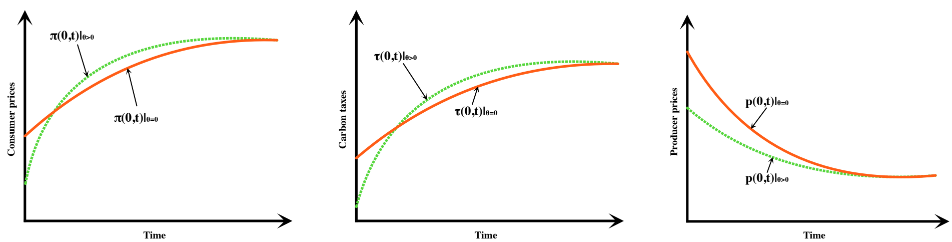
As can be seen in (15.1)-(15.3), due to the uncertainty about the time of innovation, a positive probability of innovation ($\theta > 0$) will not change the long-run equilibrium of carbon tax, producer price and consumer price before the innovation (i.e., in system mode $k = 0$). However, the possible innovation will affect the transitional dynamics of these variables in addition to their initial values. The results are summarized in the following proposition.

Proposition 3 *Looking at our model before a possible innovation, we have the following statements: (i) The possibility of innovation will first lower and later raise the consumer price; (ii) If environmental damage is sufficiently high, the carbon tax will be first lowered, but later raised by the possibility of innovation; (iii) The producer price will always be lowered by the possibility of innovation, if the environmental damage is high enough.*

Proof. Recall from (26.3) that the derivative of consumer price (in mode 0) w.r.t. the hazard rate of innovation is calculated as:

$$\frac{\partial \pi(0,t)}{\partial \theta} = -\frac{1}{4}\frac{\partial z}{\partial \theta}[2 - b(c-z)t](S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}.$$

It has been shown in Proposition 2 that, for $t = 0$, the effect of innovation possibility on the consumer price (i.e.,$\frac{\partial \pi(0,0)}{\partial \theta}$) is negative. For $t \neq 0$, since $c - z > 0$, we can find a $t^* > 0$ to make $2 - b(c-z)t^* = 0$. Recall that $\frac{\partial z}{\partial \theta} < 0$ (see Appendix A1), and thus we have $\frac{\partial \pi(0,t)}{\partial \theta} < 0$ for $0 \leq t < t^*$ and $\frac{\partial \pi(0,t)}{\partial \theta} > 0$ for $t > t^*$. This implies that, for $0 \leq t < t^*$, the consumer price with the expectation of possible innovation would be lower than that in the case without such an expectation (i.e., $\pi(0,t)|_{\theta>0} < \pi(0,t)|_{\theta=0}$) , whereas for $t > t^*$ the relationship is the contrary. Figure 1(a) illustrates this result.



a. Consumer price b. Carbon tax c. Producer price

Figure 1. Effect of possible innovation on the temporary trajectories of carbon tax and energy prices

Similarly, for the carbon tax, we have from (26.1) that:

$$\frac{\partial \tau(0,t)}{\partial \theta} = -\frac{1}{6}\frac{\partial z}{\partial \theta}(2 + 3w_2bt)(S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}.$$

Because $\frac{\partial z}{\partial \varepsilon} = \frac{-2(1+\frac{\theta}{r})}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}} < 0$ and $w_2 = \frac{1}{3}\left[z - \frac{4\varepsilon}{r}\right]$, we have $\frac{\partial w_2}{\partial \varepsilon} = \frac{1}{3}[\frac{\partial z}{\partial \varepsilon} - \frac{4}{r}] < 0$. Besides, it can be found that $z \to -\infty$, thus $w_2 \to -\infty$ if $\varepsilon \to +\infty$. That is, if the environmental damage ε is high enough, we have $w_2 < 0$, which implies that we can find a $t^{**} > 0$ which satisfies $2 + 3w_2bt^{**} = 0$. Thus we have $\frac{\partial \tau(0,t)}{\partial \theta} < 0$ for $0 \leq t < t^{**}$ and $\frac{\partial \tau(0,t)}{\partial \theta} > 0$ for $t > t^{**}$, which implies $\tau(0,t)|_{\theta>0} < \tau(0,t)|_{\theta=0}$ for $0 \leq t < t^{**}$ and $\tau(0,t)|_{\theta>0} > \tau(0,t)|_{\theta=0}$ for $t > t^{**}$. Therefore, if the environmental damage is high enough, the carbon tax with possible innovation will be first below, but later above, the carbon tax in the case with no innovation, as illustrated in Figure 1(b).

As for the producer price, we have from (26.2) that:

$$\frac{\partial p(0,t)}{\partial \theta} = -\frac{1}{12}\frac{\partial z}{\partial \theta}\left[2 - 3b(c + w_2 - v_2)t\right](S_0 - S_\infty)\exp\left\{-\frac{1}{2}b(c-z)t\right\}.$$

Recall from Table 1 that $w_2 - v_2 = -\frac{1}{3}[z + \frac{8\varepsilon}{r}]$. If $\varepsilon \to +\infty$, we have $z \to -\infty$ and $\frac{8\varepsilon}{r} \to +\infty$. However, the order of infinity is lower for z because of the square root. Therefore, we have $z + \frac{8\varepsilon}{r} \to +\infty$, and thus $w_2 - v_2 \to -\infty$, if $\varepsilon \to +\infty$. In other words, if the environmental damage ε is high enough, we can have $c + w_2 - v_2 < 0$, which implies that we will have $[2 - 3b(c + w_2 - v_2)t] > 0$ and thus $\frac{\partial p(0,t)}{\partial \theta} < 0$ for all $t \geq 0$. That is, if the environmental damage is high enough, the producer price with the expectation of possible innovation will be lower than that in the case without such an expectation (i.e., $p(0,t)|_{\theta>0} < p(0,t)|_{\theta=0}$) before the producer prices for the two cases converge to the same long-run equilibrium (recall p_∞ is independent of the hazard rate of innovation θ). Figure 1(c) provides an illustration. ■

These results reflect the fact that the CO_2 concentration in both cases (the pre-innovation regime in the case with possible innovation and the case with no innovation) will converge to the same long-run equilibrium level, which implies that the total amount of fossil energy consumed in both cases is the same and the area under the temporal path of fossil energy demand should also be the same. This, in turn, implies that the area under the temporal path of the consumer price (which determines the fossil energy demand) would be the same for both cases as well. Since we have shown in Proposition 2 that the initial consumer price will be lower with the possible innovation (compared with the case of no innovation), the temporal paths of the consumer price in the two cases need to intersect to get the same area under the temporal path. The monotonic property of consumer price implies that the paths in the two cases intersect only once.

As mentioned in Section 2, with strategic interactions between energy consumers and producers, the carbon tax will be increasing over time and the (wellhead) fuel price will be decreasing if the environmental damage is sufficiently high. Given that the consumer price is always increasing over time, the proportion of (wellhead) fuel price in the consumer price will be decreasing if the damage is high enough, which implies that, if the environmental damage is sufficiently high, the temporal trajectory of consumer price will depend mainly on that of the carbon tax. Therefore, the temporal paths of the carbon taxes need to intersect such that the temporal paths of the consumer price can intersect. Since the initial carbon tax is lower for the case with possible innovation than the case without, as shown in Proposition 2, we will see that the carbon tax with the expectation of possible innovation would be first below, but later above, the carbon tax without such an expectation. The intersection of the temporary paths for carbon taxes and the decreasing proportion of producer price in the consumer price can leave room for the (wellhead) fuel price in the two cases (with and without possible innovation) not to intersect.

It should be emphasized that Proposition 3 is established based on the underlying assumption that the model system is still in mode 0, i.e., even though the innovation can happen (in the case of $\theta > 0$), it has not happened yet. Since the time of innovation is uncertain, it can happen at any time. If the innovation occurs at some time that is earlier than the critical time t^* or t^{**}, the conclusions in Proposition 3 should be modified accordingly, given that the occurrence of innovation will bring cheap non-polluting technology. For instance, if the innovation time $t_I < t^{**}$, the carbon tax in the case of $\theta > 0$ may never be higher than it is in the case of $\theta = 0$, given that carbon tax will be zero after the innovation.

One of the implications from Proposition 3 is that the fossil fuel demand (thus CO_2 emissions) in the case with possible innovation will be first above, but later below, the demand (and thus emissions) in the case with no innovation. Since the temporal paths of CO_2 concentration (cumulative emissions) in both cases are monotonically increasing over time and have the same initial and long-run equilibrium level (recall that S_∞ is independent of θ), one can expect that the CO_2 concentration level in the case with the expectation of possible innovation will be above the concentration level in the case without such an expectation for any instant of time $t \in (0, t_I)$, as formally demonstrated in the following proposition.

Proposition 4 *For any instant of time $t \in (0, t_I)$, the CO_2 concentration with the expectation of possible innovation is higher than that in the case without such an expectation.*

Proof. Recall that the evolution of CO_2 concentration level (before the occurrence of innovation) along the equilibrium path is characterized by (13):

$$S(t) = S_\infty + (S_0 - S_\infty) \exp\left\{-\frac{1}{2}b(c-z)t\right\} \quad if\, t < t_I,$$

where $S_\infty = \dfrac{r\pi^c}{rc + 2\varepsilon}$ is the long-run equilibrium concentration level (in mode 0). As claimed in Section 2, since S_∞ is independent of the hazard rate of innovation θ, the long-run equilibrium CO_2 concentration level with the possibility of innovation will be the same as that in the case where there is no possibility of innovation.
However, the possible innovation will have an effect on the temporal trajectory of CO_2 concentration (from the initial level) to reach the long-run equilibrium level. To see this, take the derivatives of the $S(t)$ with respect to the hazard rate of innovation θ and one can obtain:

$$\frac{\partial S(t)}{\partial \theta} = (S_0 - S_\infty) \exp\left\{-\frac{1}{2}b(c-z)t\right\} (\frac{1}{2}b\frac{\partial z}{\partial \theta}t) \quad if\, t < t_I.$$

Given $S_0 < S_\infty$ and the negative sign of $\frac{\partial z}{\partial \theta}$ (see Appendix A1), one can know that $\frac{\partial S(t)}{\partial \theta} > 0$ will hold for any instant of time $t \in (0, t_I)$, which implies $S(t)|_{\theta>0} > S(t)|_{\theta=0}$ for $t \in (0, t_I)$. That is, for $t \in (0, t_I)$, the CO_2 concentration in the case with possible innovation will be higher than that in the case with no innovation. ■

This result suggests that the expectation of possible innovation will lead to a higher transitional CO_2 concentration before the innovation, which reflects the fact that the fossil fuel demand in early days is higher in the case with possible innovation, compared with the case with no innovation. In this respect, the possible innovation plays a role similar to that of a larger discount rate in the consumption of fossil fuels: consume more in the early days and less in the latter days.

3.2 Effect of possible innovation on the global efficient strategy

In addition to the effect of possible innovation on the non-cooperative solution, one would also like to see the effect of innovation in the case of cooperation between the two players. To see this, one can calculate the derivatives of global efficient strategy (25) with respect to the hazard rate of innovation θ as:

$$\frac{\partial \pi^G(0,t)}{\partial \theta} = -\frac{\partial m_2}{\partial \theta}[1 - b(c - m_2)t](S_0 - S_\infty)\exp\{-b(c - m_2)t\}, \tag{28.1}$$

where we made use of the fact that $S_\infty^G = S_\infty$. For $t = 0$, we have

$$\frac{\partial \pi^G(0,0)}{\partial \theta} = -\frac{\partial m_2}{\partial \theta}(S_0 - S_\infty). \tag{28.2}$$

In Appendix B1, we show that $\frac{\partial m_2}{\partial \theta} < 0$ for all $\theta \geq 0$. Therefore, given $S_0 < S_\infty$, we have $\frac{\partial \pi^G(0,0)}{\partial \theta} < 0$ for $\theta \geq 0$, which implies that $\pi^G(0,0)|_{\theta>0} < \pi^G(0,0)|_{\theta=0}$. That is, a positive probability of innovation will lower the initial consumer price in the global efficient solution as well, which is consistent with the effect of innovation in the Markov-perfect Nash equilibrium summarized in Proposition 2.

For $t \neq 0$, since $c - m_2 > 0$, similar arguments as in Proposition 3 can be applied here. That is, we can find a $t^{***} > 0$ to make $1 - b(c - m_2)t^{***} = 0$. Recall that $\frac{\partial m_2}{\partial \theta} < 0$ (see Appendix B1), and thus we have $\frac{\partial \pi^G(0,t)}{\partial \theta} < 0$ for $0 \leq t < t^{***}$ and $\frac{\partial \pi^G(0,t)}{\partial \theta} > 0$ for $t > t^{***}$, which implies that, similar to the non-cooperative solution, the consumer price in the cooperative solution would also be lower with possible innovation (that has not happened yet) than in the case with no innovation (i.e., $\pi^G(0,t)|_{\theta>0} < \pi^G(0,t)|_{\theta=0}$) for $0 \leq t < t^{***}$, whereas the relationship is the contrary for $t \geq t^{***}$.

As for the effect of innovation on the dynamics of CO_2 concentration in the cooperative case, since we have: $S^G(t) = S_\infty + (S_0 - S_\infty)\exp\{-b(c - m_2)t\}\ \ if\, t < t_I$ (see (24) and note that $S_\infty^G = S_\infty$), we can get:

$$\frac{\partial S^G(t)}{\partial \theta} = (S_0 - S_\infty)\exp\{-b(c - m_2)t\}(b\frac{\partial m_2}{\partial \theta}t) \quad if\, t < t_I. \tag{28.3}$$

Given $S_0 < S_\infty$ and the negative sign of $\frac{\partial m_2}{\partial \theta}$ (see Appendix B1), one can know from (28.3) that $\frac{\partial S^G(t)}{\partial \theta} > 0$ will hold for any $t \in (0, t_I)$, which implies that $S^G(t)|_{\theta>0} > S^G(t)|_{\theta=0}$ will hold for $t \in (0, t_I)$. That is, in the cooperative case, the possibility of innovation will also lead to a higher transitional CO_2 concentration.

Therefore, it can be seen that the effect of possible innovation in the cooperative case is consistent with that in the non-cooperative case. That is, the possibility of innovation will reduce the initial consumer price. And the consumer price with the expectation of possible innovation (that has not happened yet) will first be lower but later higher than the consumer price without the possibility of innovation.

3.3 Comparison of effects in the two cases

The result that the possible innovation will reduce the initial consumer price in both the non-cooperative case and the cooperative case implies that the expectation of possible innovation will stimulate higher near-term fossil fuel consumption, and thus higher near-term CO_2 emissions, no matter whether the fossil-fuel consuming countries compete or cooperate with the producing countries. But will the magnitude of such an effect be different in the two (cooperative and non-cooperative) cases? To investigate this question, some further calculations are necessary.

By comparing (28.2) with (26.3), we have:

$$\frac{\partial \pi^G(0,0)}{\partial \theta} - \frac{\partial \pi(0,0)}{\partial \theta} = \left(\frac{1}{2}\frac{\partial z}{\partial \theta} - \frac{\partial m_2}{\partial \theta} \right)(S_0 - S_\infty), \tag{29}$$

Based on the expressions for $\frac{\partial z}{\partial \theta}$ and $\frac{\partial m_2}{\partial \theta}$, it is not difficult to show that, as $\varepsilon \to +\infty$, we have $\frac{1}{2}\frac{\partial z}{\partial \theta} - \frac{\partial m_2}{\partial \theta} \to \sqrt{\varepsilon} \cdot sign\left(\frac{b}{r\sqrt{2b(1+\frac{\theta}{r})}} - \frac{b}{r\sqrt{6b(1+\frac{\theta}{r})}} \right) \to +\infty$. This implies that, if the environment damage is high enough, we can get $\frac{1}{2}\frac{\partial z}{\partial \theta} - \frac{\partial m_2}{\partial \theta} > 0$, thereby making $\frac{\partial \pi^G(0,0)}{\partial \theta} - \frac{\partial \pi(0,0)}{\partial \theta} < 0$. Together with the above-demonstrated results $\frac{\partial \pi^G(0,0)}{\partial \theta} < 0$ and $\frac{\partial \pi(0,0)}{\partial \theta} < 0$, we know that the decrease in the initial consumer price due to the possible innovation is greater in the cooperative case, which implies that the increase in the initial fossil fuel consumption (or equivalently, initial CO_2 emissions) as a response to the possible innovation can be more dramatic in the global efficient solution than in the Markov-perfect Nash equilibrium, if the environment damage is sufficiently high.

The increase in the initial emissions due to the possible innovation in cheap carbon-free technology is consistent with the 'green paradox' argument in the literature. That is, some climate policies designed to abate carbon emissions might actually increase the emissions, at least in the short run. The results here suggest that, even though this 'green paradox' effect of possible innovation can be found in both the non-cooperative case and cooperative case, the increase in initial carbon emissions can be less remarkable in the non-cooperative case, i.e., in the presence of strategic interactions of carbon taxation and energy pricing between the energy producer side and the consumer side, provided that the environmental damage of cumulative emissions is sufficiently high. This result indicates that the 'green paradox' effect of possible innovation can be somewhat restrained by the presence of strategic interactions (a rent contest) between resource producers and consumers.

4 Optimal R&D investment

4.1 R&D investment by the consumers

The hazard rate for the innovation of a carbon-free technology to occur at a particular time is exogenously given in the previous sections. In reality, the probability of technology breakthroughs will depend on the R&D efforts of players. Given that the new technology (cheap and clean) will eat the profits of producers, it is reasonable to assume that only the consumer side will make an effort in the R&D of this new technology. Therefore, in this section, the consumers' coalition is allowed to affect the time of innovation by investing in R&D starting from time 0, thereby making the hazard rate of innovation θ a function of the consumer coalition's R&D effort, y. The instantaneous cost of R&D effort is denoted as $C(y)$. To make things simple, let us follow the literature (see, e.g., Bahel, 2011) and assume $\theta(y) \equiv y$ and $C(y) \equiv y^2$. Also, as in Bahel (2011), we assume that the level of R&D effort remains constant (before the innovation happens), thus maintaining the stationarity of random process for innovation.

At time 0, the consumers' coalition will choose the optimal R&D effort to maximize its (expected) welfare, taking into account the cost of R&D efforts:

$$\max_{y \geq 0} \;\; W(0, S_0, y) - \int_0^{+\infty} e^{-rt} [\int_t^{+\infty} h(t_I) dt_I] C(y) dt, \tag{30}$$

where $W(0, S_0, y)$ is the value function for the consumers' coalition (evaluated at initial CO_2 concentration $S(0) = S_0$) obtained in Section 2.2, which is a function of the hazard rate of innovation θ and thus a function of the R&D effort y (since $\theta \equiv y$), and t_I

is the instant of time at which the innovation is made. Because t_I is random, one needs to consider the probability that the innovation has not been made by a specific instant of time (after the innovation, there is no need to undertake R&D anymore). $\int_t^{+\infty} h(t_I)d_I = 1 - H(t) = e^{-yt}$ is the probability that the innovation has not been made by time t. $\int_0^{+\infty} e^{-rt}[\int_t^{+\infty} h(t_I)dt_I]C(y)dt$ is thus the total expected effort cost for R&D investment (which has been discounted to time $t = 0$). By integration, one can further find that $\int_0^{+\infty} e^{-rt}[\int_t^{+\infty} h(t_I)dt_I]C(y)dt = \dfrac{y^2}{r+y}$.

The first-order condition (interior solution) for the maximization problem (30) is:

$$\frac{\partial W(0, S_0, y)}{\partial y} = \frac{y^2 + 2ry}{(r+y)^2}. \tag{31}$$

The left-hand side of (31) is the marginal benefit of R&D effort and the right-hand side is the marginal cost. It should be noted that the marginal cost of R&D effort at $y = 0$ is equal to zero (i.e., $\left.\frac{y^2+2ry}{(r+y)^2}\right|_{y=0} = 0$). Therefore, if the marginal benefit at $y = 0$ is greater than zero (i.e., $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0} > 0$), one can conclude that (with the satisfied second-order condition), it is worthwhile for the consumers' coalition to exert a positive R&D effort.

Based on the value function for the consumers' coalition (evaluated at the initial concentration level S_0), $W(0, S_0) = w_0 + w_1 S_0 + \frac{1}{2}w_2[S_0]^2$, where w_0, w_1 and w_2 are functions of θ (thus functions of R&D effort y) as in Table 1, we can obtain $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0} = \frac{\partial w_0(y=0)}{\partial y} + \frac{\partial w_1(y=0)}{\partial y} S_0 + \frac{1}{2}\frac{\partial w_2(y=0)}{\partial y}[S_0]^2$. Since $\frac{\partial z(\theta=0)}{\partial \theta} < 0$ (see Appendix A1) and $\frac{\partial x(\theta=0)}{\partial \theta} > 0$ (see Appendix A2), one can make the following judgment based on expressions for w_2 and w_1 in Table 1: $\frac{\partial w_2(y=0)}{\partial y} = \frac{1}{3}\frac{\partial z(y=0)}{\partial y} < 0$ and $\frac{\partial w_1(y=0)}{\partial y} = \frac{1}{3}\frac{\partial x(y=0)}{\partial y} > 0$ (remember that $\theta \equiv y$).

Furthermore, it can be found from the expression for w_0 in Table 1 (making use of $x = \frac{4r\pi^c}{4r+3b(c-z)} - \pi^c$ and $\theta \equiv y$) that:

$$\frac{\partial w_0(y=0)}{\partial y} = \underbrace{-\frac{b}{8r^2}\left[\frac{4r\pi^c}{4r+3b(c-z|_{y=0})}\right]^2}_{<0} \underbrace{+\frac{b}{4r}\left[\frac{4r\pi^c}{4r+3b(c-z|_{y=0})}\right]\frac{\partial x(y=0)}{\partial y}}_{>0} \underbrace{+\frac{\bar{u}}{r^2}}_{>0}$$
$$> -\frac{b}{8r^2}\left[\frac{4r\pi^c}{4r+3b(c-z|_{y=0})}\right]^2 + \frac{\bar{u}}{r^2} > -\frac{b}{8r^2}(\pi^c)^2 + \frac{\bar{u}}{r^2}.$$

Recall that $\bar{u} = \frac{1}{2}a\pi^c + \frac{1}{2}b(p_N)^2 - ap_N$, and we have $\bar{u} \to \frac{1}{2}a\pi^c$ if $p_N \to 0$, which implies that, if $p_N \to 0$, then$-\frac{b}{8r^2}(\pi^c)^2 + \frac{\bar{u}}{r^2} \to -\frac{a}{8r^2}\pi^c + \frac{a}{2r^2}\pi^c = \frac{3a}{8r^2}\pi^c$. Consequently, one knows that $\frac{\partial w_0(y=0)}{\partial y} > 0$ if $p_N \to 0$. That is, if the carbon-free technology is sufficiently cheap, we have $\frac{\partial w_0(y=0)}{\partial y} > 0$. Besides, one can easily verify that $\lim\limits_{y \to +\infty} \frac{\partial z}{\partial y} = 0$ (thus $\lim\limits_{y \to +\infty} \frac{\partial w_2}{\partial y} = 0$), $\lim\limits_{y \to +\infty} \frac{\partial x}{\partial y} = 0$ (thus $\lim\limits_{y \to +\infty} \frac{\partial w_1}{\partial y} = 0$), and $\lim\limits_{y \to +\infty} \frac{\partial w_0}{\partial y} = 0$. This implies that $\lim\limits_{y \to +\infty} \frac{\partial W(0,S_0,y)}{\partial y} = 0$. Based on these calculations, the following proposition can be established and demonstrated.

Proposition 5 *With a sufficiently low price for the new carbon-free technology, it would be in the best interest of the consumers' coalition to exert a positive R&D effort on the new technology for any initial CO_2 concentration $0 \le S_0 < S_\infty$. The optimal R&D effort y^* is an increasing function of the initial CO_2 concentration level: the higher the initial CO_2 concentration level, the greater the optimal R&D effort.*

Proof. As mentioned above, the marginal benefit of R&D effort by the consumers' coalition (evaluated at zero effort) is given by:

$$\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0} = \frac{\partial w_0(y=0)}{\partial y} + \frac{\partial w_1(y=0)}{\partial y} S_0 + \frac{1}{2}\frac{\partial w_2(y=0)}{\partial y}[S_0]^2,$$

where S_0 is the initial CO_2 concentration level.

One can further find that $\frac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0}|_{y=0} = \frac{\partial w_1(y=0)}{\partial y} + \frac{\partial w_2(y=0)}{\partial y} S_0$. It is shown in Appendix A3 that $\frac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0}|_{y=0} > 0$ holds for all $0 \le S_0 < S_\infty$, which implies that $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0}$ is an increasing function of the initial CO_2 concentration levelS_0 for $0 \le S_0 < S_\infty$. It has been shown that, with a sufficiently low price for the new technology, we have $\frac{\partial w_0(y=0)}{\partial y} > 0$. Given that $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0}$ is an increasing function of S_0 for $0 \le S_0 < S_\infty$, we have $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0} \ge \frac{\partial W(0,S_0,y)}{\partial y}|_{y=0,S_0=0} = \frac{\partial w_0(y=0)}{\partial y}$, thereby making $\frac{\partial W(0,S_0,y)}{\partial y}|_{y=0} > 0$ hold for any initial CO_2 concentration $0 \le S_0 < S_\infty$, which implies that, if the price for the new technology is sufficiently low, the marginal benefit of R&D effort evaluated at zero effort would be always positive.

Recall that the marginal cost of R&D effort at $y = 0$ is zero (i.e., $\left.\frac{y^2+2ry}{(r+y)^2}\right|_{y=0} = 0$). Therefore, with a sufficiently low price for the new technology, the marginal benefit of R&D effort is greater than its marginal cost at $y = 0$. However, if $y \to +\infty$, the marginal benefit of R&D effort is lower than the marginal cost (recall that $\lim\limits_{y \to +\infty} \frac{\partial W(0,S_0,y)}{\partial y} = 0$). Therefore, continuity requires that there exists a $y^* > 0$, such that the first order condition (31) holds and the second order condition for maximization is satisfied. This implies that it is in the best interest of the consumers' coalition to exert a positive R&D effort for any initial CO_2 concentration level $0 \leq S_0 < S_\infty$.

It can also be shown that the optimal R&D effort that the consumers' coalition should exert for inventing the new technology is closely related to the initial CO_2 concentration level. More specifically, recall from (31) that the first order condition for optimal R&D effort y^* is $\frac{\partial W(0,S_0,y^*)}{\partial y^*} - \frac{(y^*)^2+2ry^*}{(r+y^*)^2} = 0$, which defines an implicit function $G(S_0, y^*) = 0$. The second-order condition for the maximization of (30) implies that $\frac{\partial^2 W(0,S,y^*)}{\partial^2 y^*} - \frac{2r^2}{(r+y^*)^3} < 0$, i.e., $\frac{\partial G(S_0,y^*)}{\partial y^*} < 0$. Applying the implicit function theorem, we have:

$$\frac{\partial y^*}{\partial S_0} = -\frac{\partial G(S_0, y^*)}{\partial S_0} / \frac{\partial G(S_0, y^*)}{\partial y^*}.$$

It has been demonstrated in Appendix A3 that $\frac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0} > 0$ holds for $0 \leq S_0 < S_\infty$, which implies $\frac{\partial G(S_0,y^*)}{\partial S_0} = \frac{\partial^2 W(0,S_0,y^*)}{\partial y^* \partial S_0} > 0$. Since $\frac{\partial G(S_0,y^*)}{\partial y^*} < 0$ and $\frac{\partial G(S_0,y^*)}{\partial S_0} > 0$, one can know that $\frac{\partial y^*}{\partial S_0} = -\frac{\partial G(S_0,y^*)}{\partial S_0} / \frac{\partial G(S_0,y^*)}{\partial y^*} > 0$, which implies that the optimal R&D effort for the consumers' coalition is an increasing function of the CO_2 concentration level, i.e., the higher the initial CO_2 concentration level, the greater the optimal R&D effort. ■

It is interesting to see that it would be optimal for the consumers to invest in R&D for any CO_2 concentration level. Note that the R&D investment will create an expectation for the new clean technology. It has been shown above that such an expectation will trigger consumers and producers to lower their carbon taxes and prices (respectively) in earlier periods, which leads to higher emissions and greater damages in the near term. However, the consumers still want to conduct R&D, even if the CO_2 concentration is already high. Furthermore, the urgency to invest in R&D for stimulating innovation in the carbon-free technology would be greater if the starting CO_2 concentration level is higher. This reflects the fact that the innovation of the new technology, which creates no emissions, would protect the environment from further CO_2 emissions from fossil fuels.

4.2 Global efficient R&D investment

The optimal R&D by the consumers' coalition only takes into account its own welfare and ignores the producers' profits, which implies that it is not the global efficient R&D

investment. The achievement of global efficient R&D would require a global planner rather than the consumers' coalition to make decisions on R&D investment. Specifically, the global planner will solve the following maximization problem to choose the optimal R&D:

$$\max_{y\geq 0} \quad M(0, S_0, y) - \int_0^{+\infty} e^{-rt}[\int_t^{+\infty} h(t_I)dt_I]C(y)dt, \tag{32}$$

where $M(0, S_0, y)$ is the value function (evaluated at initial CO_2 concentration$S(0) = S_0$) for the global planner (as obtained in Section 2.3), which is a function of hazard rate θ and thus a function of R&D effort y. The first-order condition (interior solution) implies:

$$\frac{\partial M(0, S_0, y)}{\partial y} = \frac{y^2 + 2ry}{(r + y)^2}. \tag{33}$$

Similar to the case when the consumers' coalition is making the R&D decision, if the marginal benefit of R&D at $y = 0$ is greater than zero (i.e., $\frac{\partial M(0,S_0,y)}{\partial y}|_{y=0} > 0$), one can conclude that (with the satisfied second-order condition) a positive R&D effort is worth exerting by the global planner. Given that $M(0, S_0) = w_0 + w_1 S_0 + \frac{1}{2} w_2 [S_0]^2$, where m_0, m_1 and m_2 are functions of θ ($\theta \equiv y$), as in Table 2, we can obtain$\frac{\partial M(0,S_0,y)}{\partial y}|_{y=0} = \frac{\partial m_0(y=0)}{\partial y} + \frac{\partial m_1(y=0)}{\partial y} S_0 + \frac{1}{2} \frac{\partial m_2(y=0)}{\partial y} [S_0]^2$. It has been shown in Appendix B1 and B2 that $\frac{\partial m_2(\theta=0)}{\partial \theta} < 0$and $\frac{\partial m_1(\theta=0)}{\partial \theta} > 0$. Moreover, from the expression for m_0 in Table 2 and after some calculations, we have:

$$\begin{aligned} \frac{\partial m_0(y=0)}{\partial y} &= \underbrace{-\frac{b}{2r^2}\left[\frac{r\pi^c}{r + b(c - m_2|_{y=0})}\right]^2}_{<0} \underbrace{+\frac{b}{r}\left[\frac{r\pi^c}{r + b(c - m_2|_{y=0})}\right]\frac{\partial m_1(y=0)}{\partial y}}_{>0} \underbrace{+\frac{\bar{u}}{r^2}}_{>0} \\ &> -\frac{b}{2r^2}\left[\frac{r\pi^c}{r + b(c - m_2|_{y=0})}\right]^2 + \frac{\bar{u}}{r^2} > -\frac{b}{2r^2}(\pi^c)^2 + \frac{\bar{u}}{r^2}. \end{aligned}$$

Following similar reasoning to that of $\frac{\partial w_0(y=0)}{\partial y} > 0$ if $p_N \to 0$, one can easily show $\frac{\partial m_0(y=0)}{\partial y} > 0$ if $p_N \to 0$. That is, if the price of the carbon-free technology is sufficiently low, $\frac{\partial m_0(y=0)}{\partial y} > 0$ will hold.

Besides, one can easily verify that $\lim\limits_{y\to+\infty} \frac{\partial m_2}{\partial y} = 0$, $\lim\limits_{y\to+\infty} \frac{\partial m_1}{\partial y} = 0$, and $\lim\limits_{y\to+\infty} \frac{\partial m_0}{\partial y} = 0$, which implies that $\lim\limits_{y\to+\infty} \frac{\partial M(0,S_0,y)}{\partial y} = 0$. Therefore, following a similar procedure as that in the proof of Proposition 5 and making use of the results in Appendix B3, which shows that $\frac{\partial^2 M(0,S_0,y)}{\partial y \partial S_0}|_{y=0} > 0$ holds for all $0 \leq S_0 < S_\infty$, we can show that it is also always optimal for a global planner to invest in R&D, if the price of new technology is sufficiently low, and that the global efficient R&D investment (denoted as y^{**}) is an increasing function of initial CO2 concentration as well.[12]

4.3 Consumers' R&D VS global efficient R&D

We have shown that it is always optimal to choose a positive R&D effort for both the consumers' coalition and a global planner, if the price of the new technology is sufficiently low, and that the optimal R&D efforts for both of them should be larger if the initial CO_2 concentration level is higher. However, it might be of great interest to investigate the relative magnitude of optimal R&D investment in the two cases. That is, how large is the optimal R&D investment for the consumers' coalition compared with the global efficient investment? Recall from (31) and (33) that the marginal cost function of the R&D investment is the same for the two cases. Therefore, we simply need to compare the marginal benefit of R&D investment in the case where the consumers' coalition is making the R&D decision with that in the case where the global planner makes the R&D decision instead. By doing this, the following proposition can be established and demonstrated.

Proposition 6 *If the environmental damage is sufficiently high, the consumers' coalition will tend to over-invest in R&D for the new technology, compared with the global efficient investment.*

Proof. Recall that the marginal benefit of R&D for the consumers' coalition and the global planner are $\frac{\partial W(0,S_0,y)}{\partial y} = \frac{\partial w_0}{\partial y} + \frac{\partial w_1}{\partial y} S_0 + \frac{1}{2}\frac{\partial w_2}{\partial y}[S_0]^2$ and $\frac{\partial M(0,S_0,y)}{\partial y} = \frac{\partial m_0}{\partial y} + \frac{\partial m_1}{\partial y} S_0 + \frac{1}{2}\frac{\partial m_2}{\partial y}[S_0]^2$ (where y is the R&D effort and we have hazard rate of innovation $\theta \equiv y$), respectively. The difference between these two is:

$$\frac{\partial W(0,S_0,y)}{\partial y} - \frac{\partial M(0,S_0,y)}{\partial y} = \left(\frac{\partial w_0}{\partial y} - \frac{\partial w_0}{\partial y}\right) + \left(\frac{\partial w_1}{\partial y} - \frac{\partial m_1}{\partial y}\right) S_0 + \frac{1}{2}\left(\frac{\partial w_2}{\partial y} - \frac{\partial m_2}{\partial y}\right)[S_0]^2.$$

[12] The proof is omitted to save space. The complete demonstration is available from the author upon request.

It is not difficult to show after some calculations[13] that, as $\varepsilon \to +\infty$, we have $\frac{\partial w_0}{\partial y} \to \frac{\bar{u}}{r^2}$, $\frac{\partial m_0}{\partial y} \to \frac{\bar{u}}{r^2}$, $\frac{\partial w_1}{\partial y} \to 0$, $\frac{\partial m_1}{\partial y} \to 0$ and $\frac{\partial w_2}{\partial y} - \frac{\partial m_2}{\partial y} \to \sqrt{\varepsilon} \cdot sign\left(\frac{b}{r\sqrt{2b(1+\frac{y}{r})}} - \frac{2}{3}\frac{b}{r\sqrt{6b(1+\frac{y}{r})}}\right) \to +\infty$. This implies that we have $\frac{\partial W(0,S_0,y)}{\partial y} - \frac{\partial M(0,S_0,y)}{\partial y} \to +\infty$ as $\varepsilon \to +\infty$. That is, if environmental damage ε is sufficiently high, we can have $\frac{\partial W(0,S_0,y)}{\partial y} - \frac{\partial M(0,S_0,y)}{\partial y} > 0$, which implies that the marginal benefit of R&D for the consumers' coalition will be larger than that for the global planner. Based on the first-order conditions (31) and (33), it can be shown that the optimal R&D investment for the consumers' coalition y^* would be higher than the optimal investment for the global planner y^{**}, implying that the consumers' coalition can over-invest in R&D for the new technology, in the sense that its investment is higher than the global efficient level. ■

This result is mainly due to the fact that the consumers' coalition fails to take into account the effect of innovation on the producers' profits when making its R&D decision, while the global planner needs to consider the producers' profits in making its R&D decision. Given that the innovation will eat all the profits of the producers, the global planner might have some hesitation in investing the R&D for the new carbon-free technology.

5 Concluding remarks and further research

This paper uses a dynamic game to investigate the outcomes of the strategic interactions between a resource consumers' coalition and a producers' cartel, taking into account the possibility of innovation in a carbon-free technology. We attempt to answer the following questions: How will the expectation of possible innovation affect both the producers' optimal energy pricing and the consumers' optimal carbon taxation? How would the effect of possible innovation differ with/without the existence of strategic interactions between producers and consumers? How to characterize the optimal R&D for stimulating the innovation? Some important findings or policy implications are summarized as follows.

The anticipation of innovation in cheap, non-polluting resources will reduce both the initial carbon tax and the (wellhead) energy price, thereby stimulating higher initial demand for fossil fuels, and thus higher initial emissions. This is in line with

[13]Complete calculations are available from the authors upon request.

the 'green paradox' argument in the literature (e.g., Sinn, 2008), which states that it is possible that the anticipation of a cheap non-polluting renewable resource will lead fossil fuels owners to increase extraction and may have a detrimental effect on climate change. Our results suggest that, in the presence of strategic interactions or a rent contest between the resource consumers and producers, this 'green paradox' effect still exists. However, compared with the cooperative case where there is no strategic interaction or rent contest, the 'green paradox' effect triggered by possible innovation is found to be less dramatic in the presence of strategic interactions. This implies that the strategic interactions between resource consumers and producers can somewhat restrain this 'green paradox' effect.

Regarding the optimal R&D efforts for innovation, we found that, if the price of the new carbon-free technology is sufficiently low, it is in the best interest of both the consumers' coalition and a global planner to undertake R&D at any initial CO_2 concentration level, which implies that it is not too late to start R&D. Furthermore, the optimal R&D investment should be an increasing function of the initial CO_2 concentration level. That is, the higher the initial CO_2 concentration level, the larger the optimal R&D effort. However, the R&D investment made by the consumers' coalition could be higher than the global efficient level, if the environmental damage is sufficiently large.

The strategic interactions between the resource consumers' carbon taxation and producers' energy pricing strategy can be very complex when incorporating the possible innovation of carbon-free technologies. To simplify this issue, many assumptions have been made in this paper. For instance, though the model presented here provides some insights into the role of innovation and R&D in the strategic interactions of carbon taxation and energy pricing, the R&D decision by the consumers' coalition is not made simultaneously with the decisions on carbon taxation. It would be interesting to obtain both the Markovian strategy for R&D and the Markovian strategies for carbon taxation and energy pricing at the same time. This, of course, would be difficult to solve analytically and may need the assistance of numerical methods, which could also be a direction for further research.

Appendix

A1.Proof of $\frac{\partial z}{\partial \theta} < 0$

From the expression for z in Section 2, one can find its derivative with respect to the hazard rate θ ($\theta \geq 0$) as: $\frac{\partial z}{\partial \theta} = \frac{2}{3b}\Big(1 - \frac{1}{2}\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}}\Big)$.

Let us suppose that $\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}} \leq 2$, which implies that:

$\big[2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}\big]^2 \leq 4[(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})]$.

Calculating the square on the left-hand side and reordering terms, we have the contradiction: $9b^2c^2+36b^2(\frac{\varepsilon}{r})^2+36b^2c\varepsilon\frac{1}{r} \leq 0$, which allows us to establish that: $\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}} > 2$, i.e., $1 - \frac{1}{2}\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}} < 0$, thereby making $\frac{\partial z}{\partial \theta} < 0$. One can verify that, as a special case, $\frac{\partial z(\theta=0)}{\partial \theta} < 0$ (also denoted as $\frac{\partial z}{\partial \theta}|_{\theta=0} < 0$) will also hold.

A2.Proof of $\frac{\partial x}{\partial \theta} > 0$

Taking the derivative of x with respect to the hazard rate of innovation θ ($\theta \geq 0$), after some calculations, one can obtain (complete calculations are available upon request):

$$\frac{\partial x}{\partial \theta} = \frac{8\pi^c}{[4(r+\theta)+3b(c-z)]^2}\Big(\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\tfrac{\theta}{r})} - \frac{r+\theta}{2}\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}}\Big).$$

Let us suppose $\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})} \leq \frac{r+\theta}{2}\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}}$, which implies that $(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r}) \leq (r+\theta)^2+\frac{3}{2}bc(r+\theta)+3b\varepsilon(1+\frac{\theta}{r})$. Reordering terms, we have the contradiction: $\frac{3}{2}bc(r+\theta)+3b\varepsilon(1+\frac{\theta}{r}) \leq 0$, which allows us to establish that $\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})} > \frac{r+\theta}{2}\frac{2(r+\theta)+3bc+6b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+3bc(r+\theta)+6b\varepsilon(1+\frac{\theta}{r})}}$, and therefore we have: $\frac{\partial x}{\partial \theta} > 0$. As a special case, $\frac{\partial x(\theta=0)}{\partial \theta} > 0$ will hold as well.

A3. Proof of $\dfrac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0} > 0$ for $0 \leq S_0 < S_\infty$

Since $\dfrac{\partial W(0,S_0,y)}{\partial y} = \dfrac{\partial w_0}{\partial y} + \dfrac{\partial w_1}{\partial y} S_0 + \dfrac{1}{2}\dfrac{\partial w_2}{\partial y}[S_0]^2$, we have $\dfrac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0} = \dfrac{\partial w_1}{\partial y} + \dfrac{\partial w_2}{\partial y} S_0 = \dfrac{\partial (w_1 + w_2 S_0)}{\partial y}$. Noting that $w_1 + w_2 S_0 = (w_1 + w_2 S_\infty) + w_2(S_0 - S_\infty)$ and being aware of that $S_\infty = \dfrac{x + \pi^c}{c - z}$, $w_1 = \dfrac{1}{3}x$ and $w_2 = z - \dfrac{4\varepsilon}{r}$, one can obtain the following relationship after some calculations: $w_1 + w_2 S_0 = -\dfrac{2\pi^c \varepsilon}{rc + 2\varepsilon} + w_2(S_0 - S_\infty)$.

Therefore, we have $\dfrac{\partial (w_1 + w_2 S_0)}{\partial y} = \dfrac{\partial w_2}{\partial y}(S_0 - S_\infty)$. Since $\dfrac{\partial w_2}{\partial y} = \dfrac{1}{3}\dfrac{\partial z}{\partial y} < 0$ (recall $\theta \equiv y$ and see Appendix A1 for the proof of $\dfrac{\partial z}{\partial \theta} < 0$), we have $\dfrac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0} = \dfrac{\partial (w_1 + w_2 S_0)}{\partial y} > 0$ for $S_0 < S_\infty$. And it is given that the initial CO_2 concentration $S_0 \geq 0$. Therefore, we have $\dfrac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0} > 0$ for all $0 \leq S_0 < S_\infty$. As a special case, we have $\dfrac{\partial^2 W(0,S_0,y)}{\partial y \partial S_0}|_{y=0} > 0$ for $0 \leq S_0 < S_\infty$.

B1. Proof of $\dfrac{\partial m_2}{\partial \theta} < 0$

It is not difficult to find the derivative: $\dfrac{\partial m_2}{\partial \theta} = \dfrac{1}{2b}\Big(1 - \dfrac{1}{2}\dfrac{2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})}}\Big)$.

Let us suppose that $\dfrac{2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})}} \leq 2$, which implies that:

$\big(2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}\big)^2 \leq 4[(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})]$.

Calculating the square on the left-hand side and reordering terms, we have the contradiction: $16b^2c^2 + 64b^2(\frac{\varepsilon}{r})^2 + 64b^2c\varepsilon\frac{1}{r} \leq 0$, which allows us to establish that: $\dfrac{2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})}} \geq 2$, i.e., $1 - \dfrac{1}{2}\dfrac{2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})}} < 0$, thereby making $\dfrac{\partial m_2}{\partial \theta} < 0$

B2. Proof of $\dfrac{\partial m_1}{\partial \theta} > 0$

Taking the derivative of m_1 with respect to the hazard rate of innovation θ, and after some calculations (which are available from the author upon request), one can obtain:

$$\frac{\partial m_1}{\partial \theta} = \frac{\pi^c}{2[(r+\theta) + b(c - m_2)]^2}\Big(\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \tfrac{\theta}{r})} - \frac{r+\theta}{2}\frac{2(r+\theta) + 4bc + 8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2 + 4bc(r+\theta) + 8b\varepsilon(1 + \frac{\theta}{r})}}\Big).$$

Let us suppose $\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r})} \leq \frac{r+\theta}{2}\frac{2(r+\theta)+4bc+8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r})}}$, which implies that $(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r}) \leq (r+\theta)^2+2(r+\theta)bc+4b\varepsilon(1+\frac{\theta}{r})$. Reordering terms we have the contradiction: $2bc(r+\theta)+4b\varepsilon(1+\frac{\theta}{r}) \leq 0$, which allows us to establish $\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r})} > \frac{r+\theta}{2}\frac{2(r+\theta)+4bc+8b\varepsilon\frac{1}{r}}{\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r})}}$, and therefore we have: $\frac{\partial m_1}{\partial\theta} > 0$.

B3. Proof of $\frac{\partial^2 M(0,S_0,y)}{\partial y\partial S_0} > 0$ for $0 \leq S_0 < S_\infty$

Since $\frac{\partial M(0,S_0,y)}{\partial y} = \frac{\partial m_0}{\partial y}+\frac{\partial m_1}{\partial y}S_0+\frac{1}{2}\frac{\partial m_2}{\partial y}[S_0]^2$, we have $\frac{\partial^2 M(0,S_0,y)}{\partial y\partial S_0} = \frac{\partial m_1}{\partial y}+\frac{\partial m_2}{\partial y}S_0 = \frac{\partial(m_1+m_2S_0)}{\partial y}$. Noting that $m_1+m_2S_0=(m_1+m_2S_\infty)+m_2(S_0-S_\infty)$ and being aware of that $S_\infty = S_\infty^G = \frac{\pi^c+m_1}{c-m_2}$, $m_1 = \frac{(r+\theta)\pi^c}{(r+\theta)+b(c-m_2)}-\pi^c$ and $m_2 = c+\frac{1}{2b}\Big(r+\theta-\sqrt{(r+\theta)^2+4bc(r+\theta)+8b\varepsilon(1+\frac{\theta}{r})}\Big)$, after some calculations, one can obtain: $m_1+m_2S_0 = -\frac{2\pi^c\varepsilon}{rc+2\varepsilon}+m_2(S_0-S_\infty)$.

Therefore, we have $\frac{\partial(m_1+m_2S_0)}{\partial y} = \frac{\partial m_2}{\partial y}(S_0-S_\infty)$. Recalling $\theta \equiv y$ and $\frac{\partial m_2}{\partial\theta} < 0$ (see Appendix B1), we have $\frac{\partial^2 M(0,S_0,y)}{\partial y\partial S_0} = \frac{\partial(m_1+m_2S_0)}{\partial y} > 0$ for $S_0 < S_\infty$. It is given that the initial CO_2 concentration $S_0 \geq 0$. Therefore, we have $\frac{\partial^2 M(0,S_0,y)}{\partial y\partial S_0} > 0$ for all $0 \leq S_0 < S_\infty$. As a special case, we have $\frac{\partial^2 M(0,S_0,y)}{\partial y\partial S_0}|_{y=0} > 0$ for $0 \leq S_0 < S_\infty$.

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Paper II

The Harrington Paradox Squared*

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Abstract

Harrington (1988) shows that state-dependent enforcement based on past compliance records provides an explanation to the seemingly contradictory observation that firms' compliance with environmental regulations is high despite the fact that inspections occur infrequently and fines are rare and small. This result has been labeled in the literature as the "Harrington paradox." In this paper, we propose an improved transition structure for the audit framework, in which targeting is based not only on firms' past compliance record but also on adoption of environmentally superior technologies. We show that this transition structure would not only foster the adoption of new technology but also increase deterrence by changing the composition of firms in the industry toward an increased fraction of cleaner firms that pollute and violate less.

Key Words: imperfect compliance, state-dependent targeted enforcement, technology adoption, emission standards.

JEL classification: L51, Q55, K31, K42.

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*Research funding from the Swedish Research Council (FORMAS) is gratefully acknowledged. Xiao-Bing Zhang gratefully acknowledges funding from the Swedish International Development Cooperation Agency (SIDA).

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1 Introduction

Technological change is the main force improving the trade-off between economic growth and environmental quality in the long run. Therefore, the effect of environmental policies on the development and spread of new technologies is among the most important determinants of success or failure of environmental protection efforts (Aldy and Stavins 2007). Yet, environmental policy instruments impose costs on polluters. When there is room for firms to untruthfully report emissions without being caught and fined, i.e., there is imperfect enforcement, environmental policies will have lower success in creating incentives for technological development and controlling the generation of pollution than when the monitoring probability and stringency of the fines are such that truthful reporting is induced. Unfortunately, in many circumstances, the frequent monitoring and relatively high fines necessary to deter firms from under-reporting emissions are not available due to lack of accurate monitoring technology, reluctance to use high penalties, and/or budget constraints.

Harrington (1988) shows that a regulator's enforcement can be made more efficient by dividing firms into two groups according to their past compliance record. Without increasing inspection rates or fines, the regulator can lower the incidence of non-compliance by concentrating surveillance resources on firms in one of the groups (the target group), punishing violations by exile into the target group and (once there) rewarding firms found in compliance by returning them to the non-target group. This scheme generates what Harrington refers to as "enforcement leverage." Since non-compliance triggers greater future scrutiny, the expected costs of non-compliance are beyond the avoidance of immediate fines. Thus, he shows that there exists an equilibrium where firms have an incentive to comply with regulations despite the fact that the cost of compliance in each period is greater than the expected penalty.

Harrington (1988) offers an explanation for the seemingly contradictory observation that compliance rates across most industries are quite high despite the fact that inspections occur infrequently and fines are rare and small, a result labeled in the literature as the "Harrington paradox." In the present paper, we propose an improved transition structure for the audit framework, in which targeting is based not only on firms' past compliance record but also on adoption of environmentally superior technologies. We show that this transition structure would not only foster the adoption of the new technology but would also increase deterrence by changing the composition of firms in the industry toward an increased fraction of cleaner firms that pollute and violate less.

Harrington's work initiated a substantial amount of theoretical work analyzing the robustness of the results to alternative specifications of information and compliance cost structures (see Harford 1991, Harford and Harrington 1991, and Raymond 1999), providing alternative explanations to the "paradox" (see, e.g., Heyes and Rickman 1999, Livernois and McKenna 1999, and Nyborg and Telle 2004 and 2006)[1], and testing the empirical validity of his predictions (see, e.g., Helland 1998, Clark et al. 2004, Cason and Langadharan 2006, and Gray and Shimshack 2011 for a review of the literature).

Like our study, some previous studies have suggested alternative targeting methods.[2] For instance, in Friesen (2003), firms move randomly into the target group but escape based on observed compliance behavior (Friesen 2003). Notably, Liu and Neilson (2009) and Gilpatric et al. (2011) propose tournament-based dynamic targeting mechanisms. In their setting, a fixed number of firms are selected for inspection and those with the highest emissions are targeted with higher inspection probability, which induces dynamic rank-order tournaments among inspected firms, where enforcement leverage is enhanced by a competition effect. Similarly, in our setting, firms with the highest emissions (i.e., the firms that have not invested in more efficient abatement technologies) are also targeted with higher monitoring probability. In our model, however, firms have the option to adopt the new technology "in exchange" for a reduced monitoring probability. Since technology adoption serves the purpose of reducing emissions and increasing deterrence, the regulator can achieve the same or an increased level of compliance at a lower total enforcement cost.

The fact that the stringency of enforcement can be reduced if polluting agents show evidence of compliance-promoting activities is well documented in the literature. For example, Arguedas (2013)

[1]Heyes and Rickman (1999) show that if the environmental protection agency interacts with firms in more than one enforcement domain, it might be optimal to tolerate non-compliance in some sub-set of domains "in exchange" for compliance in others. Livernois and McKenna (1999) show that if firms self-report their emissions, lowering fines for non-compliance raises the proportion of firms that truthfully report their compliance status. Nyborg and Telle (2004) argue that if prosecution is costly, it might be optimal for the regulator just to issue a warning of some kind instead of prosecuting violators, and not to impose further penalties if violators move into compliance upon receipt of the warning.

[2]Like our paper, these studies also sorted firms into discrete groups and made use of the indefinite Markov state-switching model employed by Harrington. In constrast, some papers introduced a continuous reputation indicator (that summarizes the frequency and size of past violations) and used dynamic simulation techniques to analyze more efficient targeting of inspections (see, e.g., Hentschel and Randall 2000).

points out that in the Spanish legislation on hazardous waste, firms that invest in clean production processes associated with responsible water consumption are rarely inspected and, if inspected, they are rarely punished if found non-compliant. She also points out that penalty reductions in exchange for investment efforts by polluting firms can be found in the EPA's Audit Policy, where fines for non-compliance can be significantly reduced if firms install enhanced emission control devices that simplify regulators' monitoring processes.[3]

The paper is organized as follows. Section 2 presents the targeting scheme and the firm's compliance decisions. Section 3 presents the model of adoption and analyzes the impact of targeted state-dependent enforcement on the rate of technology adoption vis-a-vis Harrington's two-group targeting scheme. Section 4 studies the effects of the enforcement scheme on the emissions of adopters and non-adopters, and aggregate emissions. Section 5 studies the effects of the enforcement scheme on the resources devoted to monitoring and enforcement. Section 6 presents some numerical simulations. The final section provides a discussion and concludes the paper.

2 The Model

Consider a competitive industry consisting of a continuum of firms of mass 1 that are risk-neutral and initially homogeneous in abatement costs. The firms are required to make two dichotomous decisions: whether to adopt a new abatement technology to reduce emissions at a lower cost and whether to comply with the emission standard $\overline{q}$. We assume that the adoption decisions made by firms are observable by the regulator. However, the emissions and compliance status of firms can only be known by the regulatory agency through costly monitoring. Like Harrington (1988), we focus on the behavior of a regulatory agency whose primary goal is enforcement and not social welfare maximization. Thus, we specify the goal of the regulatory agency as minimizing the resources devoted to monitoring and enforcement consistent with achieving a given compliance rate with the emission standard $\overline{q}$ without modeling the policy process through which the level of

[3]Arguedas (2013) analyzes whether it is socially desirable that fines for exceeding pollution standards depend on the firm's level of investment in environmentally friendly technologies. Unlike this paper, she considers a static partial equilibrium framework and focuses on the effects of fines instead of an auditing. Coria and Villegas (2014) analyze the advisability of targeted enforcement of emissions taxes in a static setting. They show that the regulator can reduce aggregate emissions by engaging in a regulatory deal where a reduced monitoring probability is granted in "exchange" for adoption of new technology.

the standard is chosen.[4]

Let the abatement cost function of an individual firm be denoted $c(q)$, which is strictly convex and decreasing in the level of emissions q. The new technology allows firms to abate emissions at a lower cost $\theta c(q)$, where $\theta \in (0,1)$ is a parameter that represents the drop in abatement cost obtained by adopting the new technology. After making the adoption decision, firms decide on compliance or violation of the standard $\overline{q}$. We assume that, after monitoring a firm, the regulator is able to perfectly determine the firm's compliance status. If the monitoring reveals that the firm is non-compliant, it faces a convex penalty $\phi(q-\overline{q}) > 0$. For zero violation, the penalty is zero $\phi(0)$, yet the marginal penalty is greater than zero, i.e., $\phi'(0) > 0$.[5]

Harrington considers two groups of firms: the non-target group (G_1), which faces less stringent enforcement, and the target group (G_2), where scrutiny is high. Let π_1 and π_2 denote the probabilities that the regulator audits a firm in G_1 and G_2, respectively, where these probabilities are common knowledge among firms and $\pi_1 < \pi_2$. Moreover, firms can move from G_1 to G_2 according to transition probabilities that depend on the adoption status, current state of the system and compliance with the emission standard (see Table 1).

Adopters				
	Comply		Violate	
	G_1^A	G_2^A	G_1^A	G_2^A
G_1^A	1	0	$1-\alpha_A$	α_A
G_2^A	γ_A	$1-\gamma_A$	0	1

Non-adopters				
	Comply		Violate	
	G_1^{NA}	G_2^{NA}	G_1^{NA}	G_2^{NA}
G_1^{NA}	1	0	$1-\alpha_{NA}$	α_{NA}
G_2^{NA}	γ_{NA}	$1-\gamma_{NA}$	0	1

Table 1: Transition matrices for adopters and non-adopters

Let G_1^A (G_1^{NA}) and G_2^A (G_2^{NA}) denote the sub-group of adopters (non-adopters) in G_1 and G_2, respectively. Furthermore, let $\alpha_A(\alpha_{NA})$ denote the probability of moving an adopter (non-adopter) to group G_2 if caught violating in group G_1, and $\gamma_A(\gamma_{NA})$ denote the probability of moving an

[4]See also Garvie and Keeler (1994).

[5]Unlike our setting, Harrington (1988) assumes a linear penalty function, implying that the decision of whether or not to comply with the emission standard is of the all-or-nothing type. Though such an assumption facilitates the modeling since it provides a clear cut-off policy where all detected violations are transferred to the group with the higher monitoring probability, it might lead to unrealistic situations where firms report zero emissions and the regulator does not monitor them.

adopter (non-adopter) back to group G_1 if discovered complying in G_2. We assume that $\alpha_A \leq \alpha_{NA}$ and $\gamma_A \geq \gamma_{NA}$. In addition, we assume that $\alpha_A \geq \gamma_A$ and $\alpha_{NA} \geq \gamma_{NA}$.

Thus, our framework is general enough to encompass Harrington's state-dependent enforcement scheme (if $\alpha_A = \alpha_{NA}$ and $\gamma_A = \gamma_{NA}$, and, hence, our four-group targeting scheme converges to Harrington's two-group targeting scheme) and to allow us to analyze the effects of differentiated probabilities of transition to reward the firms that adopt the technologies (hereinafter denoted *targeted state-dependent enforcement* where $\alpha_A < \alpha_{NA}$ and $\gamma_A > \gamma_{NA}$). Finally, the framework is also general enough to analyze the effects of the allocation of adopters and non-adopters to the target and non-target groups G_1 and G_2. In particular, we analyze three different initial allocations: (1) when all firms are initially allocated to G_1, (2) when all firms are initially allocated to G_2, and (3) when adopters are initially allocated to G_1 and non-adopters to G_2, hereinafter denoted *targeted initial allocation*.[6]

As in Harrington (1988), the monitoring scheme poses a Markov decision problem to both adopters and non-adopters since they move from one group to the other depending on the compliance behavior in the previous period. For each adoption status, the firm chooses among possible strategies:

- comply when in G_1 and G_2,
- comply only if in G_1,
- comply only if in G_2,
- violate in both groups.

Let the strategy f^{jklm} describe the firm's decisions to comply with (0) or violate (1) the regulation, where j and k denote the actions taken by adopters when in groups G_1 and G_2, respectively, and let l and m denote the actions taken by non-adopters when in groups G_1 and G_2, respectively. In principle, we should have 16 possible strategies. However, since adopters' compliance cost is

[6]Note that firms in our model are homogeneous ex-ante and, hence, should comply with the regulation to the same extent. To be consistent with this assumption, we analyze the cases where all firms are initially allocated to G_1 or G_2, yet a random initial allocation of firms to G_1 or G_2 is also feasible. Let us consider a situation where a fraction χ of the firms are initially allocated to G_1 and the remaining fraction $[1 - \chi]$ are initially allocated to G_2. In this case, the results become a linear combination of our results.

lower than non-adopters' within the same group (G_1 or G_2), it is not reasonable that non-adopters comply but adopters violate. Moreover, since the expected cost of non-compliance in G_2 is higher both for adopters and non-adopters, it is not reasonable that they comply in G_1 but violate in G_2. Thus, six potential strategies remain: f^{0000}, f^{0010}, f^{0011}, f^{1010}, f^{1011}, and f^{1111}. Note that the first three strategies imply full compliance by adopters (and varying levels of compliance by non-adopters) and the last three strategies imply partial or full non-compliance by adopters and non-adopters.

Let $E_A^{jklm}(1)$ and $E_{NA}^{jklm}(1)$ denote the present value of adopters' and non-adopters' expected cost of strategy f^{jklm} when initially allocated to G_1. By analogy, let $E_A^{jklm}(2)$ and $E_{NA}^{jklm}(2)$ denote the present value of adopters' and non-adopters' expected cost of strategy f^{jklm} when initially allocated to group G_2. As in Harrington (1988), by the stationary property, the expected present value must be the cost in this period plus the expected present value discounted one period. For instance, let us compute the present values of f^{1010} for adopters when initially allocated to G_1 and G_2, respectively. In a single play of this game, if the regulator announces beforehand that the inspection probability for an adopter is π_i ($\vee\ i = 1, 2$), the adopters' cost minimization problem corresponds to[7]:

$$Min_{q_A}\left[\theta c(q_A) + \pi_i \phi(q_A - \overline{q})\right] \text{ s.t. } q_A \leq \overline{q}.$$

The optimization problem can be represented by the Lagrangian $L = \theta c(q_A) + \pi_i \phi(q_A - \overline{q}) + \omega\left[\overline{q} - q_A\right]$, where $\omega \geq 0$ is the Lagrange multiplier. The FOC defining the optimal level of emissions is given by:

$$\theta c'(q_A) + \pi_i \phi'\left[q_A - \overline{q}\right] - \omega = 0. \tag{1}$$

Under compliance, $q_A = \overline{q}$. Hence, the expected cost of the regulation is equal to $\theta c(\overline{q})$. Under non-compliance (NC), adopters select an emission level $q_A^{NC} > \overline{q}$ such that $-\theta c'(q_A^{NC}) = \pi_i \phi'\left[q_A^{NC} - \overline{q}\right]$. It holds that q_A^{NC} decreases with the monitoring probability π_i, and the expected cost of the regulation is equal to $\theta c(q_A^{NC}) + \pi_i \phi(q_A^{NC}(\pi_i) - \overline{q})$. Let $0 \leq \beta < 1$ be the discount factor. Since under the strategy f^{1010} adopters violate the standard if in G_1 and comply if in G_2,

[7] For non-adopters, $\theta = 1$.

the expected costs when initially allocated to G_1 and G_2 are, respectively:

$$E_A^{1010}(1) = \left[\theta c(q_A^{NC}(\pi_1)) + \pi_1 \phi(q_A^{NC}(\pi_1) - \overline{q})\right] + \beta \left[\pi_1 \alpha_A E_A^{1010}(2) + [1 - \pi_1 \alpha_A] E_A^{1010}(1)\right], \quad (2)$$

$$E_A^{1010}(2) = [\theta c(\overline{q})] + \beta \left[\pi_2 \gamma_A E_A^{1010}(1) + [1 - \pi_2 \gamma_A] E_A^{1010}(2)\right]. \quad (3)$$

The second term in parentheses in equation (2) represents the expected present value discounted one period. It is composed of the expected cost of being caught in violation in G_1 and sent to G_2 with probability $\pi_1 \alpha_A$ plus the expected cost of remaining in G_1 with probability $[1 - \pi_1 \alpha_A]$. By analogy, the second term in parentheses in equation (3) represents the discounted expected present value of being found in compliance in G_2 and sent to G_1 with probability $\pi_2 \gamma_A$ plus the expected cost of remaining in G_2 with probability $[1 - \pi_2 \gamma_A]$.

Solving equations (2) and (3) simultaneously yields:

$$E_A^{1010}(1) = \frac{\theta c(q_A^{NC}(\pi_1)) + \pi_1 \phi(q_A^{NC}(\pi_1) - \overline{q})}{1 - \beta} + \frac{\beta \pi_1 \alpha_A \left[\theta c(\overline{q}) - \left[\theta c(q_A^{NC}(\pi_1)) + \pi_1 \phi(q_A^{NC}(\pi_1) - \overline{q})\right]\right]}{[1 - \beta]\,[1 - \beta + \beta \pi_1 \alpha_A + \beta \pi_2 \gamma_A]},$$

$$E_A^{1010}(2) = \frac{\theta c(\overline{q})}{1 - \beta} - \frac{\beta \pi_2 \gamma_A \left[\theta c(\overline{q}) - \left[\theta c(q_A^{NC}(\pi_1)) + \pi_1 \phi(q_A^{NC}(\pi_1) - \overline{q})\right]\right]}{[1 - \beta]\,[1 - \beta + \beta \pi_1 \alpha_A + \beta \pi_2 \gamma_A]}.$$

Table 2 presents solutions to the sets of simultaneous equations giving the present values of each feasible strategy f^{jklm}. Note that the expected cost for those cases where firms are moved from one group to the other comprises two terms. The first term represents the expected cost if the firm remains in the initial group forever. The second term is an adjustment factor that reflects the likelihood of the firm being moved to the other group. This adjustment factor is positive if the expected cost is greater in the other group and negative otherwise.[8]

Note also that regardless of the *initial allocation*, the transition probabilities $(\alpha_{NA}, \gamma_{NA})$ affect only non-adopters' expected costs. By analogy, the transition probabilities (α_A, γ_A) affect only adopters' expected costs. Moreover, as in Harrington (1988), an increased probability $\alpha_A(\alpha_{NA})$ of transiting an adopter (non-adopter) to group G_2 if caught violating in group G_1 increases adopters' (non-adopters') expected costs, while the reverse holds for the probability $\gamma_A(\gamma_{NA})$ of moving an adopter (non-adopter) back to group G_1 if discovered complying in G_2.

[8]This is consistent with Friesen (2003).

Adopters	
Initially in $\mathbf{G}_1$	
00	$\frac{\theta c(\overline{q})}{1-\beta}$
10	$\frac{\theta c(q_A^{NC}(\pi_1))+\pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})}{1-\beta}+\frac{\beta\pi_1\alpha_A\left[\theta c(\overline{q})-\left[\theta c(q_A^{NC}(\pi_1))+\pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})\right]\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$
11	$\frac{\theta c(q_A^{NC}(\pi_1))+\pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})}{1-\beta+\beta\pi_1\alpha_A}+\frac{\beta\pi_1\alpha_A\left[\theta c(q_A^{NC}(\pi_2))+\pi_2\phi(q_A^{NC}(\pi_2)-\overline{q})\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A]}$
Initially in $\mathbf{G}_2$	
00	$\frac{\theta c(\overline{q})}{1-\beta}$
10	$\frac{\theta c(\overline{q})}{1-\beta}-\frac{\beta\pi_2\gamma_A\left[\theta c(\overline{q})-\left[\theta c(q_A^{NC}(\pi_1))+\pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})\right]\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$
11	$\frac{\theta c(q_A^{NC}(\pi_2))+\pi_2\phi(q_A^{NC}(\pi_2)-\overline{q})}{1-\beta}$
Non-adopters	
Initially in $\mathbf{G}_1$	
00	$\frac{c(\overline{q})}{1-\beta}$
10	$\frac{c(q_{NA}^{NC}(\pi_1))+\pi_1\phi(q_{NA}^{NC}(\pi_1)-\overline{q})}{1-\beta}+\frac{\beta\pi_1\alpha_{NA}\left[c(\overline{q})-\left[c(q_{NA}^{NC}(\pi_1))+\pi_1\phi(q_{NA}^{NC}(\pi_1)-\overline{q})\right]\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$
11	$\frac{c(q_{NA}^{NC}(\pi_1))+\pi_1\phi(q_{NA}^{NC}(\pi_1)-\overline{q})}{1-\beta+\beta\pi_1\alpha_{NA}}+\frac{\beta\pi_1\alpha_{NA}\left[c(q_{NA}^{NC}(\pi_2))+\pi_2\phi(q_{NA}^{NC}(\pi_2)-\overline{q})\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}]}$
Initially in $\mathbf{G}_2$	
00	$\frac{c(\overline{q})}{1-\beta}$
01	$\frac{c(\overline{q})}{1-\beta}-\frac{\beta\pi_2\gamma_{NA}\left[c(\overline{q})-\left[c(q_{NA}^{NC}(\pi_1))+\pi_1\phi(q_{NA}^{NC}(\pi_1)-\overline{q})\right]\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$
11	$\frac{c(q_{NA}^{NC}(\pi_2))+\pi_2\phi(q_{NA}^{NC}(\pi_2)-\overline{q})}{1-\beta}$

Table 2: Expected costs for adopters and non-adopters under different strategies

Finally, as in Harrington (1988), there are critical probabilities π_1 and π_2 that define which strategy is optimal for the firms. In our case, let $\overline{\pi}_1^A$ ($\overline{\pi}_1^{NA}$) and $\overline{\pi}_2^A$ ($\overline{\pi}_2^{NA}$) denote the critical probabilities π_1 and π_2 that make adopters (non-adopters) indifferent between compliance and violation when in G_1 and G_2, respectively. $\overline{\pi}_1^A$ and $\overline{\pi}_2^A$ are independent of the initial allocation of adopters and non-adopters to G_1 and G_2 and are implicitly defined by the equations:

$$\theta\left[c(\overline{q})-c(q_A^{NC}(\overline{\pi}_1^A)\right] = \overline{\pi}_1^A\phi(q_A^{NC}(\overline{\pi}_1^A)-\overline{q}), \tag{4}$$

$$\theta\left[c(\overline{q})-c(q_A^{NC}(\overline{\pi}_2^A)\right]-\Gamma = \overline{\pi}_2^A\phi(q_A^{NC}(\overline{\pi}_2^A)-\overline{q}), \tag{5}$$

where $\Gamma=\frac{\beta\overline{\pi}_2^A\gamma_A\left[\theta\left[c(\overline{q})-c(q_A^{NC}(\pi_1)\right]-\pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})\right]}{\left[1-\beta+\beta\pi_1\alpha_A+\beta\overline{\pi}_2^A\gamma_A\right]}$. In the case of imperfect compliance, $\pi_1<\overline{\pi}_1^A$, and hence $\Gamma > 0$. Thus, $\overline{\pi}_2^A$ is implicitly defined by equation (5), and is a non-linear function of π_1, α_A, and γ_A. As shown in Appendix A, it holds that $\overline{\pi}_2^A$ increases when π_1 or α_A increases, and decreases when γ_A increases. Vis-a-vis Harrington's enforcement scheme, targeted state-dependent enforcement reduces $\overline{\pi}_2^A$ since $\alpha_A < \alpha_{NA}$ and $\gamma_A > \gamma_{NA}$. From equations (4) and (5), it can also be seen that the larger the reduction in abatement costs due to the adoption of the new technology (i.e., the lower the parameter θ), the lower the critical probabilities $\overline{\pi}_1^A$ and $\overline{\pi}_2^A$. In other words, the more efficient the new technology is, the higher the incentives for adopters to comply.

Similar equations define the probabilities $\overline{\pi}_1^{NA}$ and $\overline{\pi}_2^{NA}$ for $\theta = 1$ and emission levels $q_{NA}^{NC}(\overline{\pi}_1^{NA})$ and $q_{NA}^{NC}(\overline{\pi}_2^{NA})$. Because, for the same monitoring probability, the expected costs of compliance are lower for adopters, the minimum monitoring probability necessary to ensure compliance is lower for adopters than for non-adopters, $\overline{\pi}_1^A < \overline{\pi}_1^{NA}$ and $\overline{\pi}_2^A < \overline{\pi}_2^{NA}$.

Given these critical probabilities, the optimal strategy f can be characterized as:

$$f = \begin{cases} f^{0000} \text{ if } \pi_1 > \overline{\pi}_1^{NA} \text{ and } \pi_2 > \overline{\pi}_2^{NA}, \\ f^{0010} \text{ if } \pi_1 \in \left[\overline{\pi}_1^A, \overline{\pi}_1^{NA}\right] \text{ and } \pi_2 > \overline{\pi}_2^{NA}, \\ f^{0011} \text{ if } \pi_1 \in \left[\overline{\pi}_1^A, \overline{\pi}_1^{NA}\right] \text{ and } \pi_2 \in \left[\overline{\pi}_2^A, \overline{\pi}_2^{NA}\right], \\ f^{1010} \text{ if } \pi_1 < \overline{\pi}_1^A \text{ and } \pi_2 > \overline{\pi}_2^{NA}, \\ f^{1011} \text{ if } \pi_1 < \overline{\pi}_1^A \text{ and } \pi_2 \in \left[\overline{\pi}_2^A, \overline{\pi}_2^{NA}\right], \\ f^{1111} \text{ if } \pi_1 < \overline{\pi}_1^A \text{ and } \pi_2 < \overline{\pi}_2^A. \end{cases}$$

3 The Adoption Rate

We assume that buying and installing the new technology implies a fixed cost that differs among firms.[9] Let k_i denote the fixed cost of adoption for firm i, and assume that k_i is uniformly distributed on the interval $(\underline{k}, \overline{k})$. Note that the differences $E_{NA}^{jklm}(1) - E_A^{jklm}(1)$ and $E_{NA}^{jklm}(2) - E_A^{jklm}(2)$ indicate how expected costs would change with the use of new technologies when firms are initially allocated to G_1 and G_2, respectively, and the difference $E_{NA}^{jklm}(2) - E_A^{jklm}(1)$ indicates how expected costs

[9]The assumption that adoption costs differ among firms is not new in the literature analyzing the effects of choice of policy instruments on the rate of adoption of new technologies; see, e.g., Requate and Unold (2001). On the other hand, Stoneman and Ireland (1983) point out that, although most theoretical and empirical literature on technological adoption focuses on the demand side alone, supply-side forces might be very important in explaining patterns of adoption in practice. Thus, e.g., costs of acquiring new technology might vary among firms due to firm characteristics, e.g., location and output, or competition among suppliers of capital goods.

would change under a targeted allocation based on adoption status. Any firm whose saving in total expected cost offsets its adoption cost will adopt the new technology. For a given strategy f^{jklm} and initial allocation of non-adopters and adopters to groups y and x, respectively, where $y, x = 1, 2$, and $y \geq x$, the rate of firms $\lambda \in [0, 1]$ adopting the more efficient abatement technology is defined by:

$$\lambda^{jklm}(y \mid x) = \int_{\underline{k}}^{\widehat{k}} f(k_i)dk = F(\widehat{k}_i) = \psi \left[E_{NA}^{jklm}(y) - E_{A}^{jklm}(x) \right] - \varsigma, \tag{6}$$

where the RHS of equation (6) follows from the definition of the uniform cumulative distribution of k_i, $\psi = \frac{1}{\overline{k} - \underline{k}}$and $\varsigma = \psi \underline{k}$. For simplicity, we assume hereinafter that $\varsigma \simeq 0$. Thus, the adoption rate is a function of the shift in abatement costs θ, the emission standard $\overline{q}$, the initial allocation of adopters and non-adopters to G_1 or G_2, the monitoring probabilities (π_1, π_2), and the transition probabilities (α_A, α_{NA}) and (γ_A, γ_{NA}). In addition, λ is inversely related to the length of the investment cost interval $(\overline{k} - \underline{k})$. [10]

In what follows, we analyze the impact of the targeted state-dependent enforcement strategy on the rate of adoption through comparative statics with respect to the transition probabilities $\alpha_A, \alpha_{NA}, \gamma_A$, and γ_{NA} (see Appendix B for detailed comparative statics of adopters' and non-adopters' expected costs under different strategies with regard to the transition probabilities).

Proposition 1 *A targeted state-dependent enforcement scheme spurs the rate of adoption of the environmentally friendly technology.*

Recall that $\lambda^{jklm}(y \mid x) = \psi \left[E_{NA}^{jklm}(y) - E_{A}^{jklm}(x) \right] \vee y, x = 1, 2$, and $y \geq x$, and that the transition probabilities α_{NA} and γ_{NA} (α_A and γ_A) affect only non-adopters' (adopters') expected costs. Hence,

$$\begin{aligned} \frac{\partial \lambda^{jklm}(y \mid x)}{\partial \alpha_{NA}} &= \psi \frac{\partial E_{NA}^{jklm}(y)}{\partial \alpha_{NA}} \geq 0, \\ \frac{\partial \lambda^{jklm}(y \mid x)}{\partial \gamma_{NA}} &= \psi \frac{\partial E_{NA}^{jklm}(y)}{\partial \alpha_{NA}} \leq 0. \end{aligned}$$

Furthermore,

[10] The more heterogeneous the firms are in terms of the investment cost, the larger the interval $(\overline{k} - \underline{k})$ and the lower the rate of adoption.

$$\frac{\partial \lambda^{jklm}(y \mid x)}{\partial \alpha_A} = -\psi \frac{\partial E_{NA}^{jklm}(x)}{\partial \alpha_A} \leq 0,$$
$$\frac{\partial \lambda^{jklm}(y \mid x)}{\partial \gamma_A} = -\psi \frac{\partial E_{NA}^{jklm}(x)}{\partial \gamma_A} \geq 0.$$

Thus, *targeted state-dependent enforcement* where $\alpha_{NA} > \alpha_A$ and $\gamma_{NA} < \gamma_A$ induces a larger rate of adoption than does Harrington's scheme based only on past compliance.

As shown in Appendix B, marginal variations in (α_{NA}, γ_{NA}) have a larger effect on the rate of adoption than do marginal variations in (α_A, γ_A) in almost all cases. Moreover, the marginal effects of (α_A, α_{NA}) on the rate of adoption are larger when firms are initially allocated to G_1. The reverse holds for (γ_A, γ_{NA}): their marginal effects on the rate of adoption are larger when firms are initially allocated to G_2.

As mentioned above, since enforcement is more stringent in G_2, it holds that $E_A^{jklm}(2) \geq E_A^{jklm}(1)$ and $E_{NA}^{jklm}(2) \geq E_{NA}^{jklm}(1)$, where equality holds only in the case where adopters/non-adopters fully comply with the regulation. Therefore, we can derive the following proposition regarding the effects of a *targeted initial allocation* on the rate of adoption.

Proposition 2 *The rate of adoption of the environmentally friendy technology under a targeted state dependent enforcement scheme is larger if the regulator also targets the initial allocation of firms based on adoption status.*

Given equation (6), the difference in the adoption rate between targeted initial allocation and the allocation where all firms are initially sent to G_1 corresponds to:

$$\lambda^{jklm}(2 \mid 1) - \lambda^{jklm}(2 \mid 2) = \psi \left[E_A^{jklm}(2) - E_A^{jklm}(1) \right] \geq 0.$$

This difference is equal to zero under full compliance by adopters, and positive otherwise.

By analogy, the difference in adoption rate between targeted initial allocation and the allocation where all firms are initially sent to G_2 corresponds to:

$$\lambda^{jklm}(2 \mid 1) - \lambda^{jklm}(1 \mid 1) = \psi \left[E_{NA}^{jklm}(2) - E_{NA}^{jklm}(1) \right] \geq 0.$$

This difference is equal to zero under full compliance by non-adopters, and positive otherwise.

Hence, compared with the allocations where all firms are sent to G_1 or G_2, targeted initial allocation leads to a higher rate of adoption. Thus, our results suggest that to speed up the pace of adoption of environmentally friendly technologies, the regulator should exert a stronger monitoring pressure on non-adopters. This result goes against previous studies of targeted enforcement policy in a static setting that suggest exerting a stronger monitoring pressure on firms with lower abatement costs since their pollution levels are more responsive to the enforcement parameters than those of firms with higher abatement costs (e.g., Garvie and Keeler (1994) Macho-Stadler and Pérez-Castrillo (2006)). Since the rate of adoption is exogenous in their analysis , they do not consider that biasing the monitoring scheme against firms with lower abatement costs reduces the potential gains from investing in new technologies, and thus, discourages adoption. A similar argument applies in the case of industrial turnover. Stringent regulations that only apply to newer or cleaner firms might slow down the turnover of pollution sources, drive up the cost of environmental protection, and increase pollution levels because they provide existing sources with perverse incentives to continue operating while "taxing" newer and cleaner entrants. See, e.g., Maloney and Brady (1988).

4 Individual and Aggregate Expected Emissions

Let $\widehat{q}_A^{jklm}(y)$ and $\widehat{q}_{NA}^{jklm}(y)$ denote the expected emissions by adopters and non-adopters under strategy f^{jklm} when initially allocated to group $y = 1, 2$. Table 3 presents the summary of expected emissions by adopters and non-adopters under different strategies.

	Adopters	
f	Initially in G_1	Initially in G_2
00	$\frac{\overline{q}}{1-\beta}$	$\frac{\overline{q}}{1-\beta}$
10	$\frac{[1-\beta+\beta\pi_2\gamma_A]q_A^{NC}(\pi_1)+\beta\pi_1\alpha_A\overline{q}}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$	$\frac{\overline{q}}{1-\beta}+\frac{\beta\pi_2\gamma_A\left[q_A^{NC}(\pi_1)-\overline{q}\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$
11	$\frac{q_A^{NC}(\pi_1)}{1-\beta+\beta\pi_1\alpha_A}+\frac{\beta\pi_1\alpha_A q_A^{NC}(\pi_2)}{[1-\beta][1-\beta+\beta\pi_1\alpha_A]}$	$\frac{q_A^{NC}(\pi_2)}{1-\beta}$
	Non-adopters	
f	Initially in G_1	Initially in G_2
00	$\frac{\overline{q}}{1-\beta}$	$\frac{\overline{q}}{1-\beta}$
10	$\frac{[1-\beta+\beta\pi_2\gamma_{NA}]q_{NA}^{NC}(\pi_1)+\beta\pi_1\alpha_{NA}\overline{q}}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$	$\frac{\overline{q}}{1-\beta}+\frac{\beta\pi_2\gamma_{NA}\left[q_{NA}^{NC}(\pi_1)-\overline{q}\right]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$
11	$\frac{q_{NA}^{NC}(\pi_1)}{1-\beta+\beta\pi_1\alpha_{NA}}+\frac{\beta\pi_1\alpha_{NA} q_{NA}^{NC}(\pi_2)}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}]}$	$\frac{q_{NA}^{NC}(\pi_2)}{1-\beta}$

Table 3: Expected emissions by adopters and non-adopters

As expected, comparing the columns of Table 3 shows that (except for the case of full compliance) expected emissions by adopters and non-adopters are larger if firms are initially allocated to G_1. Furthermore, if $\alpha_A = \alpha_{NA}$ and $\gamma_A = \gamma_{NA}$, expected emissions are higher for non-adopters than adopters in all cases, i.e., $\widehat{q}_{NA}^{jklm}(y) \geq \widehat{q}_A^{jklm}(y) \vee jklm$ and $y = 1, 2$.

For a given strategy and initial allocation of non-adopters and adopters to groups y and x, respectively, aggregate expected emissions can be represented as:

$$\widehat{Q}(y \mid x) = \lambda(y \mid x)\widehat{q}_A(x) + [1 - \lambda(y \mid x)]\,\widehat{q}_{NA}(y). \quad (7)$$

By varying the transition probabilities $(\alpha_A, \alpha_{NA}, \gamma_A, \gamma_{NA})$, we have two types of effects on aggregate emissions: a *direct effect* on adopters' or non-adopters' emissions, and an *indirect effect* on the rate of adoption. As shown in detail in Appendix C, increased probabilities (α_A, α_{NA}) have the positive effect of reducing emissions by adopters and non-adopters, respectively. In contrast, increased probabilities (γ_A, γ_{NA}) have a negative effect, leading to increased emissions. Therefore, targeted state-dependent enforcement has the positive effect of reducing emissions by means of enhancing the rate of adoption (and thus changing the composition of firms towards a larger fraction of cleaner firms). Furthermore, it has the positive (direct) effect of reducing non-adopters' emissions. Nevertheless, in some cases, this might come at the expense of increased emissions by adopters.

Proposition 3 *A targeted state-dependent enforcement scheme based on firms' past compliance and adoption of environmentally superior technologies can reduce aggregate emissions.*

Let us for a moment disregard the effects of the initial allocation of firms to G_1 or G_2. Let the superscripts T and H denote the outcomes of targeted state-dependent enforcement and Harrington's enforcement, respectively. Given equation (7), the difference in expected emissions between the two enforcement schemes corresponds to:

$$\widehat{Q}^T - \widehat{Q}^H = \left[\lambda^T - \lambda^H\right]\left[\widehat{q}_A^H - \widehat{q}_{NA}^H\right] + \left[1 - \lambda^T\right]\left[\widehat{q}_{NA}^T - \widehat{q}_{NA}^H\right] + \lambda^T\left[\widehat{q}_A^T - \widehat{q}_A^H\right]. \qquad (8)$$

Note that the first term in brackets on the RHS of equation (8) is negative and corresponds to the effect of targeted state-dependent enforcement increasing the rate of adoption (vis-a-vis Harrington's enforcement), and thus reducing expected aggregate emissions as adopters emit less than non-adopters. The second term is also negative and corresponds to the reduced emissions by non-adopters, which are monitored more stringently under targeted state-dependent enforcement and hence emit less. Finally, the third term is positive and corresponds to the increased emissions by adopters, which are monitored less stringently under targeted state-dependent enforcement and hence emit more.

Regardless of the initial allocation, $\widehat{q}_A^T = \widehat{q}_A^H$ under the strategies f^{0000}, f^{0010} and f^{0011}, implying that equation (8) simplifies to:

$$\widehat{Q}^T - \widehat{Q}^H = \left[\lambda^T - \lambda^H\right]\left[\widehat{q}_A^H - \widehat{q}_{NA}^H\right] + \left[1 - \lambda^T\right]\left[\widehat{q}_{NA}^T - \widehat{q}_{NA}^H\right] \leq 0.$$

This difference is equal to zero under f^{0000} and negative under f^{0010} and f^{0011}. Hence, aggregate emissions under targeted state-dependent enforcement are lower than or equal to those under Harrington's enforcement. The comparison is less clear for the strategies f^{1010}, f^{1011} and f^{1111}. In what follows, let us consider how targeted state-dependent enforcement affects adopters' emissions and non-adopters' emissions (that is, the second and third term of equation (8); see Appendix C for detailed comparative statics) under these three strategies.

- f^{1010}. We have that the marginal effects of the probabilities α_{NA} and γ_{NA} are larger than the marginal effects of the probabilities α_A and γ_A. Hence, vis-a-vis Harrington's enforcement, targeted state-dependent enforcement increases adopters' and reduces non-adopters' emissions. The overall effect is a net reduction in emissions as the reduction in non-adopters' emissions is larger than the increase in adopters' emissions, regardless of the initial allocation.

- f^{1011}. Targeted state-dependent enforcement increases adopters' emissions. In contrast, it has no effect on non-adopters' emissions if they are initially allocated to G_2 and reduces non-adopters' emissions if they are initially allocated to G_1. The overall effect is a net increase in emissions as the increase in adopters' emissions is larger than (any) reduction in non-adopters' emissions, regardless of the initial allocation.

- f^{1111}. Targeted state-dependent enforcement has no effect on adoption or on adopters' and non-adopters' emissions when firms are initially allocated to G_2. Hence, $\widehat{Q}^T - \widehat{Q}^H = 0$ in such case. If firms are initially allocated to G_1, it increases adopters' and reduces non-adopters' emissions. The overall effect is a net reduction of emissions as the reduction of non-adopters' emissions is larger than the increase in adopters's emissions.

Thus, we can say that, vis-a-vis Harrington's enforcement, targeted state-dependent enforcement has no effect on emissions under full compliance by adopters and non-adopters, while it unambiguously reduces emissions under the strategies f^{0010}, f^{0011}, and f^{1010}. If all firms are initially allocated to G_1, it also reduces emissions under f^{1111}. Finally, whether or not targeted state-dependent enforcement leads to lowered emissions under f^{1011} depends on the relative magnitude of the direct and indirect effects. Even if adopters' emissions might be larger than those under Harrington's enforcement, adopters emit less than non-adopters. Hence, aggregate emissions under targeted state-dependent enforcement can still be lower than under Harrington's enforcement due to the larger rate of adoption.

When it comes to the expected aggregate violations, note that, if firms were to always comply with the regulation, their expected emissions would be equal to $\frac{\overline{q}}{1-\beta}$. Thus, for a given strategy and initial allocation of non-adopters and adopters to groups y and x, respectively, the expected aggregate violations $\widehat{V}$ can be represented as:

$$\widehat{V}(y \mid x) = \widehat{Q}(y \mid x) - \frac{\overline{q}}{1-\beta}.$$

Hence, it is clear that, if targeted state-dependent enforcement reduces expected aggregate emissions, it also reduces expected aggregate violations.

Let us now analyze the effects of a targeted initial allocation on aggregate emissions.

Proposition 4 *Expected aggregate emissions under targeted initial allocation are lower than the expected aggregate emissions under an allocation that initially sends all firms to G_1. If the increase in adoption rate due to targeted initial allocation is sufficiently large, the expected aggregate emissions under targeted initial allocation are also lower than the expected aggregate emissions under an allocation that initially sends all firms to G_2.*

Given equation (7), the difference in expected aggregate emissions between targeted initial allocation and the allocation where all firms are initially sent to G_1 corresponds to:

$$\widehat{Q}(2 \mid 1) - \widehat{Q}(1 \mid 1) = [\lambda(2 \mid 1) - \lambda(1 \mid 1)] [\widehat{q}_A(1) - \widehat{q}_{NA}(1)] + [1 - \lambda(2 \mid 1)] [\widehat{q}_{NA}(2) - \widehat{q}_{NA}(1)] . \quad (9)$$

Note that the first term in brackets on the RHS of equation (9) is negative and corresponds to the effect of a targeted initial allocation increasing the rate of adoption, and thus reducing expected aggregate emissions as adopters emit less than non-adopters. The second term is also negative and corresponds to the reduced emissions by non-adopters, which are monitored more stringently under targeted initial allocation and hence emit less. So, compared with the case where both adopters and non-adopters are allocated to G_1, a targeted initial allocation would not only lead to a higher adoption rate, but also to lower expected aggregate emissions.

The difference in expected aggregate emissions between a targeted initial allocation and the allocation where all firms are initially sent to G_2 corresponds to:

$$\widehat{Q}(2 \mid 1) - \widehat{Q}(2 \mid 2) = [\lambda(2 \mid 1) - \lambda(2 \mid 2)] [\widehat{q}_A(2) - \widehat{q}_{NA}(2)] + \lambda(2 \mid 1) [\widehat{q}_A(1) - \widehat{q}_A(2)] . \quad (10)$$

As before, the firm term in brackets on the RHS of equation (10) is negative and corresponds to the effect of targeted initiall allocation increasing the rate of adoption, and thus reducing expected aggregate emissions as adopters emit less than non-adopters. The second term is positive and corresponds to the increased emissions by adopters under targeted initial allocation: if adopters would have been initially allocated to G_2, they would have emitted $\widehat{q}_A(2)$ instead of $\widehat{q}_A(1)$. Since these two effects have different signs, the final effect of the initial allocation on expected aggregate emissions depends on their relative magnitude. Let us find the conditions for when $\widehat{Q}(2 \mid 1) - \widehat{Q}(2 \mid 2) \leq 0$. We have two cases:

- $\widehat{q}_A(1) = \widehat{q}_A(2)$, which occurs under full compliance by adopters.
- $\widehat{q}_A(1) - \widehat{q}_A(2) > 0$, and $\frac{\lambda(2|1)-\lambda(2|2)}{\lambda(2|1)} \geq \frac{\widehat{q}_A(1)-\widehat{q}_A(2)}{\widehat{q}_{NA}(2)-\widehat{q}_A(2)}$.

That is, if the increase in adoption rate due to a targeted initial allocation $\lambda(2 \mid 1) - \lambda(2 \mid 2)$ is sufficiently large, the expected aggregate emissions can be lower than when adopters and non-adopters are initially allocated to G_2.

5 Enforcement Costs

As Harrington (1988), we assume that the regulator wishes to minimize the resources devoted to monitoring and enforcement consistent with achieving a target compliance rate. For a given cost per visit for the regulatory agency equal to m (that does not differ between adopters and non-adopters)[11], we compute the expected costs of enforcing compliance among adopters and non-adopters for each strategy f^{jklm} and initial allocations to G_1 and G_2. These costs are denoted as $\widehat{m}_A^{jklm}(y)$ and $\widehat{m}_{NA}^{jklm}(y)$, respectively. Results are presented in Table 4.

[11] Millock et al. (2002) and Millock et al. (2012) analyze the incentives provided by different policy instruments for the adoption of new environmental monitoring technologies. Like in our study, in these studies the choice of installing a technology separates agents into two categories, yet their focus is on the optimal choice and stringency of policy instruments while ours is on differentiated monitoring probabilities. Furthermore, unlike our study, in these studies adoption of technological monitoring devices serves the purpose of transforming non-point sources into point sources, thus reducing the monitoring cost m.

Adopters		
f	Initially in G_1	Initially in G_2
00	$\frac{m\pi_1}{1-\beta}$	$\frac{m\pi_2}{1-\beta+\beta\pi_2\gamma_A} + \frac{\beta\pi_2\gamma_A m\pi_1}{[1-\beta][1-\beta+\beta\pi_2\gamma_A]}$
10	$\frac{m\pi_1}{[1-\beta]} + \frac{\beta\pi_1\alpha_A m[\pi_2-\pi_1]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$	$\frac{m\pi_2}{1-\beta} - \frac{\beta\pi_2\gamma_A m[\pi_2-\pi_1]}{[1-\beta][1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A]}$
11	$\frac{m\pi_1}{1-\beta+\beta\pi_1\alpha_A} + \frac{\beta\pi_1\alpha_A m\pi_2}{[1-\beta][1-\beta+\beta\pi_1\alpha_A]}$	$\frac{m\pi_2}{1-\beta}$
Non-adopters		
f	Initially in G_1	Initially in G_2
00	$\frac{m\pi_1}{1-\beta}$	$\frac{m\pi_2}{1-\beta+\beta\pi_2\gamma_{NA}} + \frac{\beta\pi_2\gamma_{NA} m\pi_1}{[1-\beta][1-\beta+\beta\pi_2\gamma_{NA}]}$
10	$\frac{m\pi_1}{[1-\beta]} + \frac{\beta\pi_1\alpha_{NA} m[\pi_2-\pi_1]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$	$\frac{m\pi_2}{1-\beta} - \frac{\beta\pi_2\gamma_{NA} m[\pi_2-\pi_1]}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}]}$
11	$\frac{m\pi_1}{1-\beta+\beta\pi_1\alpha_{NA}} + \frac{\beta\pi_1\alpha_{NA}\pi m\pi_2}{[1-\beta][1-\beta+\beta\pi_1\alpha_{NA}]}$	$\frac{m\pi_2}{1-\beta}$

Table 4: Expected cost of enforcing adopters and non-adopters

Since by construction we target surveillance resources to non-adopters, it is not surprising to see that $\widehat{m}_{NA}^{jklm}(y) \geq \widehat{m}_{A}^{jklm}(y)$. Moreover, since enforcement is more stringent in G_2, it holds that $\widehat{m}_{A}^{jklm}(2) \geq \widehat{m}_{A}^{jklm}(1)$ and $\widehat{m}_{NA}^{jklm}(2) \geq \widehat{m}_{NA}^{jklm}(1)$.

For a given strategy and initial allocation of non-adopters and adopters to groups y and x, respectively, the total expected enforcement cost can be characterized as:

$$\widehat{M}(y \mid x) = [\lambda(y \mid x)\widehat{m}_A(x) + [1 - \lambda(y \mid x)]\, \widehat{m}_{NA}(y)] \tag{11}$$

Like in the case of expected aggregate emissions, varying the transition probabilities creates two types of effects: a *direct effect* on enforcement cost, and an *indirect effect* on the rate of adoption. As shown in detail in Appendix D, increased probabilities (α_A, α_{NA}) increase the cost of enforcing compliance among adopters and non-adopters, respectively. In contrast, increased probabilities probabilities (γ_A, γ_{NA}) reduce the cost of enforcing compliance of adopters and non-adopters. Therefore, a targeted state-dependent enforcement has the positive indirect effect of reducing the total expected enforcement cost by means of enhancing the rate of adoption (and thus changing the composition of firms towards a larger fraction of firms whose cost of enforcement is lower). Nevertheless, this comes at the expense of an increased cost of enforcing compliance among non-adopters.

Proposition 5 *A targeted state-dependent enforcement scheme based on firms' past compliance and adoption of environmentally superior technologies can reduce the total expected cost of enforcing an emission standard.*

Let us disregard for the moment the effects of the initial allocation of firms to G_1 or G_2. Let the supercripts T and H denote the outcomes of targeted state-dependent and Harrington's enforcement, respectively. Given equation (11) and since under Harrington's enforcement the cost of enforcing compliance among adopters and non-adopters is the same, the difference in the total expected cost of enforcing an emission standard between the two enforcement schemes corresponds to:

$$\widehat{M}^T - \widehat{M}^H = \lambda^T \left[\widehat{m}_A^T - \widehat{m}_A^H\right] + \left[1 - \lambda^T\right] \left[\widehat{m}_{NA}^T - \widehat{m}_{NA}^H\right]. \tag{12}$$

The first term in brackets on the RHS of equation (12) is negative and corresponds to the lowered expected cost of enforcing compliance among adopters who are monitored less stringently under targeted state-dependent enforcement. The second term is positive and corresponds to the increased expected of enforcing compliance among non-adopters who are monitored more stringently under targeted state-dependent enforcement. Since these two effects have different signs, the sign of the difference in (12) depends on their relative magnitude. Let us find the conditions for when $\widehat{M}^T - \widehat{M}^H \leq 0$. We have:

$$\frac{\lambda^T}{1 - \lambda^T} \geq \frac{\widehat{m}_A^H - \widehat{m}_A^T}{\widehat{m}_{NA}^T - \widehat{m}_{NA}^H}. \tag{13}$$

That is, if the adoption rate induced by targeted state-dependent enforcement is sufficiently large, this enforcement scheme can reduce the total expected cost of enforcing an emission standard vis-a-vis Harrington's enforcement. How large must the adoption rate be to induce a reduced expected cost of enforcing the standard? The answer depends on how targeted state dependent enforcement affects adopters' and non-adopters' enforcement cost. Let us analyze the effects of targeted state dependent enforcement under each feasible strategy when all firms are initially allocated to G_1 by means of comparative statics with respect to the transition probabilities (see Appendix D for detailed comparative statics).

- f^{0000}. We have that $\widehat{m}_A^T = \widehat{m}_A^H = \widehat{m}_{NA}^T = \widehat{m}_{NA}^H$ and hence, $\widehat{M}^T - \widehat{M}^H = 0$ regardless of λ^T.

- f^{0010} and f^{0011}. Targeted state dependent enforcement has no effect on the cost of enforcing compliance among adopters and increases the cost of enforcing compliance among non-adopters, and hence $\widehat{M}^T - \widehat{M}^H > 0$ regardless of λ^T.

- f^{1010}, f^{1011} and f^{1111}. Targeted state dependent enforcement reduces the cost of enforcing compliance among adopters and increases the cost of enforcing compliance among non-adopters. If condition (13) holds, the overall effect is however a net reduction in the cost of enforcement as the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

Let us assume now that all firms are initially allocated to G_2

- f^{0000}, f^{0010}, f^{0011} and f^{1010}. Targeted state dependent enforcement reduces the cost of enforcing compliance among adopters and increases the cost of enforcing compliance among non-adopters. If condition (13) holds, the overall effect is however a net reduction in the cost of enforcement as the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

- f^{1011}. Targeted state dependent enforcement reduces the cost of enforcing compliance among adopters and has no effect on the cost of enforcing compliance among non-adopters, and hence $\widehat{M}^T - \widehat{M}^H < 0$ regardless of λ^T.

- f^{1111}. We have that $\widehat{m}^T_A = \widehat{m}^H_A = \widehat{m}^T_{NA} = \widehat{m}^H_{NA}$ and hence, $\widehat{M}^T - \widehat{M}^H = 0$ regardless of λ^T.

Thus, we can say that targeted state-dependent enforcement leads to a reduced cost of enforcement under f^{1011} if all firms are initially allocated to G_2. Provided condition (13) holds, it has no effect or the positive effect of reducing the cost of enforcement under f^{0000} , f^{1010}, f^{1011} and f^{1111}. Finally, whether or not targeted state-dependent enforcement leads to lowered enforcement costs under f^{0010} and f^{0011} depends on the initial allocation. In particular, the expected cost of enforcement is not lower than Harrington's when all firms are initially allocated to G_1.

In sum, even if the cost of enforcing compliance among non-adopters might be larger under targeted state-dependent enforcement than under Harrington's enforcement, the fact that targeted state-dependent enforcement changes the composition of firms towards a larger fraction of firms for which the cost of enforcement is lower implies that its total enforcement cost can be still lower if the adoption rate is sufficiently large.

Proposition 6 *The expected enforcement costs under targeted initial allocation are lower than the expected enforcement costs under an allocation that initially sends all firms to G_2. If the increase in adoption rate due to targeted initial allocation is sufficiently large, the expected enforcement costs under targeted initial allocation are also lower than the expected enforcement costs under an allocation that initially sends all firms to G_1.*

Given equation (11), the difference in expected enforcement costs between targeted initial allocation and the allocation where all firms are initially sent to G_1 corresponds to:

$$\widehat{M}(2 \mid 1) - \widehat{M}(1 \mid 1) = [\lambda(2 \mid 1) - \lambda(1 \mid 1)] [\widehat{m}_A(1) - \widehat{m}_{NA}(1)] + [1 - \lambda(2 \mid 1)] [\widehat{m}_{NA}(2) - \widehat{m}_{NA}(1)] \,. \tag{14}$$

The first term in brackets on the RHS of equation (14) is negative and corresponds to the effect of targeted initial allocation increasing the rate of adoption, and thus reducing the expected cost of enforcement as adopters demand less surveillance resources than non-adopters. The second term is positive and corresponds to the increased expected of enforcing compliance among non-adopters who are monitored more stringently under targeted initial allocation. Since these two effects have different signs, the final effect of the initial allocation on the expected enforcement cost depends on their relative magnitude. Let us find the conditions for when $\widehat{M}(2 \mid 1) - \widehat{M}(1 \mid 1) \leq 0$. We have two cases:

- $\widehat{M}(2 \mid 1) - \widehat{M}(1 \mid 1) = 0$ when $\widehat{m}_A(1) = \widehat{m}_{NA}(1)$, and $\lambda(2 \mid 1) = 1$.
- $\widehat{M}(2 \mid 1) - \widehat{M}(1 \mid 1) < 0$ when $\widehat{m}_A(1) - \widehat{m}_{NA}(1) < 0$, and $\frac{\lambda(2|1) - \lambda(1|1)}{1 - \lambda(2|1)} \geq \frac{\widehat{m}_{NA}(2) - \widehat{m}_{NA}(1)}{\widehat{m}_{NA}(1) - \widehat{m}_A(1)}$.

That is, if the increase in adoption rate $\lambda(2 \mid 1) - \lambda(1 \mid 1)$ due to targeted initial allocation is sufficiently large, the total enforcement cost can be lower than when both adopters and non-adopters are initially allocated to G_1.

The difference in the expected enforcement cost between targeted initial allocation and the allocation where all firms are initially sent to G_2 corresponds to:

$$\widehat{M}(2 \mid 1) - \widehat{M}(2 \mid 2) = [\lambda(2 \mid 1) - \lambda(2 \mid 2)] [\widehat{m}_A(2) - \widehat{m}_{NA}(2)] + \lambda(2 \mid 1) [\widehat{m}_A(1) - \widehat{m}_A(2)] \,. \tag{15}$$

As before, the first term in brackets on the RHS of equation (15) corresponds to the effect of targeted initial allocation increasing the rate of adoption, and thus reducing the expected cost of enforcement as adopters demand less surveillance resources than non-adopters. The second term corresponds to the reduction in the cost of monitoring adopters; under targeted initial allocation, adopters cause an expected enforcement cost of $\widehat{m}_A(1)$ instead of $\widehat{m}_A(2)$. Hence, compared with when both adopters and non-adopters are allocated to G_2, targeted initial allocation would not only lead to a higher adoption rate but also to a lower expected enforcement cost.

6 Numerical Simulations

In this section, we present a numerical example of the effects of the targeted state-dependent enforcement on the adoption rate, aggregated emissions and total enforcement cost. In line with the assumptions of the model, let the abatement cost function be given by $c(q) = c_0 - c_1 q + \frac{c_2}{2} q^2$, where $c'(q) = c_2 q - c_1 < 0$, and $c''(q) = c_2 > 0$. The penalty function is given by $\phi(q - \overline{q}) = \varphi_1(q - \overline{q}) + \frac{\varphi_2(q-\overline{q})^2}{2}$, where $\phi'(q - \overline{q}) = \varphi_1 + \varphi_2(q - \overline{q}) > 0$, and $\phi''(q - \overline{q}) = \varphi_2 > 0$. Then, given a monitoring probability $\pi_i \vee i = 1, 2$, the emission levels $q_A^{NC}(\pi_i)$ and $q_{NA}^{NC}(\pi_i)$ in a single play of this game are given by:[12]

$$
\begin{aligned}
q_A^{NC}(\pi_i) &= \overline{q} + \frac{\theta\left[c_1 - c_2\overline{q}\right] - \pi_i\varphi_1}{\pi_i\varphi_2 + \theta c_2}, \\
q_{NA}^{NC}(\pi_i) &= \overline{q} + \frac{\left[c_1 - c_2\overline{q}\right] - \pi_i\varphi_1}{\pi_i\varphi_2 + c_2}.
\end{aligned}
$$

Let $c_0 = 50$, $c_1 = 10$, and $c_2 = 1$. Moreover, let $\theta = 0.65$, which implies that technology adoption allows for a 35% reduction in the abatement cost. The total number of firms is set at $n = 100$. The cost of adopting the new technology is assumed to be uniformly distributed in the interval $[20,\ 100]$. The emission standard is set at $\overline{q} = 5$. The coefficients for the penalty functions are set at $\varphi_1 = 20$ and $\varphi_2 = 1$ and the discount factor is set at $\beta = 0.95$. Finally, the unitary inspection cost m is equal to 1. Regarding the stringency of the enforcement scheme, we assume that $\pi_1 = 0.15$ and $\pi_2 = 0.5$. Moreover, under a two-group enforcement scheme, $\alpha_A = \alpha_{NA} = 0.5$, and $\gamma_A = \gamma_{NA} = 0.25$. Under a targeted state-dependent enforcement, $\alpha_A = 0.4$, $\alpha_{NA} = 0.6$, $\gamma_A = 0.35$, and $\gamma_{NA} = 0.15$.

[12] See equation (1).

Table 5 presents the adoption rate, expected aggregate emissions, and expected total enforcement cost under targeted state-dependent enforcement and Harrington's two-group enforcement scheme for each feasible strategy when all firms are initially allocated to G_1 and G_2. Table 6 compares the outcomes of both enforcement schemes under targeted initial allocation where non-adopters are initially allocated to G_2 and adopters to G_1.

		Two Groups			**Four Groups**		
f	**Initial Allocation**	λ	$\widehat{Q}$	$\widehat{M}$	λ	$\widehat{Q}$	$\widehat{M}$
0000	(1 | 1)	0.844	10000	300.00	0.844	10000	300.00
	(2 | 2)	0.844	10000	507.41	0.844	10000	469.56
0010	(1 | 1)	0.538	11130	396.00	0.589	10839	419.04
	(2 | 2)	0.629	10639	571.72	0.694	10367	552.73
0011	(1 | 1)	0.664	10481	438.02	0.683	10406	439.88
	(2 | 2)	0.844	10000	584.38	0.844	10000	545.94
1010	(1 | 1)	0.545	11352	507.81	0.596	11118	503.91
	(2 | 2)	0.633	10827	653.65	0.700	10626	629.53
1011	(1 | 1)	0.671	10766	574.71	0.691	10738	537.37
	(2 | 2)	0.849	10262	706.09	0.850	10323	638.12
1111	(1 | 1)	0.668	10648	711.34	0.688	10602	694.37
	(2 | 2)	0.844	10000	1000	0.844	10000	1000

Table 5: Targeted state-dependent enforcement vs. a two-group targeting scheme

As expected, when adopters and non-adopters fully comply with the regulation, there are no differences in adoption rate or expected aggregate emissions between targeted state-dependent enforcement and a two-group enforcement scheme, regardless of the initial allocation. Nevertheless, when firms are initially allocated to G_2, the cost of enforcement is lower for the targeted state-dependent enforcement. For the remaining feasible strategies, targeted state-dependent enforcement induces a higher rate of adoption, lower emissions, lower total enforcement cost, or a combination of these changes.

		Two-Groups			Four-Groups		
f	**Initial Allocation**	λ	$\widehat{Q}$	$\widehat{M}$	λ	$\widehat{Q}$	$\widehat{M}$
0000	(2 | 1)	0.844	10000	332.41	0.844	10000	333.00
0010	(2 | 1)	0.629	10639	431.34	0.694	10367	440.42
0011	(2 | 1)	0.844	10000	409.38	0.844	10000	409.38
1010	(2 | 1)	0.635	10907	560.97	0.702	10705	539.33
1011	(2 | 1)	0.851	10374	581.34	0.851	10421	528.30
1111	(2 | 1)	0.848	10219	755.28	0.848	10248	722.51

Table 6: Initial targeted allocation under a targeted state-dependent enforcement vs. a two-group targeting scheme

Table 6 (compared with Table 5) shows that, as expected, targeted initial allocation generates less emissions than an allocation that sends all firms to G_1. If all firms are initially sent to G_2, the comparison is less clear, but we can say that aggregate emissions are higher under targeted initial allocation under most feasible strategies. Finally, when it comes to total enforcement costs, as expected, targeted initial allocation generates a lower total cost of enforcement than does an allocation that sends all firms to G_2. If all firms are initially sent to G_1, the comparison is less clear, but we can say that total enforcement costs are higher under targeted initial allocation under most feasible strategies.

Given our choice of parameters, the critical probabilities that define the optimal strategy are equal to $(\overline{\pi}_1^A, \overline{\pi}_2^A) = (0.163, 0.290)$ and $(\overline{\pi}_1^{NA}, \overline{\pi}_2^{NA}) = (0.250, 0.481)$. Hence, the optimal strategy corresponds to f^{1010}. Thus, with regard to a two-group enforcement scheme, targeted state-dependent enforcement induces a higher rate of adoption, lower emissions and lower total enforcement cost under all allocations of adopters and non-adopters to the target and non-target groups G_1 and G_2.

7 Conclusions

A significant fraction of the literature on environmental regulation has focused on how environmental policies are and should be enforced. Harrington (1988) shows that a suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement. Regulators can define a monitoring schedule for firms according to their past compliance records or their potential emissions. If firms face a targeted enforcement strategy where those with higher potential emissions are monitored more closely, a plausible response may be to adopt a new and more efficient abatement technology that allows them to reduce potential emissions and thus avoid more stringent monitoring. Using a four-group targeting scheme (denoted *targeted state-dependent enforcement*), we have analyzed the effects of an audit framework where targeting is based not only on firms' past compliance record but also on adoption of environmentally superior technologies.

The results suggest that targeted state-dependent enforcement has a deterrent effect and can help reduce total enforcement costs. Firstly, it changes the composition of firms in the industry toward an increased fraction of cleaner firms that pollute and violate less. Secondly, it provides non-adopters with stronger incentives to comply because surveillance resources are targeted more heavily toward non-adopters. Finally, due to the increased fraction of adopters for which the cost of enforcement is lower, the total enforcement costs can be reduced.

The fact that the technology adoption rate is influenced by monitoring strategy is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the emission standard to be imposed. Such a regulator may use a differentiated monitoring strategy to induce technology adoption and thereby reduce aggregate emissions for a given politically feasible emission standard. Consequently, targeted monitoring strategies should not be ruled out as a plausible enforcement policy if the interaction between monitoring probabilities and technology adoption is taken into consideration.

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Appendix A

The critical probability $\bar{\pi}_2^A$ is determined by equation (5), which defines an implicit function

$$f(\bar{\pi}_2^A, \pi_1, \alpha_A, \gamma_A) = \theta[c(\bar{q}) - c(q_A^{NC}(\bar{\pi}_2^A))] - \Gamma - \bar{\pi}_2^A \varphi(q_A^{NC}(\bar{\pi}_2^A) - \bar{q}) = 0,$$

where

$$\Gamma = \beta\overline{\pi}_2^A\gamma_A \frac{\left[\theta\left[c(\overline{q}) - c(q_A^{NC}(\pi_1)\right] - \pi_1\phi(q_A^{NC}(\pi_1) - \overline{q})\right]}{\left[1-\beta+\beta\pi_1\alpha_A+\beta\overline{\pi}_2^A\gamma_A\right]} > 0 \text{ if } \pi_1 < \bar{\pi}_1^A.$$

By the implicit function theorem, we have:

$$\frac{\partial \bar{\pi}_2^A}{\partial \pi_1} = -\frac{\partial f/\partial \pi_1}{\partial f/\partial \bar{\pi}_2^A}.$$

Differentiating $f(.)$ with respect to π_1 yields:

$$\frac{\partial f}{\partial \pi_1} = -\frac{\partial \Gamma}{\partial \pi_1} = \frac{[1-\beta+\beta\bar{\pi}_2^A\gamma_A]\beta\bar{\pi}_2^A\gamma_A\varphi(q_A^{NC}(\pi_1) - \bar{q}) + \beta\alpha_A\beta\bar{\pi}_2^A\gamma_A\left[\theta[c(\bar{q}) - c(q_A^{NC}(\pi_1))]\right]}{[1-\beta+\beta\pi_1\alpha_A+\beta\bar{\pi}_2^A\gamma_A]^2} > 0.$$

Differentiating $f(.)$ with respect to π_2 yields:

$$\frac{\partial f}{\partial \bar{\pi}_2^A} = -\varphi(q_A^{NC}(\bar{\pi}_2^A) - \bar{q}) - (1-\beta+\beta\pi_1\alpha_A)\frac{\Gamma}{\bar{\pi}_2^A(1-\beta+\beta\pi_1\alpha_A+\beta\bar{\pi}_2^A\gamma_A)} < 0.$$

Hence, $\frac{\partial \bar{\pi}_2^A}{\partial \pi_1} > 0$.

By analogy, we differentiate $f(.)$ with respect to the transition probabilities α_A and γ_A, which yields:

$$\begin{aligned}
\frac{\partial f}{\partial \alpha_A} &= -\frac{\partial \Gamma}{\partial \alpha_A} = \frac{\beta\pi_1\Gamma}{1-\beta+\beta\pi_1\alpha_A+\beta\bar{\pi}_2^A\gamma_A} > 0, \\
\frac{\partial f}{\partial \gamma_A} &= -\frac{\partial \Gamma}{\partial \gamma_A} == -\frac{(1-\beta+\beta\pi_1\alpha_A)\Gamma}{\gamma_A(1-\beta+\beta\pi_1\alpha_A+\beta\bar{\pi}_2^A\gamma_A)} < 0.
\end{aligned}$$

Hence, $\frac{\partial \bar{\pi}_2^A}{\partial \alpha_A} = -\frac{\partial f/\partial \alpha_A}{\partial f/\partial \bar{\pi}_2^A} > 0$ and $\frac{\partial \bar{\pi}_2^A}{\partial \gamma_A} = -\frac{\partial f/\partial \gamma_A}{\partial f/\partial \bar{\pi}_2^A} < 0$.

Appendix B

Let us compute the derivatives of adopters' and non-adopters' expected costs under different strategies with respect to the probabilities (α_A, γ_A) and $(\alpha_{NA}, \gamma_{NA})$.

Effects of (α_A, γ_A)

As shown in Table 2, regardless of the *initial allocation*, the transition probabilities (α_A, γ_A) affect only adopters' expected costs. Since under the strategies f^{0000}, f^{0010} and f^{0011} adopters already comply, decreasing α_A or increasing γ_A has no effect on emissions, abatement or rate of adoption. Thus , $\frac{\partial E_A^{0000}(y)}{\partial \alpha_A} = \frac{\partial E_A^{0010}(y)}{\partial \alpha_A} = \frac{\partial E_A^{0011}(y)}{\partial \alpha_A} = 0$, and $\frac{\partial E_A^{0000}(y)}{\partial \gamma_A} = \frac{\partial E_A^{0010}(y)}{\partial \gamma_A} = \frac{\partial E_A^{0011}(y)}{\partial \gamma_A} = 0 \vee y = 1, 2$.

Instead, if the strategies f^{1010} or f^{1011} are optimal, the derivatives $\frac{\partial E_A^{1010}(y)}{\partial \alpha_A}$ and $\frac{\partial E_A^{1011}(y)}{\partial \alpha_A}$ are the same, positive, and given by:

$$\begin{aligned}
\frac{\partial E_A^{1010}(1)}{\partial \alpha_A} &= \beta\pi_1 \left[1-\beta+\beta\pi_2\gamma_A\right] \frac{\left[\theta c(\overline{q}) - \left[\theta c(q_A^{NC}(\pi_1)) + \pi_1\phi(q_A^{NC}(\pi_1)-\overline{q})\right]\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A\right]^2} > 0, \\
\frac{\partial E_A^{1010}(2)}{\partial \alpha_A} &= \frac{\beta\pi_2\gamma_A}{1-\beta+\beta\pi_2\gamma_A} \frac{\partial E_A^{1010}(1)}{\partial \alpha_A} > 0.
\end{aligned}$$

If f^{1111} is optimal, $\frac{\partial E_A^{1111}(2)}{\partial \alpha_A} = 0$. In contrast, $\frac{\partial E_A^{1111}(1)}{\partial \alpha_A} > 0$ and corresponds to:

$$\frac{\partial E_A^{1111}(1)}{\partial \alpha_A} = \beta\pi_1 \frac{\left[\left[\theta c(q_A^{NC}(\pi_2)) + \pi_2\phi(q_A^{NC}(\pi_2)-\overline{q})\right] - \left[\theta c(q_{NA}^{NC}(\pi_1)) + \pi_1\phi(q_{NA}^{NC}(\pi_1)-\overline{q})\right]\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A\right]^2} > 0.$$

The derivatives $\frac{\partial E_A^{1010}(y)}{\partial \gamma_A}$ and $\frac{\partial E_A^{1011}(y)}{\partial \gamma_A}$ are the same, negative, and given by:

$$\begin{aligned}
\frac{\partial E_A^{1010}(1)}{\partial \gamma_A} &= -\frac{\beta\pi_2\alpha_A}{1-\beta+\beta\pi_2\gamma_A} \frac{\partial E_A^{1010}(1)}{\partial \alpha_A} < 0, \\
\frac{\partial E_A^{1010}(2)}{\partial \gamma_A} &= -\frac{\pi_2\left[1-\beta+\beta\pi_1\alpha_A\right]}{\beta\pi_1\gamma_A} \frac{\partial E_A^{1010}(2)}{\partial \alpha_A} < 0.
\end{aligned}$$

If policy f^{1111} is optimal, $\frac{\partial E_A^{1111}(y)}{\partial \gamma_A} = 0, \vee\ y = 1, 2$.
In sum, from the analysis above, it is clear that $\frac{\partial E_A^{jklm}(y)}{\partial \alpha_A} \geq 0$ and $\frac{\partial E_A^{jklm}(y)}{\partial \gamma_A} \leq 0$.

Effects of $(\alpha_{NA}, \gamma_{NA})$

Note that, regardless of the *initial allocation*, the transition probabilities $(\alpha_{NA}, \gamma_{NA})$ affect non-adopters' expected costs. Since under the policy f^{0000} non-adopters already comply, increasing α_{NA} or decreasing γ_{NA} has no effect on the rate of adoption. Thus, $\frac{\partial E_{NA}^{0000}(y)}{\partial \alpha_{NA}} = \frac{\partial E_{NA}^{0000}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$.

If the strategy f^{0010} or f^{1010} is optimal, the derivatives $\frac{\partial E^{0010}_{NA}(y)}{\partial \alpha_{NA}}$ and $\frac{\partial E^{1010}_{NA}(y)}{\partial \alpha_{NA}}$ are the same, positive and given by:

$$\begin{aligned}\frac{\partial E^{0010}_{NA}(1)}{\partial \alpha_{NA}} &= \beta\pi_1\left[1-\beta+\beta\pi_2\gamma_{NA}\right]\frac{\left[c(\overline{q})-\left[c(q^{NC}_{NA}(\pi_1))+\pi_1\phi(q^{NC}_{NA}(\pi_1)-\overline{q})\right]\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}\right]^2}>0,\\ \frac{\partial E^{0010}_{NA}(2)}{\partial \alpha_{NA}} &= \frac{\beta\pi_2\gamma_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial E^{0010}_{NA}(1)}{\partial \alpha_{NA}}>0.\end{aligned}$$

If the strategy f^{0011} , f^{1011} or f^{1111} is optimal, $\frac{\partial E^{0011}_{NA}(y)}{\partial \alpha_{NA}}$, $\frac{\partial E^{1011}_{NA}(y)}{\partial \alpha_{NA}}$ and $\frac{\partial E^{1111}_{NA}(y)}{\partial \alpha_{NA}}$ are the same, and equal to zero if the firms are initially allocated to G_2. In contrast, the derivatives $\frac{\partial E^{0011}_{NA}(1)}{\partial \alpha_{NA}}$, $\frac{\partial E^{1011}_{NA}(1)}{\partial \alpha_{NA}}$, and $\frac{\partial E^{1111}_{NA}(1)}{\partial \alpha_{NA}}$ are positive and given by:

$$\frac{\partial E^{0011}_{NA}(1)}{\partial \alpha_{NA}}=\beta\pi_1\frac{\left[\left[c(q^{NC}_{NA}(\pi_2))+\pi_2\phi(q^{NC}_{NA}(\pi_2)-\overline{q})\right]-\left[c(q^{NC}_{NA}(\pi_1))+\pi_1\phi(q^{NC}_{NA}(\pi_1)-\overline{q})\right]\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}\right]^2}>0.$$

The derivatives $\frac{\partial E^{0010}_{NA}(y)}{\partial \gamma_{NA}}$ and $\frac{\partial E^{1010}_{NA}(y)}{\partial \gamma_{NA}}$ are the same, negative, and given by:

$$\begin{aligned}\frac{\partial E^{0010}_{NA}(1)}{\partial \gamma_{NA}} &= -\frac{\beta\pi_2\alpha_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial E^{0010}_{NA}(1)}{\partial \alpha_{NA}}<0,\\ \frac{\partial E^{0010}_{NA}(2)}{\partial \gamma_{NA}} &= -\frac{1-\beta+\beta\pi_1\alpha_{NA}}{\beta\pi_1\gamma_{NA}}\frac{\partial E^{0010}_{NA}(2)}{\partial \alpha_{NA}}<0.\end{aligned}$$

By analogy, $\frac{\partial E^{0011}_{NA}(y)}{\partial \gamma_{NA}}$, $\frac{\partial E^{1011}_{NA}(y)}{\partial \gamma_{NA}}$, and $\frac{\partial E^{1111}_{NA}(y)}{\partial \gamma_{NA}}$ are the same, and equal to zero.

In sum, from the analysis above, it is clear that $\frac{\partial E^{jklm}_{NA}(y)}{\partial \alpha_{NA}}\geq 0$ and $\frac{\partial E^{jklm}_{NA}(y)}{\partial \gamma_{NA}}\leq 0$.

Marginal Variations in Transition Probabilities

From the analysis above, it follows that $\left|\frac{\partial E^{jklm}_{NA}(y)}{\partial \alpha_{NA}}\right|\geq\left|\frac{\partial E^{jklm}_{A}(y)}{\partial \alpha_{A}}\right|$ and $\left|\frac{\partial E^{jklm}_{NA}(y)}{\partial \gamma_{NA}}\right|\geq\left|\frac{\partial E^{jklm}_{A}(y)}{\partial \gamma_{A}}\right|$ $\vee$ $jklm\neq 1011$, implying that, at the margin, variations in $(\alpha_{NA},\ \gamma_{NA})$ have a larger effect on the rate of adoption than do marginal variations in $(\alpha_A,\ \gamma_A)$.

Moreover, it follows that $\left|\frac{\partial E^{jklm}_{A}(1)}{\partial \alpha_{A}}\right|\geq\left|\frac{\partial E^{jklm}_{A}(2)}{\partial \alpha_{A}}\right|$ and $\left|\frac{\partial E^{jklm}_{NA}(1)}{\partial \alpha_{NA}}\right|\geq\left|\frac{\partial E^{jklm}_{NA}(2)}{\partial \alpha_{NA}}\right|$, implying that the marginal effects of (α_A,α_{NA}) on the rate of adoption are larger if firms are initially allocated to G_1. The reverse holds for (γ_A,γ_{NA}), where $\left|\frac{\partial E^{jklm}_{A}(2)}{\partial \gamma_{A}}\right|\geq\left|\frac{\partial E^{jklm}_{A}(1)}{\partial \gamma_{A}}\right|$, and $\left|\frac{\partial E^{jklm}_{NA}(2)}{\partial \gamma_{NA}}\right|\geq\left|\frac{\partial E^{jklm}_{NA}(1)}{\partial \gamma_{NA}}\right|$ indicating that their marginal effects on the rate of adoption are larger if firms are initially allocated to G_2.

Appendix C

Let us compute the derivatives of adopters' and non-adopters' expected emissions with respect to the probabilities (α_A, γ_A) and $(\alpha_{NA}, \gamma_{NA})$. As shown in Table 3, regardless of the *initial allocation*, the transition probabilities (α_A, γ_A) affect only adopters' expected emissions. Since under the strategies f^{0000}, f^{0010} and f^{0011} adopters already comply, decreasing α_A or increasing γ_A has no effect on emissions, abatement or rate of adoption. In contrast, if the strategies f^{1010} or f^{1011} are optimal, the derivatives $\frac{\partial \widehat{q}_A^{1010}(y)}{\partial \alpha_A}$ and $\frac{\partial \widehat{q}_A^{1011}(y)}{\partial \alpha_A}$ are the same $\vee\ y = 1, 2$, negative, and given by:

$$\begin{aligned}
\frac{\partial \widehat{q}_A^{1010}(1)}{\partial \alpha_A} &= \frac{\beta\pi_1 \left[1-\beta+\beta\pi_2\gamma_A\right]\left[\overline{q} - q_A^{NC}(\pi_1)\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_A+\beta\pi_2\gamma_A\right]^2} < 0, \\
\frac{\partial \widehat{q}_A^{1010}(2)}{\partial \alpha_A} &= \frac{\beta\pi_2\gamma_A}{1-\beta+\beta\pi_2\gamma_A}\frac{\partial \widehat{q}_A^{1010}(1)}{\partial \alpha_A} < 0.
\end{aligned}$$

If the strategy f^{1111} is optimal, $\frac{\partial \widehat{q}_A^{1111}(2)}{\partial \alpha_A} = 0$. In contrast, $\frac{\partial \widehat{q}_A^{1111}(1)}{\partial \alpha_A}$ is given by:

$$\frac{\partial \widehat{q}_A^{1111}(1)}{\partial \alpha_A} = \frac{\beta\pi_1\left[q_A^{NC}(\pi_2) - q_A^{NC}(\pi_1)\right]}{\left[1-\beta+\beta\pi_1\alpha_A\right]^2} < 0.$$

The derivatives $\frac{\partial \widehat{q}_A^{1010}(y)}{\partial \gamma_A}$ and $\frac{\partial \widehat{q}_A^{1011}(y)}{\partial \gamma_A}$ are the same $\vee\ y = 1, 2$, positive, and given by:

$$\begin{aligned}
\frac{\partial \widehat{q}_A^{1010}(1)}{\partial \gamma_A} &= \frac{\beta\pi_2\alpha_A}{1-\beta+\beta\pi_2\gamma_A}\frac{\partial \widehat{q}_A^{1010}(1)}{\partial \alpha_A} > 0, \\
\frac{\partial \widehat{q}_A^{1010}(2)}{\partial \gamma_A} &= \frac{\pi_2\left[1-\beta+\beta\pi_1\alpha_A\right]}{\pi_1\left[1-\beta+\beta\pi_2\gamma_A\right]}\frac{\partial \widehat{q}_A^{1010}(1)}{\partial \alpha_A} > 0.
\end{aligned}$$

If the policy f^{1111} is optimal, $\frac{\partial \widehat{q}_A^{1010}(2)}{\partial \gamma_A} = 0,\ \vee\ y = 1, 2$.

Regarding the transition probabilities $(\alpha_{NA}, \gamma_{NA})$, since under f^{0000} non-adopters already comply, increasing α_{NA} or decreasing γ_{NA} has no effect on the rate of adoption. If the strategy f^{0010} or f^{1010} is optimal, the derivatives $\frac{\partial \widehat{q}_{NA}^{0010}(y)}{\partial \alpha_{NA}}$ and $\frac{\widehat{q}_{NA}^{1010}(y)}{\partial \alpha_{NA}}$ are the same $\vee\ y = 1, 2$, positive, and given by:

$$\begin{aligned}
\frac{\partial \widehat{q}_{NA}^{0010}(1)}{\partial \alpha_{NA}} &= \frac{\beta\pi_1\left[1-\beta+\beta\pi_2\gamma_{NA}\right]\left[\overline{q} - q_{NA}^{NC}(\pi_1)\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}\right]^2} < 0, \\
\frac{\partial \widehat{q}_{NA}^{0010}(2)}{\partial \alpha_{NA}} &= \frac{\beta\pi_2\gamma_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial \widehat{q}_{NA}^{0010}(1)}{\partial \alpha_{NA}} < 0.
\end{aligned}$$

If the strategy f^{0011}, f^{1011} or f^{1111} is optimal, $\frac{\partial \widehat{q}_{NA}^{0011}(y)}{\partial \alpha_{NA}}$, $\frac{\partial \widehat{q}_{NA}^{1011}(y)}{\partial \alpha_{NA}}$ and $\frac{\partial \widehat{q}_{NA}^{1111}(y)}{\partial \alpha_{NA}}$ are the same $\vee\ y = 1, 2$ and equal to zero if the firms are initially allocated to G_2. In contrast, the derivatives $\frac{\partial \widehat{q}_{NA}^{0011}(1)}{\partial \alpha_{NA}}$, $\frac{\partial \widehat{q}_{NA}^{1011}(1)}{\partial \alpha_{NA}}$ and $\frac{\partial \widehat{q}_{NA}^{1111}(1)}{\partial \alpha_{NA}}$ are negative and given by:

$$\frac{\partial \widehat{q}_{NA}^{0011}(1)}{\partial \alpha_{NA}} = \frac{\beta\pi_1\left[q_{NA}^{NC}(\pi_2) - q_{NA}^{NC}(\pi_1)\right]}{\left[1-\beta+\beta\pi_1\alpha_{NA}\right]^2} < 0.$$

The derivatives $\frac{\partial \widehat{q}_{NA}^{0010}(y)}{\partial \gamma_{NA}}and\frac{\partial \widehat{q}_{NA}^{1010}(y)}{\partial \gamma_{NA}}$ are the same $\vee$ $y = 1, 2$, positive, and given by:

$$\begin{aligned} \frac{\partial \widehat{q}_{NA}^{0010}(1)}{\partial \gamma_{NA}} &= -\frac{\beta\pi_2\alpha_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial \widehat{q}_{NA}^{0010}(1)}{\partial \alpha_{NA}} > 0, \\ \frac{\partial \widehat{q}_{NA}^{0010}(2)}{\partial \gamma_{NA}} &= \frac{\pi_2\left[1-\beta+\beta\pi_1\alpha_{NA}\right]}{\pi_1\left[1-\beta+\beta\pi_2\gamma_{NA}\right]}\frac{\partial \widehat{q}_{NA}^{0010}(1)}{\partial \alpha_{NA}} > 0. \end{aligned}$$

By analogy, $\frac{\partial \widehat{q}_{NA}^{0011}(y)}{\partial \gamma_{NA}}$, $\frac{\partial \widehat{q}_{NA}^{1011}(y)}{\partial \gamma_{NA}}$, and$\frac{\partial \widehat{q}_{NA}^{1111}(y)}{\partial \gamma_{NA}}$ are the same $\vee$ $y = 1, 2$ and equal to zero.

Marginal Variations in Transition Probabilities

From the analysis above, it follows that:

- f^{0000}. We have that $\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A} = \frac{\partial \widehat{q}_A(y)}{\partial \gamma_A} = \frac{\partial \widehat{q}_{NA}(y)}{\partial \alpha_{NA}} = \frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$. Hence, targeted state-dependent enforcement has no effect on adopters' and non-adopters' emissions.

- f^{0010}. We have that $\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A} = \frac{\partial \widehat{q}_A(y)}{\partial \gamma_A} = 0 \vee y = 1, 2$. In contrast, $\frac{\partial \widehat{q}_{NA}(y)}{\partial \alpha_{NA}} < 0 < \frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}} \vee$ $y = 1, 2$. Hence, targeted state-dependent enforcement has no effect on adopters' emissions but reduces non-adopters' emissions.

- f^{0011}. We have that $\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A} = \frac{\partial \widehat{q}_A(y)}{\partial \gamma_A} = 0 \vee y = 1, 2$. In contrast, $\frac{\partial \widehat{q}_{NA}(1)}{\partial \alpha_{NA}} < 0 = \frac{\partial \widehat{q}_{NA}(1)}{\partial \gamma_{NA}}$, while $\frac{\partial \widehat{q}_{NA}(2)}{\partial \alpha_{NA}} = \frac{\partial \widehat{q}_{NA}(2)}{\partial \gamma_{NA}} = 0$. Hence, targeted state-dependent enforcement has no effect on adopters' or non-adopters' emissions if firms are initially allocated to G_2. However, it reduces non-adopters' emissions if they are initially allocated to G_1.

- f^{1010}. We have that $\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A} < 0 < \frac{\partial \widehat{q}_A(y)}{\partial \gamma_A}$ and $\frac{\partial \widehat{q}_{NA}(y)}{\partial \alpha_{NA}} < 0 < \frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}} \vee y = 1, 2$. Moreover, $\left|\frac{\partial \widehat{q}_{NA}(y)}{\partial \alpha_{NA}}\right| > \left|\frac{\partial \widehat{q}_A(x)}{\partial \alpha_A}\right|$ and $\left|\frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}}\right| > \left|\frac{\partial \widehat{q}_A(y)}{\partial \gamma_A}\right| \vee y, x = 1, 2$ and $y \geq x$, implying that the marginal effects of the probabilities α_{NA} and γ_{NA} are larger than the marginal effects of the probabilities α_A and γ_A.

- f^{1011}. We have that $\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A} < 0 < \frac{\partial \widehat{q}_A(y)}{\partial \gamma_A} \vee y = 1, 2$. In contrast, $\frac{\partial \widehat{q}_{NA}(1)}{\partial \alpha_A} < \frac{\partial \widehat{q}_{NA}(2)}{\partial \alpha_A} = 0$ and $\frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$. Moreover, $\left|\frac{\partial \widehat{q}_A(y)}{\partial \alpha_A}\right| \geq \left|\frac{\partial \widehat{q}_{NA}(y)}{\partial \alpha_{NA}}\right|$ and $\left|\frac{\partial \widehat{q}_A(y)}{\partial \gamma_A}\right| > \left|\frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}}\right| \vee y, x = 1, 2$ and $y \geq x$, implying that the the marginal effects of the probabilities α_A and γ_A are larger than the marginal effects of the probabilities α_{NA} and γ_{NA}.

- f^{1111}. We have that $\frac{\partial \widehat{q}_A(1)}{\partial \alpha_A} < \frac{\partial \widehat{q}_A(2)}{\partial \alpha_A} = 0$ and $\frac{\partial \widehat{q}_A(y)}{\partial \gamma_A} = 0 \vee y = 1, 2$. By analogy, $\frac{\partial \widehat{q}_{NA}(1)}{\partial \alpha_A} < \frac{\partial \widehat{q}_{NA}(2)}{\partial \alpha_A} = 0$ and $\frac{\partial \widehat{q}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$. Moreover, $\left|\frac{\partial \widehat{q}_{NA}(1)}{\partial \alpha_{NA}}\right| > \left|\frac{\partial \widehat{q}_A(1)}{\partial \alpha_A}\right|$, implying that the marginal effect of the probability α_{NA} is larger than the marginal effects of the probability α_A when firms are initially allocated to G_1.

Appendix D

Let us compute the derivatives of adopters' and non-adopters' expected enforcement cost with respect to the probabilities of transition (α_A, γ_A) and $(\alpha_{NA}, \gamma_{NA})$. As shown in Table 4, regardless of the *initial allocation*, the transition probabilities (α_A, γ_A) affect only the cost of enforcing compliance among adopters. We have that $\frac{\partial \widehat{m}_A^{0000}(y)}{\partial \alpha_A} = \frac{\partial \widehat{m}_A^{0010}(y)}{\partial \alpha_A} = \frac{\partial \widehat{m}_A^{0011}(y)}{\partial \alpha_A} \vee\, y = 1, 2$. Moreover, the derivatives $\frac{\partial \widehat{m}_A^{0000}(y)}{\partial \gamma_A}, \frac{\partial \widehat{m}_A^{0010}(y)}{\partial \gamma_A}$, and $\frac{\partial \widehat{m}_A^{0011}(y)}{\partial \gamma_A}$ are the same $\vee\, y = 1, 2$. If adopters are initially allocated to G_1, these derivatives are equal to zero. If adopters are initially allocated to G_2, the derivatives with respect to γ_A are negative and given by:

$$\frac{\partial \widehat{m}_A^{0000}(2)}{\partial \gamma_A} = -\frac{\beta m \pi_2 \left[\pi_2 - \pi_1\right]}{\left[1 - \beta + \beta \pi_2 \gamma_A\right]^2} < 0.$$

If strategy f^{1010} or f^{1011} is optimal, the derivatives $\frac{\partial \widehat{m}_A^{1010}(y)}{\partial \alpha_A}$ and $\frac{\partial \widehat{m}_A^{1011}(y)}{\partial \alpha_A}$ are the same $\vee\, y = 1, 2$, positive, and given by

$$\begin{aligned} \frac{\partial \widehat{m}_A^{1010}(1)}{\partial \alpha_A} &= \frac{\beta m \pi_1 \left[1 - \beta + \beta \pi_2 \gamma_A\right]\left[\pi_2 - \pi_1\right]}{\left[1 - \beta\right]\left[1 - \beta + \beta \pi_1 \alpha_A + \beta \pi_2 \gamma_A\right]^2} > 0, \\ \frac{\partial \widehat{m}_A^{1010}(2)}{\partial \alpha_A} &= \frac{\beta \pi_2 \gamma_A}{1 - \beta + \beta \pi_2 \gamma_A} \frac{\partial \widehat{m}_A^{0010}(1)}{\partial \alpha_A} > 0. \end{aligned}$$

The derivatives $\frac{\partial \widehat{m}_A^{1010}(y)}{\partial \gamma_A}$ and $\frac{\partial \widehat{m}_A^{1011}(y)}{\partial \gamma_A}$ are the same $\vee\, y = 1, 2$, negative, and given by

$$\begin{aligned} \frac{\partial \widehat{m}_A^{1010}(1)}{\partial \gamma_A} &= -\frac{\beta \pi_2 \alpha_A}{1 - \beta + \beta \pi_2 \gamma_A} \frac{\partial \widehat{m}_A^{0010}(1)}{\partial \alpha_A} < 0, \\ \frac{\partial \widehat{m}_A^{1010}(2)}{\partial \gamma_A} &= -\frac{\beta \pi_1 \gamma_A}{1 - \beta + \beta \pi_1 \alpha_A} \frac{\partial \widehat{m}_A^{0010}(2)}{\partial \alpha_A} < 0. \end{aligned}$$

If the strategy f^{1111} is optimal, $\frac{\partial \widehat{m}_A^{1111}(2)}{\partial \alpha_A} = 0$. In contrast,

$$\frac{\partial \widehat{m}_A^{1111}(1)}{\partial \alpha_A} = \frac{\beta m \pi_1 \left[\pi_2 - \pi_1\right]}{\left[1 - \beta + \beta \pi_1 \alpha_A\right]^2} > 0.$$

Moreover, $\frac{\partial \widehat{m}_A^{1111}(2)}{\partial \gamma_A} = 0, \vee\, y = 1, 2$.

Regarding the transition probabilities $(\alpha_{NA}, \gamma_{NA})$, we have that $\frac{\partial \widehat{m}_{NA}^{0000}(y)}{\partial \alpha_{NA}} = 0 \vee\, y = 1, 2$. Moreover, the derivatives $\frac{\partial \widehat{m}_{NA}^{0000}(y)}{\partial \gamma_{NA}}$ are the same $\vee\, y = 1, 2$. If non-adopters are initially allocated to G_1, they are equal to zero. If non-adopters are initially allocated to G_2, they are negative and given by:

$$\frac{\partial \widehat{m}_{NA}^{0000}(2)}{\partial \gamma_{NA}} = -\frac{\beta m \pi_2 \left[\pi_2 - \pi_1\right]}{\left[1-\beta+\beta\pi_2\gamma_{NA}\right]^2} < 0.$$

If the strategy f^{0010} or f^{1010} is optimal, the derivatives $\frac{\partial \widehat{m}_{NA}^{0010}(y)}{\partial \alpha_{NA}}$ and $\frac{\widehat{m}_{NA}^{1010}(y)}{\partial \alpha_{NA}}$ are the same $\vee$ $y = 1, 2$, positive, and given by:

$$\begin{aligned}
\frac{\partial \widehat{m}_{NA}^{0010}(1)}{\partial \alpha_{NA}} &= \frac{\beta m \pi_1 \left[1-\beta+\beta\pi_2\gamma_{NA}\right]\left[\pi_2 - \pi_1\right]}{\left[1-\beta\right]\left[1-\beta+\beta\pi_1\alpha_{NA}+\beta\pi_2\gamma_{NA}\right]^2} > 0, \\
\frac{\partial \widehat{m}_{NA}^{0010}(2)}{\partial \alpha_{NA}} &= \frac{\beta\pi_2\gamma_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial \widehat{m}_{NA}^{0010}(1)}{\partial \alpha_{NA}} > 0.
\end{aligned}$$

The derivatives $\frac{\partial \widehat{m}_{NA}^{0010}(y)}{\partial \gamma_{NA}}and\frac{\partial \widehat{m}_{NA}^{1010}(y)}{\partial \gamma_{NA}}$ are the same $\vee$ $y = 1, 2$, negative and given by:

$$\begin{aligned}
\frac{\partial \widehat{m}_{NA}^{0010}(1)}{\partial \gamma_{NA}} &= -\frac{\beta\pi_2\alpha_{NA}}{1-\beta+\beta\pi_2\gamma_{NA}}\frac{\partial \widehat{m}_{NA}^{0010}(1)}{\partial \alpha_{NA}} < 0, \\
\frac{\partial \widehat{m}_{NA}^{0010}(2)}{\partial \gamma_{NA}} &= -\frac{\beta\pi_1\gamma_{NA}}{1-\beta+\beta\pi_1\alpha_{NA}}\frac{\partial \widehat{m}_{NA}^{0010}(2)}{\partial \alpha_{NA}} < 0.
\end{aligned}$$

If the strategy f^{0011} , f^{1011} or f^{1111} is optimal, $\frac{\partial \widehat{m}_{NA}^{0011}(y)}{\partial \alpha_{NA}}$, $\frac{\partial \widehat{m}_{NA}^{1011}(y)}{\partial \alpha_{NA}}$ and$\frac{\partial \widehat{m}_{NA}^{1111}(y)}{\partial \alpha_{NA}}$ are the same $\vee$ $y = 1, 2$ and equal to zero if the firms are initially allocated to G_2. In contrast, the derivatives $\frac{\partial \widehat{m}_{NA}^{0011}(1)}{\partial \alpha_{NA}}$, $\frac{\partial \widehat{m}_{NA}^{1011}(1)}{\partial \alpha_{NA}}$ and$\frac{\partial \widehat{m}_{NA}^{1111}(1)}{\partial \alpha_{NA}}$ are positive, and given by:

$$\frac{\partial \widehat{m}_{NA}^{0011}(1)}{\partial \alpha_{NA}} = \frac{\beta m \pi_1 \left[\pi_2 - \pi_1\right]}{\left[1-\beta+\beta\pi_1\alpha_{NA}\right]^2} > 0.$$

By analogy, $\frac{\partial \widehat{m}_{NA}^{0011}(y)}{\partial \gamma_{NA}}$, $\frac{\partial \widehat{m}_{NA}^{1011}(y)}{\partial \gamma_{NA}}$ and$\frac{\partial \widehat{m}_{NA}^{1111}(y)}{\partial \gamma_{NA}}$ are the same $\vee$ $y = 1, 2$ and equal to zero.

Marginal Variations in Transition Probabilities

From the analysis above, it follows that:

- f^{0000}. We have that $\frac{\partial \widehat{m}_{A}(y)}{\partial \alpha_{A}} = \frac{\partial \widehat{m}_{NA}(y)}{\partial \alpha_{NA}} = 0 \vee y = 1, 2$. Moreover, $\frac{\partial \widehat{m}_{A}(1)}{\partial \gamma_{A}} = \frac{\partial \widehat{m}_{NA}(1)}{\partial \gamma_{NA}} = 0$, while $\frac{\partial \widehat{m}_{A}(2)}{\partial \gamma_{A}} < \frac{\partial \widehat{m}_{NA}(2)}{\partial \gamma_{NA}} < 0$. Hence, targeted state-dependent enforcement has no effect on the cost of enforcing compliance among adopters and non-adopters if they are initially allocated to G_1. However, it reduces the enforcement cost for adopters and increases the enforcement cost for non-adopters if firms are initially allocated to G_2. Since the marginal effect of γ_A is larger than the marginal effect of γ_{NA}, the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

- f^{0010}. We have that $\frac{\partial \widehat{m}_A(y)}{\partial \alpha_A} = 0 \vee y = 1, 2$. Moreover, $\frac{\partial \widehat{m}_A(1)}{\partial \gamma_A} = 0$, while $\frac{\partial \widehat{m}_A(2)}{\partial \gamma_A} < 0$. For non-adopters, $\frac{\partial \widehat{m}_{NA}(y)}{\partial \alpha_{NA}} > 0$, while $\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}} < 0 \vee y = 1, 2$. Hence, targeted state-dependent enforcement has no effect on the cost of enforcing compliance among adopters if they are initially allocated to G_1, while it reduces the enforcement cost if they are initially allocated to G_2. For non-adopters, it increases the enforcement cost for all initial allocations.

- f^{0011}. We have that $\frac{\partial \widehat{m}_A(y)}{\partial \alpha_A} = 0 \vee y = 1, 2$. Moreover, $\frac{\partial \widehat{m}_A(1)}{\partial \gamma_A} = 0$, while $\frac{\partial \widehat{m}_A(2)}{\partial \gamma_A} < 0$. For non-adopters, $\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$, $\frac{\partial \widehat{m}_{NA}(2)}{\partial \alpha_{NA}} = 0$, while $\frac{\partial \widehat{m}_{NA}(1)}{\partial \alpha_{NA}} > 0$. Hence, targeted state-dependent enforcement has no effect on the cost of enforcing compliance among adopters if they are initially allocated to G_1, while it reduces the enforcement cost if they are initially allocated to G_2. For non-adopters, it increases the cost of enforcement if they are initially allocated to G_1.

- f^{1010}. We have that $\frac{\partial \widehat{m}_A(y)}{\partial \gamma_A} < 0 < \frac{\partial \widehat{m}_A(y)}{\partial \alpha_A}$ and $\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}} < 0 < \frac{\partial \widehat{m}_{NA}(y)}{\partial \alpha_{NA}} \vee y = 1, 2$. Moreover, $\left|\frac{\partial \widehat{m}_A(y)}{\partial \alpha_A}\right| > \left|\frac{\partial \widehat{m}_{NA}(x)}{\partial \alpha_{NA}}\right|$ and $\left|\frac{\partial \widehat{m}_A(y)}{\partial \gamma_A}\right| > \left|\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}}\right| \vee y, x = 1, 2$ and $y \geq x$, implying that the marginal effects of the probabilities α_A and γ_A are larger than the marginal effects of the probabilities α_{NA} and γ_{NA}. Hence, the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

- f^{1011}. We have that $\frac{\partial \widehat{m}_A(y)}{\partial \gamma_A} < 0 < \frac{\partial \widehat{m}_A(y)}{\partial \alpha_A} \vee y = 1, 2$. In contrast, $\frac{\partial \widehat{m}_{NA}(1)}{\partial \alpha_A} > \frac{\partial \widehat{m}_{NA}(2)}{\partial \alpha_A} = 0$, and $\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$. Moreover, $\left|\frac{\partial \widehat{m}_A(y)}{\partial \alpha_A}\right| \geq \left|\frac{\partial \widehat{m}_{NA}(y)}{\partial \alpha_{NA}}\right|$ and $\left|\frac{\partial \widehat{m}_A(y)}{\partial \gamma_A}\right| > \left|\frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}}\right| \vee y, x = 1, 2$ and $y \geq x$, implying that the marginal effects of the probabilities α_A and γ_A are larger than the marginal effects of the probabilities α_{NA} and γ_{NA}. Hence, the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

- f^{1111}. We have that $\frac{\partial \widehat{m}_A(y)}{\partial \gamma_A} = \frac{\partial \widehat{m}_{NA}(y)}{\partial \gamma_{NA}} = 0 \vee y = 1, 2$, $\frac{\partial \widehat{m}_A(2)}{\partial \alpha_A} = \frac{\partial \widehat{m}_{NA}(2)}{\partial \alpha_{NA}} = 0$, while $\frac{\partial \widehat{m}_A(1)}{\partial \alpha_A} > \frac{\partial \widehat{m}_{NA}(1)}{\partial \alpha_{NA}} > 0$. Hence, targeted state-dependent enforcement has no effect on the cost of enforcing compliance among adopters and non-adopters if they are initially allocated to G_2. Instead, it reduces the enforcement cost for adopters and increases it for non-adopters if firms are initially allocated to G_1. Note that the marginal effect of α_A is larger than the marginal effect of α_{NA}. Hence, the reduction in the enforcement cost for adopters is larger than the increase in the enforcement cost for non-adopters.

Paper III

The Benefits of International Cooperation under Climate Uncertainty: A Dynamic Game Analysis*

Xiao-Bing Zhang† and Magnus Hennlock‡

Abstract

This paper investigates the benefits of international cooperation under uncertainty about global warming through a stochastic dynamic game. We analyze the benefits of cooperation both for the case of symmetric and asymmetric players. It is shown that the players' combined expected payoffs decrease as climate uncertainty becomes larger, whether or not they cooperate. However, the benefits from cooperation increase with climate uncertainty. In other words, it is more important to cooperate when facing higher uncertainty. At the same time, more transfers will be needed to ensure stable cooperation among asymmetric players.

Keywords: Climate change, cooperation, differential game, uncertainty

JEL Classification: C61, C73, Q54

*The authors would like to thank Jessica Coria and Thomas Sterner for their helpful discussions and comments on this paper. All errors and omissions remain the sole responsibility of the authors. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7-2007-2013) under grant agreement n [266992].

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1 Introduction

Climate change is likely to have a wide range of impacts in both developed and developing countries. In the fifth assessment report by IPCC (Intergovernmental Panel on Climate Change), the international community has accepted the main mechanisms relating emissions and atmospheric CO_2 concentration with the rise in global mean temperature. With a growing consensus that the global warming is happening and it is mainly due to anthropogenic emissions of greenhouse gases (GHGs), the international community has agreed on the need for joint action to limit GHG emissions (IPCC 2007). However, current international cooperation has not been effective (Finus and Pintassilgo, 2013). One important problem is free-riding, given that climate stability is a global public good (see, e.g., Hoel 1993 and Wirl 1996). Unless there is binding international law which forces countries to participate in an agreement to reduce GHG emissions, each country can choose to stay outside the agreement and enjoy (almost) the same benefits of reduced GHGs emissions as if it participated in the agreement, while it doesn't bear any of the costs of reducing emissions (Hoel 1993).

In addition to the free-riding problem, it has been argued that the huge uncertainties surrounding climate change can be one of the reasons for the lack of cooperation (see, e.g., Kolstad 2007, Barrett and Dannenberg 2012, and Finus and Pintassilgo 2013). Due to these uncertainties, it is almost impossible to know the exact effects of one more unit of GHG emissions today on global temperature, and thus damage, in the future. This could make individual countries hesitant about investing in emission abatement and cooperating with other countries. For instance, uncertainty was one of the arguments used by former US President George W. Bush for his decision to pull the US out of the Kyoto Protocol. As quoted by Kolstad (2007), President Bush wrote in a letter to senators: "I oppose the Kyoto Protocol ... we must be very careful not to take actions that could harm consumers. This is especially true given the incomplete state of scientific knowledge." (see also Finus and Pintassilgo 2013).

If climate uncertainty could reshape the abatement strategies of individual countries, this may also have an effect on their expected welfare. However, these effects might be different depending on whether they cooperate with each other. This implies that uncertainty could have an impact on the potential welfare gains from cooperation for individual countries, thereby affecting the incentives for cooperation among countries. Therefore, it is important to investigate whether this would be true in a normative perspective and to see precisely in what way, dealing with uncertainty could reshape climate policies and change the incentives for international cooperation on climate change. In this paper, we extend the deterministic dynamic game for international pollution control in Dockner and Long (1993) to study the welfare gain from international cooperation under climate uncertainty. We analytically compare the cooperative and non-cooperative solutions of the game with the aim of answering the following questions. How does uncertainty about global warming affect the net welfare of individual countries in the respective non-cooperative and cooperative cases? How does climate uncertainty affect the benefits (welfare gains) from international cooperation (and thus the side payments among countries)? By focusing on players' payoffs under uncertainty, we show that the expected payoffs of players decrease as climate uncertainty becomes greater, whether or not they cooperate. However, the expected welfare gain from international cooperation is larger with greater climate uncertainty, implying that it is more important to cooperate when facing greater uncertainty. At the same time, however, more transfers will be needed to ensure stable cooperation among asymmetric players.

There are numerous studies on climate uncertainty and its effect on climate policy design. Some authors investigated the optimal timing to slow global warming under uncertainties (see, for instance, Conrad 1997, Pindyck 2000 and 2002, and Bahn et al. 2008), the value of learning for climate change uncertainties (e.g., Peck and Teisberg 1993, Kolstad 1996, and Kelly and Kolstad 1999), the optimal choice of policy instruments to mitigate climate change in the presence of uncertainty (e.g., Pizer 1999 and 2002, and Hoel and Karp 2001 and 2002), and the strategic interactions between producers of fossil fuels and a taxing government concerned about consumers' welfare under climate uncertainty (e.g., Wirl 2007). Moreover, literature on the effect of uncertainty (and learning) on international cooperation has emerged recently (for instance, Kolstad 2007, Kolstad and Ulph 2008 and 2011, Barrett and Dannenberg 2012, Karp 2012, and Finus and Pintassilgo 2013). Notably, Harstad (2011) investigates the harmful (short-term) climate agreements and optimal (long-term) agreement with taking into account uncertainty. Brchet et al. (2012) numerically examines the benefits of international climate cooperation under uncertainty through a stochastic integrated assessment model, finding that uncertainty generates additional benefit from cooperation, namely risk reduction.

The closest papers to ours are those by Xepapadeas (1998, 2012) and Wirl (2008). Like us, they analyze non-cooperative vs. cooperative solutions. Their focus, however, is different. Xepapadeas (1998) studies optimal policy adoption rules of emission abatement for cooperative and non-cooperative solutions under uncertainty about global warming damages, while Wirl (2008) investigates how uncertainty affects pollution control strategies in cooperative and non-cooperative solutions. Finally, Xepapadeas (2012) focuses on the cost of ambiguity and robustness in international pollution control when the regulator has concerns regarding possible misspecification of the natural system that is used to model pollution dynamics. Moreover, by limiting their analysis to players who are symmetric in terms of benefits and damages, these studies may ignore heterogeneity among players in terms of optimal emission strategies and total payoffs. We analyze the results for both the case of symmetric players and the case of asymmetric players, where side payments are needed to ensure stability of the cooperation.

The paper is organized as follows. Section 2 presents the stochastic dynamic game. Section 3 presents the non-cooperative and cooperative solutions of the game. The effects of climate uncertainty under the cases of symmetric players and asymmetric players are analyzed in Sections 4 and 5, respectively. Section 6 provides some numerical illustrations. Finally, Section 7 concludes the paper. Some proofs are relegated to the appendix.

2 The model

The deterministic part of the game is based on the international pollutant control model developed by Dockner and Long (1993). As in that paper, we assume that there are two countries (indexed by $i = 1, 2$) and a single consumption good in the world. The production of consumption good in country i results in CO_2 emissions E_i:

$$Y_i = F_i(E_i)$$

where Y_i is the output in country i. Both countries' emissions contribute to global warming. The future temperature (measured in ^oC above the pre-industrial average) is stochastic due to the uncertainty of the climate system.[1] Following the specification for climate uncertainty in Wirl (2007), the global main temperature is assumed to follow the Ito process:

$$dT(t) = [E_1(t) + E_2(t)]dt + \sigma T(t)dz, T(0) = T_0 \geq 0 \tag{1}$$

where $E_i(t)$ is measured in units that lead to an expected increase of global average temperature by 1^oC. It can be seen from (1) that the expected temperature will be determined by the accumulation of CO_2 emissions in the atmosphere and the stochastic part of the temperature is a geometric Brownian motion ($\sigma > 0$ is the relative standard error and z is a standard Wiener process).[2] As in Wirl (2007), the parameter σ can be considered a measurement of the degree of (relative) uncertainty. A larger σ would imply a greater degree of uncertainty.

Country i enjoys utility/benefit $U_i(Y_i)$ from consumption but suffers damage from global warming $D_i(T)$. As in Dockner and Long (1993) and its follow-ups, $U_i(\cdot)$ and $D_i(\cdot)$ have quadratic forms (which are prevailing in the literature, see, e.g., Wirl 2008 and Xepapadeas 2012) such that country i gets the normalized utility from consumption $U_i(F_i(E_i(t))) = a_i E_i(t) - \frac{[E_i(t)]^2}{2}$ and faces the damage of global warming $D_i(T(t)) = \frac{\varepsilon_i}{2}[T(t)]^2$, where a_i and ε_i are positive constants. The net benefit/utility for country i is therefore:

$$B_i(E_i(t), T(t)) = a_i E_i(t) - \frac{1}{2}[E_i(t)]^2 - \frac{\varepsilon_i}{2}[T(t)]^2$$

Without loss of generality, we set $a_1 = a$, and $a_2 = \varphi a$; $\varepsilon_1 = \varepsilon$, and $\varepsilon_2 = \gamma\varepsilon$. Note that if $\varphi = 1$ and $\gamma = 1$, the two countries have symmetric benefits and damages.

[1]This is where we incorporate uncertainty into the deterministic game in Dockner and Long (1993). Alternatively, one could use CO_2 stock instead of temperature as the state variable and make it follow a stochastic process. However, in the context of climate change, there is more uncertainty about temperature than carbon stock, i.e., we are unsure of how much one more unit of emissions will increase the global temperature and how large the damage would be if the temperature is increased, while CO_2 stock and current emissions can be more or less measured, implying less uncertainty surrounding the evolution of CO_2 stock. Therefore, this paper follows the specification in Wirl (2007) and uses temperature instead of CO_2 stock as the (stochastic) state variable.

[2]This specification of stochastic global temperature has some plausible properties. For instance, an increase in the mean temperature is associated with higher variance, which is consistent with the argument in Dalton (1997). See more details in Wirl (2007). Furthermore, the simple (linear) relationship between global mean temperature and accumulated emissions is well supported by the latest IPCC report (IPCC, 2013, p.28).

Without cooperation between the two countries, country i will choose CO_2 emissions E_i to maximize its discounted stream of net benefits from consumption:

$$\mathbb{E}\int_0^\infty e^{-rt}\{a_i E_i(t) - \frac{1}{2}[E_i(t)]^2 - \frac{\varepsilon_i}{2}[T(t)]^2\}dt \tag{2}$$

subject to the global temperature dynamics (1). r is the discount rate, which is assumed to be the same for both countries. The expectation sign $\mathbb{E}(\cdot)$ appears due to the uncertainty of global warming implied in (1). Therefore, we have a stochastic dynamic game where the dynamics of global mean temperature involve uncertainty. As in Wirl (2007), it is further assumed that $\sigma^2 < r$, which will ensure that the net present value of expected damage remains finite.

With cooperation between countries, the coalition of the two countries will maximize the joint net benefit stream (by choosing the CO_2 emissions in the two countries: E_1 and E_2) which is the sum of each country's net benefit:[3]

$$\mathbb{E}\int_0^\infty e^{-rt}\left\{a[E_1(t)+\varphi E_2(t)] - \frac{1}{2}\left[[E_1(t)]^2+[E_2(t)^2]\right] - \frac{\varepsilon(1+\gamma)}{2}[T(t)]^2\right\}dt \tag{3}$$

subject to the global temperature dynamics (1). The solution of the cooperative game can be considered as a first-best outcome where the countries are able to achieve an agreement for emission control. Therefore, one can get some insights into the benefits (welfare gains) from international cooperation for individual countries by comparing their payoffs under cooperative strategies with those under non-cooperative strategies. We do not impose constraints on the control variables, implying that emissions are assumed to be reversible. That is, active but costly reduction of the stock of emissions (cleanup) is assumed to be feasible.[4]

[3]We take a different approach than List and Mason (2001), who investigated the optimal institutional arrangements (local vs. central) for transboundary pollutants in a deterministic dynamic game and assumed a common time path of emissions for the two regions, i.e., $E_1(t) = E_2(t)$, in the cooperative (central authority) case. Here we relax this restriction and assume that the emissions paths for two asymmetric countries can be different to maximize their joint payoffs in the cooperative case.

[4]This assumption is also used by Xepapadeas (1998). Due to the difficulty of obtaining analytical solutions with irreversible emissions (cleanup is not feasible), the analysis in this paper is focused on the solutions with reversible emissions, and the analysis with irreversible emissions is left for further research, which will require the assistance of numerical methods for obtaining complete solutions to compare the players' payoffs across different cases (cooperative vs. non-cooperative solutions).

3 Non-cooperative and cooperative solutions

In this section, we derive the solution of the game for the non-cooperative and cooperative case, respectively. Compared with an open-loop Nash equilibrium, a Markov-perfect Nash equilibrium is more informative because it provides a subgame perfect equilibrium that is dynamically consistent. Therefore, we assume that players are playing Markovian strategies rather than open-loop strategies. Markovian strategies imply that each player will choose an emission strategy at time t based on the state of the system (i.e., temperature T) at that time.

3.1 Non-cooperative case

Define the value function for player i when the players do not cooperate as $V_i(T)$. Then, the Markovian strategies of player 1 and player 2, $E_1(T)$ and $E_2(T)$, need to satisfy the following Hamilton-Jacobi-Bellman (HJB) equations:

$$rV_1(T) = \max_{E_1} \left\{ aE_1 - \frac{1}{2}[E_1]^2 - \frac{\varepsilon}{2}T^2 + [E_1 + E_2(T)] \cdot V_1'(T) + (\frac{1}{2}\sigma^2 T^2)V_1''(T) \right\} \quad (4.1)$$

$$rV_2(T) = \max_{E_2} \left\{ a\varphi E_2 - \frac{1}{2}[E_2]^2 - \frac{\gamma\varepsilon}{2}T^2 + [E_1(T) + E_2] \cdot V_1'(T) + (\frac{1}{2}\sigma^2 T^2)V_2''(T) \right\} \quad (4.2)$$

where $V_i'(T)$ and $V_i''(T)$ are the first and second order derivatives of the value function $V_i(T)$ with respect to the state variable, i.e., global temperature T. The second derivatives of the value functions appear due to the stochastic nature of the problem (Dockner et al., 2000).

From the first-order conditions for the maximization of the right-hand side of HJB equations (4.1)-(4.2), one can find the optimal emission strategy for the two players as:

$$E_1(T) = a + V_1'(T) \quad (5.1)$$

$$E_2(T) = a\varphi + V_2'(T) \quad (5.2)$$

Plugging (5.1)-(5.2) into the HJB equations (4.1)-(4.2) and after some straightforward calculations, one can obtain:

$$rV_1(T) = \frac{1}{2}[a + V_1'(T)]^2 - \frac{\varepsilon}{2}T^2 + [a\varphi + V_2'(T)] \cdot V_1'(T) + (\frac{1}{2}\sigma^2 T^2)V_1''(T) \tag{6.1}$$

$$rV_2(T) = \frac{1}{2}[\varphi a + V_2'(T)]^2 - \frac{\gamma\varepsilon}{2}T^2 + [a + V_1'(T)] \cdot V_2'(T) + (\frac{1}{2}\sigma^2 T^2)V_2''(T) \tag{6.2}$$

Due to the linear-quadratic structure of the game, we know the value function is quadratic:

$$V_i(T) = \kappa_i + \mu_i T + \frac{1}{2}\eta_i T^2, i = 1, 2 \tag{7}$$

where κ_i, μ_i, η_i are the coefficients to be determined. Substituting (7) into (6.1)-(6.2), we have:

$$r[\kappa_1 + \mu_1 T + \frac{1}{2}\eta_1 T^2] = \frac{1}{2}[a + \mu_1 + \eta_1 T]^2 + [\varphi a + \mu_2 + \eta_2 T][\mu_1 + \eta_1 T] - \frac{\varepsilon}{2}T^2 + \frac{\sigma^2 T^2}{2}\eta_1 \tag{8.1}$$

$$r[\kappa_2 + \mu_2 T + \frac{1}{2}\eta_2 T^2] = \frac{1}{2}[\varphi a + \mu_2 + \eta_2 T]^2 + [a + \mu_1 + \eta_1 T][\mu_2 + \eta_2 T] - \frac{\gamma\varepsilon}{2}T^2 + \frac{\sigma^2 T^2}{2}\eta_2 \tag{8.2}$$

Equating the coefficients of 1, T and T^2 on both sides of (8.1) and (8.2) leads to the following system of equations:

$$\frac{1}{2}r\eta_1 = \frac{1}{2}[\eta_1]^2 + \eta_1\eta_2 - \frac{\varepsilon}{2} + \frac{\sigma^2}{2}\eta_1 \tag{9.1}$$

$$r\mu_1 = [a + \mu_1]\eta_1 + \eta_2\mu_1 + \eta_1[\varphi a + \mu_2] \tag{9.2}$$

$$r\kappa_1 = \frac{1}{2}[a + \mu_1]^2 + [\varphi a + \mu_2]\mu_1 \tag{9.3}$$

$$\frac{1}{2}r\eta_2 = \frac{1}{2}[\eta_2]^2 + \eta_1\eta_2 - \frac{\gamma\varepsilon}{2} + \frac{\sigma^2}{2}\eta_2 \tag{9.4}$$

$$r\mu_2 = [\varphi a + \mu_2]\eta_2 + \eta_1\mu_2 + \eta_2[a + \mu_1] \tag{9.5}$$

$$r\kappa_2 = \frac{1}{2}[\varphi a + \mu_2]^2 + [a + \mu_1]\mu_2 \tag{9.6}$$

By solving the system of equations (9.1)-(9.6), one can determine the coefficients for the value function $V_i(T)$, $i = 1, 2$. However, it should be emphasized that the general case (with arbitrary values of φ and γ) does not allow for explicitly analytical solutions of (9.1)-(9.6). Therefore, our analysis will concentrate on some cases where analytical results are possible, as we shall see in Sections 4 and 5 below.

3.2 Cooperative case

As mentioned above, in the cooperative case, the coalition of the two countries will choose E_1 and E_2 to maximize (3), subject to the global temperature dynamics (1). If we define the value function in this case as $W(T)$, the following HJB equation can be obtained:

$$rW(T) = \max_{E_1,E_2}\{a[E_1+\varphi E_2]-\tfrac{1}{2}[(E_1)^2+(E_2)^2]-\tfrac{(1+\gamma)\varepsilon}{2}T^2+[E_1+E_2]\cdot W'(T)+\tfrac{1}{2}\sigma^2T^2W''(T)\} \quad (10)$$

The first-order conditions for the maximization of the right-hand side yield:

$$E_1(T) = a + W'(T) \quad (11.1)$$

$$E_2(T) = a\varphi + W'(T) \quad (11.2)$$

Plugging (11.1)-(11.2) into the HJB equation (10), after some calculations we have:

$$rW(T) = [W'(T) + \frac{a(1+\varphi)}{2}]^2 + \frac{a^2(1-\varphi)^2}{4} - \frac{\varepsilon(1+\gamma)}{2}T^2 + (\frac{1}{2}\sigma^2T^2)W''(T) \quad (12)$$

Again, we know the value function is in a quadratic form:

$$W(T) = \zeta + \psi T + \frac{1}{2}\xi T^2 \quad (13)$$

where ζ, ψ, and ξ are the coefficients to determine. Plugging (13) into (12), we have:

$$r[\zeta+\psi T+\frac{1}{2}\xi T^2] = [\psi+\xi T]^2+a(1+\varphi)[\psi+\xi T]+\frac{a^2(1+\varphi^2)}{2}-\frac{\varepsilon(1+\gamma)}{2}T^2+\frac{1}{2}\sigma^2T^2\xi \quad (14)$$

Equating the coefficients on both sides, one can get the following system of equations:

$$\frac{1}{2}r\xi = \xi^2 - \frac{\varepsilon(1+\gamma)}{2} + \frac{\xi\sigma^2}{2} \tag{15.1}$$

$$r\psi = 2\psi\xi + a(1+\varphi)\xi \tag{15.2}$$

$$r\zeta = \psi^2 + a(1+\varphi)\psi + \frac{a(1+\varphi^2)}{2} \tag{15.3}$$

from which one can obtain:

$$\xi = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2 + 8\varepsilon(1+\gamma)}}{4} \tag{16.1}$$

$$\psi = \frac{a(1+\varphi)\xi}{r-2\xi} = \frac{1}{2}[\frac{ar(1+\varphi)}{(r-2\xi)} - a(1+\varphi)] \tag{16.2}$$

$$\zeta = \frac{1}{r}[\psi + \frac{a(1+\varphi)}{2}]^2 + \frac{a^2(1-\varphi)^2}{4r} \tag{16.3}$$

Thereby, we have determined the coefficients for the value function $W(T)$.

4 The case of symmetric players

In this section, we investigate the game described above under the assumption that the two countries are symmetric in benefits from emissions and damages from global warming, i.e., $\varphi = 1$ and $\gamma = 1$.

4.1 Expected payoffs

Due to the symmetry of the two countries, both countries will achieve the same payoff in the equilibrium, which implies that the value function in the non-cooperative solution would be identical for both countries, i.e., $V_1(T) = V_2(T) = V(T)$, implying that the coefficients of the value functions $V_1(T)$ and $V_2(T)$ satisfy $\kappa_1 = \kappa_2 = \kappa$, $\mu_1 = \mu_2 = \mu$, and $\eta_1 = \eta_2 = \eta$. Therefore, the symmetry of the two countries would imply that (9.1)-(9.6) can be degenerated as:

$$\frac{1}{2}r\eta = \frac{1}{2}[\eta]^2 + [\eta]^2 - \frac{\varepsilon}{2} + \frac{\sigma^2}{2}\eta \tag{17.1}$$

$$r\mu = [a+\mu]\eta + \eta\mu + \eta[a+\mu] \tag{17.2}$$

$$r\kappa = \frac{1}{2}[a+\mu]^2 + [a+\mu]\mu \tag{17.3}$$

By solving this system of equations, one can determine the coefficients for the value function $V(T)$, as in the first column of Table 1.[5] Given the initial temperature T_0, the (expected) payoff for each country in the non-cooperative case will be $V^{NC}(T_0) = V(T_0) = \kappa + \mu T_0 + \frac{1}{2}\eta[T_0]^2$.

Similarly, with the symmetric players, the coefficients for the value function under cooperation, $W(T)$, i.e., (16.1)-(16.3), would degenerate into the second column of Table 1.

Table 1. Coefficients for value functions in the case of symmetric players

$V(T)$	$W(T)$
$\kappa = \frac{1}{2r}(a+\mu)(a+3\mu)$	$\zeta = \frac{1}{r}[a+\psi]^2$
$\mu = \frac{2a\eta}{r-3\eta} = \frac{2a}{3}[\frac{r}{r-3\eta} - 1]$	$\psi = \frac{2a\xi}{r-2\xi} = a[\frac{r}{r-2\xi} - 1]$
$\eta = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2 + 12\varepsilon}}{6} < 0$	$\xi = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2 + 16\varepsilon}}{4} < 0$

4.2 Non-cooperative versus cooperative strategies

In the case of symmetric players, the emission strategies of the two players would be identical, as can be seen from (5.1)-(5.2). Taking into account the expression of the value function, one can obtain the optimal emission strategy for each country in the non-cooperative case:

$$E_i^{NC}(T) = a + \mu + \eta T \tag{18.1}$$

and the optimal emission strategy for country i in the cooperative case:

[5]Complete calculations are available from the authors upon request.

$$E_i^C(T) = a + \psi + \xi T \tag{18.2}$$

where μ, η, ψ, and ξ are as in Table 1.

In Appendix A1, we show that $\xi - \eta < 0$ and $\psi - \mu < 0$. Therefore, for the same temperature T, we have $E_i^C(T) < E_i^{NC}(T)$. That is, each country tends to over-emit CO_2 in the non-cooperative case, compared with the cooperative case. This result is consistent with the general findings of Dockner and Long (1993). If we denote the temperatures at which countries would stop emitting (i.e., would have zero emissions) for the non-cooperative and cooperative cases as $\bar{T}^{NC}$and $\bar{T}^C$, respectively, we have: $\bar{T}^{NC} = \frac{a+\mu}{-\eta}$ and $\bar{T}^C = \frac{a+\psi}{-\xi}$. Because $0 < \psi + a < \mu + a$ and $\xi < \eta < 0$ (see Table 1 and Appendix A1), we have $\bar{T}^{NC} > \bar{T}^C > 0$. That is, countries will stop emissions at a lower temperature under international cooperation.

Moreover, in Appendix A2 we show that $\frac{\partial \eta}{\partial \sigma} < 0$, $\frac{\partial \mu}{\partial \sigma} < 0$, $\frac{\partial \xi}{\partial \sigma} < 0$ and $\frac{\partial \psi}{\partial \sigma} < 0$, which implies that $\frac{\partial E_i^{NC}(T)}{\partial \sigma} = \frac{\partial \mu}{\partial \sigma} + \frac{\partial \eta}{\partial \sigma} T < 0$ and $\frac{\partial E_i^C(T)}{\partial \sigma} = \frac{\partial \psi}{\partial \sigma} + \frac{\partial \xi}{\partial \sigma} T < 0$ for a given temperature $T \geq 0$. That is, uncertainty will make countries more cautious about their emissions, whether they cooperate or not. This is consistent with the previous findings on the consequences of uncertainty in the context of the tragedy of the commons (see, e.g., Wirl 2008): larger uncertainty reduces pollution. However, in contrast to the previous studies, the focus of this paper is on the effects of climate uncertainty on the welfare of individual countries in non-cooperative as well as cooperative solutions and on the welfare gain from international cooperation. Therefore, more emphasis will be put on the effects of uncertainty on these measurements in the following sections.

4.3 Effect of uncertainty on the welfare of individual countries

Due to the symmetry of players, both countries achieve the same payoff $V^{NC}(T_0) = V(T_0)$ in the non-cooperative case, while both also obtain the same payoff $V^C(T_0) = \frac{1}{2}W(T_0)$ in the cooperative case, where T_0 is the initial temperature. To see the effect of uncertainty on an individual country's welfare, let us take the derivative of $V^{NC}(T_0)$ and $V^C(T_0)$ with respect to the parameter σ, which is the measurement of climate uncertainty. That is,

$$\frac{\partial V^{NC}(T_0)}{\partial \sigma} = \frac{\partial \kappa}{\partial \sigma} + \frac{\partial \mu}{\partial \sigma} T_0 + \frac{1}{2} \frac{\partial \eta}{\partial \sigma} [T_0]^2 \tag{19.1}$$

$$\frac{\partial V^{C}(T_0)}{\partial \sigma} = \frac{1}{2} \frac{\partial \zeta}{\partial \sigma} + \frac{1}{2} \frac{\partial \psi}{\partial \sigma} T_0 + \frac{1}{4} \frac{\partial \xi}{\partial \sigma} [T_0]^2 \tag{19.2}$$

Based on the coefficients of value functions in Table 1, the following results can be established and demonstrated for the case with symmetric players.

Proposition 1 *Larger climate uncertainty reduces the expected welfare of individual countries, whether or not they cooperate with each other.*

Proof. Since it has been shown in Appendix A2 that $\frac{\partial \eta}{\partial \sigma} < 0$, $\frac{\partial \mu}{\partial \sigma} < 0$, and $\frac{\partial \kappa}{\partial \sigma} < 0$, one can know that $\frac{\partial V^{NC}(T_0)}{\partial \sigma} = \frac{\partial \kappa}{\partial \sigma} + \frac{\partial \mu}{\partial \sigma} T_0 + \frac{1}{2} \frac{\partial \eta}{\partial \sigma} [T_0]^2 < 0$ for $T_0 \geq 0$, which implies that, in the non-cooperative case, the expected payoff for each country will be reduced by greater uncertainty about global warming.

Similarly, the negative signs of $\frac{\partial \xi}{\partial \sigma}$, $\frac{\partial \psi}{\partial \sigma}$, and $\frac{\partial \zeta}{\partial \sigma}$ (see the proofs in Appendix A2) imply $\frac{\partial V^{C}(T_0)}{\partial \sigma} = \frac{1}{2} \frac{\partial \zeta}{\partial \sigma} + \frac{1}{2} \frac{\partial \psi}{\partial \sigma} T_0 + \frac{1}{4} \frac{\partial \xi}{\partial \sigma} [T_0]^2 < 0$ for $T_0 \geq 0$. That is, the expected payoff for each country will be reduced by greater climate uncertainty in the non-cooperative case as well.

Therefore, we know that, no matter whether the two countries cooperate with each other, higher uncertainty about global warming will reduce the expected welfare of individual countries. ■

4.4 Effect of uncertainty on benefits of international cooperation

The welfare gain from international cooperation (WGIC) for each country can be calculated as the difference between the payoff in the cooperative case and that in the non-cooperative case:

$$\begin{aligned} WGIC &= V^C(T_0) - V^{NC}(T_0) \\ &= \left(\tfrac{1}{2}\zeta + \tfrac{1}{2}\psi T_0 + \tfrac{1}{4}\xi [T_0]^2\right) - \left(\kappa + \mu T_0 + \tfrac{1}{2}\eta [T_0]^2\right) \\ &= \left(\tfrac{1}{2}\zeta - \kappa\right) + \left(\tfrac{1}{2}\psi - \mu\right) T_0 + \tfrac{1}{2}\left(\tfrac{1}{2}\xi - \eta\right) [T_0]^2 \end{aligned} \tag{20}$$

It is well known that collective well-being can be increased if all countries cooperate in managing shared environmental resources such as the climate and ozone layer

(Barrett, 1994). This implies that one can always expect that the two players' combined payoff in the cooperative case would be larger than that in the non-cooperative case. Taking into account the symmetry of the two players (an equal split of the collective payoff), this leads to:

Lemma 1 *It is always beneficial for the countries to cooperate, no matter how large the climate uncertainty is.*

Though Lemma 1 directly follows from well-known general economics results, one can rigorously prove that this is true in our particular case by some straightforward calculations. In Appendix A3, we demonstrated that $\frac{1}{2}\zeta - \kappa > 0$, $\frac{1}{2}\psi - \mu > 0$, and $\frac{1}{2}\xi - \eta > 0$ hold for all σ (under the assumption that $\sigma^2 < r$). Therefore, we know from Eq. (20) that the welfare gain from cooperation for each country (for a given initial temperature $T_0 \geq 0$) is positive for all σ. That is, each country can always get a positive welfare gain from international cooperation, no matter how large the uncertainty is.

We know that the expected welfare gain from international cooperation is positive (Lemma 1). But how will the size of the welfare gain from cooperation change with climate uncertainty? To see this, take the derivative of $WGIC$ (see Eq.(20)) with respect to σ:

$$\frac{\partial WGIC}{\partial \sigma} = \left(\frac{1}{2}\frac{\partial \zeta}{\partial \sigma} - \frac{\partial \kappa}{\partial \sigma}\right) + \left(\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma}\right) T_0 + \frac{1}{2}\left(\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma}\right) [T_0]^2 \tag{21}$$

As we shall state in Proposition 2, one can demonstrate that $\frac{\partial WGIC}{\partial \sigma} > 0$, which implies that the expected welfare gain from cooperation for each country (i.e., $WGIC$) is increasing in the magnitude of climate uncertainty (i.e., increasing in parameter σ).

Proposition 2 *The expected welfare gain from international cooperation is an increasing function of climate uncertainty. The larger the uncertainty, the more each country can gain from cooperation.*

Proof. See Appendix A4. ∎

Given $\frac{1}{2}\psi - \mu > 0$ and $\frac{1}{2}\xi - \eta > 0$ (see Appendix A3), it is easy to show that: $\frac{\partial WGIC}{\partial T^0} = \left(\frac{1}{2}\psi - \mu\right) + \left(\frac{1}{2}\xi - \eta\right)[T_0] > 0$ for $T_0 \geq 0$, which implies the expected welfare gain from international cooperation for each country is increasing in the initial global temperature T_0 as well. That is, the importance of international cooperation increases with a higher initial temperature: the higher the initial temperature, the more important to have international cooperation.

5 The case of asymmetric players

We focused on the case of symmetric players in the previous section. However, in reality, countries are asymmetric: some countries are affected a lot by climate change, while others are affected less; the benefits from emissions can also be very different. Therefore, it is important to investigate the case of asymmetric players. The case of asymmetric players corresponds to the case where $\varphi \neq 1$ or/and $\gamma \neq 1$. As mentioned in Section 3, the general (asymmetric) case (with arbitrary value of φ and γ) does not allow for an explicitly analytical solution of the non-cooperative game. Therefore, following List and Mason (2001), let us focus the analysis with asymmetric players on a polar extreme case where $\gamma = 0$, which represents the extreme case where country 2 does not suffer from the environmental damage of global warming.

5.1 Expected payoffs

If we assume $\gamma = 0$, it is easy to see that the optimal emission strategy of country 2 in the non-cooperative case is to set $E_2(T) = \varphi a$, which implies country 2 is not a strategic player any more in this case, i.e., at each instant of time, country 2 will receive the instantaneous net benefit $B_2 = \frac{1}{2}(\varphi a)^2$. In other words, we would have $\kappa_2 = \frac{1}{2r}(\varphi a)^2$, $\mu_2 = 0$, and $\eta_2 = 0$ in the value function for country 2, $V_2(T) = \kappa_2 + \mu_2 T + \frac{1}{2}\eta_2 T^2$. If one plugs in the values of κ_2, μ_2, and η_2, Eqs. (9.1)-(9.3) become:

$$\frac{1}{2}r\eta_1 = \frac{1}{2}[\eta_1]^2 - \frac{\varepsilon}{2} + \frac{\sigma^2}{2}\eta_1 \tag{22.1}$$

$$r\mu_1 = [a + \mu_1]\eta_1 + \varphi a \eta_1 \tag{22.2}$$

$$r\kappa_1 = \frac{1}{2}[a + \mu_1]^2 + \varphi a \mu_1 \tag{22.3}$$

From this system of equations, one can solve for η_1, μ_1, and κ_1, as shown in the first column in Table 2. With the assumption of $\gamma = 0$, the coefficients for the value function under cooperation $W(T)$, i.e., (16.1)-(16.3), degenerate into the third column of Table 2. It can be observed from Table 2 that the following relations hold:

$$2\xi - \eta_1 = \frac{-\sqrt{(r-\sigma^2)+8\varepsilon}+\sqrt{(r-\sigma^2)^2+4\varepsilon}}{2} < 0 \tag{23.1}$$

$$2\psi - \mu_1 = \frac{a(1+\varphi)[r(2\xi-\eta_1)]}{(r-2\xi)(r-\eta_1)} < 0 \tag{23.2}$$

Table 2. Coefficients for value functions in the particular case of asymmetric players

$V_1(T)$	$V_2(T)$	$W(T)$
$\kappa_1 = \frac{1}{2r}[a+\mu_1]^2 + \frac{1}{r}\varphi a \mu_1$	$\kappa_2 = \frac{1}{2r}(\varphi a)^2$	$\zeta = \frac{1}{r}[\psi + \frac{a(1+\varphi)}{2}]^2 + \frac{a^2(1-\varphi)^2}{4r}$
$\mu_1 = \frac{\eta_1 a(1+\varphi)}{r-\eta_1} = \frac{ar(1+\varphi)}{r-\eta_1} - a(1+\varphi)$	$\mu_2 = 0$	$\psi = \frac{a(1+\varphi)\xi}{r-2\xi} = \frac{1}{2}[\frac{ar(1+\varphi)}{(r-2\xi)} - a(1+\varphi)]$
$\eta_1 = \frac{r-\sigma^2-\sqrt{(r-\sigma^2)^2+4\varepsilon}}{2} < 0$	$\eta_2 = 0$	$\xi = \frac{(r-\sigma^2)-\sqrt{(r-\sigma^2)^2+8\varepsilon}}{4} < 0$

5.2 Non-cooperative versus cooperative strategies

Recall that, without the constraint of cooperation, country 2 will behave non-strategically and the optimal emission strategy for country 2 is always to set $E_2^{NC}(T) = \varphi a$. For country 1, the optimal emission strategy under non-cooperation in this case, plugging the value function $V_1(T)$ into (5.1), is:

$$E_1^{NC}(T) = a + \mu_1 + \eta_1 T \tag{24.1}$$

The optimal emission strategies for the two countries under cooperation would be

$$E_1^C(T) = a + \psi + \xi T \tag{24.2}$$

$$E_2^C(T) = a\varphi + \psi + \xi T \tag{24.3}$$

where μ_1, η_1, ψ, and ξ are as in Table 2.

Since $\xi < 0$ and $\psi < 0$, we know that $E_2^{NC}(T) > E_2^C(T)$ for a given temperature T, i.e., country 2 tends to over-emit CO_2 in the non-cooperative case. In Appendix B1, we show $\xi - \eta_1 > 0$ and $\psi - \mu_1 > 0$, which implies $E_1^C(T) > E_1^{NC}(T)$ for the same given temperature T. That is, country 1 tends to under-emit CO_2 in the non-cooperative case, compared with the cooperative (efficient) case.

Moreover, Appendix B2 shows that $\frac{\partial \eta_1}{\partial \sigma} < 0$, $\frac{\partial \mu_1}{\partial \sigma} < 0$, $\frac{\partial \xi}{\partial \sigma} < 0$ and $\frac{\partial \psi}{\partial \sigma} < 0$ for this asymmetric case, which implies that $\frac{\partial E_1^{NC}(T)}{\partial \sigma} = \frac{\partial \mu_1}{\partial \sigma} + \frac{\partial \eta_1}{\partial \sigma} T < 0$, $\frac{\partial E_2^{NC}(T)}{\partial \sigma} = 0$ and $\frac{\partial E_i^C(T)}{\partial \sigma} = \frac{\partial \psi}{\partial \sigma} + \frac{\partial \xi}{\partial \sigma} T < 0$ $(i = 1, 2)$ for a given temperature $T \geq 0$. This implies that both countries will be more cautious about their emissions when facing greater climate uncertainty in the cooperative case, while in the non-cooperative case only country 1 will behave like this.

5.3 The possibility of cooperation

As shown before, the payoffs under international cooperation can be simply split equally to each country in the case of symmetric players, while the split of surplus is not easy in the case of asymmetric players. Therefore, let us focus on the total payoffs for the two countries in the asymmetric case. To see how beneficial international cooperation is, again, one has to compare the expected payoffs under the case of non-cooperation with those under cooperation. Specifically, the total welfare gain from international cooperation (TWGIC), i.e., the difference between the combined payoff under cooperation and that under non-cooperation, is:

$$\begin{aligned} TWGIC &= W(T_0) - [V_1(T_0) + V_2(T_0)] \\ &= \zeta + \psi T_0 + \tfrac{1}{2}\xi[T_0]^2 - (\kappa_1 + \mu_1 T_0 + \tfrac{1}{2}\eta_1[T_0]^2 + \tfrac{1}{2r}[\varphi a]^2) \\ &= \Delta + (\psi - \mu_1)T_0 + \tfrac{1}{2}(\xi - \eta_1)[T_0]^2 \end{aligned} \tag{25}$$

where $\Delta = \zeta - \kappa_1 - \frac{1}{2r}[\varphi a]^2$.

Lemma 2 *The total expected payoffs for the two countries are larger when they cooperate, no matter how large the climate uncertainty is and how asymmetric the two players are in terms of marginal benefits from emissions.*

Again, Lemma 2 follows directly from the well-known general results that collective well-being can be increased if all countries cooperate in managing shared environmental resources. We can also rigorously show that this is true for our particular case. More specifically, if one can show that (25) has a positive sign, we know that cooperation is beneficial, in the sense that it will increase the sum of the two players' expected payoffs. In Appendix B1, we show that $\xi - \eta_1 > 0$ and $\psi - \mu_1 > 0$. Let us now investigate the sign of the constant term in (25), i.e., $\Delta = \zeta - \kappa_1 - \frac{1}{2r}[\varphi a]^2$. In Appendix B3, we show that $\Delta > 0$ holds for any $\varphi > 0$. Together with $\xi - \eta_1 > 0$ and $\psi - \mu_1 > 0$ (see Appendix B1), we know from (25) that, for a given initial temperature $T_0 \geq 0$, $TWGIC = W(T_0) - [V_1(T_0) + V_2(T_0)] > 0$ for all σ ($\sigma^2 < r$) and for any $\varphi > 0$.

That is, no matter how asymmetric the two players are in terms of marginal benefits from emissions, the total surplus of cooperation would always be positive for the two countries. Also, similar to the results for the symmetric case, the positive gain from cooperation holds for all different magnitudes of climate uncertainty.

5.4 Effect of uncertainty on the benefits of cooperation

Let us first investigate the effect of uncertainty on players' payoffs in the non-cooperative case and the cooperative case, respectively. Recall that, in the non-cooperative case, the expected payoffs of the two players are $V_1(T_0) = \kappa_1 + \mu_1 T_0 + \frac{1}{2}\eta_1 [T_0]^2$ and $V_2(T) = \frac{(\varphi a)^2}{2r}$, respectively. Clearly, the expected payoff of country 2 does not depend on the level of climate uncertainty (σ) because country 2 does not suffer any climate damage ($\gamma = 0$). For country 1, Appendix B2 shows that $\frac{\partial \eta_1}{\partial \sigma} < 0$, $\frac{\partial \mu_1}{\partial \sigma} < 0$, and $\frac{\partial \kappa_1}{\partial \sigma} < 0$, which implies that $\frac{\partial V_1(T_0)}{\partial \sigma} = \frac{\partial \kappa_1}{\partial \sigma} + \frac{\partial \mu_1}{\partial \sigma} T_0 + \frac{1}{2}\frac{\partial \eta_1}{\partial \sigma}[T_0]^2 < 0$. That is, the expected (non-cooperative) payoff of country 1 will be lower for greater climate uncertainty. However, one can show that the total welfare gain from cooperation (i.e., $TWGIC$ as defined in Eq. (25)) is increasing in climate uncertainty for our case of asymmetric players as well, which is consistent with the result in the case of symmetric players, as summarized in the proposition below.

Proposition 3 *The total welfare gain from international cooperation is an increasing function of climate uncertainty. The greater the uncertainty, the larger the total gain from cooperation.*

Proof. See Appendix B4. ■

5.5 Payoff transfers to ensure stability of the cooperation

We have known that, in the asymmetric case, international cooperation is also beneficial, in the sense that cooperation will increase the sum of two players' expected payoffs over the entire time horizon. However, because country 2 suffers no damages from global warming, it does not have a direct incentive to cooperate. Nevertheless, it is possible to provide sufficient incentives for country 2 to agree to cooperate, for example, by offering a side payment mechanism, as we shall show below.

As proposed by Petrosyan (1997) and Yeung and Petrosyan (2004, 2006), to ensure that players have the incentives to cooperate for the whole game horizon, we need to ensure that both group rationality and individual rationality constraints are satisfied. Group rationality requires the players to seek a set of cooperative strategies/controls which ensure that Pareto optimality is achieved and that all potential gains from cooperation are captured. More specifically, group rationality requires the players to maximize their joint payoffs, as we have demonstrated above.

Individual rationality implies that neither player will be worse off than before under cooperation, i.e., each player receives at least the payoff he or she would have received if playing against the rest of the players. The violation of the individual rationality principle would lead to a situation in which the players deviate from the agreed-upon cooperative solution and play non-cooperatively. In the case of symmetric players discussed above, we assume that the payoffs under cooperation will be split equally among the symmetric players, and we have shown that an equal split of the payoffs under cooperation can ensure that each country receives at least the payoff it would have received if playing non-cooperatively. However, in the case of asymmetric players, the split of the payoffs is not easy to define. Therefore, following Petrosyan (1997) and Yeung and Petrosyan (2004, 2006), we formulate a payoff distribution scheme over time to ensure individual rationality, which will make the cooperation among countries time consistent, i.e., guarantee the dynamic stability of the cooperative solution. The dynamic stability of the cooperative solution involves the property that, as the game proceeds along an optimal trajectory, players are guided by the same optimality principle at each instant of time, and hence do not possess incentives to deviate from the previously adopted optimal behavior throughout the game.

Substituting (24.2) and (24.3) into the differential equation (1) yields the dynamics of the optimal (cooperative) trajectory:

$$dT(t) = [a(1+\varphi) + 2\psi + 2\xi T(t)]dt + \sigma T(t)dz, T(0) = T_0 \geq 0 \tag{26}$$

where ψ and ξ are as shown in Table 2. The solution to (26) can be expressed as:

$$T^*(t) = T_0 + \int_0^t [a(1+\varphi) + 2\psi + 2\xi T^*(\tau)]ds + \int_0^t \sigma T^*(\tau)dz(\tau) \tag{27}$$

Denote Λ_t^* as the set of realizable values of $T^*(t)$ at time t generated by the stochastic process (27) and T_t^* as an element in the set Λ_t^*. Assume that, at time instant $t > 0$ (recall that $t = 0$ is the starting time of the game) when the initial state is $T_t^* \in \Lambda_t^*$, the agreed upon optimality principle assigns an imputation vector $\pi(T_t^*) = [\pi_1(T_t^*), \pi_2(T_t^*)]$. That is, the players agree on an imputation of the total cooperative payoff $W(T_t^*)$ in such a way that the expected payoff of player i is equal to $\pi_i(T_t^*)$ and satisfies $\sum_{i=1}^2 \pi_i(T_t^*) = W(T_t^*)$. Then we know individual rationality requires that:

$$\pi_i(T_t^*) \geq V_i(T_t^*) \text{ for } i = 1, 2 \tag{28}$$

where $V_i(\cdot)$ is the value function of player i in the non-cooperative case, as defined in Section 5.1.

We know that individual rationality (28) has to hold at every instant of time $t > 0$ and that violation of individual rationality can lead to deviation from the cooperative trajectory, which implies that the Pareto optimum under cooperation is not achieved by the two players.

Following Petrosyan (1997) and Yeung and Petrosyan (2004, 2006), we can formulate a payoff distribution scheme over time so that the imputations with individual rationality can be achieved. Denote $G(\tau) = [G_1(\tau), G_2(\tau)]$ as the instantaneous payoff of the cooperative game at time $\tau \in [0, \infty)$. $G_i(\tau)$ must satisfy the following condition to ensure group rationality:

$$G_1(\tau) + G_2(\tau) = a[E_1^C(T_\tau^*) + \varphi E_2^C(T_\tau^*)] - \frac{1}{2}\left[[E_1^C(T_\tau^*)]^2 + [E_2^C(T_\tau^*)]^2\right] - \frac{\varepsilon(1+\gamma)}{2}[T_\tau^*]^2 \tag{29}$$

where the right-hand side of (29) is the sum of instantaneous net benefits of the two countries under cooperation along the cooperative trajectory $\{T_\tau^*\}_{\tau\geq 0}$. Also, along the cooperative trajectory $\{T_\tau^*\}_{\tau\geq 0}$, the imputation $\pi^i(T_\tau^*)$ should satisfy:

$$\pi_i(T_\tau^*) = \mathbb{E}_\tau\left\{\int_\tau^\infty e^{-r(s-\tau)}G_i(s)ds|T(\tau)=T_\tau^*\right\} \text{ for } i=1,2, \text{and } T_t^*\in\Lambda_t^* \tag{30}$$

where $\mathbb{E}_\tau$ is the expectation taken at time τ.

As assumed before, in the cooperative game, the players agree to maximize the sum of their expected payoffs. Let us further assume that the players divide the total cooperative payoff, satisfying the Nash bargaining outcome. Then the imputation scheme has to satisfy: at time $t=0$, an imputation $\pi_i(T_0) = V_i(T_0)+\frac{1}{2}[W(T_0)-\sum_{j=1}^2 V_i(T_0)]$ is assigned to player i ($i=1,2$); and at time $\tau\in(0,\infty)$, an imputation $\pi_i(T_\tau^*) = V_i(T_\tau^*)+\frac{1}{2}[W(T_\tau^*)-\sum_{j=1}^2 V_i(T_\tau^*)]$ is assigned to player i for $i=1,2$, and $T_\tau^*\in\Lambda_t^*$. Since we have shown above that $W(T)-\sum\limits_{j=1}^{2}V^i(T)>0$, we know that such an imputation scheme will satisfy individual rationality (28). And it can be demonstrated that a payoff distribution procedure with an instantaneous imputation rate at time $\tau\in[0,\infty)$ as follows will yield a time consistent cooperative solution that satisfies group rationality (29) and can achieve such an imputation $\pi(T_\tau^*)=[\pi_1(T_\tau^*),\pi_2(T_\tau^*)]$ that satisfies the Nash bargaining outcome and ensures individual rationality (28). [6]

$$\begin{aligned} G_i(\tau) = G_i(T_\tau^*) = &\frac{1}{2}\left\{rV_i(T_\tau^*) - V_i^{'}(T_\tau^*)[a(1+\varphi)+2\psi+2\xi T_\tau^*] - \frac{1}{2}\sigma^2T^2\cdot V_i^{''}\ (T_\tau^*)\right\} \\ &+\frac{1}{2}\left\{rW(T_\tau^*) - W'(T_\tau^*)[a(1+\varphi)+2\psi+2\xi T_\tau^*] - \frac{1}{2}\sigma^2T^2\cdot W''(T_\tau^*)\right\} \\ &-\frac{1}{2}\left\{rV_j(T_\tau^*) - V_j^{'}(T_\tau^*)[a(1+\varphi)+2\psi+2\xi T_\tau^*] - \frac{1}{2}\sigma^2T^2\cdot V_j^{''}\ (T_\tau^*)\right\} \end{aligned} \tag{31}$$

Plugging in the value functions that we obtained above (in Section 5.1), one can rewrite the payoff distribution procedure (31) as:

$$\begin{aligned} G_1(\tau) = &\frac{1}{2}\left\{r[\kappa_1+\mu_1T_\tau^*+\frac{1}{2}\eta_1(T_\tau^*)^2] + r[\zeta+\psi T_\tau^*+\frac{1}{2}\xi(T_\tau^*)^2] - r[\kappa_2+\mu_2T_\tau^*+\frac{1}{2}\eta_2(T_\tau^*)^2]\right\} \\ &-\frac{1}{4}\sigma^2(T_\tau^*)^2[\eta_1+\xi-\eta_2] - \frac{1}{2}[a(1+\varphi)+2\psi+2\xi T_\tau^*][(\mu_1+\eta_1T_\tau^*)+(\psi+\xi T_\tau^*)-(\mu_2+\eta_2T_\tau^*)] \end{aligned} \tag{32.1}$$

[6]The demonstration is straightforward by applying Theorem 5.8.3 and Proposition 5.8.1 in Yeung and Petrosyan (2006), which is therefore omitted here. It is available from the authors upon request.

$$G_2(\tau) = \frac{1}{2}\left\{ r[\kappa_2 + \mu_2 T_\tau^* + \frac{1}{2}\eta_2 (T_\tau^*)^2] + r[\zeta + \psi T_\tau^* + \frac{1}{2}\xi (T_\tau^*)^2] - r[\kappa_1 + \mu_1 T_\tau^* + \frac{1}{2}\eta_1 (T_\tau^*)^2] \right\}$$
$$- \frac{1}{4}\sigma^2 (T_\tau^*)^2[\eta_2 + \xi - \eta_1] - \frac{1}{2}[a(1+\varphi) + 2\psi + 2\xi T_\tau^*][(\mu_2 + \eta_2 T_\tau^*) + (\psi + \xi T_\tau^*) - (\mu_1 + \eta_1 T_\tau^*)] \quad (32.2)$$

where the values of κ_i, μ_i, η_i, ζ, ψ, and ξ are as in Table 2. The instantaneous payoff distribution procedure in (32.1)-(32.2) yields a time-consistent solution to the cooperative game studied above, in the sense that it will ensure that players play cooperative strategies throughout the game.

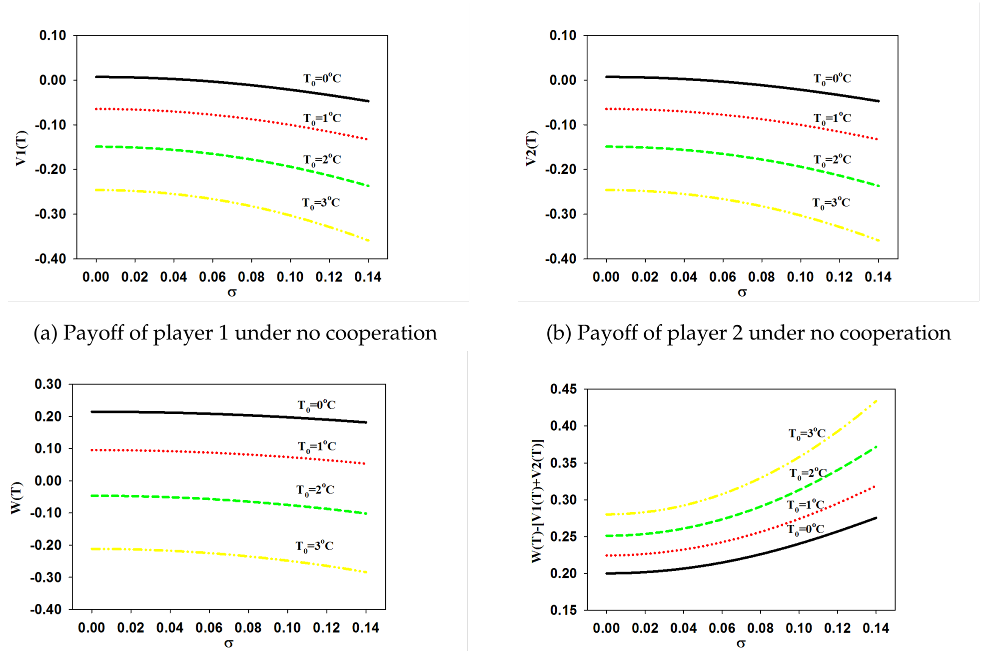
Therefore, the instantaneous payoff transfer from county j to country i at time instant τ would be:

$$F_i(\tau) = G_i(\tau) - B_i(E_i^C(T_\tau^*), T_\tau^*) = G_i(\tau) - a_i E_i^C(T_\tau^*) + \frac{1}{2}[E_i^C(T_\tau^*)]^2 + \frac{\varepsilon_i}{2}[T_\tau^*]^2 \quad (33)$$

where $E_i^C(\cdot)$ is the optimal emission strategies under cooperation, as in (24.2) and (24.3). As we shall show numerically below, for a given temperature T_0, the initial instantaneous payoff transfer ($\tau = 0$ in Eq. (33)) from county 1 to country 2 is positive and increases as climate uncertainty becomes larger. That is, the larger the uncertainty, the more compensation is needed to induce the country that does not suffer from climate damage to cooperate.

6 Numerical illustrations

To complement the theoretical analysis above, we numerically examine how the expected payoff/welfare for each country in both cases (cooperative and non-cooperative) and the welfare gain from international cooperation will change with the parameter σ, which measures the uncertainty about global warming. For instance, by setting the parameter values $a = 0.2$, $\varepsilon = 0.001$, and $r = 0.04$, one can obtain the illustrative results as depicted in Figures 1 and 2, where Figure 1 shows the effect of the uncertainty about global warming in the case of symmetric players and Figure 2 illustrates the case of asymmetric players, which we analyzed above ($\varphi = 0.5$ in the illustration).



(a) Payoff of player 1 under no cooperation

(b) Payoff of player 2 under no cooperation

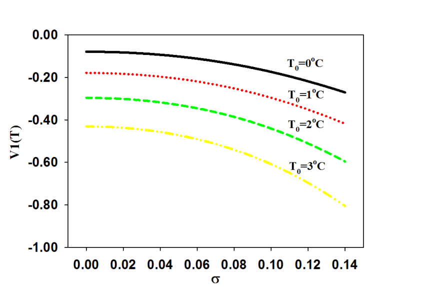
(c) Total cooperative payoff

(d) Total welfare gains from cooperation

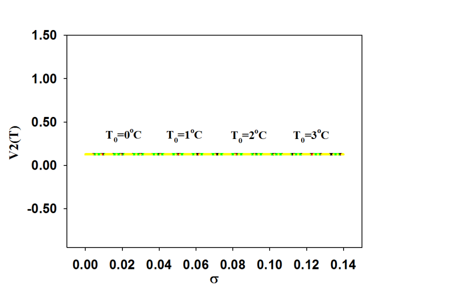
Figure 1. Effect of climate uncertainty in the case of symmetric players ($\varphi = 1, \gamma = 1$)

It can be seen from Figure 1 that players' expected payoffs will decrease with higher climate uncertainty, whether or not they cooperate. Besides, it can be observed that the welfare gain from international cooperation is an increasing function of parameter σ. These results are consistent with the theoretical predictions above for the symmetric case: even though the expected welfare of individual countries will be reduced by greater uncertainty about climate change in both the non-cooperative and cooperative cases, the (expected) welfare gain from international cooperation is an increasing function of climate uncertainty. That is, the greater the climate uncertainty, the more important it is to have international cooperation.

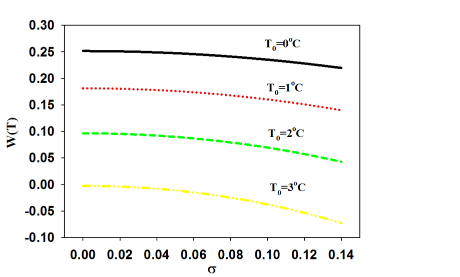
From Figure 2, one can see that the conclusions also hold for our particular case of asymmetric players where country 2 does not suffer from climate damages. It can be observed that, since player 2 does not suffer from climate damages, the uncertainty about climate change and initial temperature will not affect its expected payoff in the non-cooperative case, as illustrated by Figure 2(b). For country 1, its expected payoff in the non-cooperative case still decreases as climate uncertainty becomes larger. The total payoff under cooperation is also decreasing with uncertainty, as shown in Figure 2(c). However, the total welfare gain from cooperation is found to be an increasing function of climate uncertainty. These results are consistent with the theoretical predictions above.



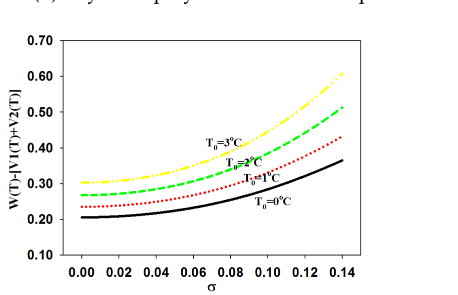
(a) Payoff of player 1 under no cooperation



(b) Payoff of player 2 under no cooperation



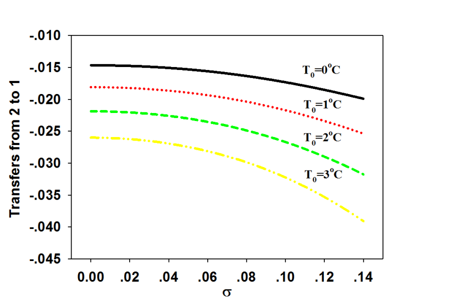
(c) Total cooperative payoff



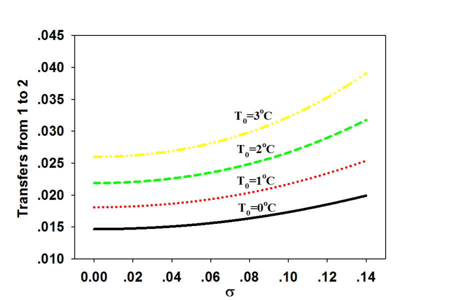
(d) Total welfare gains from cooperation

Figure 2. Effect of climate uncertainty in the case of asymmetric players ($\varphi = 0.5$, $\gamma = 0$)

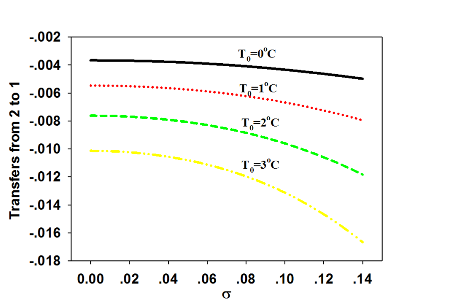
Besides, based on Eq. (33), one can illustrate the effect of uncertainty on the instantaneous payoff transfers between countries. By setting $\tau = 0$ in Eq. (33), we focus on the initial payoff transfers, given the initial temperature T_0. As can be seen in Figure 3, the transfers should go from country 1 to country 2 to ensure the stability of cooperation. Also, the greater the uncertainty, the more country 1 needs (and is willing to) to transfer to country 2 to ensure cooperation.



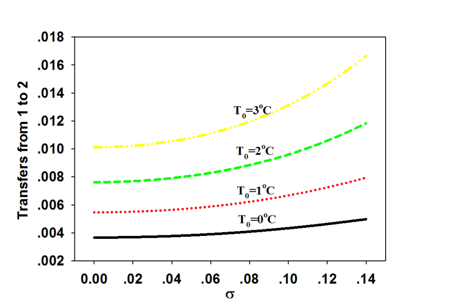
(a) Transfers to country 1 ($\varphi = 2$, $\gamma = 0$)



(b) Transfers to country 2 ($\varphi = 2$, $\gamma = 0$)



(c) Transfers to country 1 ($\varphi = 0.5$, $\gamma = 0$)



(d) Transfers to country 2 ($\varphi = 0.5$, $\gamma = 0$)

Figure 3. Effect of climate uncertainty on the initial transfers between countries

As mentioned above, the non-cooperative solutions for the more general asymmetric case ($\varphi \neq 1$ and $\gamma \neq \{0, 1\}$) cannot be obtained analytically and would need the assistance of numerical methods. That is, given the model parameters, one can numerically solve the system of equations (9.1)-(9.6) to obtain the coefficients of players' value functions with different values of climate uncertainty, and then investigate the effect of uncertainty and conduct comparisons with the cooperative solutions (see (16.1)-(16.3)).

Table 3 presents some numerical results to complement the analytical analysis above (where the asymmetric case is somewhat extreme). The bottom section in Table 3 presents the results with larger climate uncertainty, compared with the top section. In each section, the parameter values of (φ, γ) reflect the asymmetry between the two players. It can be seen from Table 3 that the total payoffs in the cooperative case (W) will decrease as the climate uncertainty becomes larger. The same will happen for the combined payoffs in the non-cooperative case (V_1+V_2). That is, climate uncertainty has a negative effect on the combined payoffs of players, whether or not they cooperate with each other. However, the welfare gain from cooperation ($W - [V_1 + V_2]$) is always positive and increases as uncertainty becomes larger, which suggests that international cooperation is more important when facing greater climate uncertainty. Besides, the numerical results show that it is possible, in the case of asymmetric players, that the non-cooperative payoff of one player is reduced by larger climate uncertainty while the non-cooperative payoff of the other player is increased by larger uncertainty. For instance, with $(\varphi, \gamma) = (1, 2)$, where the two players have identical benefits from emissions but player 2 faces more climate damages, larger climate uncertainty (a change in σ from 0.01 to 0.05) will reduce the non-cooperative payoff of player 2 (V_2) but increase that of player 1 (V_1). However, as stated above, the overall effect of increasing uncertainty is a reduction in the combined payoffs ($V_1 + V_2$).

In addition, it can be seen from Table 3 that the initial payoff transfer from player 2 to player 1 (F_1) varies as the asymmetry between players or the degree of climate uncertainty changes.[7] For instance, when the two players are fully symmetric, there is no need of a payoff transfer between them. In contrast, with $\gamma = 0$, i.e., player 2 does not suffer from climate damage, the transfers to player 1 are negative, which implies the need for payment transfers from player 1 to player 2 to support the stability of cooperation. Also, the transfers needed to stabilize cooperation are larger when climate uncertainty is higher. With $\gamma = 2$, when player 2 faces twice as much damage as does player 1, payment transfers from player 2 to player 1 are necessary to ensure stable cooperation, and the needed transfers are larger with higher climate uncertainty.

[7] The payoff transfer from player 1 to player 2 (F_2) is just the negative of F_1 , i.e., $F_1 + F_2 = 0$, and is therefore omitted in Table 3. That is, one can see the direction of transfer from either F_1 or F_2 .

Table 3. Some more simulation results ($r = 0.04$, $a = 0.2$, $\varepsilon = 0.001$)

	$V_1(T_0 = 1)$	$V_2(T_0 = 1)$	$V_1(\cdot) + V_2(\cdot)$	$W(T_0 = 1)$	$W(\cdot) - \sum_{j=1}^{2} V_j(\cdot)$	$F_1(\tau = 0)$
			$\sigma = 0.01$			
$(\varphi, \gamma) = (1, 1)$	-0.0647	-0.0647	-0.1294	0.0955	0.2249	0.0000
$(\varphi, \gamma) = (1, 0)$	-0.6612	0.5000	-0.1612	0.2445	0.4057	-0.0089
$(\varphi, \gamma) = (2, 0)$	-2.0106	2.0000	-0.0106	0.8723	0.8829	-0.0181
$(\varphi, \gamma) = (1, 2)$	0.1957	-0.5050	-0.3093	0.0248	0.3341	0.0093
$(\varphi, \gamma) = (2, 2)$	-0.1489	-0.1594	-0.3083	0.4147	0.7229	0.0184
			$\sigma = 0.05$			
$(\varphi, \gamma) = (1, 1)$	-0.0733	-0.0733	-0.1466	0.0903	0.2369	0.0000
$(\varphi, \gamma) = (1, 0)$	-0.7059	0.5000	-0.2059	0.2362	0.4422	-0.0093
$(\varphi, \gamma) = (2, 0)$	-2.1064	2.0000	-0.1064	0.8547	0.9611	-0.0190
$(\varphi, \gamma) = (1, 2)$	0.1980	-0.5245	-0.3265	0.0210	0.3475	0.0096
$(\varphi, \gamma) = (2, 2)$	-0.1434	-0.2007	-0.3441	0.4069	0.7510	0.0191

7 Concluding remarks and further research

This paper investigates the effect of climate uncertainty on international cooperation through a stochastic dynamic game in which the global temperature increase due to CO_2 emissions is uncertain. It is shown that, even though greater climate uncertainty will reduce the expected welfare of players in both the non-cooperative and cooperative cases, it is always beneficial to cooperate with each other, and the expected welfare gain from international cooperation is larger with greater climate uncertainty. That is, the greater the uncertainty about global warming, the more important it is to have international cooperation on emission control. At the same time, more transfers will be needed to ensure stable cooperation among asymmetric players.

Our results have important policy implications. In reality, individual countries become hesitant in climate cooperation and believe that they should not act or cooperate due to the uncertainty surrounding climate change. However, our results show cooperation can always benefit a country, provided there is an appropriate side payment mechanism. Moreover, the benefits from cooperation are larger when the climate uncertainty is higher, implying that it is more important to cooperate when we are more unsure about the future temperature increase.

This study is not without limitations. For instance, the analysis presented here is based on the game's analytical solutions, which can only be obtained for the case of unconstrained emissions (i.e., reversible emissions). The case of irreversible emissions (which can be more realistic), unfortunately, does not allow for an analytical solution and a comprehensive analysis for this case may need the assistance of advanced numerical methods. Therefore, we omit the discussion of irreversible emissions in our analysis. Further research should use numerical analysis to examine how uncertainty affects the benefits of international cooperation under the assumption of irreversible emissions.

Another possible extension is to include asymmetric uncertainty in the model. That is, the level of climate uncertainty can vary significantly in different countries or regions. More specifically, the temperature means as well as variances in the two countries or regions in the model can be different. Each regional temperature is affected by emissions from both regions, though the uncertainties governing the evolution of temperatures in the two regions may be different. This problem can be modeled as a stochastic dynamic game with two state variables, which can only be solved with the assistance of numerical methods.[8] Our numerical simulations show that, for two regions that differ in climate uncertainty only, one region will be worse off in its payoff (welfare) as its own climate uncertainty becomes larger but better off as the other region's uncertainty becomes larger, in the absence of cooperation. The total welfare gains from international cooperation increase with each region's climate uncertainty, though the total payoffs of the two regions under cooperation will be reduced by higher climate uncertainty in either region. Also, the size of the initial instantaneous payoff transfer (if any) to one region to ensure stable cooperation is negatively related to its own climate uncertainty but positively related to the other region's uncertainty. That is, in order to ensure cooperation, the countries/regions with higher uncertainty in climate need to compensate the ones with lower uncertainty. A more general and analytical analysis on the effect of asymmetric uncertainty in this context can also be a direction for further research.

[8]The details of the extended model and its numerical solutions can be obtained from the authors upon request.

Appendix

A1.Proof of $\xi - \eta < 0$ and $\psi - \mu < 0$ in the case of symmetric players.

Proof. From Table 1, we know that:

$$\xi - \eta = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2 + 16\varepsilon}}{4} - \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2 + 12\varepsilon}}{6}.$$

It can be noticed that we would have $\xi - \eta = 0$ had it been the case that $\varepsilon = 0$, i.e., $(\xi - \eta)\,|_{\varepsilon=0} = 0$. Furthermore, it is easy to show that

$$\frac{\partial[\xi-\eta]}{\partial\varepsilon} = -\frac{2}{\sqrt{(r-\sigma^2)^2+16\varepsilon}} + \frac{1}{\sqrt{(r-\sigma^2)^2+12\varepsilon}} = -\frac{1}{\sqrt{\frac{1}{4}(r-\sigma^2)^2+4\varepsilon}} + \frac{1}{\sqrt{(r-\sigma^2)^2+12\varepsilon}} < 0$$

for any $\varepsilon > 0$. By the mean value theorem, it can be known that $(\xi - \eta)\,|_{\varepsilon>0} - (\xi - \eta)\,|_{\varepsilon=0} < 0$. That is, $\xi - \eta < 0$ will hold with our assumption $\varepsilon > 0$.

Also, from Table 1 one can obtain $\psi - \mu = \frac{2ar(\xi-\eta) - 2a\xi\eta}{(r-2\xi)(r-3\eta)}$. Because we have shown above that $\xi - \eta < 0$ and we know that $\xi < 0$ and $\eta < 0$, we have $\psi - \mu < 0$. ■

A2. Proof of $\frac{\partial\eta}{\partial\sigma} < 0$, $\frac{\partial\mu}{\partial\sigma} < 0$, $\frac{\partial\kappa}{\partial\sigma} < 0$, $\frac{\partial\xi}{\partial\sigma} < 0$, $\frac{\partial\psi}{\partial\sigma} < 0$, and $\frac{\partial\zeta}{\partial\sigma} < 0$ for the symmetric case.

Proof. Based on the expressions for η, μ, and κ in Table 1, we can obtain the following derivatives:

$$\frac{\partial\eta}{\partial\sigma} = -\frac{1}{6}\underbrace{\left(2\sigma - \frac{2\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+12\varepsilon}}\right)}_{>0} < 0 \tag{A2.1}$$

$$\frac{\partial\mu}{\partial\sigma} = \frac{2ar}{(r-3\eta)^2}\underbrace{\frac{\partial\eta}{\partial\sigma}}_{<0} < 0 \tag{A2.2}$$

$$\frac{\partial\kappa}{\partial\sigma} = \frac{1}{r}[2a+3\mu]\underbrace{\frac{\partial\mu}{\partial\sigma}}_{<0} \tag{A2.3}$$

Since $\mu = \frac{2a}{3}[\frac{r}{r-3\eta} - 1]$ (see Table 1), we have: $2a + 3\mu = \frac{2ar}{r-3\eta} > 0$, which implies $\frac{\partial\kappa}{\partial\sigma} < 0$. Similarly, based on the expressions for ξ, ψ, and ζ in Table 1, we have:

$$\frac{\partial \xi}{\partial \sigma} = -\frac{1}{4}\underbrace{\left(2\sigma - \frac{2\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+16\varepsilon}}\right)}_{>0} < 0 \tag{A2.4}$$

$$\frac{\partial \psi}{\partial \sigma} = \frac{2ar}{(r-2\xi)^2}\underbrace{\frac{\partial \xi}{\partial \sigma}}_{<0} < 0 \tag{A2.5}$$

$$\frac{\partial \zeta}{\partial \sigma} = \frac{1}{r}[2(a+\psi)\underbrace{\frac{\partial \psi}{\partial \sigma}}_{<0}] \tag{A2.6}$$

Given $\psi = a[\frac{r}{r-2\xi} - 1]$ (see Table 1), we have $a + \psi = \frac{ar}{r-2\xi} > 0$, and thus, $\frac{\partial \zeta}{\partial \sigma} < 0$. ■

A3. Proof of $\frac{1}{2}\zeta - \kappa > 0$, $\frac{1}{2}\psi - \mu > 0$, and $\frac{1}{2}\xi - \eta > 0$ for the symmetric case.

Proof. From Table 1 we have:

$$\frac{1}{2}\xi - \eta = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2+16\varepsilon}}{8} - \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2+12\varepsilon}}{6}$$

It can be noticed that we would have $\frac{1}{2}\xi - \eta = 0$ had it been the case that $\varepsilon = 0$, i.e.,$\left(\frac{1}{2}\xi - \eta\right)|_{\varepsilon=0} = 0$. Furthermore, it is straightforward to show that

$$\frac{\partial[\frac{1}{2}\xi - \eta]}{\partial \varepsilon} = -\frac{1}{\sqrt{(r-\sigma^2)^2+16\varepsilon}} + \frac{1}{\sqrt{(r-\sigma^2)^2+12\varepsilon}} > 0$$

for any $\varepsilon > 0$. By the mean value theorem, it can be known that $\left(\frac{1}{2}\xi - \eta\right)|_{\varepsilon>0} - \left(\frac{1}{2}\xi - \eta\right)|_{\varepsilon=0} > 0$. That is, $\frac{1}{2}\xi - \eta > 0$ will always hold with our assumption $\varepsilon > 0$. Also, from Table 1 one can obtain $\frac{1}{2}\psi - \mu = \frac{a[r(\xi-2\eta)+\xi\eta]}{(r-2\xi)(r-3\eta)}$. Because it has been shown above that $\frac{1}{2}\xi - \eta > 0$ and we know that $\xi < 0$ and $\eta < 0$, we have $\frac{1}{2}\psi - \mu > 0$.

Furthermore, after some calculations, one can obtain from Table 1 that $\frac{1}{2}\zeta - \kappa = \frac{1}{2r}[(\psi - 2\mu)(a + \psi + a + \frac{3}{2}\mu) + \frac{1}{2}\psi\mu]$. Since we have shown above that $\frac{1}{2}\psi - \mu > 0$ (i.e., $\psi - 2\mu > 0$) and we know that $a + \psi = \frac{ar}{r-2\xi} > 0$ and $a + \frac{3}{2}\mu = \frac{ar}{r-3\eta} > 0$, we have $\frac{1}{2}\zeta - \kappa > 0$. ■

A4. Proof of Proposition 2.

Proof. From (A2.1) and (A2.4) in Appendix A2, one can easily find that:

$$\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma} = -\frac{1}{8}\left(2\sigma - \frac{2\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+16\varepsilon}}\right) + \frac{1}{6}\left(2\sigma - \frac{2\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+12\varepsilon}}\right)$$

Clearly, $\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma} = 0$ if ε were equal to zero, i.e., $\left(\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma}\right)|_{\varepsilon=0} = 0$.

One can show $\frac{\partial^2[\frac{1}{2}\xi-\eta]}{\partial\sigma\partial\varepsilon} = 2\sigma(r-\sigma^2)\left\{\frac{1}{[(r-\sigma^2)^2+12\varepsilon]^{3/2}} - \frac{1}{[(r-\sigma^2)^2+16\varepsilon]^{3/2}}\right\} > 0$ for all $\varepsilon > 0$. By the mean value theorem, we know that $\left(\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma}\right)|_{\varepsilon>0} - \left(\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma}\right)|_{\varepsilon=0} > 0$ will hold. That is, under our assumption of non-zero damage (i.e., $\varepsilon > 0$), $\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma} > 0$ will hold. Also, we know from (A2.2) and (A2.5) in Appendix A2:

$$\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma} = \frac{1}{2}\frac{2ar}{(r-2\xi)^2}\frac{\partial \xi}{\partial \sigma} - \frac{2ar}{(r-3\eta)^2}\frac{\partial \eta}{\partial \sigma} > \left[\frac{2ar}{(r-2\xi)^2} - \frac{2ar}{(r-3\eta)^2}\right]\frac{\partial \eta}{\partial \sigma}$$

The last inequality holds due to $\frac{1}{2}\frac{\partial \xi}{\partial \sigma} > \frac{\partial \eta}{\partial \sigma}$, which we have just shown above.
Since $0 < -\frac{1}{2}\left((r-\sigma^2) - \sqrt{(r-\sigma^2)^2+12\varepsilon}\right) < -\frac{1}{2}\left((r-\sigma^2) - \sqrt{(r-\sigma^2)^2+16\varepsilon}\right)$, i.e., $0 < -3\eta < -2\xi$, we know $\frac{2ar}{(r-2\xi)^2} - \frac{2ar}{(r-3\eta)^2} < 0$. Together with $\frac{\partial \eta}{\partial \sigma} < 0$ (see Appendix A2), we have $\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma} > 0$.

Moreover, we can obtain from (A2.3) and (A2.6) (see Appendix A2):

$$\frac{1}{2}\frac{\partial \zeta}{\partial \sigma} - \frac{\partial \kappa}{\partial \sigma} = \frac{1}{2}\frac{1}{r}[2(a+\psi)\frac{\partial \psi}{\partial \sigma}] - \frac{1}{2r}[(4a+6\mu)\frac{\partial \mu}{\partial \sigma}] > \frac{1}{r}(2\psi-3\mu)\frac{\partial \mu}{\partial \sigma}$$

where the above-proven result $\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma} > 0$ was applied in the last inequality.
Since $\frac{1}{2}\left((r-\sigma^2) - \sqrt{(r-\sigma^2)^2+16\varepsilon}\right) < \frac{1}{2}\left((r-\sigma^2) - \sqrt{(r-\sigma^2)^2+12\varepsilon}\right)$, i.e., $2\psi < 3\mu$, and $\frac{\partial \mu}{\partial \sigma} < 0$ (see (A2.2)), we have $\frac{1}{2}\frac{\partial \zeta}{\partial \sigma} - \frac{\partial \kappa}{\partial \sigma} > 0$.

Given that $\frac{1}{2}\frac{\partial \zeta}{\partial \sigma} - \frac{\partial \kappa}{\partial \sigma} > 0$, $\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma} > 0$ and $\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma} > 0$, one can know $\frac{\partial WGIC}{\partial \sigma} = \left(\frac{1}{2}\frac{\partial \zeta}{\partial \sigma} - \frac{\partial \kappa}{\partial \sigma}\right) + \left(\frac{1}{2}\frac{\partial \psi}{\partial \sigma} - \frac{\partial \mu}{\partial \sigma}\right)T_0 + \frac{1}{2}\left(\frac{1}{2}\frac{\partial \xi}{\partial \sigma} - \frac{\partial \eta}{\partial \sigma}\right)[T_0]^2 > 0$. This implies that the greater the uncertainty about global warming, the more gain we can expect from international cooperation. ■

B1. $\xi - \eta_1 > 0$, $\psi - \mu_1 > 0$ **for the particular case of asymmetric players.**

Proof. From Table 2, we have:

$$\xi - \eta_1 = \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)+8\varepsilon}}{4} - \frac{(r-\sigma^2) - \sqrt{(r-\sigma^2)^2+4\varepsilon}}{2}$$

It can be noticed that we would have $\xi - \eta_1 = 0$ had it been the case that $\varepsilon = 0$, i.e.$(\xi - \eta_1)\,|_{\varepsilon=0} = 0$. Furthermore, it is easy to show that

$$\frac{\partial[\xi - \eta_1]}{\partial \varepsilon} = -\frac{1}{\sqrt{(r-\sigma^2)^2+8\varepsilon}} + \frac{1}{\sqrt{(r-\sigma^2)^2+4\varepsilon}} > 0$$

for any $\varepsilon > 0$. By the mean value theorem, it can be known that $(\xi - \eta_1)\,|_{\varepsilon>0} - (\xi - \eta_1)\,|_{\varepsilon=0} > 0$. That is, $\xi - \eta_1 > 0$ will hold with our assumption of $\varepsilon > 0$.

Furthermore, after some calculations one can show that:

$$\psi - \mu_1 = \frac{a(1+\varphi)\xi}{r-2\xi} - \frac{a(1+\varphi)\eta_1}{r-\eta_1} = \frac{a(1+\varphi)[r(\xi-\eta_1)+\xi\eta_1]}{(r-2\xi)(r-\eta_1)} > 0$$

The last inequality holds due to $\xi < 0$, $\eta_1 < 0$, and $\xi - \eta_1 > 0$. ■

B2. Proof of $\frac{\partial \eta_1}{\partial \sigma} < 0$, $\frac{\partial \mu_1}{\partial \sigma} < 0$, $\frac{\partial \kappa_1}{\partial \sigma} < 0$, $\frac{\partial \xi}{\partial \sigma} < 0$, $\frac{\partial \psi}{\partial \sigma} < 0$, and $\frac{\partial \zeta}{\partial \sigma} < 0$ for the asymmetric case.

Proof. Based on the expressions for η_1, μ_1, and κ_1 in Table 2, we can obtain the following derivatives:

$$\frac{\partial \eta_1}{\partial \sigma} = -[\underbrace{\sigma - \frac{\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+4\varepsilon}}}_{>0}] < 0 \tag{B2.1}$$

$$\frac{\partial \mu_1}{\partial \sigma} = \frac{ar(1+\varphi)}{(r-\eta_1)^2}\underbrace{\frac{\partial \eta_1}{\partial \sigma}}_{<0} < 0 \tag{B2.2}$$

$$\frac{\partial \kappa_1}{\partial \sigma} = \frac{1}{r}[\mu_1 + a]\frac{\partial \mu_1}{\partial \sigma} + \frac{1}{r}\varphi a\frac{\partial \mu_1}{\partial \sigma} = \frac{1}{r}[\mu_1 + (1+\varphi)a]\underbrace{\frac{\partial \mu_1}{\partial \sigma}}_{<0} \tag{B2.3}$$

Since $\mu_1 + (1+\varphi)a = \frac{ar(1+\varphi)}{r-\eta_1} > 0$, we have $\frac{\partial \kappa_1}{\partial \sigma} < 0$.
Based on the expressions of ξ, ψ, and ζ in Table 2, we have:

$$\frac{\partial \xi}{\partial \sigma} = -\frac{1}{2}[\sigma - \underbrace{\frac{\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+8\varepsilon(1+\gamma)}}}_{>0}] < 0 \tag{B2.4}$$

$$\frac{\partial \psi}{\partial \sigma} = \frac{ar(1+\varphi)}{(r-2\xi)^2}\underbrace{\frac{\partial \xi}{\partial \sigma}}_{<0} < 0 \tag{B2.5}$$

$$\frac{\partial \zeta}{\partial \sigma} = \frac{2}{r}[\psi + \frac{a(1+\varphi)}{2}]\underbrace{\frac{\partial \psi}{\partial \sigma}}_{<0} \tag{B2.6}$$

Being aware of $\psi + \frac{a(1+\varphi)}{2} = \frac{ar(1+\varphi)}{2(r-2\xi)}$, we have $\frac{\partial \zeta}{\partial \sigma} < 0$. ■

B3. Proof of $\Delta = \zeta - \kappa_1 - \frac{1}{2r}[\varphi a]^2 > 0$ for any $\varphi > 0$.

Proof. Making use of the expression of ζ and κ_1 in Table 2, we have:

$$\Delta = \zeta - \kappa_1 - \frac{1}{2r}[\varphi a]^2 = \frac{1}{r}[\psi + \frac{a(1+\varphi)}{2}]^2 + \frac{a^2(1-\varphi)^2}{4r} - \frac{1}{2r}[a+\mu_1]^2 - \frac{1}{r}[\varphi a]\mu_1 - \frac{1}{2r}[\varphi a]^2$$

Since $\psi + \frac{a(1+\varphi)}{2} = \frac{ar(1+\varphi)}{2(r-2\xi)}$ and $\mu_1 = \frac{\eta_1[a(1+\varphi)+\mu_2]}{r-(\eta_1+\eta_2)} = \frac{\eta_1 a(1+\varphi)}{r-\eta_1}$, we know that Δ is a quadratic function of φ. Let us denote $\Delta = Z\varphi^2 + Y\varphi + X$, where the coefficient of φ^2 can be found as:

$$\begin{aligned} Z &= \frac{a^2r^2}{4r(r-2\xi)^2} + \frac{a^2}{4r} - \frac{\eta_1^2 a^2}{2r(r-\eta_1)^2} - \frac{\eta_1 a^2}{r(r-\eta_1)} - \frac{a^2}{2r} \\ &= \frac{a^2}{4r}[1 + \frac{r^2}{(r-2\xi)^2} - \frac{2r^2}{(r-\eta_1)^2}] \end{aligned}$$

If we denote $\Omega = 1 + \frac{r^2}{(r-2\xi)^2} - \frac{2r^2}{(r-\eta_1)^2}$, then we have $Z = \frac{a^2}{4r}\Omega$. It can be noticed that we would have $Z = \frac{a^2}{4r}[1 + \frac{r^2}{r^2} - \frac{2r^2}{r^2}] = 0$ had it been the case that $\varepsilon = 0$, i.e., $Z|_{\varepsilon=0} = \frac{a^2}{4r}[1 + \frac{r^2}{r^2} - \frac{2r^2}{r^2}] = 0$. Furthermore, it is not difficult to show after some tedious but straightforward calculations that $\frac{\partial Z}{\partial \varepsilon} = \frac{a^2}{4r}\frac{\partial \Omega}{\partial \varepsilon} = a^2 r[\frac{\partial \xi}{\partial \varepsilon}/(r-2\xi)^3 - \frac{\partial \eta_1}{\partial \varepsilon}/(r-\eta_1)^3]$. Since we have $\frac{\partial \xi}{\partial \varepsilon} = \frac{-1}{\sqrt{(r-\sigma^2)+8\varepsilon}}$ and $\frac{\partial \eta_1}{\partial \varepsilon} = \frac{-1}{\sqrt{(r-\sigma^2)^2+4\varepsilon}}$, we know that:

$$\frac{\partial \xi}{\partial \varepsilon}/(r-2\xi)^3 - \frac{\partial \eta_1}{\partial \varepsilon}/(r-\eta_1)^3 = -\frac{1}{\left((r-2\xi)^3\sqrt{(r-\sigma^2)^2+8\varepsilon}\right)} + \frac{1}{\left((r-\eta_1)^3\sqrt{(r-\sigma^2)^2+4\varepsilon}\right)} > 0$$

where we make use of $2\xi < \eta_1 < 0$ (see (23.1) and Table 1 in the text) for the last inequality. Therefore, we have $\frac{\partial Z}{\partial \varepsilon} = a^2 r[\frac{\partial \xi}{\partial \varepsilon}/(r-2\xi)^3 - \frac{\partial \eta_1}{\partial \varepsilon}/(r-\eta_1)^3] > 0$. By the mean value theorem, we know $Z|_{\varepsilon>0} - Z|_{\varepsilon=0} > 0$, i.e., $Z > 0$ under our assumption of $\varepsilon > 0$.

The coefficient of φ in Δ can be calculated as:

$$\begin{aligned} Y &= \frac{2a^2r^2}{4r(r-2\xi)^2} - \frac{2a^2}{4r} - [\frac{2\eta_1^2 a^2}{2r(r-\eta_1)^2} + \frac{2\eta_1 a^2}{2r(r-\eta_1)}] - \frac{\eta_1 a^2}{r(r-\eta_1)} \\ &= \frac{a^2}{2r}[r^2/(r-2\xi)^2 - (r^2 + 2r\eta_1 - \eta_1^2)/(r-\eta_1)^2] \end{aligned}$$

Denoting $\Gamma = r^2/(r-2\xi)^2 - (r^2 + 2r\eta_1 - \eta_1^2)/(r-\eta_1)^2$, we have $Y = \frac{a^2}{2r}\Gamma$. Clearly, $Y = \frac{a^2}{2r}[\frac{r^2}{r^2} - \frac{r^2}{r^2}] = 0$ would hold had it been the case that $\varepsilon = 0$, i.e., $Y|_{\varepsilon=0} = \frac{a^2}{2r}[\frac{r^2}{r^2} - \frac{r^2}{r^2}] = 0$. Taking the derivative of Y with respect to ε and doing some further arrangements yield:

$$\frac{\partial Y}{\partial \varepsilon} = 2a^2 r[\frac{\partial \xi}{\partial \varepsilon}/(r-2\xi)^3 - \frac{\partial \eta_1}{\partial \varepsilon}/(r-\eta_1)^3]$$

We have shown above that $\frac{\partial \xi}{\partial \varepsilon}/(r-2\xi)^3 - \frac{\partial \eta_1}{\partial \varepsilon}/(r-\eta_1)^3 > 0$, which implies $\frac{\partial Y}{\partial \varepsilon} > 0$. By the mean value theorem, one knows that $Y|_{\varepsilon>0} - Y|_{\varepsilon=0} > 0$, i.e., $Y > 0$ under our assumption of $\varepsilon > 0$.

Besides, when $\varphi = 0$, we have $\Delta = X = \frac{1}{r}[\psi^2 + a\psi] - \frac{1}{2r}[\mu_1^2 + 2a\mu_1]$, and thus, $rX = \psi^2 + a\psi - \frac{1}{2}\mu_1^2 - a\mu_1 = (\psi - \mu_1)(a + \psi + \frac{1}{2}\mu_1) + \psi\mu_1$. Also, we know that, with $\varphi = 0$, we have $\frac{1}{2}(\mu_1 + a) = \frac{ar}{2(r-\eta_1)} > 0$ and $\psi + \frac{a}{2} = \frac{ar}{2(r-2\xi)} > 0$, which implies $a + \psi + \frac{1}{2}\mu_1 > 0$. Taking into account that $\psi - \mu_1 > 0$ (see Appendix B1), $\psi < 0$, and $\mu_1 < 0$, we know $rX > 0$ thus $X > 0$.

Since we have shown that $Z > 0$, $Y > 0$, and $X > 0$, we know that $\Delta = Z\varphi^2 + Y\varphi + X > 0$ would hold for any $\varphi > 0$. ■

B4. Proof of Proposition 3.

Proof. As stated in (25) in the main text, the total gain of cooperation for the two countries would be:

$$\begin{aligned} TWGIC &= W(T_0) - [V_1(T_0) + V_2(T_0)] \\ &= \zeta + \psi T_0 + \tfrac{1}{2}\xi[T_0]^2 - (\kappa_1 + \mu_1 T_0 + \tfrac{1}{2}\eta_1[T_0]^2 + \tfrac{1}{2r}[\varphi a]^2) \\ &= \Delta + (\psi - \mu_1)T_0 + \tfrac{1}{2}(\xi - \eta_1)[T_0]^2 \end{aligned}$$

where $\Delta = \zeta - \kappa_1 - \frac{1}{2r}[\varphi a]^2$. From (B2.1) and (B2.4) in Appendix B2, one can easily find:

$$\frac{\partial[\xi - \eta_1]}{\partial\sigma} = -\frac{1}{2}[\sigma - \frac{\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2 + 8\varepsilon(1+\gamma)}}] + [\sigma - \frac{\sigma(r-\sigma^2)}{\sqrt{(r-\sigma^2)^2+4\varepsilon}}]$$

Clearly, $\frac{\partial[\xi-\eta_1]}{\partial\sigma} = 0$ if ε were equal to zero, i.e., $\frac{\partial[\xi-\eta_1]}{\partial\sigma}|_{\varepsilon=0} = 0$. One can show that: $\frac{\partial^2[\xi-\eta_1]}{\partial\sigma\partial\varepsilon} = 2\sigma(r-\sigma^2)[\frac{1}{[(r-\sigma^2)^2+4\varepsilon]^{3/2}} - \frac{1}{[(r-\sigma^2)^2+8\varepsilon]^{3/2}}] > 0$ for all $\varepsilon > 0$. By the mean value theorem, we know that: $\frac{\partial[\xi-\eta_1]}{\partial\sigma}|_{\varepsilon>0} - \frac{\partial[\xi-\eta_1]}{\partial\sigma}|_{\varepsilon=0} > 0$, i.e., under our assumption of $\varepsilon > 0$, $\frac{\partial[\xi-\eta_1]}{\partial\sigma} > 0$ will always hold. Also, we know from (B2.2) and (B2.5) in Appendix B2 that:

$$\frac{\partial[\psi - \mu_1]}{\partial\sigma} = \frac{ar(1+\varphi)}{(r-2\xi)^2}\frac{\partial\xi}{\partial\sigma} - \frac{ar(1+\varphi)}{(r-\eta_1)^2}\frac{\partial\eta_1}{\partial\sigma} > [\frac{ar(1+\varphi)}{(r-2\xi)^2} - \frac{ar(1+\varphi)}{(r-\eta_1)^2}]\frac{\partial\eta_1}{\partial\sigma}$$

where the last inequality holds due to $\frac{\partial[\xi-\eta_1]}{\partial\sigma} > 0$ (which has been shown above). Since $2\xi - \eta_1 < 0$(see (23.1)), one knows that $\frac{\partial[\psi-\mu_1]}{\partial\sigma} > 0$.
Similarly, after some calculations, one can find:

$$\frac{\partial\Delta}{\partial\sigma} = \frac{a(1+\varphi)}{r-2\xi}\frac{\partial\psi}{\partial\sigma} - \frac{a(1+\varphi)}{r-\eta_1}\frac{\partial\mu_1}{\partial\sigma} > [\frac{a(1+\varphi)}{r-2\xi} - \frac{a(1+\varphi)}{r-\eta_1}]\frac{\partial\mu_1}{\partial\sigma} > 0$$

Given that $\frac{\partial\Delta}{\partial\sigma} > 0$, $\frac{\partial[\psi-\mu_1]}{\partial\sigma} > 0$, and $\frac{\partial[\xi-\eta_1]}{\partial\sigma} > 0$, which we have shown above, one can know from (25) that $\frac{\partial[W(T_0)-(V_1(T_0)+V_2(T_0))]}{\partial\sigma} = \frac{\partial\Delta}{\partial\sigma} + \frac{\partial[\psi-\mu_1]}{\partial\sigma}T_0 + \frac{\partial[\xi-\eta_1]}{\partial\sigma}[T_0]^2 > 0$, which implies that the greater the uncertainty about global warming, the more gain we can expect from international cooperation, which is consistent with the result in the case of symmetric players. ■

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