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Three Essays on International Environmental Agreements: Extensions to Cooperative R&D, Learning, and Social Preferences

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ABSTRACT

Three Essays on International Environmental Agreements: Extensions to Cooperative R&D, Learning, and Social Preferences

by

Ross Andrew Mohr

This dissertation considers the theoretical aspects of countries' incentives to cooperate on environmental good provision and resolve free-rider incentives, in particular with the formation of an International Environmental Agreement (IEA).

In the first chapter, "International Environmental Agreements with Cooperative Research & Development," I consider how allowing countries to invest in abatement cost-reducing R&D to make pollution abatement cheaper can change incentives to participate in the IEA. Since introducing R&D directly changes the incentives to abate pollution, I also consider two different cooperation regimes: pollution abatement and R&D investment can either be provided independently with two separate agreements, or countries may choose to negotiate provision of both goods in a single, joint agreement. I show that when the joint treaty achieves a high enough level of participation, which implies a threshold amount of R&D investment, even non-signatories find it individually rational to abate pollution. That is, the resulting technology lowers the cost of pollution abatement enough so that the behavior of non-signatories tips toward the full cooperative outcome for pollution abatement, eliminating the incentive to free-ride. In this case, a joint agreement for cooperation on the environment and R&D increases pollution abatement and aggregate welfare.

Following a short chapter reviewing the weakly renegotiation-proof equilibrium, the third chapter, "Sustaining Full Cooperation in an International Environmental Agreement through Learning and R&D," analyzes the effects of learning and R&D on an IEA by assuming that countries are uncertain regarding the benefits of pollution abatement. This paper shows that uncertainty improves the likelihood of obtaining a Pareto-optimal IEA, which is constructed as a weakly renegotiation-proof equilibrium in an infinitely repeated game, by allowing for a wider range of discount factors to sustain cooperation than in the no uncertainty case. Finally, this paper analyzes whether or not new knowledge gained through R&D is beneficial for sustaining cooperation and finds that achieving the Pareto-optimal IEA tends to be less likely if R&D reduces uncertainty. The mechanism driving these results is that uncertainty leads to a higher expected net loss from punishment to a defecting country, which implies that deviations are better deterred under uncertainty than with no uncertainty.

In the fourth chapter, titled "Renegotiation-Proof International Environmental Agreements with Social Preferences," I turn from purely self-interested agents and examine how social preferences, in particular, preferences for equity and efficiency, affect the likelihood of cooperation among countries to abate pollution when compared to the case of agents that are only self-interested. It is shown that an IEA with any level of cooperation, including full cooperation, exists as a weakly renegotiation-proof equilibrium for high enough discount factors. As social preferences grow stronger, the range of discount factors that can support cooperation increases, which implies that cooperation is more likely under social preferences. The key effect driving this result is that social preferences cause the net loss from the punishment of a defecting country to increase, which better deters deviations from cooperation.

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Chapter 1

International Environmental Agreements with Cooperative Research & Development

1 Introduction

Two of the main reasons given for the failure of the Kyoto Protocol is that it lacked significant participation (many of the world's highest emitters are not members) and that many signatories have not actually complied with their emissions targets (Barrett 2008).[1] A primary cause of both low participation and insufficient compliance is that the perceived costs of pollution abatement greatly outweigh the benefits.[2] Thus, lowering abatement costs by funding research and development (R&D) of new technologies has recently gained a higher priority as part of the solution to reducing greenhouse gas emissions. However, *required* R&D funding has not yet been included in any international environmental agreement (IEA); rather, existing IEAs such as the Montreal Protocol, which phased-out the use of ozone-destroying chemicals, promote R&D cooperation among members and even encourage technology diffusion to non-

[1]Cooperation has also been difficult because actions must be *self-enforcing*; that is, since participation is voluntary and an agreement cannot be enforced by a World Government, it must be in a country's best interest to join the agreement and to comply with its prescription.

[2]The benefits and costs of pollution abatement are also subject to uncertainty. See Chapter 3 of this dissertation (Mohr 2014).

members (Barrett 2003).[3] One of the goals of this paper is to analyze how required R&D funding, either as part of membership in an IEA or for the separate (but complementary) purpose of cooperative R&D, changes the incentives to join an IEA and to reduce pollution.

In the period since the negotiation of the Framework Convention on Climate Change, there have been several efforts at cooperative R&D Agreements (RDA). For instance, the United States has bilateral Science and Technology (S&T) agreements with 37 countries.[4] However, these agreements mostly serve to coordinate activities and facilitate collaboration, as they typically do not set explicit funding goals or targets for the countries. This is also the case for the Carbon Sequestration Leadership Forum: it seeks to develop lower-cost technologies for carbon capture and sequestration through international collaboration, but does not impose any binding commitments on its members.[5] Not all attempts at cooperative R&D, however, only aim to coordinate actions. The Seventh Framework Programme (FP7) of the European Community (EC), adopted on December 18, 2006 with a total budget of 32,413 million Euro (with 1890 million Euro to environmental and climate change research), serves to fund and coordinate R&D projects from 2007 to 2013.[6,7]

Since pollution abatement and the knowledge spillovers from R&D investment are both public goods with free-rider incentives, there are two market failures and both goods will likely be under-provided (Jaffe, Newell, and Stavins 2005). Thus, I consider a model in which countries may cooperate on the provision of *both* goods and begin the analysis with the general question: Can cooperative investment in R&D to produce abatement cost-reducing tech-

[3] Heal and Tarui (2010) also provide the example of the Asia-Pacific Partnership on Clean Development & Climate, which is a non-binding agreement to promote pollution abatement and R&D cooperation, among other environmental goals. See http://www.app.gov/

[4] For a complete list of countries and dates of Entry-Into-Force, see http://www.state.gov/g/oes/rls/fs/2009/115031.htm

[5] For more information, see http://www.cslforum.org/index.html

[6] For a complete list of members, including additional bilateral S&T agreements for funding and coordination, see http://ec.europa.eu/research/fp7/index_en.cfm

[7] Golombek and Hoel (2005) doubt the effectiveness of a RDA with funding commitments because the amount of R&D investment is difficult to monitor. However, Newell (2008) says that “with regard to energy, the International Energy Agency already collects annual data on public energy R&D spending by [member] countries, a process that could be adjusted if necessary to serve a more formal purpose” (pg. 24).

nologies increase participation in the IEA and, thus, increase global pollution abatement and welfare?

In analyzing this question, this paper makes two main contributions to the literature. The first contribution focuses on the treatment of R&D knowledge spillovers with respect to environmental cooperation incentives. Some previous papers have assumed that knowledge spillovers from cooperative R&D can be completely restricted from non-signatories or at least treated as an imperfect club good (Carraro and Siniscalco 1997, Buchner *et al.* 2005). However, as Barrett notes, "International agreements routinely encourage cooperation in R&D. But in no case do they seek to deprive non-signatories of the fruits of this cooperation” (Barrett 2003, p. 309). Furthermore, it may actually be in a member country’s best interest to share the new technology with a non-member if it leads to even more pollution abatement. Thus, I relax this club good assumption on R&D spillovers and assume that all countries have access to the resulting technology *without restriction*; that is, regardless of a country’s membership in the IEA, it may use the new abatement cost-reducing technology produced by R&D.

The second contribution of this paper is to consider two different treaty structures, which provides more insight into how the treaties change the incentives of the countries.[8] In one treaty regime, cooperation on abatement and R&D investment are negotiated independently as two separate agreements, and in the second one members cooperatively provide both abatement and R&D in one joint agreement.[9] I assume that countries are symmetric, which implies identical *ex ante* expected payoffs; thus, all countries will *ex ante* prefer the cooperation regime that has the greatest expected payoff.

The first result of the model is that when abatement and R&D investment are provided by two separate agreements, R&D investment does not act directly as an IEA participation incentive, and the RDA is formed by a subset of IEA members. However, the new technology

[8]The words *agreement* and *treaty* are used interchangeably.

[9]These two different cooperation regimes are also analyzed in Carraro and Marchiori (2004). More details are provided in the following section.

from R&D investment does allow members of the IEA to abate pollution at lower cost than before, which increases global welfare. Then, I show that the joint agreement, in which members agree to provide both abatement and R&D investment, achieves a higher level of R&D investment but a lower level of pollution abatement than if there were two separate agreements.

The main result of this paper is that when the jointly-negotiated agreement sustains a high enough participation rate to cross a certain threshold (which also implies a threshold level of R&D investment) the resulting technology lowers the cost of abatement enough such that the behavior of non-signatories tips, and it actually becomes individually rational for non-signatories to abate pollution. In this case, coordination is needed so that the threshold level of R&D investment is met. I show that the joint agreement emerges endogenously as the preferred cooperation regime and unambiguously increases aggregate welfare. Thus, cooperative R&D investment may be able to tip the behavior of non-signatories so that all countries find it in their best interest to abate pollution, eliminating the incentive to free-ride on pollution abatement.

2 Related Literature

Early IEA research provides the pessimistic and paradoxical result that when the potential gains to cooperation are large, a self-enforcing IEA suffers from a low participation rate and cannot improve much over the non-cooperative level of pollution abatement; however, when the gains to cooperation are small, a self-enforcing IEA can sustain a high level of participation, but the outcome still will not be much better than the non-cooperative outcome.[10] Carraro and Siniscalco (1995, 1997) show that it is possible (theoretically, at least) to deter free-riding on the IEA and increase participation incentives by linking an IEA with R&D

[10] This result can be found in Barrett (1994), Carraro and Siniscalco (1993), and Hoel (1992). Barrett (2003) provides a comprehensive survey of the IEA literature.

cooperation.[11,12] Continuing in this line of research, Buchner *et al.* (2005) analyze how linking the Kyoto Protocol with R&D cooperation may change the participation incentives of the United States; however, they find that the linkage would not be *credible* and that the US would remain a non-signatory.[13]

A crucial assumption that drives the results of Carraro and Siniscalco (1997) and Buchner *et al*. (2005) is that R&D knowledge is a club good: IEA members share knowledge spillovers between themselves, but can completely restrict spillovers from non-signatories. The reason for this is that if the benefit from new abatement cost-reducing technologies is restricted to signatories only, then linking the IEA with R&D cooperation should increase participation incentives for the IEA. Furthermore, Carraro and Marchiori (2004) analyze how the incentives to abate pollution change when countries can choose to form an agreement to cooperatively provide both abatement and R&D (a linked agreement), but still assuming that R&D is a club good. I also consider a joint treaty in this paper; however, Carraro and Marchiori (2004) assume that abatement, a pure public good, is more prone to free-riding than R&D and so R&D knowledge is again used as a participation incentive. Treating R&D innovations as a club good may make the economics of cooperation on pollution abatement more favorable, but as noted in the introduction, it is not necessarily realistic; thus, contrary to the three papers referenced in this paragraph, I assume that abatement cost-reducing technology resulting from R&D is freely available to all countries.

The model in this paper most closely resembles that of Barrett (2006), who considers a

[11]In one of the first analyses of issue linkage, Cesar and de Zeeuw (1996) show that payoff asymmetries in Prisoner's Dilemma games can be resolved efficiently by linkage.

[12]Although the main focus of this paper is IEA participation incentives and abatement provision, early theoretical results showing that cooperation can internalize R&D knowledge spillovers can be found in Katz (1986), d'Aspremont and Jacquemin (1988), and Poyago-Theotoky (1995).

[13]*Credibility* means that the threat to exclude a country from R&D cooperation if it does not cooperate on the environmental agreement is binding. Tol, Lise, and van der Zwaan (2000) and Barrett (2003) also discuss the credibility of linked negotiations.

treaty system to fund and promote adoption of a "breakthrough" technology.[14,15] He shows that if there are increasing returns to adoption in the breakthrough abatement technology, then there is a tipping point such that if the number of countries adopting the technology passes this amount, it becomes in the best interest of all other countries to adopt the technology. This paper does not consider a breakthrough technology, *per se*, but rather that the cost of pollution abatement can be reduced through R&D investment. Similarly to Barrett (2006), though, I examine a case in which R&D investment has a tipping point, but here it affects a county's pollution abatement incentives, not the incentives for more countries to invest in R&D.

In general, R&D knowledge and new technology can spillover to other countries in several ways, including: selling the new technology to foreign firms and countries, reverse-engineering of a patented technology, or simply sharing knowledge. Newell (2008) also suggests that since patents are used to protect the value to the inventor, perhaps one goal of a RDA could be to purchase the new technology for public use (or award a prize to the inventor), thus allowing for even greater R&D spillovers while still securing intellectual property rights.

Barrett (2009) gives a general overview of the technologies, both carbon-free and carbon-reducing, that may be included in a "climate-technology revolution" and discusses the viability of those technologies, the risks versus benefits, and other economic considerations. In this paper, the way that R&D investment is modeled is broadly compatible with resulting in any new technology that reduces the abatement costs of existing, greenhouse gas-emitting technologies, and "breakthrough" carbon-free technologies, such as wind or solar, are only treated as the limiting case of fully-cooperative R&D investment. Abatement cost-reducing technologies that are consistent with my model include those that are complementary to existing polluting technologies - for example, a new technology to reduce the cost of carbon capture and se-

[14] In general, a "breakthough" technology can be thought of as a zero-emissions energy technology. Hoffert *et al.* (2002) survey a wide variety of energy technologies in terms of current limitations and potential future breakthroughs.

[15] Buchner and Carraro (2005) also consider a climate agreement based solely on R&D cooperation. In their model, R&D knowledge spillovers are an imperfect club good.

questration or to reduce the cost of decarbonizing ("cleaning") fossil fuel before combustion (end-of-pipe technologies).

3 Model

3.1 Benchmark IEA

Before introducing the R&D component of the model, I begin by deriving the properties of the linear, self-enforcing IEA, which has been used recently by Barrett (2001, 2003) and Kolstad (2007)[16]. Despite being an extremely simplified version of reality, the linear payoff function does allow one to derive analytical results, and it does produce results that are consistent with more general functional forms (Barrett 2003). Let there be $N \geq 3$ countries that each make a one-shot decision to either Abate or Pollute. Assume that all countries have *ex ante* identical payoff functions. Since pollution abatement is a global public good, the abatement of one country benefits all other countries. Let each country's payoff be a linear function of the benefit from total abatement and its own abatement cost. The payoff of country $i \in N$ is:

$$\pi_i(q_i, Q) = b(q_i + Q_{-i}) - cq_i, \tag{1}$$

where $q_i \in \{0, 1\}$ is the choice to Abate or Pollute ($q_i = 1$ if country i plays Abate) and Q_{-i} is the total amount of abatement by all countries except country i, so that $Q = \sum_{j=1}^{N} q_j = q_i + Q_{-i}$ is the total amount of pollution abatement. Note that since Abate takes the value $q_i = 1$, the total amount of pollution abatement, Q, is also the *number* of countries that abate pollution. The parameter $b > 0$ denotes the marginal benefit of abatement (by any country), and $c > 0$ is the marginal cost of abatement.

The principle characteristic of global pollution problems is that since all countries bene-

[16] See Barrett (2003) for a more complete treatment of this model.

fit from the abatement efforts of a single country, each country would prefer to free-ride on the efforts of others, and pollution abatement is under-provided. In the context of this linear, discrete choice model, Pollute ($q_i = 0$) is a country's dominant strategy, and the Nash equilibrium of this problem is that all countries play Pollute.[17] This implies that

$$\pi_i(0, Q_{-i}) - \pi_i(1, 1 + Q_{-i}) > 0, \tag{2}$$

which reduces to $c > b$. Furthermore, since all countries act out of self-interest, the socially optimal outcome in which all countries play Abate will not be achieved, even though doing so would make all countries better-off. All countries are made better-off by playing Abate when

$$\sum_{i=1}^{N} \pi_i(1, N) = \sum_{i=1}^{N} [bN - c] > 0\,, \tag{3}$$

which implies that $Nb > c$. In words, the primitive characteristic of this simplified version of the global pollution problem is that the marginal cost of abatement is greater than the marginal *individual* benefit of abatement but is less than the marginal *aggregate* benefit of abatement. Finally, this also implies that the total gain from full cooperation, $N(Nb - c)$, is positive.

The size of the self-enforcing IEA is derived as the subgame perfect equilibrium of a two-stage game. In the first stage, the membership stage, all countries decide individually whether or not to be a member of the IEA. In the second stage, the abatement stage, members of the IEA collectively choose to either Abate or Pollute in order to maximize their aggregate payoff, and non-signatories of the IEA simultaneously and non-cooperatively choose to either Abate or Pollute.[18] Solving the game by backwards induction, in the second stage non-signatories will always play Pollute, their dominant strategy. Then, assume that k countries join the IEA in the first stage. These k countries will maximize their collective payoff in the second stage

[17] In this paper, I only consider pure strategies.

[18] In Barrett (1994), the IEA is modeled as a three-stage game in which signatories act as Stackelburg leaders. However, it is conventional with linear payoffs to model signatories and non-signatories acting simultaneously since the discrete nature of the problem precludes strategic reactions by non-signatories.

by playing Abate if

$$\pi_{i \in k}(1, k) = bk - c \geq 0, \tag{4}$$

which implies $k \geq \frac{c}{b}$. This condition ensures that each signatory is made better off by playing Abate. Finally, since the number of countries in the IEA is an integer, let $k = k^*$ be the smallest integer such that $k \geq \frac{c}{b}$. Thus, the equilibrium size of the IEA formed in the first stage satisfies

$$\frac{c}{b} + 1 > k^* \geq \frac{c}{b}.\text{[19]} \tag{5}$$

The resulting payoffs to members and non-members are

$$\pi_{i \in k} = bk^* - c, \text{ and} \tag{6}$$

$$\pi_{i \notin k} = bk^*, \text{ respectively,} \tag{7}$$

and the aggregate payoff of all countries is

$$\Pi_{IEA} = Nbk^* - k^*c. \tag{8}$$

In order for the IEA of size k^* to be *self-enforcing*, signatories cannot become better off by defecting from the treaty and playing Pollute, nor can non-signatories become better off by acceding to the treaty.[20] As a consequence of assuming symmetric countries and a linear payoff function, every country $i \in k^*$ is pivotal, which implies that any defection will cause all other members to play Pollute resulting in all countries having a payoff of zero. Also, it is not rational for any non-signatory to accede to the agreement because members are required to play Abate and the abatement cost that the country would incur, c, is greater than the additional benefit, b.

Finally, I can summarize the main result of the basic IEA model. Note that the size of

[20] In other words, self-enforcement requires that treaty membership be individually rational. This is derived from cartel stability (d'Aspremont, Jacquemin, Gabszeweiz, and Weymark 1983).

the IEA, k^*, is decreasing in b, but that the total gain from full cooperation, $N(Nb - c)$, is increasing in b. In words, when the potential gains from international cooperation on pollution abatement are large, fewer countries will cooperate.

3.2 Including R&D Investment

Now, in addition to choosing Abate or Pollute, each country also simultaneously chooses to either invest in R&D or not, which is denoted by "R&D" and "No R&D," respectively. Since both abatement and R&D investment are public goods, all countries benefit equally from the abatement efforts of any country, and all countries *may* benefit from any country's R&D. However, only a country that abates pollution (and incurs the abatement cost) will directly benefit from R&D investment because the only benefit of R&D in this model is to lower the cost of pollution abatement.

As in the benchmark IEA model, each country's payoff is a linear function of its choices and the actions of all other countries. The payoff of country i is now:

$$\pi_i(q_i, x_i, Q, X) = bQ - c[1 - \varepsilon(x_i + X_{-i})]q_i - dx_i \tag{9}$$

where $x_i \in \{0, 1\}$ is the choice to invest in R&D or not ($x_i = 1$ if country i invests in R&D) and X_{-i} is the total amount of R&D investment by all countries except country i, so that $X = \sum_{j=1}^{N} x_j = x_i + X_{-i}$ is the total amount of R&D investment (and also the *number* of countries investing in R&D). I assume that R&D knowledge is a pure public good with full spillovers. This is most plausible if the new technology from R&D, which I show later is always provided cooperatively, is "owned" by a RDA and then made available to any other countries "costlessly" and without restriction (Newell 2008). The parameter $\varepsilon \in (\frac{d}{Nc}, \frac{1}{N})$ represents the *effectiveness* of R&D investment, which is interpreted as the rate at which the resulting technology from R&D investment reduces the abatement cost. The upper bound on

ε is necessary so that as X approaches N (full cooperation in R&D investment, the abatement cost $c(1-\varepsilon X)$ stays positive. The lower bound on ε, as will be explained later in the paper, is necessary to bound the sizes of the agreements below N. Finally, the marginal cost of R&D investment is d, and the pollution abatement variables are defined as in the previous section.

The marginal cost term, $c(1-\varepsilon X)$, embodies this paper's main assumptions for R&D investment. I assume that the total amount of R&D investment produces a new technology that reduces abatement costs by a proportion of the total amount invested, as discussed in the background literature section, and that this new technology is available to all countries without restriction.[21] Thus, for a total amount of R&D investment, X, the marginal cost of abatement *for all countries* shrinks by the proportion $(1-\varepsilon X)$; however, if the total amount of R&D investment is zero ($X=0$), then the model simply reverts to the standard IEA in the previous section.

Since this is an extension of the benchmark IEA model, the main properties of the global pollution problem still hold, and Pollute is still a dominant strategy for country i, no matter if country i invests in R&D or not and taking the actions of all others as given. Thus,

$$\pi_i(0, x_i, Q, X) - \pi_i(1, x_i, Q, X) > 0 \tag{10}$$

must hold, which implies that $c(1-\varepsilon X) > b$ and $X \in [0, \frac{c-b}{c\varepsilon})$.[22] As in the benchmark case, the dominant strategy is Pollute because the marginal cost of abatement is greater than the marginal benefit of abatement. Since this is true in the absence of R&D ($X=0$), the inequality $c > b$ still holds. The upper bound on X implies that if the total amount of R&D investment is high enough (greater than $\frac{c-b}{c\varepsilon}$), then the resulting technology causes Pollute to no longer be a dominant strategy. That is, if abatment costs are reduced enough through R&D investment,

[21] I also assume that there is no uncertainty: R&D investment produces a new technology with 100 percent probability. I also assume that there are no time lags in diffusing and adopting the new technology since this is a one-time decision. Finally, I assume that there is no cost to adopting and implementing the new technology.

[22] The upper bound on X is derived by rearranging the dominant strategy condition.

then the primitives of the pollution problem change. Clearly, this restriction on X plays a large role in determining how countries cooperatively provide abatement and will be examined in more detail later in the paper. However, for this section of the paper and through Section 5, Pollute is the dominant strategy for the abatement choice, which implies that $X \in [0, \frac{c-b}{c\varepsilon})$; in other words, $X \in [0, \frac{c-b}{c\varepsilon})$ puts the focus on the case in which cooperation is needed most.

As noted in the introduction, R&D investment also suffers from a free-rider incentive (since any country would prefer to let another do the research) and is under-provided with respect to the fully-cooperative, social optimum. In the context of this discrete choice model, No R&D ($x_i = 0$) is a country's dominant strategy for the choice to invest in R&D or not. The first implication is that the strategy {Pollute, No R&D} strictly dominates the strategy {Pollute, R&D}, which implies that $d > 0$. The interpretation is that since the only *direct* benefit of investing in R&D is a reduction in a country's own abatement cost, no country would ever choose to invest in R&D unless it is also choosing to abate pollution.[23]

The second, stronger implication of the free-rider incentive for R&D investment is even if a country has chosen to abate pollution, it would still prefer to free-ride on another country's R&D. Thus, No R&D is also a dominant strategy for country i even if it is playing Abate. This implies that

$$\pi_i(1, 0, Q, X) - \pi_i(1, 1, Q, X) > 0, \tag{11}$$

which reduces to $d > c\varepsilon$. In words, No R&D is a dominant strategy when the marginal cost of investing in R&D is greater than the marginal reduction in the abatement cost (the marginal benefit of R&D). Finally, in the non-cooperative Nash equilibrium, all countries play {Pollute, No R&D}, $Q = X = 0$, and the payoff to each country is zero.

For the combined problem of providing pollution abatement and R&D investment, the efficient, social optimum consists of all countries providing the two goods; in other words,

[23] If the RDA is not providing the new technology and countries or firms are selling it to others, then d could be interpreted as the "net cost" of investment. But in the context of the discrete choice model, under-provision still implies that $x_i = 0$ is a dominant strategy, which implies $d > 0$.

the greatest aggregate payoff is achieved when all countries cooperate. The first implication of this is simply an extension of the discussion in the previous section: in the absence of any R&D investment, all countries would be better-off playing Abate. This implies that

$$\sum_{i=1}^{N} \pi_i(1, 0, N, 0) = \sum_{i=1}^{N}[bN - c] > 0, \tag{12}$$

which holds if $Nb > c$, as in the simple IEA case. Similarly, if the social optimum of R&D provision could be achieved, then the aggregate payoff would be greater than in the non-cooperative outcome. Since the only direct effect of R&D investment is to reduce one's own abatement costs, only countries that abate have any incentive of also providing R&D, and full cooperation on R&D will only be sustained when all countries are also abating pollution. Thus, the aggregate payoff when all countries play {Abate, R&D} (full cooperation) is greater than if all countries only played {Abate, No R&D} when

$$\sum_{i=1}^{N} \pi_i(1, 1, N, N) - \sum_{i=1}^{N} \pi_i(1, 0, N, 0) > 0, \tag{13}$$

which reduces to $Nc\varepsilon > d$.[24] In summary, the fundamental characteristics of the problem of providing abatement and R&D investment, which are both public goods and suffer from free-rider incentives, imply the following inequalities derived from the linear payoff function:

$$Nb > c > c(1 - \varepsilon X) > b \text{ for } X \in [0, \frac{c-b}{c\varepsilon}), \text{ and} \tag{14}$$

$$Nc\varepsilon > d > c\varepsilon. \tag{15}$$

[24]Additionally, the aggregate payoff for the efficient, full cooperative outcome ($Q = X = N$) is greater than the aggregate payoff of the inefficient Nash equilibrium, which is true as long as $N(b + c\varepsilon) > c + d$. This condition, though, is redundant.

4 IEA with Cooperative R&D

4.1 Game Structure

Given the properties of the two public good provision problems and the conditions implied by the model, no single country has any incentive to supply either pollution abatement or R&D investment on its own, and the total provision of goods in the absence of cooperation is $Q = X = 0$ (the Nash equilibrium). The only way that positive amounts of either good will be supplied is if a coalition forms to cooperatively provide the good. The goal of the rest of this paper is to analyze how cooperative R&D investment and the resulting abatement cost-reducing technology affect a country's incentive to cooperatively abate pollution.

This paper analyzes two different treaty structures, which will provide more insight into how treaties affect the incentives of the players in the game. In this model, countries may either cooperate on R&D independently of their IEA membership, or they may choose to negotiate R&D investment jointly with pollution abatement as a single, linked agreement. I assume that a country's membership in the IEA poses no additional requirements for that country's R&D investment, and vice versa.

In this paper, the countries play a one-shot, two-stage, non-cooperative game, which is similar to Carraro and Marchiori (2004), and the sizes of the agreements derive from a sub-game perfect equilibrium. Before the proper two-stage game, there is a pre-stage in which each country decides non-cooperatively which treaty regime should be pursued. I assume that countries are symmetric, which implies identical *ex ante* expected payoffs; thus, all countries will *ex ante* prefer the cooperation regime that yields the greatest expected payoff.

In the pre-stage if countries choose to negotiate two separate treaties, then they play two, parallel treaty games. In the first stage, the membership stage, each country decides simultaneously whether to be a member of both the IEA and RDA, only the IEA or RDA, or to not cooperate at all. In the second stage, the provision stage, signatories of either agreement simultaneously choose to collectively provide the good. That is, members of the IEA choose to abate if doing so maximizes their collective payoff, and members of the RDA choose to invest in R&D if doing so maximizes their collective payoff. I allow for there to be overlap in memberships: some members of the RDA may also be members of the IEA, and vice versa. Since this stage of the treaty game happens at the same time for both the IEA and the RDA, I abstract away from a timing issue: I assume that the new abatement cost-reducing technology resulting from the cooperative R&D investment of the RDA is available *at the same time* as when signatories of the IEA make their abatement decision. Thus, signatories of the IEA make their abatement decision taking into account the cost reduction from R&D investment. Simultaneously, in the provision stage non-members of any of the agreements non-cooperatively make their abatement and R&D investment decisions.

If in the pre-stage, however, countries agree to provide both pollution abatement and R&D investment in one agreement, then in the membership stage countries will choose whether or not to be a member of the joint agreement. In the provision stage, members of the joint agreement will choose to abate pollution *and* invest in R&D if this maximizes their collective payoff. Note that in the joint agreement, signatories cannot choose to provide only one good or the other: either both goods are provided or neither. Again, I abstract away from a timing issue: I assume that signatories of the joint agreement make their abatement decision taking into account the cost reduction from the new technology, even though technically abatement and R&D investment are provided *at the same time*. Simultaneously, in the provision stage non-members of the joint agreement non-cooperatively choose their abatement and R&D investment.

4.2 Two Separate Agreements: IEA and RDA

I begin with the case when in the pre-stage, countries choose to negotiate two separate agreements: the IEA and RDA. Recall that the provision problem for abatement and R&D investment in this model is summarized by conditions (14) and (15) and proceed by backwards induction. In the provision stage, non-signatories of either agreement will play their dominant strategy of Pollute or No R&D. Also in the second stage, members of the IEA decide collectively whether to play Abate or Pollute, and members of the RDA decide collectively to play R&D or No R&D. For example, a country that is a member of the IEA, but not the RDA, would play No R&D in the provision stage. A country may be a member of both agreements. Recall that the only *direct* benefit of a country's R&D investment is to lower its own abatement cost. So if a country chooses to not abate pollution, then it has absolutely no incentive to invest in R&D, regardless of its membership status in either agreement. So if the RDA exists and has a positive number of members, then they must also all be members of the IEA (and play Abate). Let k_E be the number of members in the IEA, k_R be the number of members in the RDA, and k_{EO} be the number of members in the IEA *only*. Then, $k_E = k_{EO} + k_R$, and all members of the RDA are also members of the IEA.

Continuing with the provision stage, I derive conditions such that all members of the IEA play Abate and that all members of the RDA play R&D. A member of both agreements will play Abate and R&D if it cannot gain by leaving the RDA to only be a member of the IEA and if it cannot get a higher payoff by simply being a free-rider on both agreements. The condition that ensures that this member cannot gain by defecting from the RDA is

$$\pi_{i \in k_R}(1, 1, k_E, k_R) - \pi_{i \in k_{EO}}(1, 0, k_E, 0) \geq 0, \tag{16}$$

which implies that $k_R \geq \frac{d}{c\varepsilon}$.[25] Thus, as long as this condition holds, members of the RDA will play {Abate, R&D}. If a member of both agreements defected from the IEA, then all countries would play Pollute, there would be no gain to R&D investments, and so the RDA would also no longer provide R&D investment either. The condition that ensures that a member of both

[25] $\pi_{i \in k_R}(1, 1, k_E, k_R) - \pi_{i \in k_{EO}}(1, 0, k_E, 0) = bk_E - c(1 - \varepsilon k_R) - d - (bk_E - c)$. Note that any defection from the RDA causes all remaining members to play No R&D. Thus, $X = 0$, but there are still k_E countries that abate.

agreements cannot gain by defecting from the IEA is

$$\pi_{i \in k_R}(1, 1, k_E, k_R) \geq 0, \tag{17}$$

which implies that $k_E \geq \frac{1}{b}[c(1 - \varepsilon k_R) + d]$. So, the number of countries in the IEA is a function of the amount of R&D investment, k_R. Finally, I address countries that only belong to the IEA and not to the RDA. A member of the IEA will play Abate if its payoff is at least as great as its payoff from non-cooperation. Thus,

$$\pi_{i \in k_{EO}}(1, 0, k_E, k_R) \geq 0, \tag{18}$$

which implies that $k_E \geq \frac{c}{b}(1 - \varepsilon k_R)$. However, $k_E \geq \frac{c}{b}(1 - \varepsilon k_R)$ is not large enough to ensure that a member of both agreements has a positive payoff; thus, $k_E \geq \frac{1}{b}[c(1 - \varepsilon k_R) + d]$ is the necessary condition.

The stage 1 equilibrium, when each country makes its membership decision, determines the equilibrium sizes of the agreements, k_E^* and k_R^*. As in the benchmark IEA case, define $k_R = k_R^*$ as the smallest integer at least as large as $\frac{d}{c\varepsilon}$ and define $k_E = k_E^*$ as the smallest integer at least as large as $\frac{1}{b}[c(1 - \varepsilon k_R) + d]$.

Proposition 1 *If the IEA and RDA are negotiated as two separate agreements and conditions (14) and (15) hold, then the equilibrium sizes of the IEA and RDA satisfy:*

$$\frac{1}{b}[c(1 - \varepsilon k_R^*) + d] + 1 \quad > \quad k_E^*(k_R^*) \geq \frac{1}{b}[c(1 - \varepsilon k_R^*) + d] \textit{ and} \tag{19}$$

$$\frac{d}{c\varepsilon} + 1 \quad > \quad k_R^* \geq \frac{d}{c\varepsilon}, \textit{ respectively.} \tag{20}$$

Note that condition (15) implies that $\frac{d}{c\varepsilon} > 1$, and comparing this with the above condition for k_R^* shows that the RDA has at least two members, when it exists. One can obtain the outermost bounds on k_E^* by substituting in the equilibrium necessary conditions for k_R^*. Using

$\frac{d}{c\varepsilon} + 1 > k_R^*$ yields the inequality $k_E^* > \frac{c}{b}(1-\varepsilon)$, and using $k_R^* \geq \frac{d}{c\varepsilon}$ gives the inequality $\frac{c}{b} + 1 > k_E^*$. Thus, the following bounds also hold:

$$\frac{c}{b} + 1 > k_E^* > \frac{c}{b}(1-\varepsilon). \tag{21}$$

This condition shows that although the size of the IEA now depends on the amount of R&D investment, there is not necessarily a change in the amount of countries providing pollution abatement. In fact, there is *possibly* (though unlikely) now one less country in the IEA than in the benchmark case, which means that $k^* \geq k_E^*$. Also, note that when the RDA exists, there is now $X = k_R^*$ amount of R&D investment, and condition (14) implies that $k_R^* < \frac{c-b}{c\varepsilon}$.

Since every country is pivotal, the two agreements are internally stable because a defection from either agreement would cause the remaining members to revert back to playing their dominant strategies (Pollute and No R&D), which would make the defecting country worse off. Additionally, it can be easily shown that both the IEA and the RDA are stable from accession (for a non-signatory, the marginal cost of joining an agreement is greater than the marginal benefit). Thus, the IEA and the RDA are self-enforcing.

By comparing the aggregate equilibrium payoff of this cooperation regime with the aggregate payoff of the benchmark IEA model, one can determine the welfare effect of including R&D investment with the potential for cooperative provision into the model. Members of both the IEA and RDA, members of just the IEA, and non-members of the IEA (free-riders) have the following equilibrium payoffs, respectively:

$$\pi_{i \in k_R} = bk_E^* - c(1 - \varepsilon k_R^*) - d, \tag{22}$$

$$\pi_{i \in k_{EO}} = bk_E^* - c(1 - \varepsilon k_R^*), \text{ and} \tag{23}$$

$$\pi_{i \notin k_E} = bk_E^*. \tag{24}$$

Comparing these payoffs, note that $\pi_{i \notin k_E} > \pi_{i \in k_{EO}} > \pi_{i \in k_R} \geq 0$, which means that free-riders on the IEA have the highest payoff while a member of both the IEA and the RDA has the lowest payoff. The aggregate equilibrium payoff when there are two separate agreements is

$$\Pi_S = Nbk_E^* - k_E^* c(1 - \varepsilon k_R^*) - k_R^* d.^{26} \tag{25}$$

Proposition 2 *When abatement cost-reducing R&D is provided by a RDA and provided that the size of the IEA is unchanged ($k^* = k_E^*$), the aggregate equilibrium payoff to all countries increases.*

Proof. The statement is true if and only if $\Pi_S \geq \Pi_{IEA}$. After substituting and rearranging the inequality, the resulting inequality is

$$k_R^*(c\varepsilon k_E^* - d) \geq (Nb - c)(k^* - k_E^*). \tag{26}$$

The left-hand side is weakly positive since $k_E^* \geq k_R^* \geq \frac{d}{c\varepsilon}$. Recall that the discussion following condition (21) implied that it is *possible* (though unlikely) that k_E^* is smaller than k^* by 1. If this is the case, then the right-hand side is positive, and I am unable to derive an unambiguous result. However, if the size of the IEA is unchanged ($k^* = k_E^*$), then the right-hand side equals 0. In this case, $\Pi_S \geq \Pi_{IEA}$ holds. ■

In this model, including R&D investment does not increase the aggregate payoff, *per se*, because it is modeled as a discrete choice with an incentive to free-ride. However, when countries cooperate to form a RDA alongside an IEA, the gains from cheaper abatement outweigh the cost of R&D investment, and in aggregate, all countries are better off.

As with the benchmark IEA model, I will briefly discuss the static properties of k_R^*, k_E^*, and the total gain to full cooperation, $N[Nb - c(1 - \varepsilon N) - d]$.[27] The basic result from the simple IEA case is that when the potential gains to cooperation are large, the size of the agreement

[26] k_R^* countries have the payoff $\pi_{i \in k_R} = bk_E^* - c(1 - \varepsilon k_R^*) - d$, k_{EO}^* countries have the payoff $\pi_{i \in k_{EO}} = bk_E^* - c(1 - \varepsilon k_R^*)$, and $(N - k_E^*)$ countries have the payoff $\pi_{i \notin k_E} = bk_E^*$.

[27] $\sum_{i=1}^{N} \pi_i(1, 1, N, N) = N[Nb - c(1 - \varepsilon N) - d]$.

will be small. Or, on the other hand, a high level of cooperation will only be sustained when it is not really needed (low potential gain to full cooperation). The same story holds with respect to the new IEA, k_E^*: it is decreasing in b, but the total gain to cooperation is increasing in b. Focusing on the marginal cost of R&D investment, d, though, gives an ambiguous result. A decrease in d increases the total gain to cooperation. But while a decrease in d lowers the amount of signatories to the RDA, it has an ambiguous effect on the size of the k_E^*. This is because both the cost of R&D investment, d, and the benefit of lower abatement costs, $c\varepsilon k_R^*$, play a role in determining k_E^*, but have opposite effects. So the inverse relationship between the size of an agreement and the gains to cooperation is mostly still intact.

4.3 Jointly-Negotiated Agreement

Now, I turn to the agreement that follows the pre-stage when countries prefer to provide both pollution abatement and R&D investment with a single, jointly-negotiated agreement and, as before, proceed by backwards induction. In stage 2, non-members of the agreement would choose to play {Pollute, No R&D} since that is the dominant strategy. To analyze provision by treaty members in the second stage, first assume that there are k_J members in the joint agreement. The k_J signatories will each play {Abate, R&D} if the individual payoff from doing so is at least as big as the payoff of playing {Pollute, No R&D}. Since the individual payoff to all players is zero when there is no abatement or R&D, the k_J signatories will each play {Abate, R&D} as long as

$$\pi_{i \in k_J}(1, 1, k_J, k_J) = bk_J - c(1 - \varepsilon k_J) - d \geq 0, \tag{27}$$

which holds for $k_J \geq \frac{c+d}{b+c\varepsilon}$. To solve the membership stage, define $k_J = k_J^*$ as the smallest integer at least as large as $\frac{c+d}{b+c\varepsilon}$.

Proposition 3 *If both pollution abatement and R&D investment are provided by a single,* *jointly-negotiated agreement and conditions (14) and (15) hold, then the equilibrium size of the agreement satisfies:*

$$\frac{c+d}{b+c\varepsilon} + 1 > k_J^* \geq \frac{c+d}{b+c\varepsilon}. \tag{28}$$

As in the previously discussed agreements, any defection by a signatory causes all remaining signatories to revert back to their dominant strategy, in this case {Pollute, No R&D}, and all countries are made worse off. Also, if a non-signatory accedes to the agreement, then it must play {Abate, R&D}. It follows from conditions (14) and (15) that the marginal net benefit for a non-signatory to accede to the joint treaty is negative. The appropriate condition for this is

$$b - c[1 - \varepsilon(k_J^* + 1)] - d < 0, \tag{29}$$

which can be rearranged as

$$k_J^* < \frac{c-b}{c\varepsilon} + \frac{d}{c\varepsilon} - 1. \tag{30}$$
[28]

However, it is sufficient that $X = k_J^* < \frac{c-b}{c\varepsilon}$ by condition (14).

Finally, the joint agreement has the same inverse relationship between its size and the potential benefits of full cooperation as do the previously discussed agreements. The net benefit of full cooperation, $N[Nb - c(1 - \varepsilon N) - d]$, is increasing in b and decreasing in d, but k_J^* is decreasing in b and increasing in d, respectively. The main difference between this comparison and that made for the case of two separate treaties is that a change in d, the marginal cost of R&D investment, no longer results in an ambiguous effect. With two separate treaties, an increase in d results in higher membership in the RDA, but has an ambiguous effect on the size of of IEA, k_E^*, and the amount of abatement. However, when negotiations are joined an increase in d clearly increases the size of the agreement, k_J^*, which results in higher aggregate abatement and R&D investment.

[28] By condition (15), $\frac{d}{c\varepsilon} > 1$ which implies that $\frac{c-b}{c\varepsilon} + \frac{d}{c\varepsilon} - 1 > \frac{c-b}{c\varepsilon}$.

5 Comparative Statics and Pre-Stage

The main results of the model, as summarized in Propositions 1 and 3, have determined the equilibrium sizes of the three possible agreements, and I now show how they rank and compare welfare outcomes. Recall that since the choice of abatement and R&D investment are both discrete, the number of countries in a particular agreement is equal to the amount of the good being provided. Thus, in the case of two separate agreements, $Q = k_E^*$ and $k_R^* = X$, and in the case of a single, joint agreement, $Q = X = k_J^*$.

Proposition 4 *Let conditions (14) and (15) hold. Then,* $k_J^* \leq k_E^*$ *if and only if* $k_R^* \leq \frac{c+d}{b+c\varepsilon}$*. Thus, the sizes of the three agreements satisfies:*

$$k_R^* \leq k_J^* \leq k_E^*. \tag{31}$$

Proof. Suppose that $k_J^* \leq k_E^*$. A *necessary* condition for the *weak* inequality $k_J^* \leq k_E^*$ is that $\frac{c+d}{b+c\varepsilon} \leq \frac{1}{b}[c(1-\varepsilon k_R^*)+d]$, which is just the lower bounds on the agreement sizes. Simplifying and rearranging results in $k_R^* \leq \frac{c+d}{b+c\varepsilon}$. But since $\frac{c+d}{b+c\varepsilon} \leq k_J^*$ defines the size of the joint agreement, the sizes of the three agreements satisfies: $k_R^* \leq k_J^* \leq k_E^*$. ■

Note that $k_R^* \leq k_J^*$ means that the joint agreement provides more R&D investment than the RDA, which implies a greater reduction in abatement costs; however, $k_R^* \leq k_J^*$ also means that, in terms of the effect on aggregate payoff, more countries incur the cost of R&D investment. Also, $k_J^* \leq k_E^*$ means that the joint agreement provides less pollution abatement than the IEA. Thus, this proposition implies that if the countries choose to negotiate provision of the two goods jointly as one agreement, then in equilibrium there will be less pollution abatement, but more R&D, than if the two agreements were negotiated separately. In other words, in the joint agreement there is less abatement, but each unit of abatement costs less due to the higher amount of R&D. On the other hand, when there are two separate agreements more countries abate pollution than would in the joint agreement, but they do so at a higher per-unit cost.

Recall that since $k_R^* \leq k_E^*$, some countries in the IEA may still be free-riding on the RDA; the joint agreement eliminates this possibility since all members incur both the abatement and investment costs. Thus, the intuition behind this result is that the joint agreement represents a trade-off in benefits and costs with respect to the two, separate treaties, which implies that the size of the joint agreement lies in between the IEA and RDA. However, if countries only care about pollution abatement, then clearly the joint agreement would leave all countries worse off than under the IEA and RDA.[29,30]

To determine the outcome on economic welfare, I compare the aggregate equilibrium payoffs between the two different cooperation regimes. If negotiations are joined in a single agreement, then the equilibrium payoffs for signatories and non-signatories are the following:

$$\pi_{i \in k_J} = bk_J^* - c(1 - \varepsilon k_J^*) - d, \text{ and} \tag{32}$$

$$\pi_{i \notin k_J} = bk_J^*, \tag{33}$$

which results in the aggregate equilibrium payoff

$$\Pi_J = Nbk_J^* - k_J^*[c(1 - \varepsilon k_J^*) - d]. \tag{34}$$

The jointly-negotiated agreement is a welfare improvement on the two, separate treaties if $\Pi_J \geq \Pi_S$. To aid comparison, substituting equations (25) and (34) gives

$$Nbk_J^* - k_J^*[c(1 - \varepsilon k_J^*) - d] \geq Nbk_E^* - k_E^* c(1 - \varepsilon k_R^*) - k_R^* d. \tag{35}$$

[29] Carraro and Marchiori (2004) derive a similar result that the size of the joint agreement is between the IEA and RDA. However, in their analysis they begin with the assumption that the RDA is larger than the IEA (it is assumed that there is less free-riding on the RDA because R&D is a club good), so their ranking of agreement sizes goes in the reverse order.

[30] Since $N \geq k_R$, it is true that $N \geq \frac{d}{c\varepsilon}$. Rearranging gives $\varepsilon \geq \frac{d}{Nc}$, which is the lower bound given in the earlier section.

Then, rearranging and grouping terms yields

$$c[k_E^*(1-\varepsilon k_R^*) - k_J^*(1-\varepsilon k_J^*)] \geq Nb(k_E^* - k_J^*) + d(k_J^* - k_R^*), \tag{36}$$

and all terms in regular parenthesis are positive. The term on the left-hand side is the total abatement cost savings from the joint agreement versus the IEA and RDA. It highlights the trade-off of more abatement being provided with less cost reduction under two, separate agreements (the term $k_E^*(1-\varepsilon k_R^*)$) compared with less abatement being provided with more cost reduction in the joint agreement (the term $k_J^*(1-\varepsilon k_J^*)$). I am unable to sign the entire bracketed term on the left-hand side, and it is positive or negative depending on parameter values. The first term on the right-hand side is the total net benefit of abatement of the IEA over the joint agreement, and the second term on the right-hand side is the total R&D cost savings of the RDA over the joint agreement. Since the entire right-hand side is positive, though, one cannot determine analytically if $\Pi_J \geq \Pi_S$.[31] However, a special case yields the following result:

Proposition 5 *If $k_R^* \leq k_J^* = k_E^*$ and conditions (14) and (15) hold, then $\Pi_J \geq \Pi_S$.*

Proof. Substituting $k_J^* = k_E^*$ in condition (36) yields $c\varepsilon k_J^*(k_J^* - k_R^*) \geq d(k_J^* - k_R^*)$, which is true since $k_J^* \geq k_R^* \geq \frac{d}{c\varepsilon}$. ■

Since Proposition 4 only ensures the weak inequality $k_J^* \leq k_E^*$, it is certainly a possibility that $k_J^* = k_E^*$. In this case, the number of countries providing abatement (and incurring the abatement cost) is same in either cooperation regime, which implies that the welfare comparison reduces to a comparison of the net benefit of R&D investment in the joint agreement versus the RDA. Since in this case the joint agreement produces more R&D investment and reduces abatement costs by more than the RDA, the joint agreement yields a higher aggregate payoff than the two separate agreements.

[31] Simulating the payoffs with different parameter values does not show any clear relationship or yield any conclusions about possible conditions where one payoff is always greater than the other.

The discussion in this section can now be extended to examine the pre-stage. In the pre-stage, countries non-cooperatively choose between the two treaty regimes. However, since the subgame perfect equilibria are not unique, a country does not "know" if it will be a signatory or non-signatory at the beginning of the game - a country only knows its possible equilibrium payoffs depending on its potential memberships. Furthermore, without imposing any further preferences for abatement or free-riding on countries, one cannot say, for example, that a country that would be a member of both the IEA and RDA under separate agreements would also choose to be a member of the joint agreement. The only information available to a country at the preliminary voting stage is its expected equilibrium payoff under joint negotiations and its expected payoff under two separate agreements. Thus, to determine the outcome of the pre-stage, I compare the expected payoffs.[32]

The expected equilibrium payoff of a country under two separate agreements is

$$E(\pi_i|S) = \frac{k_R^*}{N}\pi_{i\in k_R} + \frac{(k_E^* - k_R^*)}{N}\pi_{i\in k_{EO}} + \frac{(N - k_E^*)}{N}\pi_{i\notin k_E}, \tag{37}$$

which after simplifying equals $\frac{\Pi_S}{N}$. Similarly, the expected equilibrium payoff of a country under the joint agreement can be shown to equal $\frac{\Pi_J}{N}$. Naturally, a comparison of the expected payoffs at this point results in the same inability to draw an unambiguous conclusion as does comparing aggregate payoffs. All that can be concluded is that whichever cooperation regime results in the greater expected equilibrium payoff for each country will be the one that all countries prefer, and as before, this conclusion depends on parameter values. However, the special case considered in Proposition 5 can be extended to the following result:

Corollary 1 *If $k_R^* \leq k_J^* = k_E^*$ and conditions (14) and (15) hold, then $\Pi_J \geq \Pi_S$. Thus, the jointly-negotiated agreement weakly increases aggregate welfare over the two separate agreements and is chosen in the pre-stage as the preferred cooperation regime.*

[32]This method of comparing *ex ante* expected payoffs is also used in Barrett (2002) and Finus and Maus (2008).

Corollary 2 *Additionally, if* $k_R^* = k_J^* = k_E^*$*, then* $\Pi_J = \Pi_S$ *and all countries are indifferent between the two cooperation regimes.*

With the exception these two special cases, I am unable to draw any further conclusions regarding when a certain cooperation regime will be preferred.

Up to this point, this paper has modeled the provision problem of two public goods in a simple way: countries prefer to free-ride on both goods, which leads to a non-cooperative Nash equilibrium with no provision ($Q = X = 0$). In the context of the discrete choice model, the properties of the problem implied conditions (14) and (15), which included the restriction on R&D investment, $X \in [0, \frac{c-b}{c\varepsilon})$. Written in terms of the sizes of the RDA and joint agreement, this is equivalent to $k_R^* \leq k_J^* < \frac{c-b}{c\varepsilon}$. Even though this restriction, which depends on parameter values, is a bit artificial, it has been used to focus on the case in which cooperation on abatement is needed most. In the next section, I reconsider this condition and analyze how this changes the incentives to cooperate.

6 Tipping Non-signatory Behavior Through R&D

Although the fundamentals of the provision problem remain intact (free-rider incentives result in a non-cooperation), I now consider the possibility that the joint agreement is large enough and produces a sufficient amount of R&D investment such that Pollute no longer strictly dominates Abate for non-members. Hence, conditional on the level of R&D investment passing the tipping point, the abatement game has two Nash equilibria: all countries play Pollute or all countries play Abate. To achieve the fully cooperative outcome for abatement, coordination is needed to establish the joint agreement of size $k_J^* \geq \frac{c-b}{c\varepsilon}$, and the amount of R&D $X = \frac{c-b}{c\varepsilon}$ serves as a tipping point.[33] Furthermore, since $k_R^* \leq k_J^*$, the joint agreement achieves the

[33] There is a difference between full *cooperation* and full *participation*. As I show later in this section, full cooperation is possible (all countries abate) without full participation (not all countries belong to the joint agreement).

R&D investment threshold for a larger range of parameters than the RDA.

As in the earlier derivation of the equilibrium sizes of the agreements, the joint agreement must be internally stable, which is true as long as the net marginal benefit of joining the joint agreement for a non-signatory is negative (see condition (30)). In order to analyze the effects of only the joint treaty reaching the R&D tipping point, I assume that equilibrium size of the RDA still satisfies $k_R^* < \frac{c-b}{c\varepsilon}$. Thus, the following condition summarizes the new restrictions on the amount of R&D investment (and the sizes of the agreements):

$$k_R^* < \frac{c-b}{c\varepsilon} \leq k_J^* < \frac{c-b}{c\varepsilon} + \frac{d}{c\varepsilon} - 1. \tag{38}$$

In words, even though the benefit of pollution abatement now outweighs the cost, the marginal cost of investing in R&D, d, is still too high to make accession to the joint treaty profitable (for a non-member). Since condition (14) is no longer completely accurate, it is now replaced by

$$Nb > c > c(1 - \varepsilon k_R^*) > b > c(1 - \varepsilon k_J^*), \tag{39}$$

where k_R^* and k_J^* satisfy condition (38). This ensures that only the joint agreement, and not the RDA, tips the abatement decision of non-signatories. The main difference between conditions (14) and (39) is the inequality $b > c(1 - \varepsilon k_J^*)$, which means that the marginal benefit of abating pollution is greater than the marginal cost *as long as* the joint agreement exists. The condition given in (15) is still valid. Now, I reconsider the equilibrium agreement sizes and aggregate payoffs with the new conditions and game structure.

First of all, there is no change in the *relative* sizes of the coalitions, and Proposition 4 ($k_R^* < k_J^* \leq k_E^*$) still holds; note that the only change is the strict inequality between k_R^* and k_j^*, which is due to condition (38). However, the main difference in the model now is the actions of non-members of the joint agreement. Previously, these non-members would completely free-ride on the joint agreement and play {Pollute, No R&D}. Now that the joint agreement produces enough R&D to pass the tipping point, condition (39) summarizes the incentives of the underlying abatement game and Pollute no longer strictly dominates Abate for non-members. The implication is that in the equilibrium of the joint cooperation regime there are still k_J^* members of the joint agreement that play {Abate, R&D}, but now the non-signatory countries also play Abate. And as long as $k_J^* < \frac{c-b}{c\varepsilon} + \frac{d}{c\varepsilon} - 1$, non-signatory countries still do not invest in R&D. Thus, the joint agreement still produces more R&D investment than the RDA, but now there is also more overall pollution abatement when negotiations are joined than with the IEA.

With all N countries, both signatories *and* non-signatories, abating pollution under the joint agreement, the equilibrium payoffs become

$$\pi'_{i \in k_J} = Nb - c(1 - \varepsilon k_J^*) - d, \text{ and} \tag{40}$$

$$\pi'_{i \notin k_J} = Nb - c(1 - \varepsilon k_J^*). \tag{41}$$

The aggregate equilibrium payoff of the joint agreement is now

$$\Pi'_J = N^2 b - Nc(1 - \varepsilon k_J^*) - k_J^* d.\text{[34]} \tag{42}$$

Proposition 6 *Let conditions (15), (38), and (39) hold. Then,* $\Pi'_J \geq \Pi_S$.

Proof. Following the discussion in the previous section, the jointly-negotiated agreement is a welfare improvement on the status quo if $\Pi'_J > \Pi_S$. Substituting from (25) and (42) gives

$$N^2 b - Nc(1 - \varepsilon k_J^*) - k_J^* d > Nbk_E^* - k_E^* c(1 - \varepsilon k_R^*) - k_R^* d. \tag{43}$$

[34] k_J^* countries have the payoff $\pi_{i \in k_J}$, and $(N - k_J^*)$ countries have the payoff $\pi_{i \notin k_J}$.

Rearranging and grouping terms yields

$$(Nb - c)(N - k_E^*) + k_J^*(Nc\varepsilon - d) > k_R^*(c\varepsilon k_E^* - d). \tag{44}$$

Since $N \geq k_E^*$ and conditions (15) and (39) ensure $Nc\varepsilon > d$ and $Nb > c$, the left-hand side is strictly positive. To complete the proof, it suffices to show that $k_J^*(Nc\varepsilon - d) > k_R^*(c\varepsilon k_E^* - d)$. This is true because $k_J^*(Nc\varepsilon - d) > k_R^*(Nc\varepsilon - d) \geq k_R^*(c\varepsilon k_E^* - d)$, where $k_E^* \leq N$. This proves that $\Pi'_J > \Pi_S$. ■

As in the previous section, it is a simple extension to determine which cooperation regime will be preferred by all countries. All that one needs to do is compare the *ex ante* expected equilibrium payoffs between the two cooperation regimes.

Corollary 3 *Let conditions (15), (38), and (39) hold. Then, the jointly-negotiated agreement strictly increases aggregate welfare over the two separate agreements and is chosen in the pre-stage as the preferred cooperation regime.*

Proof. The expected equilibrium payoff of a country under two separate agreements is given in equation (37), and the expected payoff for a country under joint negotiations is $E(\pi_i | J) = \frac{k_J^*}{N}\pi_{i \in k_J} + \frac{(N-k_J^*)}{N}\pi_{i \notin k_J}$, which after simplifying equals $\frac{\Pi'_J}{N}$. Since $\frac{\Pi'_J}{N} > \frac{\Pi_S}{N}$, all countries prefer the jointly-negotiated agreement, and aggregate welfare unambiguously increases. ■

These two results show that when the joint agreement sustains a level of participation high enough so that the level of R&D investment passes the tipping point, aggregate welfare strictly increases. Thus, although only the members of the joint agreement invest in R&D, all countries now abate pollution: signatories of the joint agreement abate pollution because doing so maximizes their joint payoff, and non-signatories abate pollution because that is their dominant strategy. Furthermore, even though the joint agreement does not sustain full participation, full cooperation on abatement is achieved. What enables this fully cooperative outcome is that the joint agreement is large enough such that the level of R&D investment and, hence, abatement cost reduction are enough to tip non-signatory behavior. In this case, it is in all countries' best interest to provide both pollution abatement and R&D investment with a single agreement. Thus, a high enough level of cooperative R&D investment can push the abatement strategies of non-signatories over a tipping point and eliminate the incentive to free-ride on pollution abatement.[35]

The results of this section, however, are not quite as positive as they may seem. Recall that the potential gain to full cooperation, $N[Nb - c(1 - \varepsilon N) - d]$, is decreasing in d, but that the size of the joint agreement is increasing in d. Furthermore, higher levels of d, keeping N, b, c and ε constant, is what enables the joint agreement to pass the threshold level of R&D investment. Thus, for higher levels of the cost of investment, participation in the joint agreement is greater, but the gains to cooperation fall; and when the cost of investment is high enough so that the tipping point is reached, the gains to cooperation are even less than before.

7 Conclusion

Faced with the failure of the Kyoto Protocol to reduce emissions of greenhouse gases, countries are realizing that the way forward will require reducing the costs of pollution abatement. However, this introduces the problem of providing another public good, R&D investment. As noted in the introduction, nearly all cooperative R&D agreements serve only to facilitate knowledge spillovers and most do not explicitly require funding by member countries. Thus, this paper considers the problem of cooperatively providing two public goods, pollution abatement and R&D investment, which both suffer from free-riding and under-provision. To try to gain more insight into the incentives to cooperate, I analyze two different cooperation regimes: forming a separate IEA and RDA or forming a single, joint agreement to provide both goods.

I model the provision of abatement and R&D investment in a linear, discrete choice model,

[35] For even higher values of d, $k_R^* > \frac{c-b}{c\varepsilon}$ is possible, and the RDA tips the behaviors of non-signatories under the two separate agreements. However, this occurs for an even smaller range of parameters than for k_J^*, and it can be shown that in this case the joint agreement still emerges as the preferred cooperation regime.

and I assume that the total amount of R&D investment produces a new technology that reduces abatement costs by a proportion of the total amount invested and that this new technology is available to all countries costlessly and without restriction. I find that even though the aggregate payoff increases when countries may cooperatively provide R&D investment with the RDA, I cannot show definitively which cooperation regime is preferred in the equilibrium. This is because of the tradeoff inherent in the joint agreement: it provides less abatement than the IEA, but at lower cost since it provides more R&D than the RDA. Finally, I consider the special case in which the joint treaty invests in a sufficient amount of R&D such that the new technology causes Pollute to no longer strictly dominate Abate for non-signatories. In this case, I show that the signatories of the joint agreement still provide abatement and R&D investment, and non-signatories only free-ride on R&D - all countries now provide abatement. Thus, the joint treaty provides a strict increase in welfare over two separate treaties and emerges endogenously as the unanimously preferred treaty structure.

The IEA literature has a history of pessimistic results, and I admittedly do not provide very positive results even considering the special case with the R&D tipping point. Clearly, the tipping point is a special feature of this linear payoff function and will not arise in a model with strictly convex cost functions. Also, the tipping results of Section 6 only hold due to the main assumption of this paper: that abatement cost-reducing technology resulting from R&D is freely available to all countries. Despite other papers on this topic assuming that the benefits of R&D are only available to IEA members (a club good), I make the opposite assumption because IEA members typically do not withhold abatement cost-reducing technologies from non-signatories (Barrett 2003). If the club good assumption is imposed on this paper's model, then only the results of Section 5 are still true.[36]

Furthermore, there are numerous other unrealistic simplifications: *ex ante* symmetric countries in both abatement and R&D (which implies that all signatories are pivotal), no room for

[36] My results are difficult to compare with those of Carraro and Siniscalco (1997), which makes the club good assumption, due to differences in the payoff functions.

strategic reaction by non-signatories, identical spillovers across countries, no uncertainty in R&D innovation, and no time lags in developing, diffusing, and adopting the new technology. These simplifying assumptions are necessary for this paper's analysis because it is written, in part, as a complement to the many simulation papers in the current IEA literature[37], and one of the goals of this paper is to provide transparent, analytic results wherever possible.

However, the main results are still suggestive of possible future cooperation outcomes. For instance, there has not yet been any attempt at an agreement which requires signatories to commit to both binding abatement *and* R&D investment targets. In the context of this paper's simple model, a joint agreement is better at reducing free-riding on R&D than is the RDA and with potentially only a small reduction in abatement with respect to the IEA (Proposition 4). The implication for future climate treaty negotiations is that even though R&D investment is important for lowering abatement costs, a joint treaty may be needed to keep participation incentives all pointed in the same direction.

Another suggestive point, which is discussed by Barrett (2006), is that cooperative R&D projects should be chosen strategically; thus, cooperative R&D projects for technologies that may encourage free-riders to abate at more socially-optimal levels should be pursued, even if there may be *better* technologies possible.[38] In this case, a joint agreement to provide both abatement and R&D investment would provide a better aggregate outcome, and cooperative R&D projects should focus on technologies that are more likely to be diffused and adopted by all countries, which would encourage lower levels of emissions among even non-cooperating countries.

[37]For instance, Carraro and Siniscalco (1997), Buchner *et al.* (2005), and Buchner and Carraro (2005).

[38]For completeness, I again note that my model is very similar to Barrett (2006), although he only considers cooperation on R&D investment.

Chapter 2

A Review of the Weakly Renegotiation-Proof Equilibrium: Theory and Applications

1 Introduction

As early as the work of Friedman (1971), who showed that any feasible payoff greater than the stage-game Nash equilibrium payoff can be attained as a subgame-perfect equilibrium in an infinitely repeated game provided that players are patient enough, researchers have analyzed how cooperation among players (or collusion among firms) can be sustained by the threat to punish defections. One concern in the theory, however, is that a subgame-perfect strategy may not be credible if renegotiation among players is possible. The following example highlights this problem.

Consider the infinitely repeated, two-player Prisoner's Dilemma. A subgame-perfect equilibrium of this game consists of players cooperating indefinitely, with any deviation from cooperation being followed by non-cooperation indefinitely (the *grim trigger strategy*). However, when faced with actually punishing a defection (and entering the non-cooperation phase), the two players will renegotiate back to cooperation because doing so is mutually beneficial. In other words, since the non-cooperation phase results in lower payoffs for both players forever, the player who did not cheat would rather overlook the defection and avoid imposing punishment, which implies that the two players simply return to cooperation. Thus, if players can renegotiate the strategy during play, this subgame-perfect equilibrium is not credible.

Define a *continuation equilibrium* payoff as the payoff of any possible equilibrium following any history and at any time period of the game. In the motivating example above, there are two continuation equilibrium payoffs associated with the grim trigger strategy: the payoffs from cooperation and the payoffs resulting from punishment. If players find themselves faced with imposing a punishment but can renegotiate during play, they will skip the punishment and return to cooperation because the cooperation continuation equilibrium Pareto-dominates the non-cooperation continuation equilibrium.

The purpose of the renegotiation-proof equilibrium concept is to eliminate subgame-perfect equilibria that are not credible in the sense that they have continuation equilibria that are Pareto-dominated by other continuation equilibria.

2 Renegotiation-Proof Equilibrium Theories

Farrell and Maskin (1989) and Bernheim and Ray (1989) independently developed renegotiation-proof equilibrium concepts that are complementary to each other.[1] Farrell and Maskin (1989) propose that a subgame-perfect equilibrium is *weakly renegotiation-proof* (WRP) if there does not exist a continuation equilibrium of that strategy that is strictly Pareto-dominated by another continuation equilibrium of that strategy[2]. Thus, returning to the infinitely repeated, two-player Prisoner's Dilemma, the grim trigger strategy is a subgame-perfect equilibrium, but it is not a WRP equilibrium since the continuation payoff associated with cooperation Pareto-dominates the continuation payoff from punishment. After deriving necessary and sufficient conditions for the existence of the set of WRP equilibrium payoffs, the authors apply the result to a series of illustrative examples (Prisoner's dilemma, Cournot and Bertrand com-

[1] I will focus on Farrell and Maskin (1989), though, because it is more widely cited.
[2] Bernheim and Ray (1989) refer to this concept as *internal consistency*.

petition, and an advertising game).[3]

Despite the focus of repeated-game research on achieving Pareto-efficiency through cooperation, note that a WRP equilibrium does not have to be Pareto-efficient; rather, the continuation equilibria of a WRP equilibrium simply cannot be Pareto-ranked. Thus, since the WRP concept may be judged to be too weak, one may consider the more restrictive *strongly-perfect equilibrium*, which only allows Pareto-efficient continuation equilibria. However, this refinement may actually be too strong, and "it should not be considered an objection to a proposed WRP equilibrium to point out that it is Pareto-dominated by another subgame-perfect equilibrium that is itself *not* WRP" (Farrell and Maskin 1989, pp. 348-9). The reason is that a Pareto-dominating subgame-perfect equilibrium may not be credible. Thus, the authors introduce the *strongly renegotiation-proof* (SRP) equilibrium: a WRP equilibrium is SRP if none of its continuation equilibria are Pareto-dominated by another WRP equilibrium.[4] Although WRP equilibria always exist for patient enough players, it is shown that SRP equilibria may not always exist (see the Bertrand example).

Although the model in Farrell and Maskin (1989) is for only two players, the authors claim that their results are easily generalized to n players. However, they do not believe that WRP and SRP equilibria are necessarily appropriate for games of more than two players since one should consider the possibility of a cooperative deviation of a group smaller than the entire set of players. Bernheim and Ray (1989) do not allow for coordinated deviations by subsets of players either, but in slight contrast to the former paper, the results of this paper are actually derived for a game of n players.

Deviation by a subset of players is an important consideration because the WRP and SRP equilibrium concepts (as well as the consistency concepts of Bernheim and Ray 1989) only apply to a deviation by *all* players (*i.e.* players must unanimously choose to renegotiate to a

[3] Also see Van Damme (1989) regarding WRP equilibria in the Prisoner's Dilemma.

[4] Bernheim and Ray (1989) define a parallel concept, *strong consistency*, which coincides with Farrell and Maskin's SRP equilibrium.

different continuation equilibrium; renegotiation must be a Pareto-improvement). Bernheim *et al.* (1987) explore beneficial deviations by subsets of players by introducing the concepts of *coalition-proof Nash equilibria* and *perfectly coalition-proof Nash equilibria* for finite games.

The basic idea of the coalition-proof Nash (CPN) equilibrium is that an agreement must be Pareto-efficient among all self-enforcing agreements, and an agreement is called *self-enforcing* if no subset of players can make a mutually beneficial deviation, taking the actions of all other players as given. Further, by way of a recursive definition for CPN equilibria, any possible deviations must also be self-enforcing in that there are no sub-coalitions of original deviators that can mutually gain by deviating. The authors are not able to show that a CPN equilibrium exists in general; rather, they illustrate existence and non-existence through examples of simple games.

The authors then extend the CPN equilibrium concept to a finitely repeated game. This concept is called a perfectly coalition-proof Nash (PCPN) equilibrium. As in the CPN equilibrium, the authors are not able to show general existence for the PCPN equilibrium. The two-player version of this concept shares many of the properties of Farrell and Maskin's (1989) WRP equilibrium (and internal consistency in Bernheim and Ray 1989). However, as stated previously, Farrell and Maskin do not consider more than two players, nor do Bernheim and Ray (1989) consider deviations by subsets of players. Although the PCPN equilibrium addresses one of the objections to the WRP and SRP equilibrium concepts, the PCPN equilibrium is not a refinement of the WRP or SRP equilibrium concepts.

Finally, Abreu *et al.* (1993) object to the use of Pareto-dominance in the other renegotiation-proofness theories because they feel that unanimity gives any one player too much bargaining power. For example, in contrast to the definition of the WRP equilibrium, players may only renegotiate to a different continuation equilibrium if doing so makes *all* players at least as well off. Thus, the authors propose the *consistent bargaining equilibrium* (CBE). A subgame-perfect equilibrium is a CBE if the continuation equilibrium with the harshest punishment (and lowest payoff) results in at least as high a payoff as the harshest punishment of any other subgame-perfect equilibrium. They believe that the CBE reflects a more plausible solution to renegotiation-proofness since no player would object to the "least worst" punishment that satisfies subgame-perfection. Abreu *et al.* (1993) then prove the existence of a CBE for symmetric games and for strategies with stick and carrot punishment schemes (see Abreu 1986), and they show how to compute both the highest payoff sustainable by a CBE and the "least worst" punishment.

3 Non-Environmental Economics Applications

Of all the fields in economics, it seems that environmental economics (international environmental agreements, in particular) has used the WRP equilibrium most often and applied it the most thoroughly. Despite a search of Farrell and Maskin (1989) turning up 175 articles in the Web of Science, nearly all of these articles just make a passing reference to the WRP equilibrium and do not apply the definition or model. However, the following non-environmental economics papers do apply the WRP concept in interesting ways.

McCutcheon (1997) questions whether the Sherman Act actually makes it more difficult for firms to collude. Historically, judges have tended to be lenient, and fines have typically been small. Thus, the law makes it costly to collude, but not costly *enough*. Rather, supposing that firms tacitly collude, the law does make it more costly to renegotiate a collusive agreement since firms do not want to communicate too much. This reinforces collusion because punishments (in the marketplace) are carried out rather than renegotiated. McCutcheon models a Bertrand game and finds a WRP strategy (with a collusive phase and a punishment phase) such that for various values of renegotiation costs, numbers of firms, and the discount factor, the Sherman Act actually supports collusion as an equilibrium.

McGillivray and Smith (2000) use an infinitely repeated Prisoner's Dilemma to analyze international cooperation and is very much written in the style of Barrett (1999), which is discussed in the following section. The novel approach here, though, is the use of an *agent-specific* grim trigger strategy. This strategy differs from the usual grim trigger strategy in that here a country's citizens may choose to replace their leader (at a cost) after he defects from cooperation with another country. Rather than triggering defection forever, defection only last until that country replaces its leader, then cooperation is resumed. By holding a country's leader accountable in this way, this strategy can support cooperation. The authors show that if the discount factor is high enough, then the agent-specific grim trigger strategy is both a subgame-perfect equilibrium and is SRP.

Driffill and Schultz (1992) consider the "social contracts" of post-war Europe - non-binding cooperative understandings between governments and workers (trade unions) to keep wages low and to achieve higher employment (Austria and Sweden are the leading examples). Since it was tough for trade unions to moderate their wage demands, governments typically offered tax cuts or, in the case of this paper's model, economic stabilization in the form of spending. This paper has the government and the trade union playing a non-cooperative game by choosing government spending and wages each period, respectively. The authors find subgame-perfect equilibria in which both the government and union get the most desired results (highest utility). However, after restricting the equilibrium payoff sets by applying the WRP and SRP equilibrium concepts, the spending and wage outcomes are found to not favor either party.

Finally, Baliga and Evans (2000) argue along similar lines as Farrell and Maskin (1989) in showing the existence of a SRP equilibrium in a repeated game with side-payments. Assuming that players have quasi-linear utility in wealth and can make transfers, the authors construct a strategy that includes transfers in the cooperative phase and fines in the punishment phase (as well as min-maxing the cheater) and show that this strategy is SRP.

4 Applications to International Environmental Agreements

The literature on international environmental agreements (IEAs) can be divided into two groups based on the equilibrium concept used. Early IEA research, which began with Barrett (1994) and Carraro and Siniscalco (1993), and the majority of subsequent research on this topic uses a one-shot, multi-stage game in which membership to the IEA is chosen, then emissions (or abatement) levels are chosen by the signatories and non-signatories to the agreement. The equilibrium concept in this case, *stability*, is from the cartel literature (d'Aspremont *et al.* 1983). The main focus is on how cooperation can overcome the incentive to free-ride on the emissions reductions of other countries, and the equilibrium number of countries in an IEA is determined when there is no member of the agreement that can gain by defecting from cooperation and if there is no non-member of the agreement that can gain by joining. The integer number of countries that satisfies this stability concept determines the number of signatories in the agreement.

The other equilibrium concept, which is used much less frequently, is the WRP equilibrium. These papers use an infinitely repeated game, in which the terms of the IEA (a strategy profile that includes cooperation and punishment) and membership are determined at the onset, and each period countries choose their emissions (or abatement) to follow the terms of the treaty. One of the key drivers of the following results is that a WRP equilibrium requires that it must be individually rational for at least one country (typically, it will be a subset of signatory countries) to follow through with a punishment if a country cheats. High payoffs to cooperation may be a barrier to a WRP treaty because renegotiation back to cooperation, rather than punishing a defection, becomes more enticing. Thus, either the payoffs to cooperation must be lowered, typically by lowering the level of abatement during the cooperative phase, or the payoffs to punishment must be raised, perhaps by reducing the number of countries that participate in dealing the punishment. The papers in this branch of the IEA literature can then be separated into two groups depending on how the analysis proceeds.

Beginning with the original paper by Farrell and Maskin, who state that characterizing the set of all WRP equilibria is "difficult," one may instead derive the set of payoffs supported by WRP equilibrium strategies. Farrell and Maskin (1989) take this approach in most of that paper's examples by prescribing a simple punishment to be followed, which is to *minimax the offender* (the punishers hold the cheater to the lowest individually rational payoff in their power). For example, in a Cournot duopoly firms produce the monopoly level of output during cooperation, and a defection by one firm is punished by that firm producing nothing for the next period and the other firm producing any level of output such that it is individually rational to follow through with the punishment (the main condition needed for a WRP equilibrium). After the punishment period, cooperation would then resume. Farrell and Maskin do not detail any other aspects of this strategy, nor do they describe any other WRP strategy; the goal is simply to characterize the set of payoffs supported by WRP strategies.

The first IEA paper to use the WRP equilibrium concept, Barrett (1994), also characterizes the set of WRP payoffs. Following a similar analysis as Farrell and Maskin (1989), Barrett uses a minimax-the-offender punishment, and by manipulating the resulting payoffs he derives the maximum number of cooperating countries that can sustain a WRP equilibrium and finds a similar result to the one-shot game model - that the amount of cooperating countries will only be large if the gains to cooperation are small.[5,6]

The other approach to analyzing IEAs as infinitely repeated games is to specify a particular strategy and show that it is both subgame-perfect and WRP, and the number of countries in the agreement is then derived from the resulting equations. Barrett (1999) shows that a strategy of "Getting Even" (in which a country cooperates in a period unless it has defected fewer times than have other countries) is a WRP equilibrium that supports less than full participation unless

[5] Barrett actually goes one step stronger here by requiring that payoffs during the punishment phase be Pareto-efficient, which Farrell and Maskin (1989) call *strongly perfect*; see Section 2 of this Review.

[6] Using a slightly different approach, Finus and Rundshagen (1998) characterize the set of WRP equilibrium levels of emissions in a two-country model where countries may cooperate by using either an emissions tax or quota.

the number of countries is sufficiently small, which confirms earlier pessimistic IEA results. Barrett (2002) shows that a "Penance" strategy (in which a cheating country is punished by having to abate at an optimal level in the next period) is not only a WRP equilibrium, but that by also lowering the level of abatement during cooperation (and consequently the payoff to cooperation), full participation can be sustained (but not Pareto-optimality). He then shows that if the number of countries is sufficiently large, then the full participation agreement (the "consensus" agreement) will be preferred by all countries to the standard IEA (which has less than full participation). Finally, he shows that if one requires that an agreement be SRP, which implies that signatories must not only punish a cheater but that the punishment must also maximize the signatories' collective payoff, then an agreement with full participation does not exist.[7]

Asheim *et al.* (2006) builds on the repeated-game framework of Barrett (1999) and shows that rather than having just one treaty, two simultaneous (regional) treaties can sustain more overall cooperation and Pareto-dominate a regime of just one treaty. The main intuition for this result is that not all countries in the world punish a defection - only the countries in the particular region with the cheater. This makes it easier to achieve the WRP requirement that the payoff for the punishing countries is greater than the payoff of simply continuing with cooperation. Froyn and Hovi (2008) extend the Asheim *et al.* (2006) result and show that by further reducing the number of countries that punish a defection to an optimal level that just satisfies the WRP requirements, there exists a WRP equilibrium with full participation. The results of both Asheim *et al.* (2006) and Froyn and Hovi (2008) are slightly stronger than Barrett's (2002) result in that greater participation is gained through the punishment scheme, not by reducing abatement levels during cooperation.

Finally, Asheim and Holtsmark (2009) show that by relaxing the linear payoff model with

[7]Barrett (2002) refers to WRP as *weak collective rationality* and refers to SRP as *strong collective rationality* because, as other authors have noted, Farrell and Maskin (1989) do not define renegotiation-proof concepts for more than two players.

discrete choices (used in Barrett 1999, 2002, and Asheim *et al.* 2006) to a model of continuous abatement choices with quadratic abatement costs, a Pareto-optimal IEA exists as a WRP equilibrium for a high enough discount factor and a small enough number of countries. Thus, they show that abatement levels and participation need not necessarily trade off when finding a WRP agreement (as in Barrett 2002). They also show that if the discount factor is too low and the number of countries is too high, then the level of abatement falls during both cooperation and punishment compared to the Pareto-optimal IEA; however, full participation can still be achieved.

The authors devise *simple strategy profiles* as in Abreu (1988), which implies that a unilateral deviation by a signatory leads to a one-period punishment in the next period. The punishment phase follows a Penance strategy, in which half of the signatories punish the deviation by lowering their abatement for one period while the cheater abates at the Pareto-optimal level, then all signatories return to cooperation.[8] This punishment scheme has been shown in previous papers to satisfy the requirements of a WRP equilibrium by keeping the payoff to punishment sufficiently high. One advantage of the Asheim and Holtsmark (2009) punishment scheme over that of Asheim *et al.* (2006) is that in the latter paper (two regional agreements; punishment for one region's defection occurs within that same region) a defection by a country causes the other region to be harmed twice - once by the defection and again by the punishment (both actions lower global abatement). The former paper's model doesn't have that drawback.

One can also compare the continuous choice model of Asheim and Holtsmark (2009) with the linear, discrete choice model of Froyn and Hovi (2008) in terms of how high the discount factor needs to be to achieve Pareto-optimality. In the former paper, the main condition for a Pareto-optimal, WRP equilibrium is that the discount factor must be sufficiently high and number of countries must be sufficiently small; it is shown that with 200 countries the discount

[8]More precisely, the subset of signatories that punish a defection consists of either $n/2$ (if n is even) or $(n+1)/2$ (if n is odd) countries where n is the number of countries.

factor must be at least 0.99 and that a discount factor of 0.95 reduces the depth of the treaty to less than 20% of the Pareto-optimal level of abatement. However, in the latter paper a discount factor of 0.95 is sufficient for Pareto-optimality, regardless of the number of countries.

5 Conclusion

The purpose of the renegotiation-proof equilibrium is to eliminate subgame-perfect equilibria that are not credible in the sense that they have continuation equilibria that are Pareto-dominated by other continuation equilibria. In the first section of this review, I motivate the problem with a simple Prisoner's Dilemma example, and then I summarize the theoretical approaches to the renegotiation-proof equilibrium. After reviewing a selection of non-environmental economics applications of the theory, I then turn to applications of the WRP equilibrium for international environmental agreements. In the context of cooperation, the WRP equilibrium implies that it must be in the interest of at least one party to the treaty to follow through with a punishment (and subsequently lower all payoffs) rather than to ignore a defection and continue with cooperation.

Chapter 3

Sustaining Full Cooperation in an International Environmental Agreement through Learning and R&D

1 Introduction

This paper analyzes the effects of learning and research and development (R&D) in an infinitely repeated international environmental agreement (IEA) in which countries are uncertain regarding the benefits of pollution abatement. The central challenge of international environmental problems is that the pollution abatement of one country also benefits other countries, which results in strong incentives for countries to free-ride on other countries' mitigation actions. Due to the public good property of pollution abatement, cooperative solutions are needed to improve on the suboptimal levels of abatement currently being provided. However, cooperation tends to be scarce when it is needed most because the incentive to free-ride can be so powerful (for an overview, see Barrett 2003). Furthermore, in a setting with repeated interaction, which is the focus of this paper, cooperating countries must also be able to deter (with the threat of punishment) defections and free-riding.

In addition to the incentive to free-ride, another reason for the lack of international environmental cooperation is the uncertainty regarding the benefits and costs of pollution abatement, which may influence the strategic actions of countries and may result in either more or less countries cooperating with potentially ambiguous effects on global pollution abatement and welfare.[1] Acquiring more information about the benefits of abatement may not necessarily be beneficial; for example, if countries learn that abating pollution is more beneficial than they had originally thought, then the incentive to free-ride on the abatement of others increases. While most research efforts on this topic have focused on the strategic effects of information, the effects of uncertainty and learning on the likelihood of countries sustaining full cooperation in an IEA has not yet been studied.

Thus, the main research question is: In an infinitely repeated IEA in which countries are uncertain regarding the benefits of pollution abatement, how does learning (resolving uncertainty) affect the likelihood of sustaining a Pareto-optimal agreement with full cooperation when compared to the baseline case without uncertainty?[2] In addressing this question, this paper also determines how uncertainty affects the number of countries needed to punish a defection from the IEA and the strength of the punishment. Finally, this paper considers the role of the knowledge gained through R&D, which is interpreted differently in the model than the previously mentioned "learning," and how R&D may make cooperation easier or more difficult to sustain depending on what is learned. Since more information may not necessarily work in favor of cooperation, the purpose of this paper is to provide insight into how learning may affect the ability of countries to maintain a cooperative regime.

This paper uses a model in which identical countries play an infinitely repeated game, the benefits of pollution abatement are a pure public good, the marginal benefit of abatement is constant, and the marginal cost of abatement is linear. The assumptions regarding marginal

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[1] The strategic effects of uncertainty and learning on IEA formation has been studied by Ulph (2004), Kolstad (2007), Kolstad and Ulph (2008), and Finus and Pintassilgo (2012).

[2] The *likelihood* of sustaining cooperation refers to the range of discount factors $\delta \in [\hat{\delta}, 1)$ ($\hat{\delta}$ is often called the *critical* discount factor), and a wider range of discount factors (a lower value of $\hat{\delta}$) is associated with a higher likelihood of cooperation.

benefits and marginal costs are meant as a compromise between tractability and reality. I introduce uncertainty by assuming that countries are uncertain about the true value of the marginal benefit of abatement and may resolve their uncertainty by learning its true value at the beginning of each period with some positive probability.[3] This paper utilizes a strategy profile proposed by Asheim and Holtsmark (2009) and provides conditions such that the strategy is a weakly-renegotiation proof (WRP) equilibrium (Farrell and Maskin 1989).[4] The WRP equilibrium is a natural choice for analyzing infinitely repeated IEAs because it requires that a punishment be strong enough to deter defections (and to satisfy subgame-perfection), but not so strong as to cause the punishing countries to not follow through with the punishment.[5] As I discuss in the next section, the vast majority of the literature analyzes IEAs as a one-shot game and not as an infinitely repeated game, and to my knowledge this is the first paper to include uncertainty in an infinitely repeated game of environmental cooperation.

The main result is that uncertainty leads to conditions in which the Pareto-optimal IEA exists as a WRP equilibrium for a wider range of discount factors than in the case with no uncertainty. Resolving uncertainty through learning, however, reduces this range and makes sustaining cooperation more difficult. The mechanism driving this result is that uncertainty leads to a higher expected net loss from punishment to a defecting country because the punishing countries may have more information available during a punishment phase than when the deviation occurred, which allows for deviations from cooperation to be *over*-punished in expectation. This implies that deviations are better deterred under uncertainty and that sustaining full cooperation in an IEA is more likely.

Finally, I consider how the results of R&D affect the punishment for defection and the

[3]This form of uncertainty, systematic uncertainty, in which all countries share uncertainty over the same variable (in this case, the benefits of pollution abatement) has been recently studied by Kolstad (2007) and Kolstad and Ulph (2008).

[4]The structure of the results and proofs in this paper also owe a debt to Asheim and Holtsmark (2009). Two of their results are shown as corollaries to the results here.

[5]As I show later, the punishment for a defection involves a group of countries lowering their abatement levels for one period. Since pollution abatement is a public good, the punishment results in lower payoffs for some, but not all, members of the IEA.

critical discount factor needed to sustain a Pareto-optimal IEA. Note, however, that in this model countries only choose their level of abatement; they do not choose a level of R&D investment.[6] Rather, in the comparative statics section of this paper, instantaneous changes in key parameters, such as the probability of learning the true value of the marginal benefit of abatement or the variance of the marginal benefit of abatement (which is related to the expected loss from punishment), are interpreted as resulting from R&D. Whether or not R&D is beneficial for sustaining cooperation depends on what is being learned. Specifically, if R&D either results in an increase in the probability of learning the true value of the marginal benefit of abatement (for most parameter values) or in a lower variance of the marginal benefit of abatement, then it becomes more difficult to sustain full cooperation because the expected net loss from punishment decreases; in these cases, the pro-cooperative effects of over-punishment due to uncertainty are lessened. Thus, this paper finds that achieving the Pareto-optimal IEA tends to be less likely if R&D reduces uncertainty.

2 Related Literature

This paper contributes to two areas of the IEA literature, which are reviewed in this section. First, I discuss the small number of papers that analyze IEAs that arise as a WRP equilibrium in an infinitely repeated game. Then, this paper turns to the literature regarding the effects of uncertainty and learning on the strategic interaction among countries as they choose whether or not to be members of an IEA. Finally, note that at a more general level the IEA literature derives from the literature on the private provision of a public good (Bergstrom *et al*. 1986).

The bulk of IEA research uses a one-shot, multi-stage game in which membership to the IEA is determined, then emissions (or abatement) levels are chosen by the signatories and non-signatories to the agreement.[7] The main result is that when the potential gains to cooperation

[6] See Mohr (2014), Carraro and Siniscalco (1997), and Hong and Karp (2012) for examples in which countries choose to make investments to lower abatement costs.

[7] See Barrett (1994) and Carraro and Siniscalco (1993) for early IEA research and Barrett (2003) for an

are high (and an agreement would be most beneficial), the incentive to free-ride is strong and only a small IEA emerges.[8]

A few papers, however, have approached the problem of international environmental cooperation in the context of an infinitely repeated game, which puts more emphasis on the punishments needed to sustain cooperation, and have utilized the WRP equilibrium of Farrell and Maskin (1989).[9] The WRP equilibrium is an important concept for the study of repeated IEAs because it eliminates subgame-perfect equilibria in which players (or countries in this paper) may *renegotiate* to a different path of the game by finding a multilateral improvement. As a motivating example, consider the infinitely repeated, two-player Prisoner's Dilemma, of which the infinitely repeated, n-country IEA game is a close relative. A subgame-perfect equilibrium of this game consists of both players cooperating indefinitely, with any deviation from cooperation being followed by non-cooperation indefinitely (the *grim trigger* strategy). However, when faced with actually punishing a defection (and entering the non-cooperation phase), the two players will renegotiate back to cooperation because doing so is mutually beneficial. In other words, since the non-cooperation phase results in lower payoffs for both players forever, the player who did not cheat would rather overlook the defection and avoid imposing punishment, which implies that the two players simply return to cooperation. Thus, if players can renegotiate the strategy during play, this subgame-perfect equilibrium will not stand. In the same sense, countries in an IEA will need to punish defections, and the WRP equilibrium ensures that the punishment will actually be followed. In the context of cooperation, this equilibrium concept typically implies that it must be in the interest of at least one party to the treaty to follow through with a punishment (which results in lower payoffs for

overview.

[8]The one-shot IEA model typically uses an equilibrium concept, *stability*, from the cartel literature (d'Aspremont *et al*. 1983), in which the equilibrium number of countries (and emissions or abatement levels) in an IEA is determined when there is no member of the agreement that can gain by defecting from cooperation and there is no non-member of the agreement that can gain by joining.

[9]Barrett (1994, 1999, 2002), Asheim *et al*. (2006), and Froyn and Hovi (2008) all follow this approach. In general, a *penance* strategy, in which a cheating country is punished by having to abate at an optimal level in the next period while other signatories lower their abatement for one period, is used to derive a WRP equilibrium.

some, but not all, members of the IEA) rather than to ignore a defection and continue with cooperation.

This paper is an extension of the model of Asheim and Holtsmark (2009), who show that by relaxing the linear payoff model with discrete choices (used in Barrett 1999, 2002, and Asheim *et al.* 2006) to a model of continuous abatement choices with quadratic abatement costs, a Pareto-optimal IEA exists as a WRP equilibrium for a high enough discount factor and a small enough number of countries. They also show that if the discount factor is too low and the number of countries is too high, then the level of abatement falls during both cooperation and punishment compared to the Pareto-optimal IEA; however, full participation can still be achieved. This paper extends these results by introducing uncertainty and learning and then providing a comparison between the cases of uncertainty and no uncertainty.

Beginning with Na and Shin (1998) and continuing more recently with Kolstad (2007), Kolstad and Ulph (2008), and Finus and Pintassilgo (2012), the literature that analyzes IEAs with uncertainty and learning highlights the strategic role of learning when countries are uncertain over a key parameter and shows how learning affects IEA membership and abatement levels. One of this paper's contributions to the literature on uncertainty and learning in IEAs is that in contrast to the papers just mentioned, which all analyze a one-shot game, this paper models an infinitely repeated game. In doing so, the focus is on how cooperation is sustained, not how it is initially achieved.

Na and Shin (1998) analyze IEAs in a world in which there is uncertainty over the distribution of the benefits of pollution abatement, which results in the countries being heterogeneous after the uncertainty has been resolved, and use a strictly concave payoff function (as does this paper). They show that resolving uncertainty before the treaty is negotiated reduces global welfare because smaller coalitions form.[10] The authors argue that when uncertainty has not been resolved, countries do not know how different they may be, so a larger coalition with

[10]They do, however, assume only three countries, which causes some of their results to be special cases.

larger expected payoffs emerges. Thus, when countries learn the true degree of asymmetry in their abatement benefits, cooperation becomes harder to achieve.[11]

Kolstad (2007) analyzes a linear payoff function with systematic uncertainty in the cost of environmental damages, where damage costs may be either high or low with some probability. Uncertainty may be resolved before an IEA forms (full learning), after the IEA forms but before emissions are chosen (partial learning), or not at all (no learning). In contrast to Na and Shin (1998), it is assumed that all countries are *ex ante* and *ex post* identical: when uncertain, all countries share the same expectations over environmental damages, and if learning occurs all countries realize the same value for damages. It is shown that learning (whether partial or full) tends to decrease the size of the IEA and lowers global welfare. Thus, learning and the subsequent strategic interactions lead to worse outcomes in expectation.[12]

In the uncertainty literature, the paper most similar to mine (in terms of generality and payoff function) is Finus and Pintassilgo (2012), which uses Na and Shin (1998) as its baseline model and attempts to generalize its results to *n* countries and to extend those of Kolstad (2007) to a payoff function with linear benefits of abatement and quadratic abatement costs. The authors contrast recent research results with reality raising the following point: despite recent papers showing that learning tends to make IEAs worse off (less membership and lower global welfare), even more research is being conducted now to reduce uncertainties. In generalizing the model of Na and Shin (1998), in which there is uncertainty over the distribution of benefits, the authors confirm that learning has a negative effect on IEA size and total expected payoffs. In generalizing Kolstad (2007), the authors find that learning increases expected abatement and payoffs, which is a stronger, more positive result than Kolstad originally found. The intuition is that cooperation is easier among similar agents, contrasted with the re-

[11]In a related paper, Kolstad (2005) shows that when learning reveals asymmetries in a two-country model, a cooperative agreement is more *difficult* to achieve. Here, *difficulty* refers to the gross expected amount of side payments needed to achieve a Pareto-improving agreement.

[12]See also Kolstad and Ulph (2008), which extends Kolstad (2007) and Ulph (2004), a paper generally qualitatively similar to Kolstad (2007), and reinforces the results of both.

sults of Na and Shin, in which the agreements are harder to obtain if players already know the (unequal) distribution of benefits.

As I pointed out earlier, my paper does not analyze the strategic role of learning; rather, the effects of uncertainty, learning, and R&D arise in this paper from a comparison of the expected gain from defecting from the agreement and the discounted, expected loss from punishment. However, the results of this paper do tend to be pessimistic in terms of the effects of learning on cooperation, as are the results of Na and Shin (1998), Kolstad (2007), and Kolstad and Ulph (2008). Also, in reference to the comment in Finus and Pintassilgo (2012) mentioned above, this paper discusses how learning may be beneficial or detrimental for sustaining cooperation.

3 Model

This paper models an infinitely repeated IEA game in which countries are uncertain about the value of the marginal benefit of abatement and may resolve their uncertainty by learning its true value at the beginning of each period with some positive probability. The goal is to construct a strategy that has an IEA as its equilibrium path and specifies punishments for deviations from the equilibrium path, and then to provide conditions so that the strategy is a weakly renegotiation-proof equilibrium and can achieve a Pareto-optimal IEA. However, before delving into the full model under uncertainty, I first present the basic elements of the model with no uncertainty.

3.1 Certainty

Let there be $n \geq 2$ identical countries, where $N = \{1, 2, ..., n\}$ is the set of all countries. Each country i chooses its level of emissions abatement $q_i \geq 0$ in every period of the infinitely repeated game in discrete time. Since all countries share the same atmosphere, abatement is a public good; thus, each country benefits from the abatement by all other countries in addition to its own. Each country i has the following stage-game payoff each period:

$$\pi_i(q_i, Q_{-i}) = b\sum_{j=1}^{n} q_j - \frac{c}{2}q_i^2, \tag{1}$$

where $b, c > 0$ and $Q_{-i} = \sum_{i \neq j}^{n} q_j$. This payoff function, in which the marginal benefit of abatement by all countries, b, is constant, and the marginal cost of abatement by country i is linear (where c is a cost parameter), has been chosen as a compromise between a more complicated reality and the desire for clean, analytical solutions. Also, I assume that there is no existing stock of greenhouse gases that changes each period as a function of the previous period's abatement decisions; rather, countries play an infinitely repeated game with (1) as the stage-game payoff. The purpose of this assumption is to better focus on how uncertainty (to be introduced in the next section) affects the incentives to punish a deviation from the IEA.[13]

If countries act non-cooperatively, then they maximize their own payoff in each stage and abate

$$q^1 = \frac{b}{c},$$

which is not only the Nash equilibrium level of abatement, but is also a dominant strategy in the stage game. Thus, in the discussion of cooperation later on in the paper q^1 is always the "best" deviation from cooperation.

If all countries cooperate, then they maximize the sum of their payoffs and abate at level

$$q^n = \frac{nb}{c}.$$

Thus, a Pareto-optimal agreement involves full participation (that is, all n countries are members to the agreement) and each country setting its abatement equal to q^n.

Since there is no global body to enforce a fully cooperative agreement, however, countries

[13]For example, Ulph (2004) assumes that emissions accumulate over a two-period game. The effect is to amplify the incentive to free-ride.

will have the incentive to free-ride and to defect from a cooperative agreement.[14] In a repeated-game, though, cooperation can be sustained by the threat to punish potential defections. After introducing uncertainty in the next section, I describe the strategy profile needed to implement an IEA.

3.2 Uncertainty

Now, suppose that countries do not know the true value of the parameter b. When the marginal benefit of abatement is unknown, let it be represented by the random variable β from distribution $f(\beta)$, where $b_l > 0$ is a realization of β that occurs with probability θ_l.[15] I assume that countries have a common prior belief on $f(\beta)$ (*i.e.* identical *ex ante* expectations of β), and if uncertainty is resolved, then all countries realize the same value of β (*i.e.* all countries realize the same type β, and there is no private information).[16] Denote the expected value of the marginal benefit of abatement by $\bar{\beta}$.

The timing of the game with uncertainty and learning is as follows (see Figure 1). First, in a pre-game period, a treaty is negotiatied under uncertainty, and the terms of the treaty detail the level of abatement by signatories during both cooperative and punishment phases. At the very beginning of the first period of play, which in this model is period $t = 0$, all countries may learn the true value of the marginal benefit of abatement with probability $\gamma \in (0, 1)$ or remain uncertain with probability $(1 - \gamma)$.[17] If countries do resolve their uncertainty and can

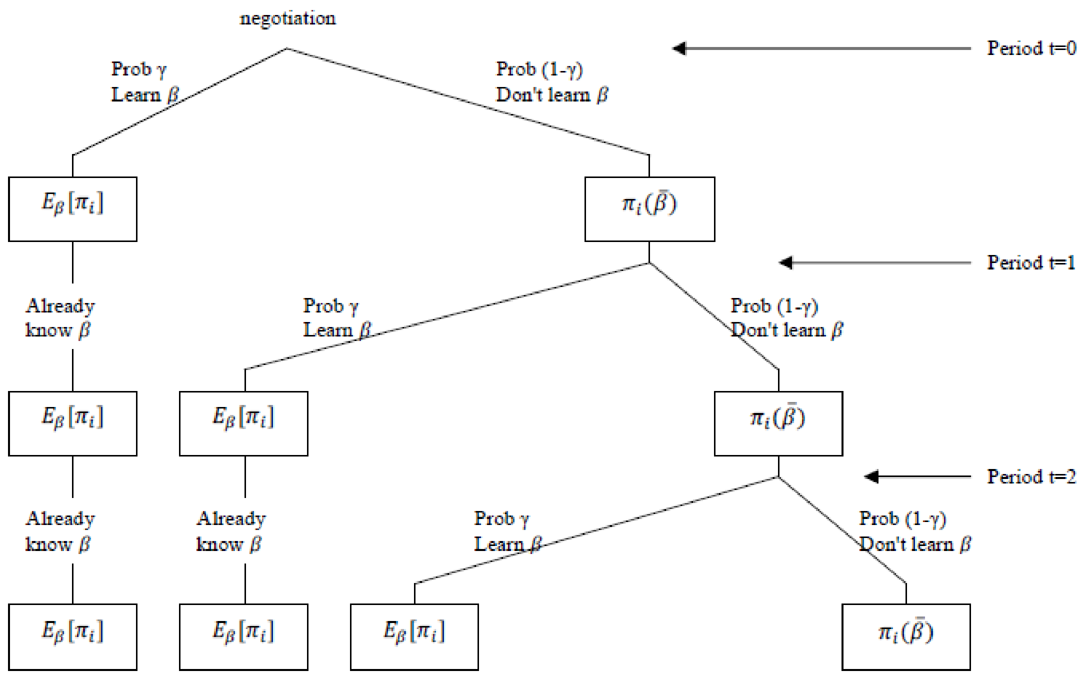
[14]See Barrett (2005) for an analysis of the one-shot IEA with this payoff function. He shows that for an IEA with m signatories, each of the signatories sets their abatement equal to mb/c, which, like q^1 and q^n above, is a multiple of b/c. That abatement levels for this payoff function can all be written as multiples of b/c provides simplification this paper.

[15]This model is general enough to not necessitate the use of any particular distribution for β.

[16]A feature common to Kolstad (2007), Kolstad and Ulph (2008), certain cases of Finus and Pintassilgo (2012), and to this paper is that all countries share uncertainty over the same variable, which is referred to as *systematic* uncertainty. This implies that countries play a game of incomplete information, and in the case of this paper, a dynamic game, which may suggest using Bayesian equilibrium in the manner of Harsanyi (1967). However, given the assumptions listed above, a Bayesian approach is not necessary.

[17]I use the word "learn" to mean that countries have resolved their uncertainty over abatement benefits. However, in the context of this model, "learning" may also be understood as nature signaling a type β from the distribution $f(\beta)$ that is observed publicly by all countries.

Figure 1: Timing of the game with uncertainty and learning (through period t = 2)



condition their actions on the true state of the world, then in period $t = 0$ each country has payoff (1) with the realized value of β replacing b. The expected payoff for each country is

$$E_\beta[\pi_i(q_i, Q_{-i})] = \sum_{l=1} \theta_l \left[b_j \sum_{j=1}^{n} q_j(b_l) - \frac{c}{2} q_i(b_l)^2 \right], \tag{2}$$

where the abatement levels are conditional on the realized value of β. To keep the equations in the next section and in Figure 1 more compact, this expected payoff will be abbreviated as as $E_\beta[\pi_i]$.

If countries do not resolve their uncertainty at the beginning of period $t = 0$, then certainty equivalence applies (the payoff function is linear in the random variable) and each country takes its marginal benefit of abatement to be equal to $\bar{\beta}$. In this case, the expected payoff for each country is

$$E_\beta[\pi_i(q_i, Q_{-i})] = \bar{\beta} \sum_{j=1}^{n} q_j - \frac{c}{2} q_i^2, \tag{3}$$

which will be abbreviated as $\pi_i(\bar{\beta})$.

Now, if countries did not resolve their uncertainty in period $t = 0$, then at the very beginning of period $t = 1$ countries may again learn the the true value of β with probability γ or remain uncertain with probability $(1 - \gamma)$. If countries already resolved their uncertainty over β in period $t = 0$, then nothing changes; the expected payoff for each country remains $E_\beta[\pi_i]$. When countries make their abatement decisions in period $t = 1$, the probability that they know β and have expected payoff $E_\beta[\pi_i]$ is $\gamma + \gamma(1 - \gamma)$, and the probability that they remain uncertain and have expected payoff $\pi_i(\bar{\beta})$ is $(1 - \gamma)^2$.

Figure 1 continues this process for one more time period. When countries make their abatement decisions in period $t = 2$, the probability that they know β and have expected payoff $E_\beta[\pi_i]$ is $\gamma + \gamma(1 - \gamma) + \gamma(1 - \gamma)^2$, and the probability that they remain uncertain and have expected payoff $\pi_i(\bar{\beta})$ is $(1 - \gamma)^3$. In general, the probability that countries have learned the true value of β in period t (and can condition their period t abatement decisions on it) is $\gamma \sum_{\tau=0}^{t}(1 - \gamma)^\tau = [1 - (1 - \gamma)^{t+1}]$, and the probability that countries have not resolved their uncertainty in period t is $(1 - \gamma)^{t+1}$.[18] Let $E_{\gamma\beta}[\pi_i(t)]$ denote the expected payoff to country i over the two states of the world where uncertainty over β may or may not be resolved in period t. Then for any period t, a country's expected payoff is

$$E_{\gamma\beta}[\pi_i(t)] = [1 - (1 - \gamma)^{t+1}]E_\beta[\pi_i] + (1 - \gamma)^{t+1}\pi_i(\bar{\beta}), \tag{4}$$

and where $E_\beta[\pi_i]$ and $\pi_i(\bar{\beta})$ are defined in (2) and (3), respectively. Finally, let the average expected discounted payoff to country i be equal to

$$(1 - \delta)\sum_{t=0}^{\infty} \delta^t E_{\gamma\beta}[\pi_i(t)],$$

[18] Note that as $t \to \infty$, $\gamma \sum_{\tau=0}^{t}(1 - \gamma)^\tau \to 1$ since $(1 - \gamma) \in (0, 1)$; thus, uncertainty is fully resolved in the limit.

where $\delta \in (0, 1)$ is the discount factor.[19]

For any period t, the abatement levels of each country in each of the previous periods comprise the history of the game going into period t. A strategy for country i defines country i's level of abatement for every possible history. The strategy profile used in this model is an extension from that used in Asheim and Holtsmark (2009), which is a simple strategy profile from Abreu (1988). In the context of this paper, a simple strategy profile is an $(n+1)$-vector of abatement paths that contains the IEA (the equilibrium path) and n punishment paths, one for each country. Any deviation by a single country i from the equilibrium path causes all countries to switch to country i's punishment path, which imposes a one-period punishment on country i, and then a return to cooperation. Further deviation by country i simply restarts the punishment. Deviation by country j from country i's punishment path leads to a one-period punishment for country j. Simultaneous deviations by more than one country from the equilibrium path are ignored.

The specifics of the IEA and the punishment scheme are as follows. Let $M = \{i_i, ..., i_m\} \subseteq N$ be the signatories to the IEA and let the number of signatories be $m \leq n$. The terms of the IEA are contained in the path $\mathbf{a}^s$, where

$$\mathbf{a}^s = (\underbrace{q_\beta^s, ..., q_\beta^s}_{j \in M}, \underbrace{q_\beta^1, ..., q_\beta^1}_{j \in N \setminus M}), (\underbrace{q_\beta^s, ..., q_\beta^s}_{j \in M}, \underbrace{q_\beta^1, ..., q_\beta^1}_{j \in N \setminus M}), ...,$$

and $q_\beta^s = s\beta/c$, $s > 1$, is the level of abatement by each signatory, which is conditional on β and whether or not learning occurs (I will use the subscript β when abatement levels are conditional on β). Note that all non-signatories abate with their individually optimal level $q_\beta^1 = \beta/c$.

Cooperation is sustained by the threat to punish deviations from $\mathbf{a}^s$. If country i deviates from $\mathbf{a}^s$, it is punished by a subset of signatories $P_i(n) \subset M$ that will lower their abatement

[19] The discount factor, δ, is equal to $\delta = e^{-r\Delta}$, where r is the rate of time discounting and Δ is the period length (or detection lag). The discount *rate* is equal to $1 - \delta$.

to $q_\beta^p = p\beta/c,\ p \geq 0$, in the period after the deviation and then return their abatement to q_β^s in the following period. The purpose of the punishment, of course, is to harm the defecting country; however, note that since abatement is a public good, all countries are harmed during a punishment phase.[20] Denote the number of countries in $P_i(n)$ by k so that $k = |P_i(n)|$. The remaining signatories (including country i) continue to abate at level q_β^s during the punishment. Since country i's punishment will be to immediately raise its abatement back up to the cooperative level q^s as a penance for its defection, country i is not a member of the punishing group $P_i(n)$. All non-signatories continue to abate at their individually optimal level, q_β^1. Thus, let the punishment path for signatory $i \in M$ be $\mathbf{p}_i^s$, where

$$\mathbf{p}_i^s = (\underbrace{q_\beta^p, ..., q_\beta^p}_{j\in P_i}, \underbrace{q_\beta^s, ..., q_\beta^s}_{j\in M\backslash P_i}, \underbrace{q_\beta^1, ..., q_\beta^1}_{j\in N\backslash M}), (\underbrace{q_\beta^s, ..., q_\beta^s}_{j\in M}, \underbrace{q_\beta^1, ..., q_\beta^1}_{j\in N\backslash M}), (\underbrace{q_\beta^s, ..., q_\beta^s}_{j\in M}, \underbrace{q_\beta^1, ..., q_\beta^1}_{j\in N\backslash M}), ...$$

If the defecting signatory i deviates from $\mathbf{p}_i^s$, then $\mathbf{p}_i^s$ is simply restarted. If a different signatory j deviates from $\mathbf{p}_i^s$, then punishment path $\mathbf{p}_j^s$ is started. If a non-signatory deviates from either the IEA path, $\mathbf{a}^s$, or a punishment path, $\mathbf{p}_i^s$, it can be ignored and does not need to be punished, which implies that the punishment path of a non-signatory is just $\mathbf{a}^s$. Thus, the simple strategy profile of interest consists of the following $(n+1)$ paths:

$$(\underbrace{\mathbf{a}^s}_{IEA}, \underbrace{\mathbf{p}_{i_1}^s, ..., \mathbf{p}_{i_m}^s}_{j\in M}, \underbrace{\mathbf{a}^s, ..., \mathbf{a}^s}_{j\in N\backslash M}) \tag{5}$$

The strategy profile is a subgame-perfect equilibrium in expectation if for every subgame (that is, for every repeated game following every possible history of play) and given the strategies of all other players, no single player can gain by deviating from its strategy. For the simple strategy profile in (5), subgame-perfection requires that no country can make a beneficial deviation (in terms of getting a higher discounted expected payoff) from its strategy,

[20] For the same reason, one incentive that punishing countries have to actually follow through with a punishment is that doing so lowers their individual cost of abatement by more than they lose in aggregate benefits.

regardless of whether the country is on the cooperative path $\mathbf{a}^s$ or on a punishment path $\mathbf{p}_i^s$. A subgame-perfect equilibrium is weakly renegotiation-proof if for a given history of play there do not exist two continuation equilibrium payoffs where one strictly Pareto-dominates the other (Farrell and Maskin 1989). In the context of this model, the simple strategy profile in (5) is weakly-renegotiation proof if it is subgame-perfect and *all* countries (signatories and non-signatories) do not strictly prefer to ignore a deviation and revert back to the cooperative path $\mathbf{a}^s$. In other words, following a deviation from signatory i at least *one* signatory must gain from implementing punishment path $\mathbf{p}_i^s$, rather than reverting to $\mathbf{a}^s$.

4 Results

4.1 Subgame-Perfection and Weak Renegotiation-Proofness

The first result summarizes the necessary and sufficient conditions such that under uncertainty the simple strategy profile detailed above is a weakly renegotiation-proof equilibrium in expectation.[21] To explain the theorem and provide intuition, I compare the outcome under uncertainty to the no uncertainty case, which yields a proposition on the net effects of uncertainty. The main result of this section, which is a condition for the existence of a Pareto-optimal IEA as a weakly renogotiation-proof equilibrium, follows as an application of the theorem. Finally, I compare the condition needed for the Pareto-optimal IEA under uncertainty to the no uncertainty case.

[21] Proofs of Theorem 1 and Proposition 1 can be found in the Appendix.

Theorem 1 *Suppose that countries are uncertain over β, may resolve their uncertainty at the beginning of each period with probability $\gamma \in (0,1)$, and have expected payoffs (2), (3), and (4). Then the simple strategy profile in (5) is a weakly renegotiation-proof equilibrium in expectation if and only if $s > p$ and*

$$\frac{\max\left\{(s-1)^2,(p-1)^2\right\} A(t)}{2\delta(s-p)A(t+1)} \leq k \leq \frac{1}{2}(s+p), \text{ where} \tag{6}$$
$$A(t) = [1-(1-\gamma)^{t+1}]E[\beta^2] + (1-\gamma)^{t+1}\bar{\beta}^2.$$

By showing that the strategy is subgame-perfect, a lower bound on k is derived to ensure that there is at least a certain number of punishing countries so that the punishment deters defections in expectation (the left inequality). Then, by showing that the strategy is a WRP equilibrium, an upper bound on k is derived because the punishment cannot be too strong (the right inequality). Thus, the implication of Theorem 1 and the bounds on k is that in expectation the punishment must be strong enough to deter cheating, but not so strong that signatories would rather just ignore their punishment duties - at least one signatory must gain by following the punishment. Finally, note that the conditions in Theorem 1 do not depend on m, the number of signatories, or n, the number of countries, but k must satisfy $k < m \leq n$.[22]

Before further explaining the theorem and the effects of uncertainty, I first provide the analogous result for the case of no uncertainty.[23]

Corollary 1 *Assume that there is no uncertainty; i.e. $\gamma = 1$. Then the simple strategy profile determined by (5) with $s > 1$ and $p \geq 0$ is a weakly renegotiation-proof equilibrium for $\delta \in (0,1)$ if and only if k, s, and p satisfy $s > p$ and*

$$\frac{1}{2\delta}\frac{\max\left\{(s-1)^2,(p-1)^2\right\}}{(s-p)} \leq k \leq \frac{1}{2}(s+p). \tag{7}$$

[22] Technically, k must be an integer to satisfy Theorem 1.
[23] This corollary corresponds to Theorem 1 of Asheim and Holtsmark (2009).

I will first explain the conditions for subgame-perfection, which are the left inequalities in (6) and (7), highlight their differences, and provide intuition. Following Abreu (1988), the strategy is subgame-perfect in expectation if no country can benefit from a one-period deviation in either cooperative subgames or punishment subgames. In the Appendix it is shown that for a cooperative subgame, in which all countries were on path $\mathbf{a}^s$ in the previous period (period $t-1$), signatory i cannot gain in expectation from deviating from $\mathbf{a}^s$ provided that

$$\delta k(s-p)A(t+1) \geq \frac{1}{2}(s-1)^2 A(t) \tag{8}$$

where

$$A(t) = [1-(1-\gamma)^{t+1}]E[\beta^2] + (1-\gamma)^{t+1}\bar{\beta}^2.$$[24]

The right side of inequality (8) represents the expected gain from a deviation in period t, and the left side of the inequality represents the discounted expected loss from being punished in period $t+1$. Notice that if there is no uncertainty (i.e. $\gamma = 1$), then $A(t)$ and $A(t+1)$ cancel, which essentially leaves the left-side inequality of (7). Thus, $A(t)$ is the portion of the expected payoffs arising from the uncertainty over β in period t, given the expected knowledge of β in period t. Notice that the only difference between (6) with (7) is that the condition for subgame-perfection in the uncertainty case contains $A(t)/A(t+1)$ in the left side inequality. Finally, it will be important in what follows to note that all expected payoffs are are strictly convex in either $\bar{\beta}$ or in realizations of β, when evaluated at the appropriate abatement levels.[25] Thus, the expected gain from deviation and the expected loss from punishment are also strictly convex in either $\bar{\beta}$ or in realizations of β, which can be seen by the presence of β^2 and $\bar{\beta}^2$ in $A(t)$.

Since uncertainty affects both the expected gain from deviation and the expected loss from punishment, the *net* effect needs to be determined. That is, does uncertainty lead to a harsher net expected punishment (which better deters cheaters) or a higher net gain from defection

[25] See footnote 8 and the definitions of q^s and q^p. This fact is also detailed in the Appendix.

(which favors cheating)? The answer can be found by taking the difference between $A(t+1)$ and $A(t)$, which leads to the following proposition.

Proposition 1 *Suppose that countries are uncertain over β, may resolve their uncertainty at the beginning of each period with probability $\gamma \in (0,1)$, and have expected payoffs (2), (3), and (4). Then the simple strategy profile in (5) yields an increase equal to $\gamma(1-\gamma)^{t+1}Var[\beta]$ in the net expected loss from punishment, when compared to the no uncertainty case ($\gamma = 1$).*

The result is that uncertainty increases the net expected loss from punishment, which implies that cheating is better deterred under uncertainty than with no uncertainty. The proof shows that $A(t+1) = A(t) + \gamma(1-\gamma)^{t+1}Var[\beta]$, which implies that $A(t)/A(t+1) < 1$. Thus, the k needed to satisfy subgame-perfection may be smaller under uncertainty than with no uncertainty (compare (6) with (7)).[26] In other words, if the expected loss from punishment is now larger compared to the expected gain from deviation, then fewer countries may be needed to impose the punishment, all else equal.[27]

So, why does uncertainty lead to a larger net expected loss from punishment relative to the no uncertainty case? The key observation is that since a punishment occurs in the period following a defection, countries have an opportunity to learn the true value of β *after* a defection and to potentially use that information to punish a cheater more harshly than would otherwise be possible. To see this, consider the following example that assumes a discrete, two-valued distribution:

$$\beta = \left\{ \begin{array}{l} b_H \text{ with probability } \theta \\ b_L \text{ with probability } (1-\theta) \end{array} \right\}, \tag{9}$$

where $0 < b_L < b_H$ and $\bar{\beta} = \theta b_H + (1-\theta) b_L$.

[26] Note that $A(t)/A(t+1) \to 1$ as $t \to \infty$. So although the lower bound on k is smaller under uncertainty than in the no uncertainty case, it converges to the no uncertainty case as $t \to \infty$.

[27] Note that p, the parameter that determines the level of abatement by punishing countries during a punishment phase, need not change.

Assume that at the beginning of some period t, countries do not learn the true value of β, which means that countries take their marginal abatement benefit to be equal to $\bar{\beta}$. Now, suppose that a country defects from cooperation by abating at level $q^1 = \bar{\beta}/c$. Before the punishment is carried out in period $t+1$, however, countries may realize a value of β with probability γ or remain uncertain. If no learning occurs, then abatement levels during the punishment are $q^s = s\bar{\beta}/c$ for the group of non-punishing countries (which includes the cheater since his punishment is to return to the cooperative level of abatement) and $q^p = p\bar{\beta}/c$ for the group of punishing countries k. In this case, there is no overall effect on subgame-perfection, which simply results in the left-side inequality of (7).

However, suppose that countries do resolve their uncertainty and realize either b_L or b_H at the beginning of period $t+1$. If b_L is learned, then this works in favor of the cheating country. Despite the countries in k punishing at a lower level of abatement, $q^p = pb_L/c$, which lowers the cheater's payoff by more than if uncertainty were to persist (as in the previous paragraph), the cheater's new cooperative level of abatement (as well as that of the rest of the non-punishing countries) is $q^s = sb_L/c$, which is not as high, nor as costly, as the abatement level when the initial deviation occurred. However, the overall effect, all else equal, is that learning $\beta = b_L$ following a defection causes the loss from punishment to be smaller than it would be if nothing had been learned at all, which essentially *under*-punishes a cheating country. In this case, a higher number of punishing countries k would be required to ensure subgame-perfection.

On the other hand, suppose that $\beta = b_H$ is learned at the beginning of period $t+1$ following a defection. Then, the opposite happens: following a defection, the cheater returns to cooperation at a higher, more costly, level of abatement $q^s = sb_H/c$, and the punishing countries in k also abate at a higher level $q^p = pb_H/c$. The overall effect here is that the loss from punishment is larger than in either of the two cases previously described, which *over*-punishes a defecting country and may allow for a fewer number of countries to enact the punishment and still satisfy subgame-perfection.

Combining these three cases and showing that the strategy is subgame-perfect in expectation yields the result that the expected net loss from punishment is higher under uncertainty than with no certainty. Intuitively, countries over-punish deviations in expectation to counteract learning outcomes that would be favorable for the cheater (e.g. learning that $\beta = b_L$). Driving this result is the observation that all expected payoffs are are strictly convex in either $\bar{\beta}$ or in realizations of β, which implies that the expected gain from deviation and the expected loss from punishment are also strictly convex in either $\bar{\beta}$ or in realizations of β.[28] Thus, convexity of expected payoffs (and an application of Jensen's inequality) ensures that the expected payoff when learning may occur (which is associated with $E[\beta^2]$ terms) is greater than the expected payoff when countries remain uncertain (which is associated with $\bar{\beta}^2$ terms) and that the over-punishment associated with possibly learning $\beta = b_H$ outweighs the under-punishment associated with possibly learning $\beta = b_L$ which leads to, in expectation, a net loss from punishment that is larger under uncertainty than with no uncertainty. The final implication is that the k needed to satisfy subgame-perfection may be smaller under uncertainty than with no uncertainty due to the stronger expected punishment (again, compare (6) with (7)).

Returning to the result in Proposition 1, which states that the net expected loss from punishment under uncertainty is greater than that with no uncertainty by $\gamma(1-\gamma)^{t+1}Var[\beta]$, this is the probability of learning the true value of β in period $t+1$, which is when punishment occurs for a deviation in period t, multiplied by the difference between expected payoffs when β is learned and when countries remain uncertain, $Var[\beta]$. Thus, more uncertainty (in the form of a higher $Var[\beta]$) leads to even larger net expected losses from punishment. The next section of the paper further analyzes this relationship.

In proving that the strategy is a weakly renogotiation-proof equilibrium in expectation, the upper bound on k is derived (the right inequality of (6)). Despite the presence of uncertainty,

[28] As is noted above and in the Appendix.

the condition for weak renogotation-proofness is unchanged from the no uncertainty case (see (7)). The reason is that there is no comparison in payoffs between time periods; thus, any effects of uncertainty and learning are nullified in expectation. More generally, the requirements of WRP are independent of history and time – one only needs to compare the single-period, expected payoff of cooperation to the single-period, expected payoff of punishment, regardless of history.

One can now show that the strategy in (5) can support a weakly renegotiation-proof, Pareto-optimal IEA in expectation, in which all countries participate and abate $q^n = nb/c$, for high enough discount factors $\delta < 1$. That discount factors are "high enough" to support cooperation is simply another way of stating that subgame-perfection is satisfied, all else equal, as long as countries place enough value on the expected loss from punishment relative to the expected gain from deviation (since higher values of δ imply that countries value future payoffs more).

Proposition 2 *Suppose that countries are uncertain over β, may resolve their uncertainty at the beginning of each period with probability $\gamma \in (0,1)$, and have expected payoffs (2), (3), and (4). Then a Pareto-optimal IEA exists in expectation as a weakly renogotiation-proof equilibrium of the simple strategy profile in (5) for discount factors, δ, that satisfy*

$$\delta \in \left[\frac{(n-1)A(t)}{nA(t+1)}, 1\right).$$

Proof. To show this result, first let the number of punishing countries, k, be equal to $\frac{n}{2}$ if n is even and $\frac{(n+1)}{2}$ if n is odd.[29] This choice for k is made for two reasons: it is high enough to sufficiently punish deviations (subgame-perfection), and it is just low enough so that punishing countries are not harmed too much during punishment (weak renegotiation-proofness, which

[29]This proof is essentially the same as the discussion on p. 524 of Asheim and Holtsmark (2009).

is exactly satisfied by the choice of k). Next, set $s = n$ and $p = 1$ and apply (6) to get

$$\frac{1}{2\delta}\frac{(n-1)A(t)}{A(t+1)} \leq k \leq \frac{1}{2}(n+1).$$

There are two cases to consider: either n is even or n is odd. Note that in both cases, the right inequality is satisfied. If n is even, then the left inequality is satisfied if $\delta \geq (n-1)A(t)/nA(t+1)$, and if n is odd, then the left inequality is satisfied if $\delta \geq (n-1)A(t)/(n+1)A(t+1)$. The former condition suffices, which yields the result.[30] ■

Before explaining the proposition and the effects of uncertainty, I first provide the analogous result for the case of no uncertainty.[31]

Corollary 2 *Assume that there is no uncertainty; i.e. $\gamma = 1$. Then a Pareto-optimal IEA exists as a weakly renogotiation-proof equilibrium of the simple strategy profile in (5) for discount factors, δ, that satisfy*

$$\delta \in \left[\frac{(n-1)}{n}, 1\right).$$

I will first discuss the no uncertainty case in the corollary, and then describe how uncertainty affects the results. The implication of the result in the corollary is that the Pareto-optimal IEA will be sustained more easily for either a small amount of countries or very high discount factors, where high discount factors may be due to either low time discounting or short period length. For higher amounts of countries, more and more patience is required (or countries must value the future at higher levels) in order to implement the Pareto-optimal IEA.

Proposition 2, however, shows that under uncertainty the Pareto-optimal IEA can be achieved for a larger range of discount factors than with no uncertainty since $A(t)/A(t+1) < 1$. In this case, countries do not need to value the future as highly (or be as patient) as in the no uncertainty case to achieve full cooperation. The intuition follows from the discussion of Theorem 1. Uncertainty leads to a greater expected net loss from punishment relative to the

[30] The choice of k also satisfies k being an integer. See footnote 22.

[31] This Corollary corresponds to Proposition 1 of Asheim and Holtsmark (2009).

no uncertainty case. All else equal (including keeping k constant), this implies that deviations from the IEA are better deterred under uncertainty, and thus, the discount factor may be smaller and still satisfy subgame-perfection. The Pareto-optimal IEA is easier to sustain under uncertainty, particularly if a large number of countries would otherwise require a higher discount factor for cooperation. Put another way, if a long period length or a high rate of time discounting contibute to a low discount factor, then with no uncertainty the Pareto-optimal IEA may be impossible to implement if there is also a relatively large amount of countries; however, if there is uncertainty, then may be more slack in the subgame-perfection constraint, and sustaining the Pareto-optimal IEA becomes more likely.[32]

4.2 Statics

Although climate change R&D is not modeled explicitly in this paper, knowledge gained through R&D affects the uncertainties in this problem; however, it may either help resolve uncertainties or it may just introduce new challenges and uncertainties. For example, new results from climate change R&D may allow scientists to narrow the range of possible outcomes, perhaps in terms of temperature increases, climate sensitivity, adaptation costs, or economic impacts in general. Conversely, scientists may find out that they just did not know as much as they had previously thought, as may be the case if research leads to more possible outcomes than were previously throught. In other words, R&D may lead to more questions than answers. In this model, countries only benefit from generic emissions abatement, so the myriad benefits of reducing emissions and avoiding emissions damages are simply included in the marginal benefit term.

This section explains how the results of the previous section are affected by changes in uncertainty; in particular, the focus is on changes in γ and in $E[\beta^2]$. In this paper, uncertainty is over the marginal benefit of abatement parameter, β, and its true value may be learned at

[32]Recall that $A/(A+\gamma Var[\beta]) \to 1$ as $t \to \infty$. So although the lower bound on δ is smaller under uncertainty than in the no uncertainty case, it converges to the no uncertainty case as $t \to \infty$.

the beginning of each period with probability γ. All else equal, countries are *less* uncertain in this model when the probability of resolving uncertainty over β at the beginning of each period is large (a higher γ explicitly, but may also be interpreted as there being fewer elements in the sample space of β) or countries are relatively late in the repeated game (high t). Also of interest is $Var[\beta]$; researchers may discover that the range of possible realizations of β is narrower or wider than previously thought. Here, a change in $E[\beta^2]$ is meant to substitute for a change in $Var[\beta]$; this could occur, for example, if the tail of the probability density function of β thickens while leaving $\bar{\beta}$ unchanged. I assume that R&D causes an increase in γ if new results allow scientists to eliminate elements of the sample space of β (or to assign zero probabilities to certain elements of the sample space of β). I also assume that R&D causes an increase in $E[\beta^2]$ if scientists learn that the range of outcomes of β is greater than previously thought.[33]

Let the lower bound on the number of punishing countries k be denoted by $\hat{k}$ so that

$$\hat{k} = \frac{\max\left\{(s-1)^2, (p-1)^2\right\}}{2\delta(s-p)} \frac{A(t)}{A(t+1)},$$

and let the lower bound on the discount factor δ needed to sustain the Pareto-optimal IEA be denoted by $\hat{\delta}$ so that

$$\hat{\delta} = \frac{(n-1)}{n} \frac{A(t)}{A(t+1)},$$

where $A(t+1) = A(t) + \gamma(1-\gamma)^{t+1} Var[\beta]$. The following Proposition summarizes the comparative statics results on $\hat{k}$ and $\hat{\delta}$ (proofs can be found in the Appendix).

Proposition 3 *(i) For a change in* γ*: If* $\gamma(t+2)E[\beta^2] > A(t+1)$*, then* $\frac{\partial \hat{k}}{\partial \gamma} > 0$ *and* $\frac{\partial \hat{\delta}}{\partial \gamma} > 0$*; otherwise,* $\frac{\partial \hat{k}}{\partial \gamma} \leq 0$ *and* $\frac{\partial \hat{\delta}}{\partial \gamma} \leq 0$.
(ii) For a change in $E[\beta^2]$*: both* $\frac{\partial \hat{k}}{\partial E[\beta^2]} < 0$ *and* $\frac{\partial \hat{\delta}}{\partial E[\beta^2]} < 0$.

[33]More precisely, the assumption is that R&D may cause a mean-preserving spread (or contraction) of β, so that only a change in $E[\beta^2]$ occurs and affects $Var[\beta]$ while $\bar{\beta}^2$ remains unchanged.

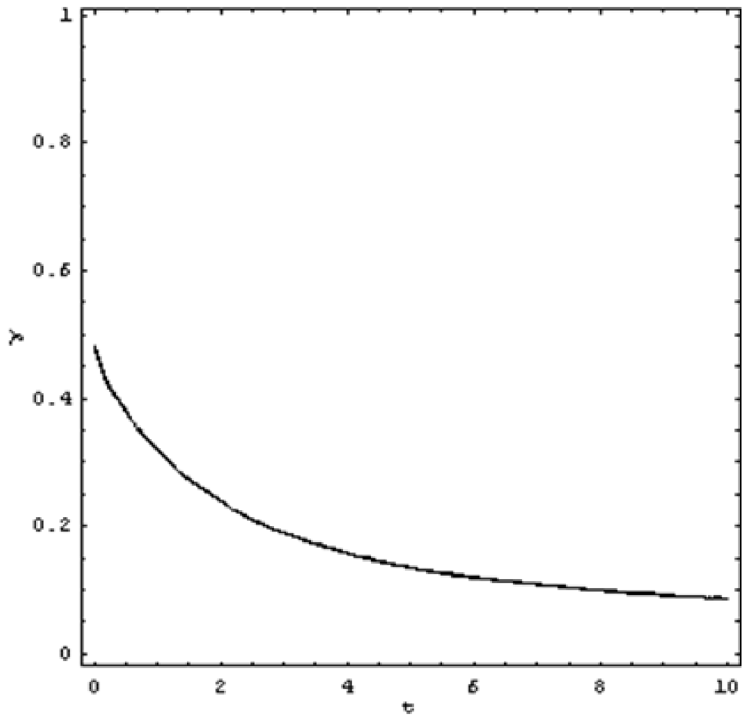
The first part of the proposition says that provided that a certain parameter restriction is met, then an increase in the probability of learning the true value of β in period t causes both $\hat{k}$ and $\hat{\delta}$ to increase.[34] The implication is that reducing uncertainty tends to make cooperation more difficult to sustain because a smaller range of discount factors will be permitted in a WRP equilibrium. The second part of the proposition says that a decrease in $E[\beta^2]$ leads to an increase in both $\hat{k}$ and $\hat{\delta}$. Again, the implication is that reducing uncertainty (in the form of narrowing the range of possible outocomes of β) makes cooperation more difficult to sustain.

Before discussing the meaning of the parameter restrictions, I will first provide the intuition for part (i) of the proposition. To begin, note that both $\hat{k}$ and $\hat{\delta}$ are affected by a change in γ in the same two ways, but that the two effects may go in opposite directions. First, an increase in γ speeds up the rate at which uncertainty is resolved as t increases (this effect is captured in $A(t)$ in both $\hat{k}$ and $\hat{\delta}$). The effect of this is to increase both $\hat{k}$ and $\hat{\delta}$ because reducing uncertainty through this route reduces the relative strength of the expected punishments over the expected gains from defection. However, the second effect of an increase in γ directly affects the expected loss from punishment through the term $\gamma(1-\gamma)^{t+1}Var[\beta]$, which increases or decreases both $\hat{k}$ and $\hat{\delta}$ depending on parameter values (recall that an increase in $\gamma(1-\gamma)^{t+1}Var[\beta]$ increases the expected net loss from punishment). As this paper discusses in the next paragraph, for *most* parameter values the first effect dominates the second effect, which implies that an increase in γ leads to an increase in both $\hat{k}$ and $\hat{\delta}$. To more precisely determine the overall effect on $\hat{k}$ and $\hat{\delta}$, we must inspect the relationship between some of the parameters.

In the Appendix, it is shown that the sign of $\left(\gamma(t+2)E[\beta^2] - A(t+1)\right)$ is the key to determining the signs in part (i) of the proposition. In particular, we will examine the relationship between γ and t and make use of Figures 2 and 3 to show that for *most* parameter values we have $\partial\hat{k}/\partial\gamma > 0$ and $\partial\hat{\delta}/\partial\gamma > 0$. In both figures, the curve shows the values of

[34]This parameter restriction is met for *most* parameter values and is discussed further in this section.

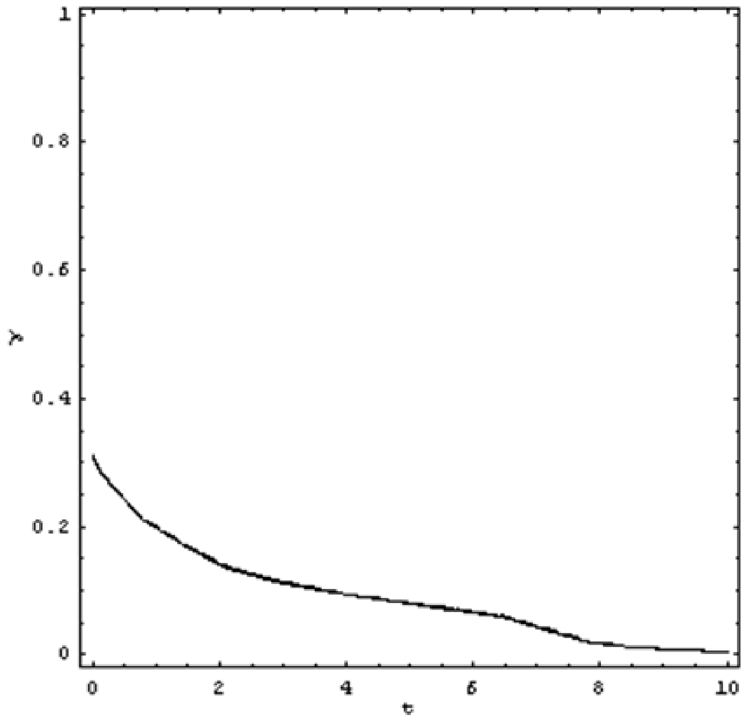
Figure 2: $Var[\beta] = 0.1$



γ and t that result in $\left(\gamma\,(t+2)E[\beta^2] - A(t+1)\right) = 0$, while the upper and lower regions correspond to the values of γ and t that result in $\left(\gamma\,(t+2)E[\beta^2] - A(t+1)\right)$ being positive and negative, respectively. In Figure 2, $Var[\beta] = 0.1$, and in Figure 3 $Var[\beta] = 2$ (by increasing $E[\beta^2]$ only). In both examples, the upper region is much larger than the lower region, which implies that for *most* values of γ and t the first effect mentioned in the previous paragraph dominates the second effect, and we have $\partial\hat{k}/\partial\gamma > 0$ and $\partial\hat{\delta}/\partial\gamma > 0$ (provided that $Var[\beta] > 0$). Thus, in the upper region an increase in γ leads to an increase in both $\hat{k}$ and $\hat{\delta}$. In other words, for *most* values of γ and t, reducing uncertainty makes cooperation more difficult to sustain. As a final emphasis, the importance is not in the substance or meaning of the parameter restriction; rather, the key observation is simply that the restriction is satisfied for most of the parameter space.

A few final notes about part (i) of the proposition. In the lower region of the figures,

Figure 3: $Var[\beta] = 0.2$



we have $\partial\hat{k}/\partial\gamma \leq 0$ and $\partial\hat{\delta}/\partial\gamma \leq 0$. The reason for this is that of the two effects of an increase in γ, the effect of increasing the expected loss from punishment by increasing the term $\gamma(1-\gamma)^{t+1}Var[\beta]$ becomes the dominant effect, which decreases both $\hat{k}$ and $\hat{\delta}$ and makes cooperation easier to sustain. Also, the lower region becomes more relevant if the length of each period is relatively long. Since countries are more likely to be in the upper region of the parameter space the longer the game continues, if the length of each period is relatively long, then lower values of t are more relevant.

The intuition for the second part of the proposition is much more straightforward. To explain why an increase in $E[\beta^2]$ causes a decrease in $\hat{k}$, it helps to consider the explanation following Theorem 1. A higher value of $E[\beta^2]$, which increases $Var[\beta]$, increases the discounted, expected loss from punishment relative to the expected gain from deviation. This implies that perhaps even fewer countries would be needed to punish a deviation and still satisfy subgame-perfection. Similarly, an increase in $E[\beta^2]$ causes a decrease in $\hat{\delta}$. Since a higher value of $E[\beta^2]$ (or a mean-preserving increase in $Var[\beta]$) increases the discounted, expected net loss from punishment, deviations are better deterred. This implies that the Pareto-optimal IEA may be sustained for an even larger range of discount factors.

Whether or not R&D is beneficial for sustaining a Pareto-optimal agreement depends on what is being learned and to a lesser extent on parameter values. The overall message of Proposition 3 is that achieving the Pareto-optimal IEA tends to be more difficult if R&D reduces uncertainty. The first part of the proposition implies that for most parameter values an increase in the probability of learning the true value of the marginal benefit of abatement is detrimental to sustaining cooperation. The second part of the proposition says that a decrease in the variance of the marginal benefit of abatement also makes cooperation more difficult. In both cases, the discounted, expected net loss from punishment is diminished, which implies that deviations are more difficult to deter and that the range of discount factors that will support a Pareto-optimal IEA decreases. One practical concern is that it is likely that a decrease in $Var[\beta]$ (or a decrease in $E[\beta^2]$) would be viewed positively in the scientific community since a narrower range of marginal abatement benefits may imply a narrower range of economic outcomes. In the context of this model, though, the Pareto-optimal IEA would become more difficult to sustain due to weaker expected punishments, which implies that a higher discount factor would be required.

5 Conclusion

This paper analyzes the effects of learning and R&D on an IEA by assuming that countries are uncertain regarding the benefits of pollution abatement. I introduce uncertainty by assuming that countries are uncertain about the value of the marginal benefit of abatement and may resolve their uncertainty by learning its true value at the beginning of each period. This paper then shows how the simple strategy profile proposed by Asheim and Holtsmark (2009) extends to the case with uncertainty, and I show that uncertainty allows the Pareto-optimal IEA to exist as a WRP equilibrium for a wider range of discount factors than in the baseline case. The main driver of this result is that uncertainty leads to a greater expected net loss from punishment relative to the no uncertainty case, which implies that defections from the IEA are better deterred. The upshot is that if a long period length or a high rate of time discounting contibute to a low discount factor, then with no uncertainty the Pareto-optimal IEA may be impossible to implement if there is also a relatively large amount of countries; however, if there is uncertainty, then sustaining the Pareto-optimal IEA becomes more likely.

Finally, by using comparative statics this paper analyzes whether or not new knowledge gained through R&D is beneficial for sustaining cooperation and finds that it depends on what is learned (and on parameter values, to a lesser extent). In general, this paper finds that achieving the Pareto-optimal IEA tends to be less likely if R&D reduces uncertainty. Specifically, if R&D results in either an increase in the probability of learning the true value of the marginal benefit of abatement (for *most* parameter values) or in a lower variance of the marginal benefit of abatement, then it becomes more difficult to sustain full cooperation. In both cases, the discounted, expected net loss from punishment is diminished, which implies deviations are not as easily deterred and that the range of discount factors that will support a Pareto-optimal IEA decreases.

In discussing the contributions of this paper with respect to the other papers that analyze IEAs with uncertainty, recall that repeated games tend to emphasize full cooperation and the punishments needed to enforce cooperation rather than focusing on the strategic interaction between countries, which determines the number of countries that cooperate and the subsequent expected abatement levels and payoffs. However, in focusing on full participation and Pareto-optimality, this paper removes the countries' incentives to use information strategically against each other, which has been shown to result in negative outcomes for one-shot games (Kolstad 2007, Kolstad and Ulph 2008, and Finus and Pintassilgo 2012). Although this paper is a model of infinitely repeated interaction and focuses on a different aspect of cooperation, the results generally agree with those of Kolstad (2007) and Kolstad and Ulph (2008), which is that uncertainty tends to be beneficial for cooperation and that resolving uncertainty tends to be detrimental to cooperation.

Chapter 4

Renegotiation-Proof International Environmental Agreements with Social Preferences

1 Introduction

Global environmental problems, such as the accumulation of carbon and greenhouse gases in the atmosphere, typically require a cooperative solution to overcome an individual country's incentive to free-ride on the pollution-reducing activities of other countries. The economics literature on international environmental agreements (IEA), the term given to the cooperative solution, is generally pessimistic: cooperation will be hard to come by when the gains from cooperation are high (Barrett 2003). One concern shared by many countries seeking a cooperative environmental solution is that the terms of the agreement should be fair or equitable. For example, developing countries would prefer that developed countries take on more of the burden of lowering pollution (and incurring more abatement costs) because developed countries are largely responsible for the current stock of greenhouse gases. To the extent that developed countries agree that they should take on more of this burden, they are displaying a preference towards the well-being of other countries.[1,2] When countries interact in a repeated setting,

[1]Non-Annex I countries that ratified the Kyoto Protocol, which includes China and India, were not required to reduce pollution at all; pollution reductions were only required of developed (Annex I) countries.

[2]Lange *et al.* (2007) provides evidence that international climate policy negotiators (but not necessarily countries' governing bodies) also have preferences towards equity.

which is the focus of this paper, countries' preferences towards each other or for equity may change the incentives to cheat on an agreement or to follow through with a punishment, which may affect the ability for countries to sustain cooperation.

The global environmental problem is, in the most general sense, a problem of providing a pure public good, and research on this topic has increasingly moved in the direction of conducting experiments and obtaining evidence of individuals acting in ways that normal utility theory does not predict, particularly when players provide more than the non-cooperative amount of a public good predicted by Nash equilibrium (Chaudhuri 2011 is a recent review). One way of explaining this behavior is by assuming that individuals have social preferences. That is, in addition to caring about one's own utility, one also has concern for others, which may be represented by inequity-aversion (Fehr and Schmidt 1999) or by a preference for equity and efficiency (Charness and Rabin 2002), just to name two prominent examples. In a public goods problem, social preferences can be used to show why individuals provide more of the good or are more likely to cooperate, as they tend to do in experiments, when compared to standard utility theory. The purpose of this paper is to contribute to the understanding of how social preferences affect cooperation in a repeated setting by providing theoretical results on the underlying mechanisms for sustaining cooperation.[3]

The main research question is: if countries are assumed to have social preferences, is it easier or more difficult to sustain cooperation in an infinitely repeated IEA than under standard, material preferences?[4] To answer this question, this paper examines how social preferences affect the number of punishing countries, the discounted loss from punishment, and the gain from defection. This analysis is necessary because social preferences change the incentives towards defecting and punishment. For example, if countries care strongly about each other,

[3]Kolstad (2012), Kosfeld *et al.* (2009), and Lange (2006) have analyzed the effects of social preferences on the formation of coalitions in a one-shot setting.

[4]The *difficulty* or *likelihood* of sustaining cooperation refers to the range of discount factors $\delta \in [\hat{\delta}, 1)$ ($\hat{\delta}$ is often called the *critical* discount factor), and a wider range of discount factors (a lower value of $\hat{\delta}$) is associated with countries being able to sustain cooperation with more ease (or higher likelihood).

then they may be reluctant to punish a cheater too harshly because doing so negatively affects themselves from a social point-of-view (in addition to any material losses). A better understanding of the mechanisms underlying these interactions is needed.

The model in this paper is an infinitely repeated game in which each country has a standard, material payoff that is linear in abatement levels (both the marginal benefit and marginal cost of pollution abatement are constant) and in which pollution abatement is assumed to be a pure public good. A linear payoff function is chosen in order to derive analytical solutions and for consistency with the the experimental public goods literature, which typically uses linear payoffs. Furthermore, I assume that countries have social preferences that include a preference for equity and efficiency, where equity refers to countries being concerned about the payoff of the least well-off country and efficiency refers to the sum of all countries' payoffs. Thus, the total payoff of each country is assumed to be a weighted sum of its material and social preferences payoff functions.

For the repeated game, cooperation is shown to be a weakly renegotiation-proof (WRP) equilibrium for the given strategy, in which defections from cooperation are punished for one period by a group of other countries in the IEA. Farrell and Maskin (1989) define a subgame-perfect equilibrium as being weakly renegotiation-proof if there does not exist a continuation equilibrium of that strategy that is strictly Pareto-dominated by another continuation equilibrium of that strategy.[5] In the context of this paper, the WRP equilibrium takes the credibility inherent in subgame-perfection and adds the requirement that a punishment cannot be so harmful as to cause countries to want to ignore it. Thus, the WRP equilibrium works well in an IEA model because some punishments may be too harmful to plausibly implement from a group perspective (despite subgame-perfection being satisfied). As I discuss in the next section, a number of recent IEA papers have made use of the WRP equilibrium.

The first main result is that social preferences may *allow* for there to be a smaller number

[5] A formal definition is given in Section 4.1.

of signatories that punish a defection because social preferences cause the net loss from punishment to increase, but that weak renegotiation-proofness may *force* the number of punishing countries to decrease to keep their payoffs from becoming too low. The net loss from punishment increases primarily because the lost total abatement benefits during a punishment phase have a particularly strong influence on payoffs through the efficiency term since all countries are harmed by a loss of abatement.[6] Overall, social preferences lower the number of countries needed to punish a defection, all else equal.

The second main result concerns the range of discount factors for which cooperation can be sustained. It is shown that social preferences increase this range of discount factors, which implies that cooperation is more likely under social preferences. Driving this result is the strong effect of social preferences causing an increase in the net loss from punishment, which better deters deviations from cooperation. This implies that subgame-perfection may be achieved for lower discount factors with social preferences than with only self-interested preferences. Thus, the overall message of the paper is that social preferences have a beneficial effect on sustaining cooperation.

2 Related Literature

Traditionally, IEAs have been studied using one-shot games, focusing on the number of countries that join and the total amount of abatement provided.[7] Beginning with Barrett (1994, 1999, 2002), however, IEAs have also been analyzed in a repeated game setting. These papers, which include Asheim *et al.* (2006), Froyn and Hovi (2008), Asheim and Holtsmark (2009), and Mohr (2014), have shown that an IEA can exist as a WRP equilibrium supporting full participation, and sometimes even the Pareto optimal outcome (which includes full participation and the socially optimal level of abatement).

[6]The strategy used to derive conditons for a WRP equilibrium involves a cheating country being punished by having to abate at an optimal level in the next period while other signatories lower their abatement for one period.

[7]See Barrett (2003) for an overview.

The purpose of using weak renegotiation-proofness in addition to subgame-perfection is that some strategies that are subgame-perfect involve implausibly harsh punishments from a group point-of-view. For example, if the strategy to support cooperation in the Prisoner's Dilemma was to revert to the Nash equilibrium at the first defection, then the group would surely prefer to ignore the defection and continue cooperating. Being stuck in the non-cooperative Nash equilibrium is not feasible if players can renegotiate back to cooperation. Asheim and Holtsmark (2009), Mohr (2014), and this paper use the WRP equilibrium to focus on the number of countries that punish a defection: once subgame-perfection has determined the minimum number of countries needed to effectively punish a defection, all else equal, the WRP equilibrium is used to derive a maximum number of punishing countries so that payoffs do not decrease too much during a punishment phase.

Although the following two papers are not repeated games, the works by Kolstad (2012) and Kosfeld *et al.* (2009) both involve coalition formation with agents that have social preferences.[8] Kolstad (2012) assumes that agents have a preference for equity and efficiency (Charness and Rabin 2002) in additional to their standard utility. One benefit of assuming this form of social preferences is that it increases the chance that cooperation will not even be needed due to a reduced free-rider incentive. He shows that when a cooperative solution is needed, however, social preferences cause the size of the coalition to decrease compared to the coalition with standard preferences. Kosfeld *et al.* (2009) analyze a similar problem, but by assuming that agents are inequity-averse (Fehr and Schmidt 1999). They find the opposite result of Kolstad (2012): that social preferences increase the size of the coalition, possibly up to full participation. In models with linear payoffs (as in both Kolstad 2012 and Kosfeld et al. 2009), the equilibrium size of the coalition is always increasing in the ratio of marginal abatement costs to marginal abatement benefits. The conflicting results obtained by these two papers are due to the assumed form of social preferences: in Kolstad (2012), preferences

[8] Lange (2006) also considers the effects of social preferences on IEA formation, but uses a model less similar to mine than those mentioned here.

towards equity and efficiency are benefit-oriented and cause a decrease in the marginal cost-benefit ratio (which decreases the coalition size); however, in Kosfeld et al (2009) preferences towards inequity aversion are cost-oriented and cause an increase in the marginal cost-benefit ratio (which increases the coalition size). This difference highlights a problem in choosing a form for social preferences to take and a potential weakness in models with linear payoffs and one-shot coalition formation. In my paper, I assume the same functional form as Kolstad (2012) and leave that of Fehr and Schmidt (1999) for future research.

Two papers that are similar in spirit to mine, despite having different intentions, are Malueg (1992) and Bernheim and Stark (1988). Malueg (1992) assumes a two-firm Cournot model where each firm owns part of the other firm, which implies that each firm gets part of the other firm's profit (cross-ownership). This is essentially parallel to assuming social preferences for individuals. He shows that when firms collude in an infinitely repeated setting and play a grim trigger strategy, then the discount factor needed to sustain cooperation (the monopoly output level) trades off with the level of cross-ownership. That is, for higher levels of cross-ownership (given a certain degree of convexity in the inverse demand function), two effects must be compared: as cross-ownership increases, a firm has less to gain from cheating, which makes cooperation easier; but punishments also become weaker (because the punishment would also lower its own profits), which makes cooperation more difficult. When the effect from the weak punishment outweighs the effect of the lower gain from cheating, cooperation becomes harder to sustain, and a higher discount factor is needed.

Bernheim and Stark (1988) find the same result in a study of the effects of altruism among family members. They find that cooperation becomes more difficult to sustain as agents become more altruistic. The intuition is exactly the same as in Malueg (1992): that the effect of a weaker punishment overcomes the effect of a lower incentive to cheat. The results of Malueg (1992) and Bernheim and Stark (1988) highlight why a deeper understanding of the effects of social preferences on sustaining cooperation is needed since social preferences may affect both the loss from punishment and the gain from defection.

Duffy and Muñoz-García (2012) is the closest paper to mine in both model and results, and to my knowledge is the only other paper than mine to study the effects of social preferences on cooperation in a repeated game. The authors show that when two players play an infinitely repeated Prisoner's Dilemma where payoffs are subject to inequality aversion (Fehr and Schmidt 1999), then cooperation may be easier to sustain. More specifically, assuming that players use a grim trigger strategy, the authors show that the discount factor needed for cooperation with Fehr-Schmidt preferences is lower than that needed for standard preferences. The reason is that when players are concerned about payoff inequality, there is less incentive for an individual to defect because a proportion of the gain from cheating is subtracted from the cheaters payoff. They also show that this discount factor trades off with a preference for fairness: for higher levels of concern about one's own payoff being higher than another's payoff, the discount factor needed to sustain cooperation decreases. The differences between Duffy and Muñoz-García (2012) and my paper are that I assume social preferences over equity and efficiency (rather than inequity aversion), I use a weakly renegotiation-proof strategy (rather than the grim trigger strategy), and I assume n players (rather than two).

3 Model

This section introduces an infinitely repeated IEA game in which a country's payoff includes both a standard, material term as well as other-regarding terms (social preferences). After discussing the basics of the model, I provide a strategy in which countries cooperate and abate pollution on the equilibrium path and countries are punished for deviations from the equilibrium path.

3.1 Payoffs and Assumptions

Let there be $n \geq 2$ identical countries, where $N = \{1, 2, ..., n\}$ is the set of all countries. In each period of the infinitely repeated game (in discrete time), each country i makes a discrete choice regarding its level of emissions abatement $q_i \in \{0, 1\}$: it either chooses to Abate and sets $q_i = 1$, or it chooses to Pollute and sets $q_i = 0$. Emissions abatement is assumed to be a pure public good since all countries share the same environment; therefore, each individual country receives the total benefit of pollution abatement by all countries. Each country i has the following stage-game *material* payoff each period:

$$\pi_i(q_i, Q_{-i}) = b(q_i + Q_{-i}) - cq_i, \tag{1}$$

where Q_{-i} is the total amount of abatement by all countries except country i, so that $Q = \sum_{j=1}^{N} q_j = q_i + Q_{-i}$ is the total amount of abatement. A linear payoff function has been chosen primarily for tractability so that analytical solutions can be derived and because nearly all of the experimental public goods literature uses linear payoffs. The parameter $b > 0$ denotes the marginal benefit of abatement, and $c > 0$ is the marginal cost of abatement. To better focus this paper on the need for cooperative solutions, I assume that $c > b$, which implies that each country's dominant strategy in the stage-game is to choose Pollute ($q_i = 0$ for all i) and that the Nash equilibrium is for all to choose Pollute. Thus, cooperation is needed in order for a positive amount of pollution abatement to be provided.

In addition to a country's material payoff, I also assume that each country receives a *social* payoff. Following Kolstad (2012), who adapts the social preferences model of Charness and Rabin (2002), I assume that each country's *total* payoff is a weighted sum of their material and social payoff functions. In particular, each country's social preferences are assumed to include both a preference for equity, in which each country shows concern for the least well-off country, and efficiency, which is represented as the sum of all material payoffs. Thus, each country i has the following stage-game *total* payoff each period:

$$\Pi_i(q_i, Q_{-i}) = \lambda_i \pi_i(q_i, Q_{-i}) + \gamma_i \min_{j \in N} \pi_j(q_j, Q_{-j}) + \varepsilon_i \sum_{j=1}^{n} \pi_j(q_j, Q_{-j}), \qquad (2)$$

$$\text{where } \lambda_i, \gamma_i, \varepsilon_i \geq 0 \text{ and } \lambda_i + \gamma_i + \varepsilon_i = 1.$$

Now, I derive conditions to ensure the following two assumptions: that the social optimum is achieved when all countries choose to abate ($q_i = 1$ for all i), and that, again, the dominant action for each country in the stage-game is to pollute.[9] When all countries abate pollution, the total payoff is

$$\begin{aligned} \Pi_i(1, (n-1)) &= \lambda_i(bn - c) + \gamma_i(bn - c) + \varepsilon_i n(bn - c) \\ &= (bn - c)(\lambda_i + \gamma_i + \varepsilon_i n), \end{aligned}$$

which implies that all countries abate pollution and achieve the social optimum if $bn > c$. However, I will assume the slightly more restrictive condition $b(n-1) > c$, which is fairly innocuous and will serve to sharpen a result later.[10]

To derive a condition for the latter assumption, first assume that some country $z \neq i$ has the smallest material payoff π_z. Then country i's total payoff is

$$\begin{aligned} \Pi_i(q_i, Q_{-i}) &= \lambda_i(bQ_{-i} + bq_i - cq_i) + \gamma_i(bQ_{-i} + bq_i - cq_z) + \varepsilon_i(bnQ_{-i} + bnq_i - cQ_{-i} - cq_i) \\ &= [b(\lambda_i + \gamma_i + \varepsilon_i n) - c\varepsilon_i]Q_{-i} - \gamma_i cq_z + [\lambda_i(b - c) + \gamma_i b + \varepsilon_i(bn - c)]q_i. \end{aligned}$$

[9]This payoff function is essentially the same as that used in Kolstad (2012): the payoff function in that paper is framed in terms of public good provision and utilizes a budget constraint; the payoff function in this paper is similar in spirit, but I use notation more aligned with the IEA literature. The conditions derived in this section can also be found in Kolstad (2012), only with different notation. One notable difference, however, is that Kolstad (2012) assumes that the equity term for country i only compares other countries $j \neq i$, rather than all countries $j \in N$. This slight difference has no effect on the results in this paper.

[10]The additional restriction $b(n-1) > c$ instead of $bn > c$ really only matters if c is on the same level as n, and n will typically be large (and b could be set low, say, equal to 1) . Kolstad (2012) also assumes $b(n-1) > c$.

If the coefficient on q_i is negative, then choosing Abate can only lower country i's total payoff, which implies that Pollute will be a dominant action in the stage-game. Therefore, each country will pollute if

$$\lambda_i(b-c)+\gamma_i b+\varepsilon_i(bn-c)<0,$$

which implies that

$$c>b\left[\frac{1+\varepsilon_i(n-1)}{1-\gamma_i}\right]>b.$$

Recall that with only a material payoff, Pollute was a dominant strategy if $c>b$. The implication of the new condition is that under social preferences the marginal cost of abatement, c, relative to the marginal benefit of abatement, b, must now be even greater than with only a material payoff in order for Pollute to be a dominant strategy.[11] Also, note that as social preferences get stronger (i.e. γ_i or ε_i increase), c must be even larger to induce Pollute as a dominant strategy. Thus, although this paper focuses on cooperative solutions, the upshot of including social preferences is that it increases the likelihood of countries choosing to abate without the need for any cooperation.

In summary, this paper assumes that country i has the payoff function in (2) and that

$$b(n-1)>c>b\left[\frac{1+\varepsilon_i(n-1)}{1-\gamma_i}\right], \tag{3}$$

which ensures that when all countries choose to abate the socially optimal outcome is achieved and that Pollute is the dominant strategy of the stage-game. Furthermore, since Pollute is a dominant action, in the repeated game introduced in the next section non-signatories of the IEA will always choose to pollute.

[11]If country i has the smallest material payoff instead of a different country $z\neq i$, the resulting condition is that c does not have to be as high as what has just been derived. However, the condition in the body of the paper suffices for both cases.

3.2 Simple Strategy Profile of the Repeated Game

This paper uses a simple strategy profile (Abreu 1988) that was analyzed in Asheim *et al.* (2006) and in a related paper by Froyn and Hovi (2008), which both build on the work of Barrett (1999, 2002). The strategy outlined in this section is a *penance* strategy in the sense that if a signatory of the IEA deviates from cooperation (the equilibrium path), then in the next period its punishment will be to return to cooperation while a subset of other signatories pollute (and, thus, harm the defecting country).[12]

More specifically, a simple strategy profile is an $(n+1)$-vector of abatement paths that contains the IEA and n punishment paths, one for each country. Let $M = \{i_i, ..., i_m\} \subseteq N$ be the signatories to the IEA and let the number of signatories be $m \leq n$. Let $\mathbf{a}^s$ denote the equilibrium path, in which countries cooperate in an IEA:

$$\mathbf{a}^s = (\underbrace{q^s, ..., q^s}_{j \in M}, \underbrace{q^1, ..., q^1}_{j \in N \setminus M}), (\underbrace{q^s, ..., q^s}_{j \in M}, \underbrace{q^1, ..., q^1}_{j \in N \setminus M}), ...,$$

where signatories choose to abate (and set $q^s = 1$) and non-signatories choose to pollute (denoted by $q^1 = 0$).

Signatories of the IEA comply with the agreement because deviations from path $\mathbf{a}^s$ will be punished. If country i deviates from the IEA, then a subset of signatories $P_i(n) \subset M$, where $k = |P_i(n)|$ is the number of punishing countries, will choose to pollute (denoted by $q^p = 0$) in the period after the deviation. Thus, if signatory i deviates, it will be harmed by a one-period drop in total abatement during its punishment, and then the punishing countries $P_i(n)$ switch back to abating in the following period. During country i's punishment, it must abate pollution, as do the other $(m-k-1)$ signatories. Non-signatories continue to choose

[12]The same strategy is used by Asheim and Holtsmark (2009) and Mohr (2014); however, both of these papers use strictly concave payoff functions with continuous abatement choices. The IEA papers mentioned in the body of this paper all use linear payoff functions.

to pollute. Thus, let the punishment path for signatory $i \in M$ be $\mathbf{p}_i^s$, where

$$\mathbf{p}_i^s = (\underbrace{q^p, ..., q^p}_{j \in P_i}, \underbrace{q^s, ..., q^s}_{j \in M \setminus P_i}, \underbrace{q^1, ..., q^1}_{j \in N \setminus M}), (\underbrace{q^s, ..., q^s}_{j \in M}, \underbrace{q^1, ..., q^1}_{j \in N \setminus M}), (\underbrace{q^s, ..., q^s}_{j \in M}, \underbrace{q^1, ..., q^1}_{j \in N \setminus M}), ...$$

If signatory i deviates from its punishment path (that is, if it deviates from $\mathbf{p}_i^s$), then $\mathbf{p}_i^s$ is simply restarted. If a different signatory j deviates from $\mathbf{p}_i^s$, then punishment path $\mathbf{p}_j^s$ is started. Any deviation by a non-signatory can be ignored, which implies that the punishment path of a non-signatory is just $\mathbf{a}^s$.

To conclude this section, the simple strategy profile consists of the following $(n+1)$ paths:

$$(\underbrace{\mathbf{a}^s}_{IEA}, \underbrace{\mathbf{p}_{i_1}^s, ..., \mathbf{p}_{i_m}^s}_{j \in M}, \underbrace{\mathbf{a}^s, ..., \mathbf{a}^s}_{j \in N \setminus M}) \tag{4}$$

4 Results

There are two main results, one in each of the following subsections. The first is a theorem that provides conditions for the strategy in (4) to be a WRP equilibrium. The second main result is a condition for the existence of an IEA as a WRP equilibrium for any level of particiption, which follows as an application of the theorem. Finally, each subsection also includes comparative statics results and corollaries that cover the cases with no social preferences.

4.1 Subgame-Perfection and Weak Renegotatiation-Proofness

In this section, I derive necessary and sufficient conditions for the strategy in (4) to be a WRP equilibrium. For any period t, the abatement decisions of each country in each of the previous periods comprise the history of the game going into period t:

$$(q_1(0), ..., q_n(0)), \ (q_1(1), ..., q_n(1)), ..., \ (q_1(t-1), ..., q_n(t-1)).$$

Let the average discounted payoff to country i be equal to

$$(1-\delta)\sum_{t=0}^{\infty}\delta^t\,\Pi_i(t),$$

where $\delta \in (0,1)$ is the discount factor and $\Pi_i(t)$ is the stage-game payoff in (2) for period t when abatement levels are $(q_1(t), ..., q_n(t))$. Then, a general strategy profile $\sigma = (\sigma_1, ..., \sigma_n)$ is a subgame-perfect equilibrium if for every subgame (that is, for every repeated game following every possible history of play) and given the strategies of all other players, no single player can achieve a higher average discounted payoff by deviating from its strategy. From Farrell and Maskin (1989), a WRP equilibrium is a subgame-perfect equilibrium in which for a given history of play there do not exist continuation equilibria σ^1 and σ^2 of σ such that σ^1 strictly Pareto-dominates σ^2.

Due to the simple strategy profile in (4), when deriving conditions for the strategy to be a subgame-perfect equilibrium, there are only two types of histories to check for period t: a history in which all countries were on the equilibrium path in period $t-1$ (signatories abate and non-signatories pollute); and a history in which countries are on a punishment path due to a defection by a signatory in period $t-1$, where this defection is either from the cooperative path or another country's punishment path. For the simple strategy profile in (4), subgame-perfection requires that no country can make a beneficial, one-shot deviation (in terms of getting a higher discounted payoff) from its strategy for each of the two types of histories (Abreu 1988).

The requirement of the WRP equilibrium that there do not exist two continuation equilibrium payoffs where one strictly Pareto-dominates the other has a simple interpretaton in the context of this model: following a deviation from a signatory i, at least *one* signatory must gain from implementing punishment path $\mathbf{p}_i^s$, rather than reverting to $\mathbf{a}^s$. If this is true, then not *all* countries will strictly prefer to stay on the cooperative path and to ignore a deviation.

The results of this subsection summarize the necessary and sufficient conditions such the simple strategy profile in (4) is a WRP equilibrium. After explaining the theorem and providing intuition, I provide a result on the static properties of the number of punishing countries k.[13]

Theorem 1 *Suppose that each country has a payoff function defined by (1) and (2) and that (3) is satisfied. Then the simple strategy profile in (4) is a weakly renegotiation-proof equilibrium if and only if*

$$\frac{c(1-\gamma_i) - b[1+\varepsilon_i(n-1)]}{\delta\{b+\varepsilon_i[b(n-1)-c]\}} \leq k \leq \frac{c(1-\gamma_i-\varepsilon_i)}{b+\varepsilon_i[b(n-1)-c]}, \tag{5}$$

$$\textit{where } \lambda_i, \gamma_i, \varepsilon_i \geq 0 \textit{ and } \lambda_i + \gamma_i + \varepsilon_i = 1.$$

Theorem 1 implies that a punishment must be strong enough to deter cheating, but not so strong that all signatories would rather just ignore their punishment duties. To ensure that the strategy is subgame-perfect, there must be at least a certain number of countries that will punish a defection (the left inequality), which serves to deter a signatory from choosing to pollute. Also, note that condition (3) ensures that numerator in the left inequality in (5) is positive. Theorem 1 also implies that there cannot be too many punishing countries in a WRP equilibrium (the right inequality in (5)) because if the punishment is too strong (and payoffs are lowered too much), then signatories may prefer to simply refuse to implement the punishment. Finally, note that the conditions in Theorem 1 do not depend on m, the number of signatories, but k must satisfy $k < m \leq n$.[14] The implication is that the above condition holds for any level of cooperation and that k and δ can trade off with values of γ_i and ε_i to sustain cooperation.

To get a better intuition for the above result, it will help to have the case with no social preferences as a comparison.[15]

[13] The proof of Theorem 1 can be found in the Appendix.
[14] Technically, k must be an integer to satisfy Theorem 1.
[15] This corollary summarizes the main results of Froyn and Hovi (2008).

Corollary 1 *In the absence of social preferences (that is, $\gamma_i = \varepsilon_i = 0$, and $\lambda_i = 1$), the simple strategy profile in (4) is a weakly renegotiation-proof equilibrium if and only if*

$$\frac{c-b}{\delta b} \leq k \leq \frac{c}{b}. \tag{6}$$

In providing intuition for the results, I will begin with explaining the condition for subgame-perfection and finish with weak renegotation-proofness, and in both cases I will compare Theorem 1 with Corollary 1. I will also examine how the conditions in Theorem 1 are affected by changes in the social preferences parameters γ_i and ε_i, which will be summarized by a proposition to follow.

As described earlier, to show that the strategy is subgame-perfect, one only needs to show that no country can gain from a one-period defection, and there are only two types of subgames to check: cooperative subgames, in which all countries were on path $\mathbf{a}^s$ in the previous period, and punishment subgames, in which there was a defection in the previous period. Considering the cooperative subgame is instructive enough (the Appendix contains the full proof). Signatory i cannot gain by deviating from $\mathbf{a}^s$ if

$$\delta k \left\{b + \varepsilon_i \left[b\left(n-1\right) - c\right]\right\} \geq c\left(1-\gamma_i\right) - b\left[1 + \varepsilon_i\left(n-1\right)\right]. \tag{7}$$

In words, the discounted loss from punishment (the left side of (7)) must be at least as large as the gain from defection (the right side of (7)). Since it is assumed that $b\left(n-1\right) > c$, the loss from punishment increases in ε_i, the weight that country i puts on the efficiency component of its social preferences payoff. The main reason for this is that during a punishment phase, k signatories switch from Abate to Pollute, which is a loss of total abatement benefits that enters into each of the three payoff components (material, equity, and efficiency). Additionally, there is a "saved" total abatement cost, which is also due to the k punishing countries no longer abating. However, from the point-of-view of signatory i being punished, the "saved" abatement cost from punishing countries only contributes to its efficiency payoff term because signatory i abates during its punishment and signatories that abate have the lowest overall payoff (thus, signatory i's own abatement cost is reflected in its material and equity payoff terms). That, combined with the assumption $b(n-1) > c$, leads to the lost total abatement benefits being relatively more damaging than the "saved" total abatement cost is beneficial. Thus, the net effect is that the loss from punishment is greater with social preferences than without and that the loss from punishment increases in ε_i, given k and δ.

The gain from defection (the right side of inequality (7)) is much simpler to describe. If signatory i chooses to defect from cooperation and pollute rather than abate, then i makes itself better off materially (as it would without social preferences), but suffers due to all other payoffs being made lower, which affects i through equity and efficiency. That the gain from defection is decreasing in both γ_i and ε_i is evidence of this. Overall, since the presence of social preferences increases the loss from punishment and decreases the gain from defection, one can conclude that for a given discount factor δ it may be possible for the strategy to be a subgame-perfect equilibrium for a lower k than would be possible without social preferences.

For the strategy to be WRP, at least one country must prefer to implement the punishment rather than simply staying on the cooperative path. In the Appendix, it is shown that every country in the group of punishing countries $P_i(n)$ prefer to carry out the punishment; in other words, each signatory in in the punishing group $P_i(n)$ gets at least as large a payoff by implementing the punishment than they would by remaining on the cooperative path (in the case of these countries, the punishment means that they choose Pollute in order to harm the cheater). This implies that the payoff for implementing the punishment cannot be too low relative to their payoff when on the cooperative path. Furthermore, the payoff to the punishing countries is decreasing in k (since $k \in P_i(n)$ do not abate during the punishment), so the larger is k the more difficult it is to meet this condition. This implies that k cannot be too large, all else equal.

The effects of social preferences on weak renegotiation-proofness (and the right inequality in (5)) are as follows. First, both the equity parameter γ_i and the efficiency parameter ε_i directly lower the payoff to the punishing countries $P_i(n)$ because these countries pollute during the punishment and consequently have the highest material payoff (tied with non-signatories). Thus, any weight given to equity or efficiency tilts the payoff of the punishing countries toward the lower payoffs of the other signatories, which makes them less willing to punish. This implies that a lower k may be required so that the payoff to the punishing countries does not fall too low. This effect can be seen in the numerator of the right inequality in (5), which is decreasing in both γ_i and ε_i. The efficiency weight ε_i has the additional effect of increasing the denominator of the right inequality in (5). This effect has the same reasoning as for the loss from punishment in the cooperative subgame described above. That is, the lost total abatement benefits from punishment reduce the payoff to the punishing countries by more than the "saved" total abatement cost increases their payoff. Due to this effect, higher values of ε_i may have to be counteracted by a lower k to keep the payoff to punishing countries from falling too much.

Finally, let $\bar{k}$ be the lower bound on the number of punishing countries (*i.e.* $\bar{k}$ exactly satisfies subgame-perfection), and let $\hat{k}$ be the upper bound on the number of punishing countries (*i.e.* $\hat{k}$ exactly satisfies weak renegotiation-proofness). Then,

$$\begin{aligned}\bar{k} &= \frac{c(1-\gamma_i) - b[1+\varepsilon_i(n-1)]}{\delta\{b+\varepsilon_i[b(n-1)-c]\}}, \text{ and} \\ \hat{k} &= \frac{c(1-\gamma_i-\varepsilon_i)}{b+\varepsilon_i[b(n-1)-c]}.\end{aligned}$$

To conclude the discussion of subgame-perfection and weak renegotiation-proofness, the following proposition summarizes the effects of changes in the social preferences parameters γ_i and ε_i on the number of punishing countries k.[16]

[16] I am ignoring that k must be an integer. The conditions above can be made more rigorous by requiring that $\bar{k}$ and $\hat{k}$ are the lowest and highest integers, respectively, that satisfy the conditions.

Proposition 1 *The bounds on the number of punishing countries k are affected by social preferences in the following ways:*

(i) For a change in γ_i: both $\frac{\partial \bar{k}}{\partial \gamma_i} < 0$ and $\frac{\partial \hat{k}}{\partial \gamma_i} < 0$.

(ii) For a change in ε_i: both $\frac{\partial \bar{k}}{\partial \varepsilon_i} < 0$ and $\frac{\partial \hat{k}}{\partial \varepsilon_i} < 0$.

The overall message so far is that the presence of social preferences allows subgame-perfection to possibly hold for a smaller number of punishing countries k (all else equal) and also causes weak renegotiation-proofness to possibly require a smaller k as well. Then, if social preferences grow stronger and draw weight away from the material payoff, the condition for subgame-perfection grows even more slack because the net loss from punishment gets even larger, while the condition for weak renegotiation-proofness may become even more restrictive in order to keep the payoff to the punishing signatories from becoming too low. In short, under social preferences subgame-perfection may *allow* k to be smaller than with strict material preferences, but weak renegotiation-proofness may *force* k to be smaller. The basic reason is that while social preferences cause the net loss from punishment to increase, which better deters defections (all else equal), social preferences also induce extra harm on the punishing countries (who have the highest material payoff during a punishment phase), which means that the punishment may also have to be made weaker through a smaller k.

4.2 Sustaining Cooperation

This paper can now apply Theorem 1 to derive the range of discount factors δ that can support cooperation, and to see how social preferences may trade off with the discount factor and make cooperation more or less likely. Cooperation will be sustained when discount factors are "high enough" - that is, countries must place enough value on the future so that discounted losses from punishment outweigh any possible gains from defections. After the statements for two propositions and a corollary, I explain each of them and provide intuition.[17] First,

[17] Proofs of Propositions 2 and 3 can be found in the Appendix.

suppose that k exactly satisfies the minimum number of punishing countries needed for weak renegotiation-proofness, so that the k in Theorem 1 equals $\bar{k}$.[18] Also, let the discount factor $\delta = e^{-r\Delta}$, where r is the rate of time discounting and Δ is the period length (or detection lag).

Proposition 2 *Suppose that each country has a payoff function defined by (1) and (2), that (3) is satisfied, and that $k = \bar{k}$. Then an IEA with any level of cooperation, including full cooperation, exists as a weakly renogotiation-proof equilibrium of the simple strategy profile in (4) for discount factors δ that satisfy*

$$\delta \in \left[\frac{c\left(1-\gamma_i\right) - b\left[1+\varepsilon_i\left(n-1\right)\right]}{c\left(1-\gamma_i-\varepsilon_i\right)}, 1 \right).$$

Note that any level of cooperation can be supported because the number of signatories is not a part of (5). As a corollary, here is the result for strictly material payoffs.

Corollary 2 *In the absence of social preferences (that is, $\gamma_i = \varepsilon_i = 0$, and $\lambda_i = 1$), an IEA with any level of cooperation, including full cooperation, exists as a weakly renogotiation-proof equilibrium of the simple strategy profile in (4) for discount factors δ that satisfy*

$$\delta \in \left[\frac{c-b}{c}, 1 \right).$$

Let the critical discount factor needed to sustain cooperation (that is, the lower bound of δ) under social social preferences be denoted by $\bar{\delta}$, so that

$$\bar{\delta} = \frac{c\left(1-\gamma_i\right) - b\left[1+\varepsilon_i\left(n-1\right)\right]}{c\left(1-\gamma_i-\varepsilon_i\right)}.$$

Proposition 3 *The critical discount factor $\bar{\delta}$ is affected by social preferences in the following ways: both $\frac{\partial \bar{\delta}}{\partial \gamma_i} < 0$ and $\frac{\partial \bar{\delta}}{\partial \varepsilon_i} < 0$.*

[18] Again, I am ignoring a possible integer problem with k.

Now, I will explain the results and give intuition. First, since the discount factor $\delta = e^{-r\Delta}$, then a high rate of time preference or a long period length will cause the discount factor to be low. Also, note that the critical discount factor needed to sustain cooperation in the absence of social preferences increases as c becomes larger relative to b. Thus, in the absence of social preferences, cooperation may not be possible if c is very large compared to b and if large r and Δ cause δ to be low.[19]

However, assuming that countries have social preferences, cooperation becomes a more likely outcome because the range of discount factors that can support cooperation increases - that is, the critical discount factor falls and the range between $\bar{\delta}$ and 1 grows. Social preferences have two effects on the critical discount factor, each pulling in the opposite direction of the other, but the overall effect is that social preferences lower the critical discount factor. The first effect follows from the discussion of subgame-perfection: since the net loss from punishment increases with social preferences, defections are better deterred, which implies that subgame-perfection may be achieved for lower discount factors. The other effect follows from the discussion of weak renegotiation-proofness: social preferences harm punishing countries, which may make cooperation more difficult since that condition relies on the payoffs of punishing countries not being too low. Proposition 3 shows that the former effect outweighs the latter, which implies that as social preferences grow stronger (γ_i and ε_i increase) the range of discount factors that can support cooperation increases.

Thus, social preferences have a beneficial effect on sustaining cooperation, which can be seen in the following numerical example: suppose again that a high rate of time preference or a long period length will cause all countries' discount factor to be relatively low, say, equal to 0.8, and that $b = 1$, $c = 8$, and $n = 200$.[20] Without social preferences, Corollary 2 yields $\bar{\delta} = 0.875$, which implies that cooperation would not exist with the current strategy and parameter

[19] Mohr (2014) and Asheim and Holtsmark (2009) do a similar analysis of the relationship between the parameters of the discount factor and the range of discount factors that make cooperation possible.

[20] The values for b, c, and n are those used in Froyn and Hovi (2008).

values. However, suppose that countries have social preferences with the parameters $\gamma_i = 0.01$ and $\varepsilon_i = 0.005$ and that b, c, and n are as given above. Now, Proposition 2 provides $\bar{\delta} = 0.75$, which is low enough to sustain cooperation, and as γ_i and ε_i increase (provided that (3) is still met) $\bar{\delta}$ will fall even further. In general, social preferences makes it more likely that countries are able to sustain cooperation in an IEA.

5 Conclusion

This paper examines how social preferences, in particular preferences for equity and efficiency, affect the likelihood of cooperation among countries to abate pollution. Using a penance strategy, in which a signatory that deviates from cooperation must abate in the following period while a subset of signatories pollute, it is shown that an IEA with any level of cooperation exists as a weakly renegotiation-proof equilibrium for high enough discount factors. Then, I show that as social preferences grow stronger, the range of discount factors that can support cooperation increases, which implies that cooperation is more likely under social preferences. As discussed at length following Theorem 1, the net loss from punishment plays a key role in the results; in this case, stronger social preferences cause the net loss from the punishment to increase, which better deters deviations from cooperation.

As noted earlier, social preferences that include equity and efficiency make it more likely that cooperation may not even be needed (Kolstad 2012). However, if in a repeated setting cooperation is needed, then social preferences play a beneficial role. This result is aligned with the result in Duffy and Muñoz-García (2012). That paper uses inequity-aversion preferences and also finds that social preferences increase the range of discount factors that support cooperation. In future research, public good provision with quadratic costs should be explored, which will hopefully lead to richer results similar to those in Malueg (1992) and Bernheim and Stark (1988), which show that the effect of social preferences (or cross-holding) on cooperation may not be unambiguously positive; rather, social preferences may be beneficial or detrimental to cooperation.

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Appendix

1 Chapter 3

As a first step toward proving Theorem 1, I show that *in expectation* the simple strategy profile in (5) is subgame-perfect, which yields the following proposition.[1]

Proposition 1 *Suppose that countries are uncertain over β, may resolve their uncertainty at the beginning of each period with probability $\gamma \in (0,1)$, and have expected payoffs (2), (3), and (4). Then, the simple strategy profile in (5) is a subgame-perfect equilibrium in expectation if and only if $s > p$ and*

$$\frac{\max\left\{(s-1)^2,(p-1)^2\right\} A(t)}{2\delta(s-p)A(t+1)} \leq k, \textit{ where} \tag{10}$$
$$A(t) = [1-(1-\gamma)^{t+1}]E[\beta^2] + (1-\gamma)^{t+1}\bar{\beta}^2.$$

Proof. I begin by writing the following generic one-period expected payoffs, which are all conditional on $\bar{\beta}$ or on realizations of β. Note that for a given period t, expectation is over the random variable β, and results in the expected payoffs $E_\beta[\pi_i]$ and $\pi_i(\bar{\beta})$, which are defined in (2) and (3), respectively, depending on whether or not learning occurs. Thus, the one-period

[1]Equation numbering continues from Chapter 3.

expected payoff to signatory $i \in M$ on the equilibrium path is

$$\begin{aligned} E[\pi^s_{i\in M}] &= E\left[\beta\left[m\frac{s\beta}{c} + (n-m)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{s\beta}{c}\right)^2\right] \\ &= E\left[\frac{\beta^2}{c}\left(ms + n - m - \frac{s^2}{2}\right)\right]. \end{aligned}$$

If signatory $i \in M$ deviates from the equilibrium path (i.e. it cheats on the IEA) by reducing its abatement to $q^1(\beta)$ (its stage-game dominant strategy), then its one-period expected payoff is

$$\begin{aligned} E[\pi^d_{i\in M}] &= E\left[\beta\left[(m-1)\frac{s\beta}{c} + (n-m+1)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{\beta}{c}\right)^2\right] \\ &= E\left[\frac{\beta^2}{c}\left(ms - s + n - m + \frac{1}{2}\right)\right]. \end{aligned}$$

Now, if signatory $i \in M$ has deviated in the previous period, then punishment path $\mathbf{p}^s_i$ begins in the next period. The one-period expected payoff for signatory $l \in M \backslash P_i(n)$, which is the group of non-punishing signatories (including country i), on punishment path $\mathbf{p}^s_i$ is

$$\begin{aligned} E[\pi^p_{l\in M\backslash P_i}] &= E\left[\beta\left[(m-k)\frac{s\beta}{c} + k\frac{p\beta}{c} + (n-m)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{s\beta}{c}\right)^2\right] \\ &= E\left[\frac{\beta^2}{c}\left(ms - ks + kp + n - m - \frac{s^2}{2}\right)\right]. \end{aligned}$$

However, suppose that signatory $l \in M \backslash P_i(n)$ deviates from $\mathbf{p}^s_i$. In other words, rather than abating $q^s(\beta)$ during $\mathbf{p}^s_i$, signatory l abates at level $q^1(\beta)$. Then, its one-period expected payoff is[2]

$$
\begin{aligned}
E[\pi^{dp}_{l \in M \setminus P_i}] &= E\left[\beta\left[(m-k-1)\frac{s\beta}{c} + k\frac{p\beta}{c} + (n-m+1)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{\beta}{c}\right)^2\right] \\
&= E\left[\frac{\beta^2}{c}\left(ms - s - ks + kp + n - m + \frac{1}{2}\right)\right].
\end{aligned}
$$

Finally, if signatory $i \in M$ has deviated in the previous period, then the one-period expected payoff for signatory $j \in P_i(n)$, which is the group of punishing signatories, on punishment path $\mathbf{p}_i^s$ is

$$
\begin{aligned}
E[\pi^{p}_{j \in P_i}] &= E\left[\beta\left[(m-k)\frac{s\beta}{c} + k\frac{p\beta}{c} + (n-m)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{p\beta}{c}\right)^2\right] \\
&= E\left[\frac{\beta^2}{c}\left(ms - ks + kp + n - m - \frac{p^2}{2}\right)\right].
\end{aligned}
$$

However, suppose that signatory $j \in P_i(n)$ deviates from $\mathbf{p}_i^s$. In other words, rather than abating $q^p(\beta)$ during $\mathbf{p}_i^s$, signatory j abates at level $q^1(\beta)$. Then, its one-period expected payoff is

$$
\begin{aligned}
E[\pi^{dp}_{j \in P_i}] &= E\left[\beta\left[(m-k)\frac{s\beta}{c} + (k-1)\frac{p\beta}{c} + (n-m+1)\frac{\beta}{c}\right] - \frac{c}{2}\left(\frac{\beta}{c}\right)^2\right] \\
&= E\left[\frac{\beta^2}{c}\left(ms - ks + kp - p + n - m + \frac{1}{2}\right)\right].
\end{aligned}
$$

Notice that all of the above payoffs are strictly convex in either $\bar{\beta}$ or in realizations of β depending on if learning occurs.

Following Abreu (1988), to show that the strategy is subgame-perfect in expectation, it must be shown that no country can benefit in expectation from a one-period deviation. There are two types of subgames that must be checked: cooperative subgames and punishment subgames. For a cooperative subgame, in which all countries were on path $\mathbf{a}^s$ in the previous

[2] Superscript dp stands for "deviate from punishment."

period (period $t-1$), signatory i cannot gain in expectation from deviating from $\mathbf{a}^s$ provided that

$$\delta\{\underbrace{E_{\gamma\beta}[\pi^s_{i\in M}] - E_{\gamma\beta}[\pi^p_{i\in M\setminus P_i}]}_{\text{period } t+1}\} \geq \underbrace{E_{\gamma\beta}[\pi^d_{i\in M}] - E_{\gamma\beta}[\pi^s_{i\in M}]}_{\text{period } t},$$

which means that the discounted expected loss from deviating and being punished in period $t+1$ must be greater than the expected gain from deviating in period t. Expectations are over both the possibility that uncertainty has been resolved before abatement decisions are made in either period t or in period $t+1$ and over the different possible realizations of β. After substituting expected payoff (4) into the above expression, one finds that in expectation signatory i cannot gain by deviating if

$$\delta\{\underbrace{[1-(1-\gamma)^{t+2}][E_\beta[\pi^s_{i\in M}] - E_\beta[\pi^p_{i\in M\setminus P_i}]]}_{\beta \text{ is known in period } t+1} + \underbrace{(1-\gamma)^{t+2}[\pi^s_{i\in M}(\bar{\beta}) - \pi^p_{i\in M\setminus P_i}(\bar{\beta})]}_{\beta \text{ is unknown in period } t+1}\} \geq$$
$$\underbrace{[1-(1-\gamma)^{t+1}][E_\beta[\pi^d_{i\in M}] - E_\beta[\pi^s_{i\in M}]]}_{\beta \text{ is known in period } t} + \underbrace{(1-\gamma)^{t+1}[\pi^d_{i\in M}(\bar{\beta}) - \pi^s_{i\in M}(\bar{\beta})]}_{\beta \text{ is unknown in period } t}.$$

Now, substituting for $\pi^s_{i\in M}$, $\pi^p_{i\in M\setminus P_i}$, and $\pi^d_{i\in M}$ according to (2) and (3) yields

$$\delta\{[1-(1-\gamma)^{t+2}][\frac{E[\beta^2]}{c}k(s-p)] + (1-\gamma)^{t+2}[\frac{\bar{\beta}^2}{c}k(s-p)]\} \geq \qquad (11)$$
$$[1-(1-\gamma)^{t+1}][\frac{E[\beta^2]}{c}\frac{1}{2}(s-1)^2] + (1-\gamma)^{t+1}[\frac{\bar{\beta}^2}{c}\frac{1}{2}(s-1)^2].$$

Cancelling c and collecting terms $k(s-p)$ and $\frac{1}{2}(s-1)^2$ gives

$$\delta k(s-p)\{[1-(1-\gamma)^{t+2}]E[\beta^2] + (1-\gamma)^{t+2}\bar{\beta}^2\} \geq$$
$$\frac{1}{2}(s-1)^2\{[1-(1-\gamma)^{t+1}]E[\beta^2] + (1-\gamma)^{t+1}\bar{\beta}^2\}.$$

Finally, by denoting the term inside the braces on the right-hand side as $A(t)$, we can make the last simplification:

$$\delta k(s-p)A(t+1) \geq \frac{1}{2}(s-1)^2 A(t) \tag{12}$$

where

$$A(t) = [1-(1-\gamma)^{t+1}]E[\beta^2] + (1-\gamma)^{t+1}\bar{\beta}^2.$$

Since it has already been assumed that $s > 1$, inequality (12) implies that $s > p$. Rewriting this inequality to get a lower bound on the number of punishing countries k gives

$$k \geq \frac{(s-1)^2 A(t)}{2\delta(s-p)A(t+1)}. \tag{13}$$

Next, it must be checked that there is no way a country can gain in expectation by deviating during a punishment subgame (where there was a deviation from either $\mathbf{a}^s$ or $\mathbf{p}_i^s$ in the previous period). There are two cases to check: in expectation, neither a non-punishing signatory $l \in M \backslash P_i(n)$ nor a punishing signatory $j \in P_i(n)$ may gain from deviating from $\mathbf{p}_i^s$. First, signatory $l \in M \backslash P_i(n)$ cannot gain from deviating from $\mathbf{p}_i^s$ in expectation if

$$\delta\{\underbrace{E_{\gamma\beta}[\pi^s_{l\in M}] - E_{\gamma\beta}[\pi^p_{l\in M\backslash P_i}]}_{\text{period } t+1}\} \geq \underbrace{E_{\gamma\beta}[\pi^{dp}_{l\in M\backslash P_i}] - E_{\gamma\beta}[\pi^p_{l\in M\backslash P_i}]}_{\text{period } t}.$$

However, this condition holds whenever there are no expected beneficial deviations in the cooperative subgame, which was analyzed above. The reason is that signatories $l \in M \backslash P_i(n)$ abate $q^s(\beta)$ during the entirety of $\mathbf{p}_i^s$, as they do during $\mathbf{a}^s$. Thus, if such a country cannot gain by deviating during $\mathbf{a}$, then it will not be able to gain by deviating during $\mathbf{p}_i^s$ either since the one-period expected gain is the same. In the second case for punishment subgames, signatory

$j \in P_i(n)$ cannot gain from deviating from $\mathbf{p}_i^s$ if

$$\delta\{\underbrace{E_{\gamma\beta}[\pi^s_{j\in M}] - E_{\gamma\beta}[\pi^p_{j\in M\setminus P_j}]}_{\text{period } t+1}\} \geq \underbrace{E_{\gamma\beta}[\pi^{dp}_{j\in P_i}] - E_{\gamma\beta}[\pi^p_{j\in P_i}]}_{\text{period } t}.$$

Following the same method of substituting and simplifying as in the cooperative subgame above, one finds that the country cannot gain by deviating from $\mathbf{p}_i^s$ if

$$\delta k(s-p)A(t+1) \geq \frac{1}{2}(p-1)^2 A(t),$$

which can be rewritten as

$$k \geq \frac{(p-1)^2 A(t)}{2\delta(s-p)A(t+1)}, \tag{14}$$

and gives another lower bound on the number of punishing countries. Combining the two conditions (13) and (14) yields the sufficient condition in the proposition. To prove the "only if" part (by contradiction), first assume that in expectation the strategy in (5) is a subgame-perfect equilibrium, but that $s \leq p$.[3] Then condition (12) is violated, which implies that in expectation a signatory may gain by deviating from the treaty, which is a contradiction. So, assume that $s > p$, but that (10) is not satisfied. This implies that either (13) or (14) (or both) are not satisfied. In either case, it implies that in expectation a signatory may gain by deviating from the treaty, which is a contradiction. This completes the "only if" part of the proof. ∎

Proof of Theorem 1. Subgame-perfection is proved in the Proposition 4, which provides the lower bound on k. For the strategy in (5) to be weakly renegotiation-proof, it must be shown that not *all* countries would prefer to ignore a deviation and continue with $\mathbf{a}^s$, rather than starting $\mathbf{p}_i^s$. Signatories $l \in M\setminus P_i(n)$, which are not part of the punishing group, and non-signatories would actually prefer to ignore a deviation, since beginning $\mathbf{p}_i^s$ causes the punishing group of countries, $P_i(n)$, to reduce abatement, which reduces the expected payoffs

[3]This part of the proof mirrors the proof on p. 530 in the Appendix of Asheim and Holtsmark (2009).

of all countries. However, signatories $j \in P_i$ are made better off by implementing $\mathbf{p}_i^s$ if

$$E_{\gamma\beta}[\pi^p_{j\in P_i}(t)] \geq E_{\gamma\beta}[\pi^s_{j\in M}(t)].$$

Substituting expected payoffs yields

$$\frac{(s+p)}{2} \geq k,$$

which provides an upper bound on the number of punishing countries and completes the proof.[4] ■

Proof of Proposition 1. Start by expanding $A(t+1)$:

$$\begin{aligned} A(t+1) &= [1-(1-\gamma)^{t+2}]E[\beta^2] + (1-\gamma)^{t+2}\bar{\beta}^2 \\ &= A(t) + \gamma(1-\gamma)^{t+1}E[\beta^2] - (1-\gamma)^{t+1}\bar{\beta}^2 + (1-\gamma)^{t+2}\bar{\beta}^2, \end{aligned}$$

where $[1-(1-\gamma)^{t+1}] = \gamma\sum_{\tau=0}^{t}(1-\gamma)^{\tau}$ is used to expand the terms. Now, gathering and cancelling terms results in

$$A(t+1) = A(t) + \gamma(1-\gamma)^{t+1}Var[\beta].$$

Thus, the increase in the expected net loss from punishment is:

$$A(t+1) - A(t) = \gamma(1-\gamma)^{t+1}Var[\beta].$$

■

To aid in proving Proposition 3 in Section 4.2 (Statics), I begin with two lemmas.

[4]Mathematically, one can write out the full expression, then cancel $A(t)$ from both sides, which leaves only the terms from the no uncertainty case.

Lemma 1 *If* $\gamma(t+2)E[\beta^2] > A(t+1)$*, then* $\frac{\partial}{\partial\gamma}\left(\frac{A(t)}{A(t+1)}\right) > 0$*; otherwise,* $\frac{\partial}{\partial\gamma}\left(\frac{A(t)}{A(t+1)}\right) \leq 0$.

Proof. Using $A(t+1) = A(t) + \gamma(1-\gamma)^{t+1}Var[\beta]$ and taking the derivative, we have[5]

$$\begin{aligned}
&\frac{\partial}{\partial\gamma}\left(\frac{A}{A+\gamma(1-\gamma)^{t+1}Var[\beta]}\right) \\
&= \frac{\frac{\partial A}{\partial\gamma}(A+\gamma(1-\gamma)^{t+1}Var[\beta]) - A\left(\frac{\partial A}{\partial\gamma} + \frac{\partial}{\partial\gamma}[\gamma(1-\gamma)^{t+1}Var[\beta]]\right)}{(A+\gamma(1-\gamma)^{t+1}Var[\beta])^2} \\
&= \frac{(1-\gamma)^t Var[\beta]\left(\gamma(1-\gamma)\frac{\partial A}{\partial\gamma} - A[1-\gamma-(t+1)\gamma]\right)}{(A+\gamma(1-\gamma)^{t+1}Var[\beta])^2}.
\end{aligned}$$

Since $Var[\beta] > 0$, the sign of $\frac{\partial}{\partial\gamma}(\frac{A(t)}{A(t+1)})$ is determined by the sign of $\gamma(1-\gamma)\frac{\partial A}{\partial\gamma} - A[1-\gamma-(t+1)\gamma]$. So, we have

$$\gamma(1-\gamma)\frac{\partial A}{\partial\gamma} - A[1-\gamma-(t+1)\gamma] = \gamma(t+1)E[\beta^2] - (1-\gamma)A.$$

Finally, noting that

$$(1-\gamma)A(t) = A(t+1) - \gamma E[\beta^2],$$

we find that

$$\gamma(1-\gamma)\frac{\partial A(t)}{\partial\gamma} - A(t)[1-\gamma-(t+1)\gamma] = \gamma(t+2)E[\beta^2] - A(t+1).$$

Thus, the sign of $\frac{\partial}{\partial\gamma}\left(\frac{A(t)}{A(t+1)}\right)$ is determined by the sign of $\gamma(t+2)E[\beta^2] - A(t+1)$. ■

Lemma 2 $\frac{\partial}{\partial E[\beta^2]}\left(\frac{A(t)}{A(t+1)}\right) < 0$.

Proof. Taking the derivative gives

$$\frac{\partial}{\partial E[\beta^2]}\left(\frac{A(t)}{A(t+1)}\right) = \frac{\frac{\partial A(t)}{\partial E[\beta^2]}A(t+1) - A(t)\frac{\partial A(t+1)}{\partial E[\beta^2]}}{A(t+1)^2}.$$

[5] For the sake of concision, I will write $A(t)$ as simply A when it will not cause confusion.

Thus, the sign of $\frac{\partial}{\partial E[\beta^2]}\left(\frac{A(t)}{A(t+1)}\right)$ depends solely on the sign of the numerator. We have

$$\frac{\partial A(t)}{\partial E[\beta^2]}A(t+1) - A(t)\frac{\partial A(t+1)}{\partial E[\beta^2]} = [1-(1-\gamma)^{t+1}]A(t+1) - A(t)[1-(1-\gamma)^{t+2}]$$
$$= [1-(1-\gamma)^{t+1}][A(t) + (1-\gamma)^{t+1}\gamma Var[\beta]] - A(t)[1-(1-\gamma)^{t+1} + \gamma(1-\gamma)^{t+1}],$$

where we used $A(t+1) = A(t) + \gamma(1-\gamma)^{t+1}Var[\beta]$ and $1-(1-\gamma)^{t+2} = 1-(1-\gamma)^{t+1} + \gamma(1-\gamma)^{t+1}$. Finally, after much algebra and using $A(t) = E[\beta^2] - (1-\gamma)^{t+1}Var[\beta]$, we find that the numerator equals $-\gamma(1-\gamma)^{t+1}\bar{\beta}^2$, which is strictly negative and confirms the result. ■

Proof of Proposition 3. Note that both $\hat{k}$ and $\hat{\delta}$ are equal to a constant multiplied by $\left(\frac{A(t)}{A(t+1)}\right)$. To prove part (i), the signs of $\frac{\partial \hat{k}}{\partial \gamma}$ and $\frac{\partial \hat{\delta}}{\partial \gamma}$ are determined by the sign of $\frac{\partial}{\partial \gamma}\left(\frac{A(t)}{A(t+1)}\right)$. The result is then found by applying Lemma 1. Similarly, to prove part (ii), apply Lemma 2. ■

2 Chapter 4

Theorem 1 provides conditions for the strategy in (4) to be a weakly renegotiation-proof equilibrium, and one of the requirements is tha the strategy is subgame-perfect. This proposition begins the proof of Theorem 1, which provides necessary and sufficient conditions for subgame-perfection.[6]

Proposition 2 *Suppose that each country has a payoff function defined by (1) and (2) and that (3) is satisfied. Then the simple strategy profile in (4) is a subgame-perfect equilibrium if and only if*

$$\frac{c(1-\gamma_i) - b[1+\varepsilon_i(n-1)]}{\delta\{b+\varepsilon_i[b(n-1)-c]\}} \leq k, \tag{8}$$

where $\lambda_i, \gamma_i, \varepsilon_i \geq 0$ *and* $\lambda_i + \gamma_i + \varepsilon_i = 1$.

[6] Equation numbering continues from Chapter 4.

Proof. Since the total payoff to each country contains several terms, I begin by writing each of the one-period payoffs that will be used in the proof. First, the one-period payoff to signatory $i \in M$ on the equilibrium path is

$$\begin{aligned}\Pi^s_{i \in M} &= \lambda_i [bm - c] + \gamma_i [bm - c] + \varepsilon_i [nbm - cm] \\ &= bm [1 + \varepsilon_i (n-1)] - c [1 + \varepsilon_i (m-1)] .\end{aligned}$$

Note that signatories have the lowest payoff since they abate while non-signatories pollute, which means that the equity term consists of a signatory's payoff.[7] Furthermore, countries that abate in any period of the game will have the lowest payoff, which includes signatories during cooperation or non-punishing signatories during a punishment phase.

If signatory $i \in M$ deviates from the equilibrium path by switching from abate to pollute (its stage-game dominant strategy), then its one-period payoff is

$$\begin{aligned}\Pi^d_{i \in M} &= \lambda_i b (m-1) + \gamma_i [b (m-1) - c] + \varepsilon_i [nb (m-1) - c (m-1)] \\ &= b (m-1) [1 + \varepsilon_i (n-1)] - c \left[\gamma_i + \varepsilon_i (m-1)\right] .\end{aligned}$$

Now, suppose that signatory $i \in M$ has deviated in the previous period. Then punishment path $\mathbf{p}^s_i$ begins in the next period, and the one-period payoff for signatory $l \in M \backslash P_i (n)$, which is the group of non-punishing signatories (including country i), on punishment path $\mathbf{p}^s_i$ is

$$\begin{aligned}\Pi^p_{l \in M \backslash P_i (n)} &= \lambda_l [b (m-k) - c] + \gamma_l [b (m-k) - c] + \varepsilon_l [nb (m-k) - c (m-k)] \\ &= b (m-k) [1 + \varepsilon_l (n-1)] - c [1 + \varepsilon_l (m-k-1)] .\end{aligned}$$

[7] Kolstad (2012) assumes that the equity term for signatory i only considers countries not in the IEA, rather than all countries $j \in N$. There is no effect on the results because the only difference is that the equity term includes the abatement cost if signatories are included, but does not include abatement costs if only non-signatories are included. It can be shown that this constant will cancel from the equations. Regardless of whether signatories are included or not, the equity term includes total abatement benefits, which contributes to the results (and does not cancel from the equations).

If a signatory $l \in M \backslash P_i(n)$ deviates from punishment path $\mathbf{p}_i^s$ by choosing to pollute instead of abate, then its one-period payoff is[8]

$$\begin{aligned}
&\Pi^{dp}_{l\in M\backslash P_i(n)} \\
&= \lambda_l b(m-k-1) + \gamma_l [b(m-k-1) - c] + \varepsilon_l [nb(m-k-1) - c(m-k-1)] \\
&= b(m-k-1)[1+\varepsilon_l(n-1)] - c\left[\gamma_l + \varepsilon_l(m-k-1)\right].
\end{aligned}$$

Now, consider a signatory $j \in P_i(n)$ that belongs to the group of signatories that will punish a defection by signatory $i \in M$. The one-period payoff for a signatory $j \in P_i(n)$ on punishment path $\mathbf{p}_i^s$ is

$$\begin{aligned}
\Pi^{p}_{j\in P_i(n)} &= \lambda_j b(m-k) + \gamma_j [b(m-k) - c] + \varepsilon_j [nb(m-k) - c(m-k)] \\
&= b(m-k)\left[1+\varepsilon_j(n-1)\right] - c\left[\gamma_j + \varepsilon_j(m-k)\right].
\end{aligned}$$

Finally, a signatory $j \in P_i(n)$ would never choose to deviate from $\mathbf{p}_i^s$ because doing so would require choosing to abate instead of pollute, which would make a signatory $j \in P_i(n)$ strictly worse off compared to $\Pi^{p}_{j\in P_i(n)}$.

For the simple strategy profile in (4), subgame-perfection requires that no country can make a beneficial, one-shot deviation (in terms of getting a higher discounted payoff) from its strategy for each of the two types of subgames (Abreu 1988), where subgames are either cooperative subgames (in which countries were on equilibrium path $\mathbf{a}_i^s$ in the previous period) or punishment subgames (in which a signatory has deviated from either $\mathbf{a}_i^s$ or a punishment path $\mathbf{p}_i^s$ in the previous period). For a cooperative subgame, signatory i cannot make a beneficial deviation if

$$\delta\left[\Pi^{s}_{i\in M} - \Pi^{p}_{i\in M\backslash P_i(n)}\right] \geq \left[\Pi^{d}_{i\in M} - \Pi^{s}_{i\in M}\right],$$

[8]Superscript dp stands for "deviate from punishment."

which, after substituting the relevant payoffs, can be written as

$$\delta k \left\{ b + \varepsilon_i \left[b \left(n - 1 \right) - c \right] \right\} \geq c \left(1 - \gamma_{\ i} \right) - b \left[1 + \varepsilon_i \left(n - 1 \right) \right]. \tag{9}$$

The right side of the inequality is positive since I have assumed that $c \left(1 - \gamma_{\ i} \right) - b \left[1 + \varepsilon_i \left(n - 1 \right) \right]$ (see (3)). This inequality can be rearranged to get

$$\frac{c(1 - \gamma_{\ i}) - b[1 + \varepsilon_i (n - 1)]}{\delta\{b + \varepsilon_i [b(n - 1) - c]\}} \leq k. \tag{8}$$

Now, consider a punishment subgame in which a signatory i has deviated from $\mathbf{a}_i^s$ in the previous period, which starts punishment path $\mathbf{p}_i^s$. A non-punishing signatory (a group which includes i) cannot make a beneficial deviation if

$$\delta \left[\Pi_{i \in M}^{s} - \Pi_{i \in M \setminus P_i(n)}^{p} \right] \geq \left[\Pi_{i \in M \setminus P_i(n)}^{dp} - \Pi_{i \in M \setminus P_i(n)}^{p} \right]$$

which, after substituting the relevant payoffs, can be written as

$$\delta k \left\{ b + \varepsilon_i \left[b \left(n - 1 \right) - c \right] \right\} \geq c \left(1 - \gamma_{\ i} \right) - b \left[1 + \varepsilon_i \left(n - 1 \right) \right].$$

Note that this is the same condition that resulted in the cooperative subgame. The intuition is that since non-punishing signatories abate during a punishment phase, if they cannot gain by deviating from a cooperative phase by choosing to pollute, then they also cannot gain by deviating from a punishment phase by choosing to pollute. The remaining punishment subgame to consider is that of a punishing signatory $j \in P_i(n)$. However, since these signatories can only harm themselves by choosing to deviate from $\mathbf{p}_i^s$ (which was mentioned previously), $\Pi_{j \in P_i(n)}^{dp} - \Pi_{j \in P_i(n)}^{p}$ will be negative, which implies that a signatory $j \in P_i(n)$ cannot make a beneficial deviation for any $k \geq 0$ and $\delta \in (0, 1)$.

Thus, condition (8) suffices for all subgames and completes the "if" part of the proof. The condition (8) is also necessary because if the strategy is subgame-perfect but (8) is not true, then there exist beneficial one-period deviations from the strategy, which is a contradiction (and which proves the "only if" part). ■

Proof of Theorem 1. Now that subgame-perfection has been proved in the above proposition, all that remains to prove Theorem 1 is to derive the necessary and sufficient condition for the strategy to be a weakly renogotiation-proof equilibrium, which means that at least one country prefers to follow through with the punishment. Since the punishment phase results in a drop in abatement, non-punishing signatories $l \in M \backslash P_i(n)$ are only harmed by the punishment. Non-signatories are harmed by the punisment for the same reason. However, the k punishing countries (that pollute during the punishment phase) will prefer to follow through with the punishment if

$$\Pi^p_{i \in P_l(n)} \geq \Pi^s_{i \in M}.$$

Substituting payoffs results in

$$c\left(1 - \gamma_i - \varepsilon_i\right) \geq k\left\{b + \varepsilon_i\left[b\left(n-1\right) - c\right]\right\},$$

which can be rewritten as

$$k \leq \frac{c\left(1 - \gamma_i - \varepsilon_i\right)}{b + \varepsilon_i\left[b\left(n-1\right) - c\right]}.$$

Thus, the condition for weak renegotiation-proofness provides an upper bound on the number of punishing countries, which serves to limit the harm from the punishment. ■

Proof of Proposition 2. Setting $k = \bar{k}$ in condition (5) of Theorem 1 implies that

$$\frac{c\left(1 - \gamma_i\right) - b\left[1 + \varepsilon_i\left(n-1\right)\right]}{\delta\left\{b + \varepsilon_i\left[b\left(n-1\right) - c\right]\right\}} \leq \frac{c\left(1 - \gamma_i - \varepsilon_i\right)}{b + \varepsilon_i\left[b\left(n-1\right) - c\right]},$$

which can be rewritten as

$$\frac{c\left(1-\gamma_{i}\right)-b\left[1+\varepsilon_{i}\left(n-1\right)\right]}{c\left(1-\gamma_{i}-\varepsilon_{i}\right)} \leq \delta.$$

■

Proof. Taking the derivative with respect to γ_i yields

$$\frac{\partial\bar{\delta}}{\partial\gamma_{i}}=\frac{-c^{2}\left(1-\gamma_{i}-\varepsilon_{i}\right)+c\{(1-\gamma_{i})-b[1+\varepsilon_{i}(n-1)]\}}{c^{2}\left(1-\gamma_{i}-\varepsilon_{i}\right)^{2}}.$$

The sign is determined by the numerator, and after some cancellation can be written as

$$c\{-b-\varepsilon_{i}[b(n-1)-c]\},$$

which is negative since it has been assumed that $b(n-1) > c$. Now, taking the derivative with respect to ε_i yields

$$\frac{\partial\bar{\delta}}{\partial\varepsilon_{i}}=\frac{-bc(n-1)\left(1-\gamma_{i}-\varepsilon_{i}\right)+c\{c(1-\gamma_{i})-b[1+\varepsilon_{i}(n-1)]\}}{c^{2}\left(1-\gamma_{i}-\varepsilon_{i}\right)^{2}}.$$

Again, the sign is determined by the numerator, which can be written as

$$c\{-b-(1-\gamma_{i})[b(n-1)-c]\}$$

and is also negative since $b(n-1) > c$. ■