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Allocations and Manipulation in Kyoto Type Protocols

Sudhir A. Shah
Delhi School of Economics
Email: sudhir@econdse.org

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Centre for Development Economics
Department of Economics, Delhi School of Economics

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Abstract

We study an incomplete information, non-cooperative model of the determination of national emission endowments under a Kyoto type protocol with heterogeneous nations. The model generates a link between national types and equilibrium national emission caps. We analyze this link to (a) derive the type-contingent ordering of emission allocations, (b) study the effects of growth on emission allocations, and (c) study the strategies that nations can use to manipulate the emission allocation process. Synthesizing these results allows us to derive the implications of national heterogeneity and asymmetry of economic power in the capping process.

JEL classification: D74, H41, Q21, Q25, R11

Key words: correlated equilibrium, heterogeneity, incomplete information,
Kyoto protocol, manipulation, non-cooperative game,

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1. Introduction

1.1 Model characteristics

The Kyoto protocol (United Nations 1997) is a response to the apprehension that carbon accumulation in the atmosphere inflicts significant global damages. Although this document is vaguely exhortative on most counts, the following broad steps to restrict increments in the carbon stock can be discerned: (1) ration each participating nation's carbon emissions by specifying national emission caps, and (2) each participating nation allocates its emission endowment among domestic emitters. A third step being discussed is whether international trading of emission rights should be permitted after step (2). An overarching requirement of the protocol is that it comes into force, thereby triggering the above steps, if and only if a pre-specified set of nations, i.e., the so-called Annex I nations (see United Nations 1997), ratify the protocol. In this paper, we analyze a model that adheres to this general regulatory structure.

One set of studies of the global externality problem caused by carbon accumulation has modelled the problem as a dynamic game in which nations choose emission flows into the global carbon stock. This literature addresses questions such as: (a) When does a non-cooperative equilibrium of the game approximate a cooperative solution? (e.g., Dockner and Long 1993), and (b) What are the effects of fiscal incentives on the equilibrium strategies? (e.g., Patrick et al. 1993). Although fiscal incentives are a standard method of correcting distortions caused by externalities, this approach is incongruous with the Kyoto protocol. Step (1) of the protocol clearly opts for regulation *via* quantity rationing of emission rights rather than *via* fiscal regulation. Unlike emitters within a given nation's jurisdiction, who can be subjected to fiscal incentives by that nation, no comparable authority exists, nor is one being contemplated, for administering an international fiscal regime on emitters within sovereign nations.

A second set of studies (e.g., Barrett 1994, 1997, Black et al. 1993, Carraro and Siniscalco 1993) has used the non-cooperative game approach, and a variant of the equilibrium concept introduced in d'Aspremont et al. (1983), to ask whether nations have the incentives to participate in an agreement that rations their emissions. This literature concentrates on questions such as: (a) What structure of incentives will ensure the stability of the set of signatories to an agreement?, and (b) What is the size of a stable set of agreement signatories?

A third set of studies has analyzed analogous questions in a cooperative game setting with transferable utility (Chander and Tulkens 1992, 1995, 1997, Eyckmans 2001), using variants of the core (see Osborne and Rubinstein 1994) as the solution concept. This approach characterizes the fiscal incentives required to implement efficient emission allocations without any coalition wishing to block it.

The above-mentioned literature has not adequately addressed some of the salient sources of the controversies surrounding the (Kyoto) protocol, such as: (A) the remarkable heterogeneity of the potential participants in terms of economically relevant characteristics such as resource endowments, industry structure and technology, (B) the incompleteness of information regarding these asymmetries, and (C) an incomplete and asymmetric understanding of the effects of carbon accumulation in the atmosphere.

With respect to (A), this literature has either assumed symmetric nations or formally allowed for asymmetry without working out the theoretical consequences. With respect to (B), the literature is couched entirely in terms of complete information games, although there is no account in the models of how nations verify private information in the absence of facilitating institutions. While the protocol itself might provide the institutional basis for information verification *after* ratification, the assumption of complete information *before* the protocol comes into force seems an implausible description of the informational state of negotiating nations. With respect to (C), the protocol is implicitly viewed as a complete, futures and contingent, contract among the signatories. However, merely the recognition that (a) scientific knowledge, technology and economies will evolve over time, (b) prediction of the nature, timing and extent of dissemination of these changes is a precarious exercise, and (c) many of these changes are endogenously influenced by the decisions of the various players, should raise some doubts about an approach assuming completely describable and contractible states. The uncertainty and learning implied by these observations will inevitably lead to future renegotiations and reallocation of emission rights. Such concerns have motivated a literature (e.g., Kolstad 1996, Ulph and Maddison 1997, Ulph and Ulph 1997) on learning in the context of emission choice. Unfortunately, with the exception of Ulph and Maddison (1997), the chosen setting for this literature is a single-person decision problem rather than a multi-player game problem.

In this paper:

• We model the heterogeneity of nations and study its consequences under incomplete information. The objective is to understand the equilibrium relationship between national characteristics and national emission caps.

• We show how this relationship can be strategically manipulated by nations with the wherewithal to do so. These results also formally rationalize some of the political-economic positions taken by various parties involved in the Kyoto process.

• We view the protocol as an incomplete contract, analogous to a constitution or a charter, that lays down general principles for determining future emission rights allocations among participants without specifying the future state space and the contingent allocations.[1]

Not only does this provide a flexible paradigm for dealing with indescribable future states of the world, but also provides a framework in which various institutional arrangements and assumptions can be tried and tested. For instance, our general model embodies two basic principles. First, national sovereignty is inalienable. This view is formalized as the requirement that allocations for the protocol signatories must be self-enforcing in the Nash sense. By implicitly ruling out the existence of an international enforcer of coalitional contracts, this view eliminates the possibility of multiple coalition formation. Secondly, the decision to participate or refuse is made only at the beginning and is irrevocable. We elaborate on these issues in Section 2.

The focus of this paper is the nature of the allocation mapping and its possible manipulation, while the existing protocol literature concentrates on the participation problem. Our *general model* integrates these two problems and yet allows our questions to be asked meaningfully and independently of the participation problem. Our *special model*, which is embedded in the general model, concerns the problem of allocating emission rights among the *participants* in the protocol and the possibility of this process being manipulated.

The general model of Section 2.1 has two stages: the participation game and the allocation game. In the participation game, asymmetrically informed nations choose whether to sign the protocol or refuse, given their expectations regarding future choices by all the nations in the allocation game. In the subsequent allocation game, emission caps are allocated to the nations that sign the protocol in the participation game. We assume that the assignment of caps among the participants must be self-enforcing, which amounts to requiring that the caps have to be Nash implementable (see Maskin 1999, Osborne and

[1] We have in mind Hobbes' Leviathan, national constitutions and legal systems, charters for UN organizations and various regional groupings such as the EU, articles of association for corporations, etc. For the theoretical issues regarding the modelling of incomplete contracts, see Hart and Moore 1999, Maskin and Tirole 1999 and Tirole 1999.

Rubinstein 1994). This general model can be extended in many directions. Our special model considers one of these extensions.

The special model of Sections 2.2 and 2.3 is a two stage game. The second stage of this game coincides with the allocation game of the general model, which is now derived from a natural underlying economic structure. The analysis of this game will yield results linking the underlying economic structure to the equilibrium emission caps. The first stage of the special model involves choice of national characteristics by one of the participant nations. Given the structural model underlying the second stage allocation game, the first stage choice will have a natural interpretation as "investment". The analysis of this choice will yield our strategic manipulation results.

We end this section with some remarks connecting our model with some of the controversies regarding the Kyoto approach and some of the literature related to it.

(A) The allocation game in our model generates the caps of step (1) of the Kyoto protocol in isolation from step (2). This is necessary as the protocol views step (2) as a sovereign choice for each nation, i.e., a nation's choice of domestic allocation mechanism and the resulting allocations cannot affect step (1).

(B) Models involving coalitional analysis of international protocols (e.g., Chander and Tulkens 1992, 1995, 1997, Eyckmans 2001) require the existence of institutions that can enforce coalitional contracts and any accompanying transfers. We assume that such institutions do not exist. This view eliminates from consideration various general theoretical approaches to the modelling of coalition formation (e.g., Bernheim et al. 1987, Hart and Kurz 1983, Ray and Vohra 1997) as they rely on the possibility of arbitrary coalitions of players being able to write binding contracts. Our model embodies the view that the institutions required to enforce such contracts, say the Chander-Tulkens type transfers, on sovereign nations may not be forthcoming. This pessimism is not unjustified given the historical experience of nations being reluctant to cede sovereignty to international organizations. The assumed inability to enforce coalitional contracts also means that the class of possible coalitions in our model is severely restricted. The only potential coalition is that of the protocol signatories, with all non-signatories acting as singletons. While this may be theoretically restrictive, it is consistent with the structure envisaged under the Kyoto protocol.

(C) Our model is not intended to mime the negotiation *process* leading to emission capping. We believe that, whatever be the negotiation process, nations will not accept caps that violate the incentive constraints postulated in our model. Thus, a mimetic model of the negotiations is unlikely to uncover robust principles that cannot be gleaned from our simple model.[2] The only part of this paper that may be interpreted as miming the capping process is the best reply dynamic process considered in Section 5. As the caps generated by this process asymptotically converge to the allocations generated by our allocation game, we view the best reply dynamic not as a descriptive device, but as a computational tool for deriving equilibrium caps.

(D) Our model does not allow transfers among nations as part of the protocol because transfers distort the asymmetries that are the focus of this paper.

(E) Our model will also not take into account the possibility of post-capping emissions rights trading in the determination of the pre-trade caps. There are two reasons for making this choice. First, emission rights trading amounts to allowing transfers from buyers of such rights to the sellers, since all that a buyer gets in the bargain are emission rights, which have a positive shadow value only because the capping regime rations the quantum of such rights. Therefore, the combination of emission capping and post-capping trade is tantamount to allowing transfers, which contradicts (D). In any case, such implicit transfers are subject to the same incentive problems as explicit international transfers and it is unclear why emission capping should be used as the medium for redistributing resources. Secondly, the possibility of trading emission rights transforms them into free options with positive payoffs resulting from the positive shadow values of the scarce rights. Consequently, every nation will demand an unboundedly large allocation of emission rights. This eliminates the possibility of anchoring emission cap allocations in a systematic framework related to the distribution of resources and their sensible economic use by sovereign nations. Given the possibility of trading, the caps have to be allocated using some *ad hoc* bargaining process, a rule-of-thumb, or a normative criterion (e.g., *per capita* equality, fairness, Rawlsian maximin).

(F) Our position is not that normative criteria, such as the ones listed in (E), are irrelevant in the capping process. However, we believe that any economically sensible attempt to address normative concerns has to take into account the constraints imposed

[2] A natural game-theoretic mimetic model is a non-cooperative bargaining model. Unfortunately, apart from some very broad insights available from highly stylized and abstract models, the results from this theory are very fragile as they vary drastically with the model and bargaining protocol. For example, there are significant conceptual and technical problems in extending two-person bargaining theory to many-person bargaining theory. As there is no well-defined bargaining protocol for the capping process, we expect the results from any mimetic bargaining model to be very delicate.

by positive considerations such as those we model in this paper. More formally, we see the proper role of normative considerations as that of providing a criterion for choosing among the equilibria generated by a positive model.

(G) Emissions pose a problem because the historically given carbon stock is large, and national contributions to the current stock vary substantially. Although one ideally wants a model that addresses this stock externality problem, we restrict ourselves to the more modest future flow externality problem by implicitly assuming that the current carbon stock is accepted as a *fait accompli* by participating nations or that suitable international transfers have been made to compensate for past emissions.

(H) Our model decomposes each nation into emitting constituents and non-emitting constituents with conflicting interests. This allows us to model the *status quo* emission levels as resulting from the market solution or the business-as-usual solution. Moreover, the difference between the national interest and the interest of the national emitter yields interesting insights about the different strategic manipulations each would pursue under a capping regime.

Given the approach outlined above, we answer questions such as:[3]

• How are cap allocations related to national characteristics?

• How will autonomous growth of nations affect the distribution of emission caps in successive rounds of the allocation game? In particular, are emission levels across nations likely to converge or diverge with economic growth?

• What growth pattern will be favored by green ideologies?

• What strategic manipulations will affluent nations resort to in the allocation game?

• How will a nation's strategic choices differ from those of the firms in that nation?

• How might nations or their firms exploit the possibility of investing abroad?

1.2 Plan of paper

We set up our general model in Section 2.1 and the special model in Sections 2.2 and 2.3. The special model is a two stage game.[4] Our maintained hypotheses regarding

[3] Some of these issues were considered informally in Shah (2003) in a much more restrictive setting.

[4] Needless to say, our use of this device is not novel. However, the economic model underlying the game specification appears to be new and yields novel, natural and interesting insights regarding the possibility and directions of strategic manipulation of environmental agreements.

this game are stated in Section 2.[5] We study the second stage of the special model in Section 3. Section 3.1 contains the basic variational formulae flowing from the model and their implications. These formulae imply results regarding the ordering of national caps in Section 3.2. In Section 4, we study the first stage of the special model. Depending on the identity and decision variable of the first stage decision-maker(s), we have the socialist case (Section 4.2), the capitalist case (Section 4.3), the mixed case (Section 4.4) and the global case (Section 4.5). In Section 5, we show that, if the protocol participants use the best reply dynamic, then the resulting caps process converges to the static equilibrium allocations. We conclude in Section 6 by summarizing our results, considering some implications and suggesting extensions.

2. The models

2.1 The general model

Let N be the set of nations. Nation i's type[6] is $\theta_i \in \Theta$, where Θ is Nation i's type space. Let μ_i be the common knowledge distribution of i's type; μ_i is Nation j's belief about Nation i's type, where $j \in N - \{i\}$. Given $L \subset N$, let $\mu_L = \prod_{j \in L} \mu_j$ be the joint distribution of the types of the players in L. Let E be Nation i's action space. Nation i's preference is represented by the von Neumann-Morgenstern utility $u_i : \Theta \times E^N \to \Re$.

In Section 2.3, we interpret θ_i as a pair representing Nation i's "private capital" and "social capital"; accordingly, we will set $\Theta = \Re^2_+$. We will interpret $e_i \in E$ as Nation i's emission *cap* if i is a protocol participant. If i is a non-participant, then e_i is interpreted as Nation i's emission. As our assumptions in Section 2.3 and Proposition 2.3.6 will ensure that each participant nation's equilibrium cap is a binding constraint, we will use "emission" interchangeably with "emission cap".

The general model consists of the *participation game* followed by the *allocation game*. In the participation game, Nation i chooses a (measurable) strategy $D_i : \Theta \to \{0, 1\}$, i.e.,

5 The overly strong and omnibus nature of the hypotheses mean that we make no attempt to provide the minimal, or the most elegant, set of assumptions for our propositions. The marginal generalizations are routine. For instance, instead of simply assuming interior solutions as we have done, we could have made assumptions (e.g., Inada-type conditions) on the primitives of the model that guarantee interior solutions.

6 As is standard in incomplete information games, a player's "type" or "characteristic" is a comprehensive description of that player's private information, i.e., things known by that player but not common knowledge among all the players.

given θ_i, Nation i non-cooperatively chooses whether to participate in the protocol, denoted by $D_i(\theta_i) = 1$, or to refuse, denoted by $D_i(\theta_i) = 0$. Consequently, an outcome of the participation game is $d \in \{0,1\}^N$. Given a type profile $\theta \in \Theta^N$ and an outcome $d \in \{0,1\}^N$ of the participation game, the nations play the allocation game. The play of the allocation game determines the emissions of all the nations by the mapping $\eta : \Theta^N \times \{0,1\}^N \to E^N$.

We construct η as follows. Fix $\theta \in \Theta^N$ and $d \in \{0,1\}^N$. Let $\Lambda_j(\mu_j, d(j))$ be the posterior belief about θ_j conditional on the outcome $D_j(\theta_j) = d(j)$. Given $L \subset N$, let $\Lambda(L,d) = \prod_{j\in L} \Lambda_j(\mu_j, d(j))$ be the posterior joint distribution of the types of the players in L, conditional on their participation decisions $(D_j(\theta_j))_{j\in L} = (d(j))_{j\in L}$. If $i \in d^{-1}(0)$, then Nation i's emission is given exogenously by the mapping $\bar{e} : \Theta \to E$. If the participants, i.e., the members of $d^{-1}(1)$, implement the action profile $e \in E^{d^{-1}(1)}$, then the expected payoff of Nation $i \in d^{-1}(1)$ is

$$w_i(\theta_i, e; d) = \begin{cases} \int_{\Theta^{d^{-1}(0)}} \Lambda(d^{-1}(0), d)(dx)\, u_i\left(\theta_i, e, \bar{e}^{d^{-1}(0)}(x)\right), & \text{if } d^{-1}(0) \neq \emptyset \\ u_i(\theta_i, e), & \text{if } d^{-1}(0) = \emptyset \end{cases} \tag{2.1.1}$$

The participants jointly determine emissions as follows. An allocation $e \in E^{d^{-1}(1)}$ is proposed and each $i \in d^{-1}(1)$ non-cooperatively assents or dissents. Proposal e is an equilibrium proposal if it elicits assent from every $i \in d^{-1}(1)$, i.e.,

$$w_i(\theta_i, e; d) \geq w_i(\theta_i, e^{d^{-1}(1)-\{i\}}, b; d)$$

for every $b \in E$ and $i \in d^{-1}(1)$. This procedure generates an equilibrium mapping $e(.,d) : \Theta^{d^{-1}(1)} \to E^{d^{-1}(1)}$. Note that $e(.,d)$ is a correlated equilibrium (see Aumann 1974). Consequently, we define η as follows:

$$\eta_i(\theta, d) = \begin{cases} \bar{e}(\theta_i), & \text{if } d(i) = 0 \\ e_i(\theta^{d^{-1}(1)}, d), & \text{if } d(i) = 1 \end{cases}$$

Before proceeding further, we make some interpretative remarks. Suppose, as we will in Section 2.3, that

$$u_i(\theta_i, e) = F(\theta_i, e_i) - \Delta\left(\theta_i, \sum_{j\in N} e_j\right) \tag{2.1.2}$$

where F represents Nation i's profit and Δ represents Nation i's damage. Given this set-up, the specification of a non-participant Nation i's emission by $\bar{e}(\theta_i)$ can be rationalized as representing the business-as-usual scenario in which the domestic firms in Nation i choose national emission $e_i = \bar{e}(\theta_i)$ to maximize profit $F(\theta_i, e_i)$, instead of the state which would wish to maximize welfare $u_i(\theta_i, e)$. In effect, we are assuming that a nation's substantive choice in the participation game is between (a) maintain the *status quo* in which the domestic firms freely choose the national emission, and (b) allow the state to administer a national emission *cap* that is allocated by the protocol.

The above argument relies on the *assumption* that non-participants choose national emission e_i to maximize $F(\theta_i, e_i)$. However, this behavior can be endogenized by supplementing our model with a feature of the actual Kyoto protocol. Suppose $N = N^* \cup [0, 1]$, where N^* is a finite set of 'large' polluting nations[7] and $[0, 1]$ represents a continuum of uniformly distributed 'small' polluting nations. Then, (2.1.2) is modified to

$$u_i(\theta_i, e) = F(\theta_i, e_i) - \Delta\left(\theta_i, \sum_{j \in N^*} e_j + \int_0^1 dx\, e(x)\right) \qquad (2.1.3)$$

Suppose also that the protocol comes into force if and only if every nation in N^* participates in the protocol. Given these assumptions, if every nation in N^* participates in the protocol, then every non-participant nation will be 'small' by definition. It is clear from (2.1.3) that every non-participant Nation $i \in [0, 1]$ will choose $e_i = \bar{e}(\theta_i)$ to maximize profit $F(\theta_i, e_i)$ as we have postulated, because Nation i's choice has no effect on the total emission. Indeed, even the 'small' nations that choose to participate will behave in the same manner. Given the supplementary assumptions used in this argument, we interpret our modelling and analysis of the allocation game in Sections 2.2 and 2.3 as pertaining to an outcome d of the participation game such that $N^* \subset d^{-1}(1)$, i.e., a situation in which the protocol comes into force because all the 'large' nations choose to participate.

Unlike the non-participants, who act atomistically, the participants act as a team that chooses a *joint* emission plan $e(., d)$. As is evident from the construction of $e(., d)$, we require that the plan should be Nash implementable, with *participating nations*, instead of their domestic firms, being the relevant decision-makers regarding national emission caps. The correlation of actions by the plan is represented by the fact that the equilibrium choices of Nation $i \in d^{-1}(1)$ depend on the types of *all* the participants.

[7] These correspond roughly to the Annex I nations in the Kyoto protocol. The congruence between the two sets is not perfect as two 'large' nations, namely China and India, are not Annex I nations. Indeed, this lacuna is one of the alleged reasons for the US being unwilling to ratify the protocol.

The assumption of private values is crucial for the postulated correlation of emission caps. Given the postulated allocation procedure and private values, the incompleteness of information among the participants is immaterial in the allocation game, although heterogeneity does affect outcomes. Without private values, the presumed assent of other players to an equilibrium proposal would allow a player to update his belief about the payoff-relevant types of the other players. This "learning" may invalidate the equilibrium status of a proposal. With private values, the types of the other participants are not payoff-relevant. Therefore, even if a player updates and learns from the presumed assent of other participants, this updating of beliefs is payoff-irrelevant.

The assumption that emission caps for the participants are recommended *publicly* is necessary and sufficient for our construction of η and the use of correlated equilibrium to be meaningful. On the contrary, if (a) the recommendations are made privately, (b) the private recommendations "respect" every nation's private information, i.e., the mapping generating each nation's recommended action is "measurable" with respect to that nation's private information, and (c) the mapping generating the recommendations is common knowledge, then the appropriate solution concept is a Bayesian equilibrium (see Osborne and Rubinstein 1994). We have opted for the former solution concept to describe the outcomes of the allocation game as publicly announced proposals seem a more accurate description of international agreements.

Returning to the formal specification of the general model, Nation i's payoff in the participation game, anticipating η as the generator of actions in the allocation game, and conditional on θ and d, is $u_i(\theta_i, \eta(\theta, d))$. Given a profile of strategies $(D_j)_{j \in N}$, $d_i \in \{0, 1\}$ and $\theta \in \Theta^N$, let

$$U_i(\theta_i, D^{N-\{i\}}, d_i) = \int_{\Theta^{N-\{i\}}} \mu_{N-\{i\}}(dx) u_i\left(\theta_i, \eta\left(\theta_i, x, d_i, D^{N-\{i\}}(x)\right)\right)$$

The profile of strategies $(D_j)_{j \in N}$ is required to be a Bayesian equilibrium, i.e., for every $\theta \in \Theta^N$, $i \in N$ and $d_i \in \{0, 1\}$, we have $U_i(\theta_i, D^{N-\{i\}}, D_i(\theta_i)) \geq U_i(\theta_i, D^{N-\{i\}}, d_i)$.

Clearly, the above model can be extended in the following directions: (a) allow multiple rounds of the allocation game, (b) allow types to evolve across rounds, and (c) allow multiple entry and exit times with respect to the participation decision. Extension (a), in the absence of (b) and (c), turns the post-participation game into an incomplete information repeated game. Given the interpretation of types in Section 2.3, it is more natural to allow (b) as well, with the transition of types across rounds being, at least in part, endogenously determined. If types evolve and are common knowledge in each round of the allocation game (perhaps because the protocol mandates information sharing), then the post-participation game becomes a stochastic game. However, if types are not common knowledge in the various rounds of the allocation game, then the game is further complicated by the phenomenon of learning behavior by the players. Learning behavior by later entrants into the protocol is also implied by extension (c). In addition, (c) introduces obvious timing game issues.

The special allocation game of Sections 2.2 and 2.3 models one of the above-mentioned extensions: given a type profile $\theta \in \Theta^N$ and an outcome $d \in \{0,1\}^N$ of the participation game, some participating nation, say Nation 1, will be allowed to alter its type θ_1 to θ_1' before the allocation game. A number of variants of the special allocation game can be formulated, depending on who chooses θ_1'. For instance, if Nation 1 chooses θ_1', then it will choose θ_1' to maximize

$$\int_{\Theta^{N-\{1\}}} \Lambda(N-\{1\},d)(dx)\, u_1\left(\theta_1', \eta(\theta_1', x, d)\right) - C(\theta_1, \theta_1') \tag{2.1.4}$$

where $C(\theta_1, \theta_1')$ is the cost of moving from θ_1 to θ_1'. On the other hand, if θ_1' is chosen to maximize Nation 1's profit, then θ_1' will maximize

$$\int_{\Theta^{d^{-1}(1)-\{1\}}} \Lambda(d^{-1}(1)-\{1\},d)(dx)\, F_1\left(\theta_1', e_1(\theta_1', x, d)\right) - C(\theta_1, \theta_1') \tag{2.1.5}$$

2.2 The special allocation game

Fix a type profile $\theta \in \Theta^N$ and an outcome $d \in \{0,1\}^N$ of the participation game. Let $d^{-1}(1) = N = \{1,2\}$. Then (2.1.1) implies that $w_i(\theta_i, a; d) = u_i(\theta_i, a)$ for $i \in \{1,2\}$. The assumption that all nations participate involves no loss of generality in our analysis as the behavior of non-participants is exogenously given by the business-as-usual hypothesis and, by (2.1.1), it can be integrated out using the posterior belief about their types. $N = \{1,2\}$ is the minimal setting in which we can ask our questions sensibly and get sharp answers. It is possible to complicate the model with more players at the cost of having to qualify our propositions appropriately. Set $\Lambda_2(\mu_2, 1) = \lambda$, $E = \Re_+$ and $\theta_1 = 0$; $\operatorname{supp}\lambda$ will denote the support of λ. λ is Nation 1's posterior belief about Nation 2's type conditional on Nation 2 participating. Given these specifications, (2.1.4) simplifies to: choose θ_1' to maximize

$$\int_{\Theta} \lambda(dx)\, u_1(\theta_1', \eta(\theta_1', x, d)) - C(0, \theta_1') \tag{2.2.1}$$

and (2.1.5) simplifies to: choose θ_1' to maximize

$$\int_{\Theta} \lambda(dx)\, F_1(\theta_1', e_1(\theta_1', x, d)) - C(0, \theta_1') \tag{2.2.2}$$

Given these specifications, the special allocation game Γ is described as follows. $\{0,1,2\}$ is the set of players in Γ. Players 1 and 2 correspond to Nations 1 and 2 respectively. The extensive form of Γ is as follows. First, Nature chooses Player 2's type $\theta_2 \in \Theta$; λ is the common belief of Players' 0 and 1 about θ_2. In Stage 1 of Γ, given λ, Player 0 chooses Player 1's type $\theta_1 \in \Theta$. In Stage 2 of Γ, Players' 1 and 2 jointly choose the action profile $e = (e_1, e_2) \in \Re_+^2$. Given (θ_1, θ_2) and e, Player 0's payoff is $u_0(\theta_1, e)$, Player 1's payoff is $u_1(\theta_1, e)$ and Player 2's payoff is $u_2(\theta_2, e)$.

The choice of actions in Stage 2 is described by a team plan $e(., d) : \Theta^2 \to \Re_+^2$, i.e., $u_i(\theta_i, e(\theta, d)) \geq u_i(\theta_i, e_i', e^{N-\{i\}}(\theta, d))$ for every $\theta \in \Theta^2$, every $i \in \{1, 2\}$ and every $e_i' \in \Re_+$. Thus, $\eta(., d) = e(., d)$. In Stage 1 of Γ, Player 0 anticipates that the Stage 2 actions will be generated by a team plan $e(., d)$. Given belief λ about θ_2, Player 0 chooses $\theta_1 \in \Theta$ to maximize

$$\int_{\Theta} \lambda(dx)\, u_0(\theta_1, e(\theta_1, x, d)) \tag{2.2.3}$$

Given $\eta(., d) = e(., d)$, (2.2.3) coincides with (2.2.1) if we set

$$u_0(\theta_1, e(\theta_1, \theta_2, d)) = u_1(\theta_1, e(\theta_1, \theta_2, d)) - C(0, \theta_1) \tag{2.2.4}$$

i.e., θ_1 is chosen to maximize Nation 1's welfare, and (2.2.3) coincides with (2.2.2) if

$$u_0(\theta_1, e(\theta_1, \theta_2, d)) = F_1(\theta_1, e_1(\theta_1, \theta_2, d)) - C(0, \theta_1) \tag{2.2.5}$$

i.e., θ_1 is chosen to maximize Nation 1's profit.

Definition 2.2.6. *$\langle \theta_1, e \rangle$ is an equilibrium of Γ if $e : \Theta^2 \to \Re_+^2$ is a team plan for Γ and θ_1 maximizes (2.2.3).*

Let $\langle \theta_1, e \rangle$ be an equilibrium of Γ and let $\theta_1' = \theta_1^0$ maximize

$$\int_{\Theta} \lambda(dx)\, u_0(\theta_1', e(\theta_1, x, d))$$

Clearly, Player 0 prefers θ_1^0 to θ_1 *ex post*. It also represents *ex ante* strategic manipulation by Player 0 because it reflects Player 0's ability to choose the Stage 2 subgame *via* his Stage 1 choice.

2.3 Interpretation of special allocation game

In this section, we present a structural model that rationalizes the abstract special allocation model of Section 2.2. Given observation (A) of Section 1.1, it is sensible, for the purpose of modelling step (1) of the protocol, to aggregate Nation i's emitters into a national Firm i. Similarly, all non-emitting entities in Nation i are aggregated into a national Consumer i. We assume that Firm i does not suffer any production externality from global emissions but Consumer i suffers a global consumption externality. Thus, within Nation i, there is conflict between Firm i and Consumer i. This conflict may also be interpreted as the divergence between the interests of owners of polluting firms and the rest of society.

If Firm i, with private capital t_i, employs variable input v_i, then its profit is $g(t_i, v_i)$ and its emission is $h(t_i, v_i)$; since Firm i is the only emitter in Nation i, $g(t_i, v_i)$ and $h(t_i, v_i)$ are also Nation i's profit and emission respectively. The resulting total world emission $h(t_1, v_1) + h(t_2, v_2)$ is consumed by Consumers 1 and 2, thereby causing damage $\delta(k_i, h(t_1, v_1) + h(t_2, v_2))$ to Consumer (and Nation) i who has social capital k_i.

$\Theta = \Re_+^2$ is Nation i's type space. Nation i's type is given by the pair $\theta_i = (t_i, k_i)$. *Given our interpretation of types, international differences in private and social capital are the only sources of international heterogeneity.* Private capital t_i consists of all fixed inputs that embody the technology available to Firm i. Social capital k_i consists of all assets that are used to mitigate the damage caused by emissions; k_i embodies the technology available to Consumer i. Social capital includes water management systems, meteorological facilities, knowledge of the ways to cope with the effects of global warming (e.g., how farming needs to adapt to environmental changes), research facilities that generate such technologies, etc.

Prior to signing the protocol, Firm i maximizes profit $g(t_i, v_i)$ by choosing variable input $v(t_i)$. The resulting profit and emission for Nation i are $g(t_i, v(t_i))$ and $h(t_i, v(t_i))$ respectively, and Nation i's damage is $\delta(k_i, h(t_1, v(t_1)) + h(t_2, v(t_2)))$. We refer to this situation as business-as-usual or the *status quo*.

If Nation i's emission is capped at e_i, then domestic regulation imposes the constraint $h(t_i, v_i) \le e_i$ on Firm i. Suppose Firm i chooses variable input $v_i = v_c(t_i, e_i)$ to maximize $g(t_i, v_i)$ under this constraint. The resulting profit for Firm i and Nation i is $g(t_i, v_c(t_i, e_i))$, Nation i's emission is

$$h(t_i, v_c(t_i, e_i)) \le e_i \tag{2.3.1}$$

and its damage is

$$\delta(k_i, h(t_1, v_c(t_1, e_1)) + h(t_2, v_c(t_2, e_2))) \tag{2.3.2}$$

Consequently, Nation i's payoff (or welfare) is

$$g(t_i, v_c(t_i, e_i)) - \delta(k_i, h(t_1, v_c(t_1, e_1)) + h(t_2, v_c(t_2, e_2))) \tag{2.3.3}$$

If it is publicly recommended to (or agreed by) Nations 1 and 2 that they impose the emission caps e_1 and e_2 on Firms 1 and 2 respectively, then Nation 1 will implement the cap e_1 only if it maximizes Nation 1's expected payoff

$$g(t_1, v_c(t_1, e_1)) - \int_\Theta \Lambda(\mu_2, 1)(dx)\, \delta(k_1, h(t_1, v_c(t_1, e_1)) + h(t_2(x), v_c(t_2(x), e_2))) \tag{2.3.4a}$$

given e_2 as Nation 2's emission cap. Analogously, Nation 2 will implement cap e_2 only if it maximizes Nation 2's expected payoff

$$g(t_2, v_c(t_2, e_2)) - \int_\Theta \Lambda(\mu_1, 1)(dx)\, \delta(k_2, h(t_2, v_c(t_2, e_2)) + h(t_1(x), v_c(t_1(x), e_1))) \tag{2.3.4b}$$

given e_1 as Nation 1's cap. While Nation i chooses the emission cap to maximize expected national welfare, Firm i chooses the actual emission level to maximize its profit subject to the cap chosen by Nation i. In principle, constraint (2.3.1) may be non-binding, and consequently, the international emission profile can differ from the profile of caps. This divergence can complicate the modelling of emission capping as the costs and benefits of capping are generated by the actual emissions that result from capping, rather than the caps *per se*. Proposition 2.3.6 will eliminate this problem. *We assume the following throughout the rest of this paper.*

Assumption 2.3.5. *$g : \Re^2_+ \to \Re_+$ and $h : \Re^2_+ \to \Re_+$ are such that, for every $t \in \Re_+$,*

(a) $g(t, .)$ is strictly increasing upto a unique maximum at $v(t)$, and

(b) $h(t, .)$ is continuous and strictly increasing.

Moreover, $\delta : \Re^2_+ \to \Re_+$ is

(c) continuous, and twice continuously differentiable on $\Re^2_{++}$ with $D_{ke_+}\delta < 0$.[8]

[8] Throughout the rest of this paper, D is the differential operator; with appropriate subscripts, it indicates partial derivatives.

(d) *For every* $k > 0$, $\delta(k, .)$ *is strictly increasing and strictly convex.*

(e) *For every* $e_+ > 0$, $\delta(., e_+)$ *is strictly decreasing and strictly convex.*

Assumption (a) means that profit increases with variable input until the maximum is attained. Assumption (b) implies that emission increases with the variable input. Assumption (c) implies that greater social capital reduces a nation's vulnerability to damage. Assumption (d) means that a nation's damage increases at an increasing rate with global emission. Assumption (e) means that a nation's damage decreases with social capital but this beneficial effect is subject to diminishing returns.

Assumptions (a) and (b) imply that (2.3.1) is binding if and only if $e_i \leq h(t_i, v(t_i))$. Therefore, $e_i \leq h(t_i, v(t_i))$ implies the identity $h(t_i, v_c(t_i, e_i)) = e_i$. If $e_i \geq h(t_i, v(t_i))$, then $v_c(t_i, e_i) = v(t_i)$, i.e., the *status quo* prevails in Nation i.

Proposition 2.3.6. *If* $\theta_i = (t_i, k_i) \in \Theta$ *is the type of Nation* $i \in \{1, 2\}$ *and* (e_1^*, e_2^*) *is a pair of emission caps such that* $e_1 = e_1^*$ *(resp.* $e_2 = e_2^*$*) maximizes (2.3.4a) (resp. (2.3.4b)) given* $e_2 = e_2^*$ *(resp.* $e_1 = e_1^*$*), then* $e_i^* < h(t_i, v(t_i))$ *for* $i \in \{1, 2\}$*.*

Proof. We show that $e_1^* < h(t_1, v(t_1))$; $e_2^* < h(t_2, v(t_2))$ can be shown analogously. If $e_1 \geq h(t_1, v(t_1))$, then $v_c(t_1, e_1) = v(t_1)$ and (2.3.4a) yields Nation 1's expected payoff

$$g(t_1, v(t_1)) - \int_\Theta \Lambda(\mu_2, 1)(dx)\, \delta(k_1, h(t_1, v(t_1)) + h(t_2(x), v_c(t_2(x), e_2^*)))$$

which is invariant with respect to e_1. If $e_1 \leq h(t_1, v(t_1))$, then $h(t_1, v_c(t_1, e_1)) = e_1$ and (2.3.4a) yields Nation 1's expected payoff

$$g(t_1, v_c(t_1, e_1)) - \int_\Theta \Lambda(\mu_2, 1)(dx)\, \delta(k_1, e_1 + h(t_2(x), v_c(t_2(x), e_2^*))) \tag{2.3.7}$$

Differentiating the first term of (2.3.7) with respect to e_1 and evaluating the derivative at $e_1 = h(t_1, v(t_1))$, we have

$$\begin{aligned} D_{v_1} g(t_1, v_c(t_1, h(t_1, v(t_1)))) D_{e_1} v_c(t_1, h(t_1, v(t_1))) &= D_{v_1} g(t_1, v(t_1)) D_{e_1} v_c(t_1, h(t_1, v(t_1))) \\ &= 0 \end{aligned}$$

as $v_1 = v(t_1)$ maximizes $g(t_1, v_1)$. Differentiating the second term of (2.3.7) with respect to e_1 and evaluating the derivative at $e_1 = h(t_1, v(t_1))$, we have

$$-\int_\Theta \Lambda(\mu_2, 1)(dx)\, D_{e_+} \delta(k_1, h(t_1, v(t_1)) + h(t_2(x), v_c(t_2(x), e_2^*))) < 0$$

Therefore, $e_1 = h(t_1, v(t_1))$ cannot maximize (2.3.7). Since Nation 1's expected payoff is invariant with respect to e_1 for $e_1 \geq h(t_1, v(t_1))$, we have $e_1^* < h(t_1, v(t_1))$. ■

This means a team plan ensures that the protocol participants (specifically, the 'large' nations in N^*) always choose lower emission caps than their *status quo* emission levels. *Consequently, without loss of generality, we restrict attention to caps* $e_i \leq h(t_i, v(t_i))$ *for* $i \in \{1, 2\}$. The resulting identification of caps with chosen emission levels, represented by the identity $e_i = h(t_i, v_c(t_i, e_i))$ for $e_i \leq h(t_i, v(t_i))$, has a number of useful consequences.

First, it reduces the number of variables by identifying caps with emissions. Secondly, (2.3.2) is simplified to $\delta(k_i, e_1 + e_2)$ and Nation i's payoff in Stage 2 of Γ is simplified from (2.3.3) to

$$u_i(t_i, k_i, e_1, e_2) = f(t_i, e_i) - \delta(k_i, e_1 + e_2) \tag{2.3.8}$$

where

$$f(t_i, e_i) = g(t_i, v_c(t_i, e_i)) \tag{2.3.9}$$

for $i \in \{1, 2\}$. This is a vital simplification as it ensures that the private values assumption is satisfied when caps are allocated. Thirdly, a nation's preference, given by (2.3.8), is *not* monotonically increasing with respect to the national cap, for a larger (binding) cap induces greater emission by the national firm, thereby increasing the firm's profit, but it also increases the damage suffered by the national consumer. Thus, by attaching an endogenously generated shadow value to emission rights, our model prevents nations from pursuing arbitrarily large caps. Consequently, results in Section 4 asserting that a nation manipulates characteristics to increase its emission cap do not reflect a trivial desire to have an arbitrarily large amount of a free positive valued option, but a desire to have a *specific* larger cap for *strategic* reasons.

In Stage 1 of Γ, Player 0 chooses $\theta_1 = (t_1, k_1)$. We interpret Player 0 as either Nation 1 or Firm 1. We specialize (2.2.4) and (2.2.5) by setting $C(0, \theta_1) = C(0, (t_1, k_1)) = t_1 + k_1$, and use (2.3.8) to specify Player 0's payoff as

$$u_0(t_1, k_1, e_1, e_2) = f(t_1, e_1) - \delta(k_1, e_1 + e_2) - t_1 - k_1 \tag{2.3.10}$$

if Player 0 is Nation 1, and as

$$u_0(t_1, k_1, e_1, e_2) = f(t_1, e_1) - t_1 - k_1 \tag{2.3.11}$$

if Player 0 is Firm 1. We end this section with some assumptions that have technical and interpretational significance. *We assume the following throughout the rest of this paper.*

Assumption 2.3.12. *f, defined by (2.3.9), satisfies the following properties.*

(a) f is strictly increasing and strictly concave.

(b) f is continuous, and twice continuously differentiable on $\Re^2_{++}$.

If a firm has private capital t' and faces an emission cap e', then $D_e f(t', e')$ is the firm's shadow value of emission rights. The following definition classifies technology as locally clean (resp. dirty) if the shadow value of emission rights decreases (resp. increases) with increases in private capital.

Definition 2.3.13. *Technology f is dirty (resp. clean) at (t', e') if $D_{te} f(t', e') > 0$ (resp. $D_{te} f(t', e') < 0$).*

We assume the following throughout the rest of this paper.

Assumption 2.3.14. *(θ_1, e) is an equilibrium of Γ such that*

(a) $\theta_1 = (t_1, k_1) \gg 0$ and $e(\theta) \gg 0$ for every $\theta \in \Theta^2$, and

(b) Player 0 can be either Nation 1 or Firm 1.

3. Stage 2 of special model

3.1 Comparative statics

In this section we analyze the properties of the team plan $e : \Theta^2 \to \Re^2_+$ for Stage 2 of Γ. As e is a team plan, we have

$$D_{e_i} u_i(\theta_i, e(\theta)) = 0 \tag{3.1.1}$$

for $i \in \{1, 2\}$. By Assumptions 2.3.5 and 2.3.12, and (2.3.8), we have

$$D_{e_i e_i} u_i(\theta_i, e) < 0 \qquad \text{and} \qquad \det A(\theta, e) > 0 \tag{3.1.2}$$

for $i \in \{1, 2\}$ and $(\theta, e) \in \Theta^2 \times \Re^2_+$, where

$$A(\theta, e) = \begin{pmatrix} D_{e_1 e_1} u_1(\theta_1, e) & D_{e_1 e_2} u_1(\theta_1, e) \\ D_{e_2 e_1} u_2(\theta_2, e) & D_{e_2 e_2} u_2(\theta_2, e) \end{pmatrix}$$

Given a type profile $\theta \in \Theta^2$, (3.1.1) yields the formulae

$$\begin{aligned} D_{\theta_1} e_1(\theta) &= \frac{-D_{e_1 \theta_1} u_1(\theta_1, e(\theta)) D_{e_2 e_2} u_2(\theta_2, e(\theta))}{\det A(\theta, e(\theta))} \\ D_{\theta_1} e_2(\theta) &= \frac{D_{e_1 \theta_1} u_1(\theta_1, e(\theta)) D_{e_2 e_1} u_2(\theta_2, e(\theta))}{\det A(\theta, e(\theta))} \\ D_{\theta_1} e_+(\theta) &= \frac{D_{e_1 \theta_1} u_1(\theta_1, e(\theta)) [D_{e_2 e_1} u_2(\theta_2, e(\theta)) - D_{e_2 e_2} u_2(\theta_2, e(\theta))]}{\det A(\theta, e(\theta))} \end{aligned} \tag{3.1.3}$$

Given $e(\theta) = (e_1(\theta), e_2(\theta))$, let $e_-(\theta) = e_1(\theta) - e_2(\theta)$. Specializing (3.1.3) yields the effects of variations in private and social capital.

Proposition 3.1.4. *Let $\theta = ((t_1, k_1), (t_2, k_2))$.*

(A) If $D_{te}f(t_1, e_1(\theta)) < 0$, then $D_{t_1}e_1(\theta) < 0$, $D_{t_1}e_2(\theta) > 0$, $D_{t_1}e_+(\theta) < 0$ and $D_{t_1}e_-(\theta) < 0$.

(B) If $D_{te}f(t_1, e_1(\theta)) > 0$, then $D_{t_1}e_1(\theta) > 0$, $D_{t_1}e_2(\theta) < 0$, $D_{t_1}e_+(\theta) > 0$ and $D_{t_1}e_-(\theta) > 0$.

(C) $D_{k_1}e_1(\theta) > 0$, $D_{k_1}e_2(\theta) < 0$ and $D_{k_1}e_+(\theta) > 0$.

(A) (resp. (B)) means that the growth of private capital in a clean (resp. dirty) nation implies lower (resp. higher) domestic emission, higher (resp. lower) foreign emission, lower (resp. higher) global emission, and assuming $e_-(\theta) > 0$, convergence (resp. divergence) of national emissions. (C) means that the growth of social capital implies higher domestic emission, lower foreign emission and higher global emission.

3.2 Emission cap ordering

We first consider the ordering of emission caps implied by the ordering of social capital.

Proposition 3.2.1. *If $\theta = ((t, k_1), (t, k_2))$ and $k_1 > k_2$, then $e_1(\theta) > e_2(\theta)$.*

Proof. As $k_1 > k_2$, Assumption 2.3.5(c) implies $0 < D_{e_+}\delta(k_1, e_+(\theta)) < D_{e_+}\delta(k_2, e_+(\theta))$. This, together with (3.1.1), implies $\int_{e_2(\theta)}^{e_1(\theta)} dx\, D_{ee}f(t, x) = D_e f(t, e_1(\theta)) - D_e f(t, e_2(\theta)) < 0$. Assumption 2.3.12(a) implies $e_1(\theta) > e_2(\theta)$. ■

Ceteris paribus, nations with larger social capital have larger emissions. The ordering of emissions in terms of private capital is more complicated as Proposition 3.1.4 shows that the nature of technology affects the directions in which the emissions change as private capital varies.

Proposition 3.2.2. *If*

(a) $\theta = ((t_1, k), (t_2, k))$ and $t_1 > t_2$,

(b) $D_{te}f(t_1, e_1(\theta)) > 0$ and $D_{te}f(t_2, e_2(\theta)) > 0$ (resp. $D_{te}f(t_1, e_1(\theta)) < 0$ and $D_{te}f(t_2, e_2(\theta)) < 0$), and

(c) for every e', $D_{te}f(., e')$ is decreasing,

then $e_1(\theta) > e_2(\theta)$ (resp. $e_1(\theta) < e_2(\theta)$).

Proof. Suppose $D_{te}f(t_1, e_1(\theta)) > 0$ and $D_{te}f(t_2, e_2(\theta)) > 0$. (c) implies $D_{te}f(x, e_1(\theta)) > D_{te}f(t_1, e_1(\theta)) > 0$ for every $x \in [t_2, t_1]$. (3.1.1) implies $D_e f(t_1, e_1(\theta)) = D_e f(t_2, e_2(\theta))$.

Therefore,

$$\begin{aligned}\int_{e_1(\theta)}^{e_2(\theta)} dy\, D_{ee} f(t_2, y) &= D_e f(t_2, e_2(\theta)) - D_e f(t_2, e_1(\theta)) \\ &= D_e f(t_1, e_1(\theta)) - D_e f(t_2, e_1(\theta)) \\ &= \int_{t_2}^{t_1} dx\, D_{te} f(x, e_1(\theta)) \\ &> 0\end{aligned}$$

Assumption 2.3.12(a) implies $e_1(\theta) > e_2(\theta)$. The other case follows analogously. ■

If (a) both nations have the same social capital stock, (b) both nations have clean (resp. dirty) technology, and (c) technology becomes cleaner as private capital grows, then the nation with the greater private capital stock has lower (resp. higher) emission.

4. Stage 1 of special model

4.1 Set-up

In this section we consider Player 0's choices in Stage 1 of Γ. In Section 4.2 (resp. 4.3), we consider the socialist (resp. capitalist) case, in which Player 0 is interpreted as Nation 1 (resp. Firm 1) choosing domestic private and domestic social capital. In Section 4.4 we consider the mixed case when Nation 1 chooses domestic social capital while Firm 1 chooses domestic private capital. In Section 4.5 we consider the global case when Nation 1 or Firm 1 can choose foreign social and private capital.

We shall interpret the choices of capital stock as investment by normalizing the historically given stock to zero. Moreover, our piecemeal analysis of investment decisions is without loss of generality because the cost of investment is linear additive, as in (2.3.10) and (2.3.11).

4.2 The socialist case

Combining (2.2.3) and the interpretation of u_0 given by (2.3.10), Nation 1's problem is to choose (t_1, k_1) to maximize

$$\int_\Theta \lambda(d\theta_2)\, u_1(t_1, k_1, e(t_1, k_1, \theta_2)) - t_1 - k_1$$

Let (t^*, k^*) solve this problem. Given this solution, denote $e(t^*, k^*, \theta_2)$, $e_1(t^*, k^*, \theta_2)$, $e_2(t^*, k^*, \theta_2)$ and $e_+(t^*, k^*, \theta_2)$ by $e^*(\theta_2)$, $e_1^*(\theta_2)$, $e_2^*(\theta_2)$ and $e_+^*(\theta_2)$ respectively. Using

(3.1.1), (t^*, k^*) is characterized by

$$\int_\Theta \lambda(d\theta_2)\ \left[D_t f(t^*, e_1^*(\theta_2)) - D_{e_+}\delta(k^*, e_+^*(\theta_2)) D_t e_2^*(\theta_2)\right] = 1 \tag{4.2.1}$$

$$\int_\Theta \lambda(d\theta_2)\ \left[D_k \delta(k^*, e_+^*(\theta_2)) + D_{e_+}\delta(k^*, e_+^*(\theta_2)) D_k e_2^*(\theta_2)\right] = -1 \tag{4.2.2}$$

First consider the choice of social capital. Using Assumption 2.3.5(c) and Proposition 3.1.4(C), the benefits of investment in social capital are: (a) an increase in domestic profit caused by higher domestic emission, (b) lower domestic vulnerability to damage, and (c) a decrease in domestic damage on account of lower foreign emission. The costs are: (d) an increase in domestic damage caused by higher domestic emission, and (e) the opportunity cost of investment. The fact that emissions are always chosen by the team plan means that benefit (a) and cost (d) are always balanced at the margin. Thus, (4.2.2) ensures that marginal benefits (b) and (c) are balanced by the marginal cost (e). (b) is the direct benefit of investment in social capital, while (c) is the indirect or strategic benefit.

Let (t^0, k^0) be Nation 1's choice of private and social capital given the type contingent emissions $\theta_2 \mapsto e^*(\theta_2)$, i.e., $(t_1, k_1) = (t^0, k^0)$ maximizes

$$\int_\Theta \lambda(d\theta_2)\, u_1(t_1, k_1, e^*(\theta_2)) - t_1 - k_1$$

(t^0, k^0) is characterized by

$$\int_\Theta \lambda(d\theta_2)\, D_t f(t^0, e_1^*(\theta_2)) = 1 \tag{4.2.3}$$

$$\int_\Theta \lambda(d\theta_2)\, D_k \delta(k^0, e_+^*(\theta_2)) = -1 \tag{4.2.4}$$

$k^* > k^0$ (resp. $k^* < k^0$) is interpreted as strategic overinvestment (resp. underinvestment) by Nation 1 in domestic social capital. Proposition 3.1.4(C), (4.2.2) and (4.2.4) imply

$$\begin{aligned}\int_\Theta \lambda(d\theta_2)\, D_k \delta(k^0, e_+^*(\theta_2)) &= \int_\Theta \lambda(d\theta_2)\ \left[D_k \delta(k^*, e_+^*(\theta_2)) + D_{e_+}\delta(k^*, e_+^*(\theta_2)) D_k e_2^*(\theta_2)\right] \\ &< \int_\Theta \lambda(d\theta_2)\, D_k \delta(k^*, e_+^*(\theta_2))\end{aligned}$$

Thus,

$$\int_\Theta \lambda(d\theta_2) \int_{k^*}^{k_0} dx\, D_{kk}\delta(x, e_+^*(\theta_2)) < 0$$

which implies $k^0 < k^*$ as $D_{kk}\delta > 0$.

Proposition 4.2.5. *Nation 1 overinvests in domestic social capital, thereby strategically raising e_1, lowering e_2 and raising e_+.*

Now consider the choice of private capital. $t^* > t^0$ (resp. $t^* < t^0$) is interpreted as strategic overinvestment (resp. underinvestment) by Nation 1 in domestic private capital.

Proposition 4.2.6. *If $D_{te}f(t^*, e_1^*(\theta_2)) < 0$ (resp. $D_{te}f(t^*, e_1^*(\theta_2)) > 0$) for every $\theta_2 \in \operatorname{supp}\lambda$, then Nation 1 underinvests (resp. overinvests) in domestic private capital, thereby strategically raising e_1, lowering e_2 and raising e_+.*

Proof. Suppose $D_{te}f(t^*, e_1^*(\theta_2)) < 0$ for every $\theta_2 \in \operatorname{supp}\lambda$. (4.2.1) and (4.2.3) imply

$$\int_\Theta \lambda(d\theta_2)\, D_t f(t^0, e_1^*(\theta_2)) = \int_\Theta \lambda(d\theta_2)\, \left[D_t f(t^*, e_1^*(\theta_2)) - D_{e_+}\delta(k^*, e_+^*(\theta_2)) D_t e_2^*(\theta_2)\right]$$

Consider $\theta_2 \in \operatorname{supp}\lambda$. As $D_{te}f(t^*, e_1^*(\theta_2)) < 0$, Proposition 3.1.4(A) implies $D_t e_2^*(\theta_2) > 0$. Combining this with Assumption 2.3.5(d), we have $\int_\Theta \lambda(d\theta_2) \int_{t^*}^{t^0} dx\, D_{tt} f(x, e_1^*(\theta_2)) < 0$. Assumption 2.3.12(a) implies $t^0 > t^*$. The other case is analogous. ■

Since a team plan always chooses e_1 to be a best reply to e_2 *in terms of Nation 1's preference*, we have the following observation.

Remark 4.2.7. *Nation 1's strategic manipulations (see (4.2.1) and (4.2.2)) in Propositions 4.2.5 and 4.2.6 work by manipulating downwards Nation 2's emission.*

4.3 The capitalist case

Combining (2.2.3) and the interpretation of u_0 given by (2.3.11), Firm 1's problem is to choose (t_1, k_1) to maximize

$$\int_\Theta \lambda(d\theta_2)\, f(t_1, e_1(t_1, k_1, \theta_2)) - t_1 - k_1$$

Let (t^{**}, k^{**}) solve this problem. Denote $e(t^{**}, k^{**}, \theta_2)$, $e_1(t^{**}, k^{**}, \theta_2)$, $e_2(t^{**}, k^{**}, \theta_2)$ and $e_+(t^{**}, k^{**}, \theta_2)$ by $e^{**}(\theta_2)$, $e_1^{**}(\theta_2)$, $e_2^{**}(\theta_2)$ and $e_+^{**}(\theta_2)$ respectively. $(t^{**}, k^{**}) \gg (0, 0)$ is characterized by:

$$\int_\Theta \lambda(d\theta_2)\, [D_t f(t^{**}, e_1^{**}(\theta_2)) + D_e f(t^{**}, e_1^{**}(\theta_2)) D_t e_1^{**}(\theta_2)] = 1 \qquad (4.3.1)$$

$$\int_\Theta \lambda(d\theta_2)\, D_e f(t^{**}, e_1^{**}(\theta_2)) D_k e_1^{**}(\theta_2) = 1 \qquad (4.3.2)$$

Let (t^{00}, k^{00}) be Firm 1's choice of private and social capital given the type contingent emissions $\theta_2 \mapsto e^{**}(\theta_2)$. $k^{**} > k^{00}$ (resp. $k^{**} < k^{00}$) indicates overinvestment (resp. underinvestment) in social capital. Similarly, $t^{**} > t^{00}$ (resp. $t^{**} < t^{00}$) indicates overinvestment (resp. underinvestment) in private capital. Clearly, $k^{00} = 0$. Therefore, $k^{**} > 0$ represents overinvestment by Firm 1 in social capital. Copying the proofs of Propositions 4.2.5 and 4.2.6, we have

Proposition 4.3.3. *Propositions 4.2.5 and 4.2.6 hold with "Firm 1" replacing "Nation 1".*

A team plan chooses Nation 1's emission as a best reply to foreign emission in terms of Nation 1's preference, i.e., by balancing domestic profit considerations against domestic damage considerations. As Firm 1 does not take domestic damage into account, Nation 1's emission chosen by a team plan is sub-optimal from Firm 1's perspective. Moreover, unlike Nation 1, Firm 1 is indifferent to foreign emission. This immediately leads to the following observation.

Remark 4.3.4. *Firm 1's strategic manipulations (see (4.3.1) and (4.3.2)) in Proposition 4.3.3 work by manipulating upwards Nation 1's emission.*

We now ask: in what directions would Nation 1 like to perturb Firm 1's choice (t^{**}, k^{**})? Let

$$G(t,k) = \int_\Theta \lambda(d\theta_2)\, u_1(t,k,e(t,k,\theta_2)) - t - k$$

Proposition 3.1.4 and (4.3.1) imply that

$$D_t G(t^{**}, k^{**}) = -\int_\Theta \lambda(d\theta_2)\, D_{e_+}\delta(k^{**}, e_+^{**}(\theta_2)) D_t e_+^{**}(\theta_2)$$

Therefore, Proposition 3.1.4 implies

Proposition 4.3.5. *If $D_{te}f(t^{**}, e_1^{**}(\theta_2)) < 0$ (resp. $D_{te}f(t^{**}, e_1^{**}(\theta_2)) > 0$) for every $\theta_2 \in \operatorname{supp}\lambda$, then Nation 1 prefers a higher (resp. lower) level of private capital than Firm 1.*

We use (4.3.2), Proposition 3.1.4 and Assumption 2.3.5, to evaluate Nation 1's incentive for marginal domestic social investment at (t^{**}, k^{**}) as

$$D_k G(t^{**}, k^{**}) = -\int_\Theta \lambda(d\theta_2)\, [D_k\delta(k^{**}, e_+^{**}(\theta_2)) + D_{e_+}\delta(k^{**}, e_+^{**}(\theta_2)) D_k e_+^{**}(\theta_2)]$$

which cannot be signed unambiguously as an increase in Nation 1's social capital has two opposing effects on Nation 1's damage. On the one hand, it decreases domestic damage by reducing Nation 1's vulnerability to damage (the direct effect), but on the other hand, it increases domestic damage by inducing higher total emission (the indirect effect).

Remark 4.3.6. *If the direct effect is larger (resp. smaller) than the indirect effect, then Nation 1 prefers a higher (resp. lower) level of social capital than Firm 1.*

4.4 The mixed case

In this section, we consider a departure from Γ by interpreting Player 0 in a somewhat more complicated way. Instead of allowing just one actor, either Nation 1 or Firm 1, to play the role of Player 0, we now allow them to play this role jointly: Nation 1 chooses k_1 and Firm 1 chooses t_1.

Since Nation 1 and Firm 1 have divergent interests, we model the choices $(t', k') \gg 0$ as a Nash equilibrium, i.e., Nation 1 chooses $k = k'$ to maximize

$$\int_\Theta \lambda(d\theta_2)\, u_1(t', k, e(t', k, \theta_2)) - k$$

and Firm 1 chooses $t = t'$ to maximize

$$\int_\Theta \lambda(d\theta_2)\, f(t, e_1(t, k', \theta_2)) - t$$

We simplify notation by abbreviating $e(t', k', \theta_2)$, $e_1(t', k', \theta_2)$, $e_2(t', k', \theta_2)$ and $e_+(t', k', \theta_2)$ to $e'(\theta_2)$, $e'_1(\theta_2)$, $e'_2(\theta_2)$ and $e'_+(\theta_2)$ respectively. Consequently, using (3.1.1), we have

$$\int_\Theta \lambda(d\theta_2)\, [D_t f(t', e'_1(\theta_2)) + D_e f(t', e'_1(\theta_2)) D_t e'_1(\theta_2)] = 1 \tag{4.4.1}$$

$$\int_\Theta \lambda(d\theta_2)\, [D_k \delta(k', e'_+(\theta_2)) + D_{e_+} \delta(k', e'_+(\theta_2)) D_k e'_2(\theta_2)] = -1$$

Let k'', characterized by $\int_\Theta \lambda(d\theta_2)\, D_k \delta(k'', e'_+(\theta_2)) = -1$, be Nation 1's choice of social capital given $e'(\theta_2)$. Copying the analogous argument of Section 4.2, we have $k' > k''$. Let t'', characterized by $\int_\Theta \lambda(d\theta_2)\, D_t f(t'', e'_1(\theta_2)) = 1$, be Firm 1's choice of private capital given $e'(\theta_2)$. Copying the analogous argument of Section 4.3, we have the following result.

Proposition 4.4.2. *In the mixed case, Proposition 4.2.5 holds, and Proposition 4.2.6 holds with "Nation 1" replaced by "Firm 1".*

As in Section 4.3, we now ask: in what direction would Nation 1 like to perturb Firm 1's choice t'?

Proposition 4.4.3. *Proposition 4.3.5 holds in the mixed case.*

4.5 The global case

We now stretch the formalism Γ in another direction. In Γ, Player 0 chooses domestic private and social capital. Now suppose Player 0 can choose foreign private and social capital. This possibility can be easily integrated into Γ. Clearly, in the absence of a strategic effect, neither Nation 1, nor Firm 1, will invest in Nation 2.

By Proposition 3.1.4, an increase in Nation 2's social capital hurts Firm 1 by reducing its emission and hurts Consumer 1 by increasing the total emission. Thus, even with a potential strategic effect, Nation 1 will not invest in Nation 2's social capital.

Proposition 4.5.1. *Neither Nation 1, nor Firm 1, will invest in Nation 2's social capital.*

Suppose Nation 1 chooses to invest $\alpha^* \geq 0$ in Nation 2's private capital. Then, $\alpha = \alpha^*$ maximizes

$$\int_\Theta \lambda(dx)\,[f(t_1, e_1(\theta_1, t_2(x) + \alpha, k_2(x))) - \delta(k_1, e_+(\theta_1, t_2(x) + \alpha, k_2(x)))] - \alpha$$

If $\alpha^* > 0$, then we have the characterization

$$\int_\Theta \lambda(dx)\,[D_e f(t_1, e_1^*(x)) D_{t_2} e_1^*(x) - D_{e_+}\delta(k_1, e_+^*(x)) D_{t_2} e_+^*(x)] = 1 \tag{4.5.2}$$

where $e_1^*(x) = e_1(\theta_1, t_2(x) + \alpha^*, k_2(x))$, $e_2^*(x) = e_2(\theta_1, t_2(x) + \alpha^*, k_2(x))$ and $e_+^*(x) = e_+(\theta_1, t_2(x) + \alpha^*, k_2(x))$ for $x \in \Theta$.

If $D_{te} f(t_2(x) + \alpha^*, e_2^*(x)) > 0$ for every $x \in \operatorname{supp}\lambda$, then Proposition 3.1.4 implies $D_{t_2} e_1^*(x) < 0$ and $D_{t_2} e_+^*(x) > 0$ for every $x \in \operatorname{supp}\lambda$, which means (4.5.2) cannot hold. Therefore, $\alpha^* = 0$. If Nation 2's technology is dirty, then any increase in its private capital hurts Firm 1 by reducing its emission and hurts Consumer 1 by raising total emission. Thus, in this case, Nation 1 has no incentive to invest in Nation 2.

On the other hand, if $D_{te} f(t_2(x), e_2^*(x)) < 0$ for every $x \in \operatorname{supp}\lambda$, then Proposition 3.1.4 implies $D_{t_2} e_1^*(x) > 0$ and $D_{t_2} e_+^*(x) < 0$ for every $x \in \operatorname{supp}\lambda$. Consequently, it is possible that $\alpha^* > 0$. Nation 1 benefits strategically from investing $\alpha^* > 0$ in Nation 2's private capital as this raises Firm 1's profit by increasing e_1 and lowers Consumer 1's damage by decreasing e_+. Analogous arguments hold for the possibility of Firm 1 investing in t_2. Compared to Firm 1, Nation 1 has a stronger marginal incentive to overinvest in Nation 2's private capital.

Proposition 4.5.3. *If Nation 2's technology is dirty, then neither Nation 1, nor Firm 1, will invest in Nation 2's private capital. If Nation 2's technology is clean, then Nation 1 (resp. Firm 1) may choose* $t_2^* > 0$ *(resp.* $t_2^{**} > 0$*).*

5. Dynamics and stability

5.1 The dynamical system

In this section, we turn to the problem of determining equilibrium allocations given the type profile. We show that, for every type profile $\theta \in \Theta^2$, the allocations determined by the best reply tâtonnement converge to the equilibrium profile $e(\theta)$ provided the process starts sufficiently close to $e(\theta)$.

Let e be a team plan. Fix $\theta \in \Theta^2$ and let $e(\theta) = e^* = (e_1^*, e_2^*)$. We postulate the best reply dynamical system determining $e(\tau) = (e_1(\tau), e_2(\tau))$ for $\tau \in \Re_+$:

$$\begin{aligned} De_1(\tau) &= \beta_1(e_2(\tau); \theta_1) - e_1(\tau) \\ De_2(\tau) &= \beta_2(e_1(\tau); \theta_2) - e_2(\tau) \end{aligned} \tag{5.1.1}$$

where β_i is Nation i's best reply mapping. Note that $\tau \mapsto e^*$ is a steady state solution of (5.1.1). We ask: is $\tau \mapsto e^*$ a locally asymptotically stable solution of (5.1.1)? It is sufficient (Coddington and Levinson 1972, Chapter 13, Theorem 3.1) that all the roots of

$$B = \begin{pmatrix} -1 & D\beta_1(e_2^*; \theta_1) \\ D\beta_2(e_1^*; \theta_2) & -1 \end{pmatrix}$$

have negative real parts. Given the negative diagonal of B, a standard application of Hadamard's theorem guarantees this if B has a dominant diagonal. It is easily confirmed that

$$D\beta_1(e_2^*; \theta_1) = -\frac{D_{e_1 e_2} u_1(\theta_1, e_1^*, e_2^*)}{D_{e_1 e_1} u_1(\theta_1, e_1^*, e_2^*)} = -\frac{-D_{e_+ e_+}\delta(k_1, e_+^*)}{D_{e_1 e_1} f(t_1, e_1^*) - D_{e_+ e_+}\delta(k_1, e_+^*)}$$

Assumptions 2.3.5 and 2.3.12 imply $|D\beta_1(e_2^*)| < 1$ and $|D\beta_2(e_1^*)| < 1$. Thus, B has a dominant diagonal.

Proposition 5.1.2. *If* e *is a team plan, then* $\tau \mapsto e(\theta)$ *is a locally asymptotically stable solution of (5.1.1) for every* $\theta \in \Theta^2$.

6. Conclusions and extensions

We have constructed and analyzed an incomplete information model of emission capping with the objectives of deriving (a) the implications of international heterogeneity, and (b) the strategic manipulations that nations will undertake in this framework. Rather than re-state the results and interpretations stated in Sections 3 and 4, we enrich these interpretations by postulating that Nation 1 has clean technology while Nation 2 has dirty technology. Since selection of types in the model developed in this paper amounts to choosing levels of different types of investment, we are implicitly assuming that Nation 1 has the resources for investment while Nation 2 does not have such resources. Therefore, we adopt the suggestive nomenclature: Nation 1 is North (i.e., developed and affluent) and Nation 2 is South (i.e., less developed and poor). Given these conventions, we have the following broad results.

North overinvests in domestic social capital (Propositions 4.2.5 and 4.4.2), underinvests in domestic private capital (Proposition 4.2.6), and does not invest in the South (Propositions 4.5.1 and 4.5.3). The effect of all these manipulations is to raise North's emission, lower South's emission and raise the total emission. The results for the Northern firm are qualitatively similar (Propositions 4.3.3, 4.5.1 and 4.5.3) but there are differences.

For instance, the variable targeted for manipulation by North in the above cases is the Southern cap (Remark 4.2.7), while the variable targeted by the Northern firm is the Northern cap (Remark 4.3.4). Nor is the extent of manipulation the same. With respect to domestic private capital, North underinvests less severely than the Northern firm (Propositions 4.3.5 and 4.4.3), while the comparison is ambiguous in the case of social capital (Remark 4.3.6).

Neither North, nor the Northern firm, will invest in South, but private investment across nations of the North is possible (Proposition 4.5.3). The effect of investing abroad in another Northern nation is to raise the domestic emission while lowering foreign and total emission.

Our model yields some results regarding the ordering of emission caps. *Ceteris paribus*, nations with greater social capital have larger caps in equilibrium (Proposition 3.2.1). The result in terms of private capital depends on the assumption that larger private capital implies cleaner technology. Given this assumption, *ceteris paribus*, the emission caps of Southern nations are positively related to the size of their private capital, while the caps of Northern nations are negatively related to the size of their private capital (Proposition 3.2.2).

With respect to the effects of economic growth, one can have the following scenario suggested by Proposition 3.1.4(A) and (B), given plausible parametric conditions (essentially, we require that Northern social capital should be sufficiently large). Suppose North emits more than South, North has clean technology, South has dirty technology and technology becomes cleaner as private capital grows. As Northern and Southern private capitals grows, South emits more and North emits less, i.e., their emissions converge. As Southern private capital grows, so does its emission, until private capital becomes so large that Southern technology becomes clean. After this point, further growth of private capital lowers the emission cap and therefore also lowers national profit. Clearly, the only way for private capital to grow further is to loosen the binding emission cap. The only way for a nation with clean technology to do so is to invest in domestic social capital. Thus, *investment in social capital is not merely a desirable end in itself, but also a strategic way of gaining head-room for the growth of private capital.*

The growth of Southern private capital raises total emission, while the growth of Northern private capital lowers total emission. It follows that a "green" who wishes to minimize total emission will favor private investment (i.e., growth) in the North and not in the South. This observation points to a political conflict between the objectives of green lobbies and the developmental ambitions of the South.

The model we have studied is intended to be a positive representation of the outcomes of the capping process, while much of the discussion about this issue tends to have a strong normative tendency. As in all such policy issues, the two strands need to be harnessed together: prescriptions need to be tempered by implementability constraints. While our positive model is a means for understanding these constraints and working out some broad implications, normative considerations can easily and properly be accommodated.

A team plan represents the positive aspect of the model since it models the minimal constraints on emission cap profiles that sovereign nations will accept. However, there can be numerous team plans with varying implications for the distribution and total quantum of caps. We need a normative criterion, i.e., a team welfare function, in order to rank various team plans. Given such a criterion, it is possible to find an optimal team plan. Note that our results apply equally to *all* team plans, including the optimal one with respect to the team welfare function.

Such a framework organizes the controversies regarding emission capping into the following categories. First, there can be debate about the normative criterion to be used in choosing a team plan. For instance, international politics will determine the extent to which green concerns advocated by environmental groups and egalitarian concerns advocated by groups in the South will be incorporated in the team welfare function. Secondly, there can be discussion about how abstract concepts such as "damage", "private capital", "social capital", etc., are to be defined operationally. For example, will Northern investment in the form of "buying" and "protecting" rain forests constitute investment in social capital, and therefore, entitle the relevant Northern entity to favorable treatment in terms of emission caps? Thirdly, there can be discussion about the powers of international institutions to verify national types, monitor actions and provide incentives.

We finally make some informal remarks regarding the implications of emission rights trading in the context of our model; it is straightforward to formalize this discussion. The emission cap allocations in our model represent an equilibrium when the decision-makers regarding caps are nations. By construction, each nation's emission cap is a binding constraint on that nation's firm, i.e., in the absence of emission rights trading, all the options to emit will be exercised. As each national firm's payoff differs from that of the nation, there exist potential gains from trade in emission rights among the national firms because of the variation in shadow values of emission rights across national firms. If emission rights trading among national firms is permitted, then the post-trade allocation of emission rights must be preferred to the pre-trade allocation by each national firm since each national firm has the option of not trading. Not only do all the national firms prefer the post-trade allocation, so do all the nations because, while all the national firms are better off, each national consumer is indifferent as the aggregate emission is unchanged. So, it appears that emission rights trading is welfare-enhancing and ought to be permitted. However, if this possibility is common knowledge and foreseen at the time the caps are negotiated, then all the nations will take into account the possibility of mercantile profits, and therefore demand arbitrarily large caps in the negotiations. This, of course, undermines the very foundation of the capping regime which creates the potential gains from trade that translate into mercantile profits. Thus, in the context of our model, there is a fundamental tension between (a) the desire to anchor emission caps in a systematic economic allocation framework, and (b) the desire to exhaust all potential gains from trade after the caps are awarded. This tension is analogous to that in the contracting literature between the desire to design a contract that provides appropriate *ex ante* incentives to the contracting parties and the desire to eliminate *ex post* inefficiencies *via* renegotiation of contracts.

There remain to study a number of aspects of the general model presented here. First, it remains to study the participation game. Secondly, it is of interest to understand the link between team welfare criteria and team plans. Thirdly, it remains to consider a multi-round extension of the allocation game so that a full dynamic analysis is possible. Finally, it would also be of interest to relax the assumption of one-time, simultaneous and irrevocable participation decisions. This would introduce into the model considerations such as optimal timing and the option value of delay.

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