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Tradable tagged permit system for global pollution control

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Abstract

We propose a new tradable permit system, called "tradable tagged permit system" (TTPS), which is specifically geared to global environmental issues of long-term dynamics. This is an extended emission permit system composed of various types of permits, one for each country or class of countries. It induces countries to reveal their damages, in addition to the costs, through their permit prices. It is shown that this achieves a Pareto-superior outcome than without the system, and that the repeated application of this scheme converges to the global first-best steady state. A numerical analysis with empirical data shows that TTPS achieves most of the potential gains from global cooperation, even with an initial allocation scheme based on voluntary pledge levels that gives participation incentives for all countries. © 2001 Society for Policy Modeling. Published by Elsevier Science Inc.

Keywords: Tradable permit; Global warming; Dynamic game

1. Introduction

Global environmental issues such as global warming, ozone depletion, and acid rain are emerging as crucial factors in the new world order. In this post-Cold War era, the global efforts to address these issues often depend more on incentive-based multilateral negotiations rather than on the logic of power politics. In the

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relative absence of centralized governance infrastructure on global issues, this multilateral consensus-building process often necessitates emission control instruments that are distinct from those designed for domestic or local applications.

There exist many economic instruments that could be employed in global emission reduction including global emission taxes, external offsets, and internationally tradable emission permits. "Among these, the system of tradable emission rights (tradable entitlements) came in for the most attention and was considered to be most promising. It offers the advantages of flexibility, efficiency in pollution abatement, direct control of total emission levels, a mechanism for trading reduction in different gases, and incentives for research into pollution abatement technology" (IPCC/WGIII-II/Doc.3, IPCC Response Strategies Working Group Report). A number of other studies that have examined the options for implementing an agreement on reducing CO_2 emissions have concluded that a tradable entitlement system is one of the most promising approaches (Epstein & Gupta, 1990; Grubb, 1989; OECD, 1992; UNCTAD, 1992, 1995, etc.).

Most of the theoretical and empirical findings on tradable permit systems, however, have been focused on domestic and static environments. Due to the inherent characteristics of international environmental issues such as the global warming problem under long-term climate change dynamics, the mere application of the conventional tradable single-type permit system seems inappropriate.

In this paper, we propose a new tradable permit system, as one of property rights systems to address the public bad problem, which we believe is more suitable to long-term, international environmental problems. In light of commonly recognized drawbacks of conventional tradable permit systems, particularly in the global or international contexts, the new system should be able to accommodate the following:

1. Unfortunately, conventional permit systems explicitly consider only the polluters, not the pollutees. International environmental issues involve nations that are simultaneously polluters as well as pollutees. Depending upon the level of economic growth, the geophysical characteristics, and sociocultural settings, each nation could have varying perceptions on pollution and the resultant damages. Thus, in the new system, the aspects of pollutee as well as of the polluter of each nation should be brought into the picture.
2. Even though conventional permit systems are known for their cost-effectiveness in meeting an emission reduction target, equity among parties is not well addressed. In the international context, however, the equity issue is far more significant. In this regard, we need an economic instrument that assures "Pareto superiority," so that an unambiguous improvement in welfare and voluntary incentives for participation are ensured for all of the parties concerned. Under the conventional permit systems, though there are possibilities for assuring the Pareto criterion by an appropriately chosen rule of initial allocation of permits, there is no general rule to guarantee the criterion. This raises the difficult bargaining problem of determining the

initial allocation rules. Due to this difficulty, the incentives for voluntary participation are not well guaranteed in conventional systems, leaving many nations to be external free riders.

3. Under the conventional permit system, global target emission levels are established by an international negotiation process, possibly in each period, but incur a significant bargaining cost for long-term dynamic environmental problems. Considering the difficulties of multilateral bargaining, it seems to be more desirable to design a system that is comprised of an endogenous target adjustment process, as well as an intertemporal permit allocation scheme, both being decentralized.

What is the core idea of this new system? It is rather simple. Unlike conventional *single-type* permit systems, our proposed system involves *multiple types of permits*, one type of permit for each country or each group of similar countries (e.g., a group of island countries, nations with economies in transition, or EU countries). In a theoretical sense, the fundamental idea of the use of multiple types of permits ("*tagged permits*") could be drawn from *Lindahl equilibria* (Lindahl, 1919), *Coase's bargaining model* (Coase, 1960), or *Arrow's externality market* (Arrow, 1970). What we do here is to transform these abstract concepts into an implementable global or international tradable permit system.

2. Tradable tagged permit system (TTPS)

In this section, we present a formal description of the basic model and introduce the concept of the TTPS.

2.1. Basic formulation and preliminary results

Suppose that there are m participating countries emitting a single pollutant, say CO_2. Each country's emission is denoted by x_i ($i = 1,2,\ldots,m$). Let $x = \sum_{k=1}^{m} x_k$ and $x_{-i} = \sum_{k \neq i} x_k$. The countries have benefit and damage functions $B_i(x_i)$ and $D_i(x)$, $B_i(x_i) > 0$, $B_i''(x_i) < 0$, $D_i''(x) > 0$, $D_i'(x) > 0$. The benefit function quantifies benefits arising from the use of the environment for production and consumption activities. The damage perceived by each country is a function of the global total — a case of perfect mixing.

2.1.1. No-intervention emission profiles

Let us first look at the no-intervention case where each country acts in self-interest in the absence of a permit system. Given the emission level of other countries, say x_{-i} (the sum of emissions from all other countries), country i will maximize its benefit minus its damage:

$$\max_{x_i} B_i(x_i) - D_i(x_i + x_{-i}).$$

Solving this for each country simultaneously yields an equilibrium emission level, x_i^{N}. Then, this *no-intervention Nash equilibrium solution* $(x_1^{\mathrm{N}}, \ldots, x_m^{\mathrm{N}})$ will satisfy:

$$B_i'(x_i^{\mathrm{N}}) - D_i'(x_i^{\mathrm{N}} + x_{-i}^{\mathrm{N}}) = 0, \text{ for all } i. \tag{1}$$

2.1.2. Global first-best emission profiles

The globally most desirable ("first-best") emission profile is one that maximizes the sum of welfares (benefit minus damage) of all countries. Then, the *first-best solution*, say $(x_1^{**}, \ldots, x_m^{**})$, should satisfy the following first-order condition (Eq. (2)):

$$B_i'(x_i^{**}) - \sum_{j=1}^{m} D_j'(x_j^{**} + x_{-j}^{**}) = 0, \text{ for all } i. \tag{2}$$

One can easily verify that $\sum_k x_k^{**} < \sum_k x_k^{\mathrm{N}}$, that is, in the absence of the permit system, the total global emission quantity tends to be more than is globally desirable.

Theoretically at least, this first-best solution can be obtained if country i is levied a linear tax/subsidy at the rate of $\sum_{j \neq i} D_j'\left(\sum_k x_k^{**}\right)$, which is the sum of the marginal damages of all countries except itself in the first-best solution.

2.2. The concept of the TTPS

Instead of a single type of permit under conventional tradable permit systems, here we allow multiple types of permits, one type tagged for each country: When there are m countries, as is in our case, m types of permits are issued, allocated, and traded, and therefore m price signals are generated from m markets of permits.

The purpose of discriminating permits according to individual countries is to provide them a means to reveal their damages, as well as benefits, through their permit prices. For this, we allow each country the right to issue permits of its own type so that each country has its own price-setting power in the permit market.[1] The preferences of individual countries are revealed by the discriminated permit prices set by themselves.

Since each country is given multiple types of permits, we need to specify how each country's emission is limited by the permits held. We simply ask each country to emit no more than the least amount of permits among all types held. Let h_{ij} be the quantity of type j permits held by country i. Country i is allowed to emit less than or equal to $\min_j\{h_{ij}\}$. In other words, if a country wants to emit 1 ton of pollutant, it should retain at least a 1-ton equivalent of permits for *all* types:

[1] This implies that each country has a sufficiently large amount of permits for its own type, and therefore it would take price-setting behavior in the permit market for its own type. In fact, each country has monopoly (or monopsony) power in the permit market for its own type.

$h_{ij} \geq x_i$ for all j. As a matter of fact, a *permit bundle*, composed of one unit of every permit type, authorizes the right to emit a unit of the pollutant. This means that each country is allowed to emit the pollutant only if all of the (participating) countries agree on the pollution: *a unanimity rule*.

Another main feature of TTPS is that, instead of using controversial global emission targets and initial allocation rules, TTPS starts with rather generous initial permit allocations. The permits of all types are initially allocated rather sufficiently based on the business-as-usual development needs (presumably by developing and the least developed countries) or on self-pledges (possibly by developed countries). In this way, we can assure wide participation, since at worst each participating country is granted the status quo.

For the rigorous analysis in the next section, we present a formal description of the game rule of TTPS. TTPS could be modeled as a three-stage game: the initial allocation stage, price setting stage, and permit trading stage:

1. *Stage 0: Initial allocation stage.* An international agency issues m types of permits, one type for each country. The permits issued for "country i" are to be called "type i permits." As a benchmark scenario, we analyze TTPS under a *grandfathering rule* of initial allocation: At the starting point, country i has the tagged permits by the amount of x_i^{N} (no-intervention emission quantity) for all types. In addition, each country is given the right to issue additional permits for its own type.
2. *Stage 1: Price setting stage.* Each country simultaneously announces a buy-back price (reward rate) for permits of its own type.[2]
3. *Stage 2: Permit trading stage.* Given the set of buy-back permit prices, each country simultaneously determines its own emission level, as well as the amount of permits (of all types) to buy or sell. Each country is allowed to emit no more than the least amount of permits among all types held (the *unanimity rule*).

3. Analysis of TTPS: Single-period game

As mentioned in Section 1, TTPS is designed to apply to long-term dynamic environmental problems. A pedagogical illustration of the results under a single-period game situation is appropriate in order to make the concept of TTPS more easily understood.

Assuming the initial permits are allocated by the above-mentioned grandfathering rule,[3] TTPS can be described essentially as a two-stage game: the first is

[2] This does not imply that a country can only buy back permits of its own type; countries can also sell permits of its own type. The results in this paper are valid through such kinds of trades. The term "buy-back price" is used for the sake of simplicity in explaining the TTPS concept.

[3] An allocation procedure by voluntary pledge levels will be considered in the empirical analysis in Section 5 under a dynamic context.

a permit price (reward rate) setting stage and the second is a permit trading stage. To derive a subgame perfect equilibrium (by *backward induction*), we first examine the problem at Stage 2, where each country determines how much to emit with given permit prices. The price of "type i permit" is denoted by p_i. Let $p_{-i} = \sum_{k \neq i} p_k$.

3.1. Country i's problem in Stage 2

In the absence of a permit system, each country will choose an emission level so that its benefit minus its damage is maximized. With TTPS introduced, however, each country is subject to additional financial transactions from permit trades. At Stage 2, country i is given the permit prices offered in Stage 1, and determines its own emission level so that the sum of its benefit minus its damage and the net revenue from permit trades is maximized:

$$\max_{x_i, h_{ik}, \forall k} B_i(x_i) - D_i(x_i + x_{-i}) - p_i \cdot \sum_{k \neq i}^{m} (x_k^{\mathrm{N}} - h_{ki}) + \sum_{k \neq i}^{m} p_k \cdot (x_i^{\mathrm{N}} - h_{ik})$$

subject to $h_{ik} \geq x_i, \forall k$.

The third term denotes the cost of buying back "spare" permits of other countries (i.e., rewards to be paid) and the fourth term represents rewards to be received from other countries for its permit savings. Under the nonnegativity of permit prices, the optimality condition ensures that country i will hold permits of other countries only as much as needed, that is, $h_{ij} = x_i$ for all $j \neq i$. With this and using the notations given earlier, the formulation can be simplified as

$$\max_{x_i} B_i(x_i) - D_i(x_i + x_{-i}) - p_i \cdot (x_{-i}^{\mathrm{N}} - x_{-i}) + p_{-i} \cdot (x_i^{\mathrm{N}} - x_i),$$

and results in the optimality condition

$$B_i'(x_i) = D_i'(x_i + x_{-i}) + p_{-i}.$$

The above condition implies that under TTPS each country behaves as if it faces a tax rate, p_{-i}, the sum of permit prices of other countries. Let $x_i^*(p)$ denote the optimal emission level of country i at Stage 2, given permit prices, $p = (p_1, \ldots, p_m)$. Then, $x_i^*(p)$ is a response function of country i, that is, equilibrium emission profiles are functions of permit prices. Then, the equilibrium condition in Stage 2 can be rewritten as

$$B_i'(x_i^*(p)) = D_i'(x_i^*(p) + x_{-i}^*(p)) + p_{-i}. \tag{3}$$

3.2. Country i's problem in Stage 1

Now at Stage 1, all participating countries solve for the buy-back prices reflecting response functions $\{x_i^*(\cdot)\}$ of other countries given from Stage 2 as follows:

$$\max_{p_i} C_i(x_i^*(p)) - D_i(x^*(p)) - p_i \cdot (x_{-i}^{\mathrm{N}} - x_{-i}^*(p))$$
$$+ p_{-i} \cdot (x_i^{\mathrm{N}} - x_i^*(p)), \text{ for each } i.$$

Combining the optimality condition for the above problem with Eq. (3), we get the following condition for the Nash equilibrium permit prices, $p^* = (p_1^*, \ldots, p_m^*)$:

$$p_i^* = D_i'(x^*(p^*)) + \left[x_{-i}^{\mathrm{N}} - x_{-i}^*(p^*)\right] \Big/ \frac{\partial x_{-i}^*(p^*)}{\partial p_i}, \text{ for each } i. \tag{4}$$

Thus, a *subgame perfect equilibrium* in the two-stage game of TTPS is composed of the equilibrium emission decisions $(x_1^*(p^*), \ldots, x_m^*(p^*))$ and the permit prices $(p_1^*, \ldots, p_m^*)$ satisfying Eq. (4).

Conceptually, the Pareto superiority is trivial, since each country at the outset is given permits of all types as much as needed (at the no-intervention level), guaranteeing the status quo at worst. We present the formal assertion on the Pareto superiority with its proof presented in Appendix A.

Theorem 1: At a subgame perfect equilibrium under TTPS with the initial allocation of permits at the no-intervention levels, the total emission level is lower and every country is better off under TTPS than under the no-intervention case.

Of course, this Pareto superiority of TTPS is what will motivate more countries to participate in this new permit system, and global emissions can be reduced under TTPS, though not quite yet to the global first-best level. The performance of TTPS, however, is not clear in comparison with other policy instruments such as conventional permits or emission taxes. In particular, we cannot say whether TTPS is superior to the conventional permits systems in general environments. We can only say that TTPS gives incentives to trade permits to achieve potential gains as long as they are not exhausted. In fact, the essential characteristic of TTPS is its potential to induce parties to trade permits until the full potential gains are realized. In the following section, we show that the global first-best outcome can be attained using the dynamic model analysis of TTPS with a permanent duration of permits.

4. Dynamic model analysis

In this section, we present the dynamic version of TTPS, and show that the repeated application of TTPS could bring about the global first-best outcome in a dynamic game with *stock pollutants* (as in the case of CO_2).

4.1. Dynamic model with stock pollutants

Countries play a dynamic game with an infinite time horizon. Damages are assumed to be functions of a stock (accumulated emission), rather than a flow, of the pollutant. It is further assumed here that the damage and the cost curves are stationary. Here are some notations:

x_i^t: emission level (and thus the amount of permits held) of country i in period t. Let $x^t = \sum x_i^t$,

S^t stock of the pollutant in period t,

$D_i(S)$
damage of country i in a period when the pollution stock is S,

$B_i(x_i)$
a single period benefit of country i when its emission is x_i.

We also assume that the stock of the pollutant follows the state equation, $S^{t+1}=\gamma S^t+x^t$, where $1-\gamma$ is a natural purification rate with $0<\gamma<1$. Then, country i's welfare in period t is $B_i(x_i^t)-D_i(S^t)$ and the discounted welfare of country i over the infinite horizon becomes

$$\sum_{t=1}^{\infty} \delta^{t-1}\left[B_i(x_i^t) - D_i(S^t)\right],$$

where δ is a common discount factor, $0<\delta<1$. This is a fairly standard formulation that characterizes games of private provisions of public good and dynamic resource games, as being special cases in this matter.

Before analyzing the dynamic TTPS, we examine the global first-best solution that maximizes the total of the countries' welfare. This is achieved by a dynamic programming recursive relation:[4]

$$U(S) = \max_{x_1,\ldots,x_m}\left\{\sum_{i=1}^{m} B_i(x_i) - D_i(S) + \delta U(\gamma S + x)\right\},$$

where $x = \sum_i x_i$, and $U(S)$ is the present value of the global welfare over an

[4] Note that due to the stationary structure of the game, we eliminate the notation t since the optimal value function does not depend on time but depends only on the state variable, S.

infinite planning horizon under cooperative control strategies, given the initial pollutant stock S. The dynamic programming recursive relation indicates that the value function is derived by choosing an optimal set of emissions of all countries and can be described as the sum of the benefit minus the damage in a period and the discounted value of welfare from the next period. The discounted value of welfare starts with a stock level that periodically changes according to the state equation, $S^{t+1} = \gamma S^t + x^t$.

Combining the optimality conditions with respect to x and the envelope theorem, the steady-state stock, and emission levels, $\overline{S}^{**}$ and $\overline{x}^{**}$ such that $\overline{S}^{**} = \gamma\overline{S}^{**} + \overline{x}^{**}$, turn out to satisfy Eq. (5):

$$B_i'(x_i^{**}) - \frac{\delta}{1-\gamma\delta}\sum_k D_k'(\overline{S}^{**}) = 0, \text{ for each } i. \tag{5}$$

In other words, the global first-best steady-state stock and emissions are such that the marginal benefit from emissions is equal to the world total of the discounted sum of marginal damages starting from the next period.

4.2. Dynamic version of TTPS

Under TTPS with an infinite time horizon, the participating countries are assumed to play a two-stage simultaneous-move game in each period. We assume *permanent life of permits*. Note that the countries have no incentives to emit less than the amount of permits they hold in each period. The assumption of permanent life of permits is equivalent to the *intertemporal grandfathering* rule for permit allocation in which the initial endowment of permit bundles in each period is set equal to its actual emission from the previous period. With this observation, we can replace the initial allocation in the single period game (no-intervention emissions) by the previous period's actual emission (actual amount of permits held) and write the *discounted payoff* of each country over the infinite horizon as follows:

$$\sum_{t=1}^{\infty} \delta^{t-1}\left[B_i(x_i^t) - D_i(S^t) - p_i^t \cdot (x_{-i}^{t-1} - x_{-i}^t) + p_{-i}^t \cdot (x_i^{t-1} - x_i^t)\right],$$

where p_i^t is the price of "type i permit" in period t.

The strategy profile for each country is a set of decision rules composed of its price offer and its choice of emission level in each period, as a function of the past history of the game. Of special interest for this paper are *stationary Markovian strategies* in which the past influences current play only through its effect on a payoff-relevant state variable that summarizes the direct effect of the past on the current environment. A stationary Markovian strategy is a strategy of a country that does not depend on time (t) as well as the history of game. A *stationary Markov perfect equilibrium* (MPE) is a set of stationary Markovian strategies of all countries, each of which is a best response to other countries' stationary Markovian strategies. Though there are many possible equilibria of this dynamic game, we focus our attention to the stationary MPEs that are renegotiation-proof and subgame perfect (Fudenberg & Tirole, 1992).

We eliminate the notation t and introduce vector notation for expositional conveniences. We substitute x_i for x_i^{t-1}, p_i for p_i^t, y_i for x_i^t and define $\mathbf{x} \equiv (x_1, \ldots, x_m)$, $\mathbf{p} \equiv (p_1, \ldots, p_m)$, $\mathbf{y} \equiv (y_1, \ldots, y_m)$. Keeping in mind that the initial permit endowment in a period is set by the emissions of the previous period, we can interpret x as a vector of initial endowments and $\mathbf{y}$ as a vector of actual emissions. Let us define the payoff function of country i in a single period:

$$U_i(S, \mathbf{x}, \mathbf{p}, \mathbf{y}) \cong B_i(y_i) - D_i(S) - p_i \cdot (x_{-i} - y_{-i}) + p_{-i} \cdot (x_i - y_i).$$

Similar interpretations are valid as in the static analysis except when the damage comes from the stock of pollution.

Since a period game is composed of two stages, we need two strategy functions for each country. At Stage 1, the payoff-relevant state variables that affect the countries' (price setting) decisions are the pollution stock (S) and the initial endowment vector ($\mathbf{x}$). Therefore, the strategy function of country $\boldsymbol{i}$ at Stage 1 can be described as $p_i(S,\mathbf{x})$: Each country observes the current level of the pollution stock S and the permit endowments x (the emissions in the previous period), and sets the permit price of its type, at Stage 1 in each period. At Stage 2, however, the permit prices ($\mathbf{p}$) also affect the countries' decisions on permit trade and emission control. So we can allow the strategy function of country $\boldsymbol{i}$ at Stage 2 to be $y_i(S,\mathbf{x},\mathbf{p})$.

The analysis and computation of stationary MPEs could be achieved by two dynamic programming equations corresponding to the two stages in our case. Let $V_i(\cdot)$ and $W_i(\cdot)$ be the optimal discounted payoffs (value functions) of country i at Stage 2 and Stage 1. We can utilize the following recursive relations of dynamic programming to derive steady-stage conditions:

$$V_i(S, \mathbf{x}, \mathbf{p}) = \max_{y_i}\{U_i(S, \mathbf{x}, \mathbf{p}, \mathbf{y})$$

$$+\delta W_i(\gamma S + y, \mathbf{y})\}, \text{ for each } i \text{ (Stage 2)}$$

$$W_i(S, \mathbf{x}) = \max_{p_i} V_i(S, \mathbf{x}, \mathbf{p}), \text{ for each } i \text{ (Stage 1)}.$$

Combining the optimality condition of Stage 2 with respect to y_i and the optimality condition of Stage 1 with respect to p_i, and further applying the envelope theorem, we get the following steady-state conditions for country i where $\mathbf{S}$, $\mathbf{p}$, and $\mathbf{y}$ are the steady-state pollutant stock level, permit prices, and emission levels, respectively, such that $\overline{S} = \gamma\overline{S} + \overline{y}$. (See A.2 of Appendix A for the detailed algebraic operation.)

$$\frac{\delta}{1-\gamma\delta}\sum_k D'_k(\overline{S}) = B'_i(\overline{y}_i), \tag{6}$$

$$\overline{p}_i = \frac{\delta D_i'(\overline{S})}{(1-\delta)(1-\gamma\delta)}. \tag{7}$$

Eq. (6) indicates that at the steady state of the dynamic TTPS, the marginal benefit is equal to the global discounted sum of marginal damages, which is incidentally identical to the global first-best condition. Eq. (7) indicates that the steady-state permit price of, say, country i, is proportional to its own discounted sum of marginal damages for the infinite time horizon, multiplied by $1/(1-\delta)$ due to the infinite lifetime of permits. These personalized prices of emissions, in fact, correspond to the *Lindahlian equilibrium prices* for the public bad (pollution) in a dynamic context. We can summarize the above discussion as follows.

> *Theorem 2*: Under TTPS, the steady-state stock and emission levels in stable Markov perfect equilibria coincide with the global first-best solutions.

This is quite a significant observation, since it implies that the dynamic TTPS does *not* sustain globally inefficient steady states. As Dutta and Sundaram (1993) verified, in a noncooperative dynamic resource game (with two players), there always exists an MPE that results in an inefficient steady state. Dockner and Long (1993) derived an explicit range of steady-state pollution stocks in a quadratic game with two identical countries and showed that it contains a first-best level that can be supported by an MPE with nonlinear strategies. They argued that the emergence of first-best solutions (cooperative outcomes) does not require any institutional arrangements (threats, retaliation, etc.), but can be brought about through the use of nonlinear MPE strategies. As they pointed out, however, the problem of selecting among infinitely many pairs of nonlinear MPE strategies clearly requires some preplay communication. Moreover, their result seems to be valid only in the case of (two) symmetric players. In case of asymmetric players, say developed and developing countries in the climate change convention, just a coordination of strategies cannot support first-best solutions since some (developing) countries, without appropriate financial transfer mechanisms, may incur most of the emission reduction costs while most of the benefits from the reduction go to other (developed) countries. In this regard, TTPS could be justified as a promising institutional arrangement equipped with a financial transfer mechanism that leads to first-best steady-state outcomes without recourse to preplay negotiations or commitments to future emission strategies.

5. Illustrative empirical results: Case of global warming

We confine our attention to only CO_2, which is the most crucial greenhouse gas (GHG) from anthropogenic sources in terms of volume and contribution to

Table 1
Steady state analysis (in million tons of carbon, US$ billion)

	Canada	Germany	Italy	Japan	UK	US	China	India	Poland	CIS	Global
No-intervention Nash outcome (steady-state stock above the current level = 29.8437 CO_2 ppm)											
Emission	127.8	177.5	104.8	265.6	146.0	1236.4	506.6	137.2	116.9	977.4	3796.1
Welfare	16,370	39,842	28,089	83,816	24,920	157,937	9,603	7,785	2,201	76,940	447,503
First-best solution (steady-state stock above the current level = 23.5831 CO_2 ppm)											
Emission	114.1	167.3	99.4	256.2	134.4	1150.8	122.0	103.6	30.9	821.0	2999.8
Welfare	16,825	41,090	28,980	86,508	25,669	162,379	7663	7840	1765	78,344	457,064

global warming. As an illustrative example, let us consider a world consisting of the 10 countries that had the highest CO_2 emissions in 1989. (See Table A1 in Appendix A.) The total emission of the 10 countries covers roughly two-thirds of global emissions. In order to be able to derive MPE strategies, further restrictions must be imposed, and as usual, in this line of research, linear and quadratic approximations are postulated:

$$B_i(x_i) = a_i + b_i x_i + c_i x_i^2,\ D_i(S) = d_i S^2,\ S^{t+1} = \gamma S^t + \phi x^t,$$

where S^t is the concentration of CO_2 in the atmosphere, arising from emissions from the base period onwards, measured in tons of carbon, and ϕ is the share of CO_2 emissions that survive in the atmosphere. We let $\delta = 0.97$, $\gamma = 0.97$, and $\phi = 0.5$ as the benchmark case and employ the empirical data by Hinchy, Hanslow, and Fisher (1994) to be the parameters of benefit functions. We use Nordhaus' (1993) estimation for damage parameters, where the net economic damage from a 3°C increase in temperature is set to be a 1.33% loss of total output identically for all countries. (See Appendix A for detailed data.)

By solving a finite game with a sufficiently large time horizon, 1000 periods in this analysis, we can obtain a set of stationary MPE strategies for the no-intervention game and TTPS, and optimal control functions for the first-best solution. (For more on this methodology, refer to Hinchy et al., 1994.) The equilibrium strategy profiles are presented in Appendix A.

5.1. Steady state analysis

In Section 4, we verified that the steady state of TTPS coincides with that of the first-best solutions. Table 1 shows that the steady-state level of total emissions in the no-intervention case is 26.55% higher, and global welfare is 2.09% lower, compared with the first-best solution. Under the first-best scenario, developing countries such as China and Poland reduce their emissions by the amount of more than 70% of their no-intervention levels, while the developed countries' reductions are less than 10% of no-intervention levels. This fact implies that a global agreement on a cooperative solution needs a large amount of financial transfer from developed countries to those developing for a mutually beneficial agreement, as in the case of climate change negotiation.

5.2. Convergence of emission and stock trajectories

Figs. 1 and 2 show the total emission trajectories and CO_2 concentrations under the three scenarios. We can see that the total emissions and CO_2 concentrations under TTPS converge to the first-best solution, while in the no-intervention case they do not. Considering the long-term effects of the global warming phenomenon, the convergence of TTPS seems to be at a reasonable rate. Though we do not illustrate emission trajectories of individual countries, the

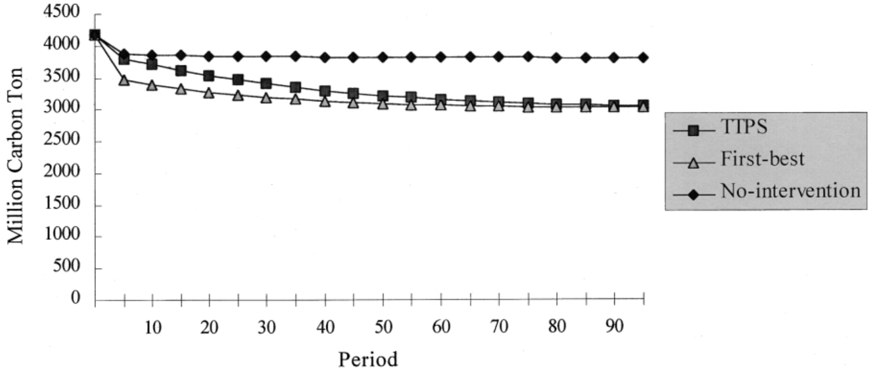

Fig. 1. Emission trajectories.

readers can verify, with the equilibrium strategy profiles given in Table A2 in Appendix A, that emissions of individual countries under TTPS also converge to the first-best solution.

5.3. *Efficiency of TTPS*

Table 2 shows the welfare of countries under four scenarios: no-intervention case, first-best solution, TTPS with the grandfathering rule, and TTPS with initial permit allocations based on voluntary pledge levels. In the last scenario, the voluntary pledge levels are attained as an equilibrium outcome of the pledge game where each country simultaneously states the amount of permits it wants to be allocated at the starting point. All countries are allocated as many permits as

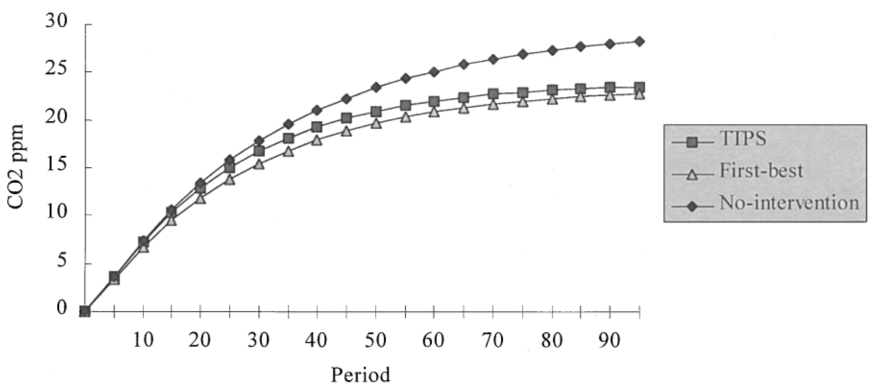

Fig. 2. Increases of CO_2 concentrations.

Table 2
Welfare analysis (US$ billion)

Scenario	Canada	Germany	Italy	Japan	UK	US	China	India	Poland	CIS	Global
No-intervention	17,142	41,723	29,413	87,769	26,097	165,413	10,171	8,152	2,305	80,571	468,756
First-best	17,323	42,252	29,793	88,922	26,408	167,197	8,902	8,139	2,023	80,973	471,932
TTPS(GF)[a]	17,463	42,035	29,760	88,044	26,417	165,652	10,386	8,452	2,583	80,797	471,588
TTPS(VP)[b]	17,449	42,037	29,751	88,074	26,409	165,690	10,378	8,435	2,565	80,818	471,606

[a] TTPS with initial allocation by grandfathering rule.
[b] TTPS with initial allocation by voluntary pledge levels.

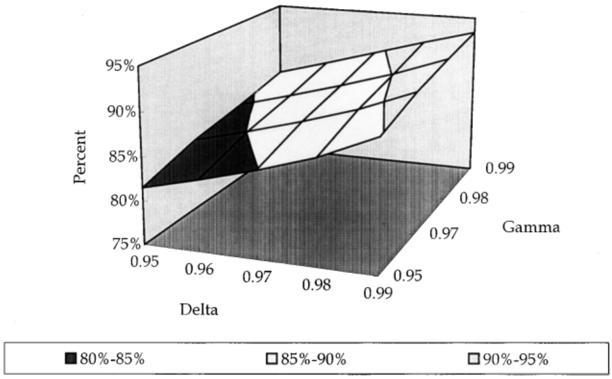

Fig. 3. Percentage of potential welfare gains achieved by TTPS.

their pledge levels and continue to play TTPS. We can see from Table 2 that TTPS achieves about 90% of total potential welfare gains, even under the voluntary pledge scheme (Fig. 3).

A sensitivity analysis indicates that the superior performance of TTPS could be sustained for a wide range of parameter values. For a reasonable range of parameter values for both δ and γ (from 0.95 to 0.99), the percentage of potential welfare gains achieved by TTPS varies from 81.5% to 93.2%. An interesting observation is that the performance of TTPs is better for higher values of δ and γ. This implies that TTPS is a policy instrument suitable for long-term dynamic environmental problems with high discount factors and low purification rates such as with the global warming or ozone depletion problem.

5.4. Equity issues and resource transfers from developed to developing countries

In consideration of equity, an interesting point from Fig. 4 is that under TTPS, the gains from trade are quite evenly distributed, and there are positive net gains for all countries, while in the first-best solution without financial transfers, some countries such as China, India, and Poland receive negative net benefits. The Herfindahl index (HI) may help us see the balance of welfare distribution.[5]

The HI of TTPS is 1022 under the grandfathering rule and 1017 under the voluntary pledge scheme (VP); this implies almost equal distribution of net welfare, while under the first-best solution, the HI rises up to 6858. Keeping in

[5] The Herfindahl index is given by $\mathrm{HI} = 10,000 \sum S_i^2$, where S_i is the market share of the i-th firm. When there are 10 identical firms in an industry, the HI is 1000. This index could be used as a good proxy measure to indicate the concentration of the benefits between individual countries.

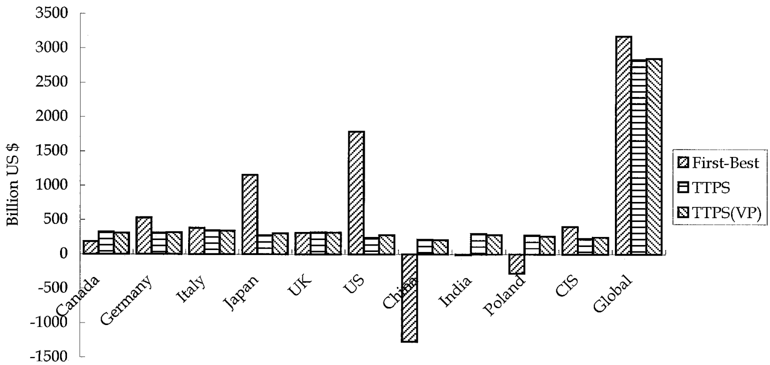

Fig. 4. Welfare increases from the no-intervention case baseline.

mind that most of the theories on equity suggest the equal sharing of additional gains as a natural focal point, this seems to be an influential incentive to induce wide participation to the global TTPS mechanism.

The balance of distribution of net benefits stems from the financial transfer process of TTPS in which developed countries with large damages set relatively high buy-back prices, and developing countries with low reduction costs cut back their emissions with financial assistance from developed countries through permit trades. Developing countries will be able to secure the capital in the form of rewards for reduced emission (or saved permits) and to use it for the implementation of environmentally friendly technologies, such as purchasing and licensing; developed countries could partially fetch the paid rewards by selling such environmentally friendly technologies. This implies that commercial technology transfer, denied by developing countries as being inequitable in climate change negotiations, is functional with much less conflict under the comprehensive structure of TTPS.

5.5. Incentive-based permit allocation, voluntary commitments, and stability of TTPS

We have seen that TTPS achieves about 90% of total potential welfare gains even with the incentive-based initial allocation scheme through voluntary pledge levels. This is a very interesting result and has important implications for real-world applications of TTPS. Under TTPS, assuming permanent life of permits, there still exists an initial allocation problem at the very starting point, such that the burden of negotiating is not eliminated. However, under TTPS with initial allocations based on voluntary pledge levels, virtually no agreements are required for initial permit allocations and furthermore, most of the total potential welfare gains are achieved in an incentive-based, decentralized manner.

Table 3
Initial permit allocations under TTPS (US$ billion)

Scenario	Canada	Germany	Italy	Japan	UK	US	China	India	Poland	CIS	Global
Voluntary pledge	161.2	183.3	127.2	218.3	169.6	1137.0	545.1	178.8	163.9	960.3	3844.7
Grandfathering	128.2	178.3	105.1	267.5	146.6	1279.0	515.1	137.7	117.2	1004.3	3878.7

By analyzing the voluntary pledge scheme, we can investigate the incentives of each country to raise its permit endowment, and forecast the negotiation process for initial permit allocation at the beginning of TTPS implementation. Table 3 indicates that the sum of self-pledge levels is, in fact, less than the sum of no-intervention emission levels, the permit endowment under the grandfathering rule. The developed countries with large GNP and therefore with large damages, such as the US and Japan, pledge their desired level of permit endowments even lower than their first-best emission levels, not to mention no-intervention levels. In this case, there are voluntary commitments to reduce emissions by developed countries. The logic behind this phenomenon is that the countries with very high damages have strong incentives to curb global emissions by way of decreasing their initial emission rights to the levels sufficient to offset increases of initial permit endowments of the other countries, particularly of developing countries. In spite of a "carbon leakage effect," as well as the large financial burden to procure the permits required to cover their emission needs, such incentives are still high under TTPS.

The voluntary pledge scheme also guarantees global participation to be a stable coalition: Each country has no incentives to deviate from global participation because the country can always find a strategy to be no worse-off under TTPS with the voluntary pledge scheme than under the case of unilateral deviation. We can design such a strategy by the following logic: (1) characterize the optimal emission trajectory in the case of unilateral action, (2) make a pledge level higher than the highest emission quantity in the trajectory, (3) follow the emission decision in the same manner as in the trajectory of (1) and discard any spare permits.

6. Summary and policy implications

We consider global pollution problems as public bad games between countries or classes of countries. We proposed a new permit system, namely, a TTPS. This is a generalized property rights system designed to be used to solve international pollution problems, where each country is considered simultaneously a pollutee as well as a polluter. The main idea is that permits should be differentiated to accommodate different countries to induce them to reveal their preferences for a cleaner environment.

For international pollution problems such as global warming and ozone depletion, perceived damages (or benefits) are often precarious and not readily quantifiable, though the cost components are less dubious. Conventional permit systems attempt to alleviate this ambiguity by ignoring this problem and focusing on the polluters' aspect rather than the pollutees'. This ignorance, however, could cause inequitable welfare distributions among participating countries, unless the system is accompanied by an appropriate transfer payment or compensation mechanism. This mechanism could be a delicate topic in multilateral negotiations, and the failure of consensus will certainly lead to threats of nonparticipation.

TTPS, however, does not require participating countries to directly reveal their damage profiles. Rather, it is up to the individual country to indirectly represent its perceived damage through its permit price (reward rate). Decentralized pricing and trading of TTPS achieve Pareto-superior outcomes when compared to the no-intervention case. Also, the risk of an inappropriate global target or global tax being set by international authorities can be mitigated under TTPS. Most importantly, the periodic application of TTPS leans toward the global first-best emission level.

With a reasonable set of data, we demonstrated a promising performance of TTPS in the global warming game. Considering the long-term effect of the global warming phenomenon, the convergence of emissions and CO_2 concentrations occurs at a reasonable rate. Most of the potential welfare gains are achieved under TTPS, even with an initial allocation of permits through the voluntary pledge scheme, and global participation can be sustained as a stable coalition. Moreover, the gains from efficient control of emissions are shared among the participating countries quite evenly so as to make it easier to induce all the countries to join TTPS, which thus serves as an equitable mechanism.

The Kyoto Protocol, approved in 1997, calls for developed countries to jointly curb their emissions of six kinds of GHGs to 5.2% below 1990 levels by the first commitment period (2008–2012). The Kyoto accord also authorizes the creation of various flexibility mechanisms containing bubble, joint implementation, clean development mechanism, and particularly international (conventional) emissions trading to help developed countries fulfill their quantitative emission limitation or reduction objectives (QELROs), which can be translated directly to an initial distribution of emission permits. It does not mention, however, about the adjustment process of QELROs for the commitment periods after 2012, and also the QELROs of developing countries even for the first commitment period. Aside from the proper working of the trading system, at least two problems need to be resolved to make the global efforts successful: First, how can we design an adjustment process of QELROs for the second or later commitment periods? Secondly, how can we mitigate the carbon leakage effect by inducing the developing countries to participate in the emission trading system with their QELROs?

The concept of TTPS could help us solve the problems equitably and efficiently. In the long term, we should make the conventional trading mechanism under the Kyoto Protocol evolve to that of TTPS so that period-by-period permit reallocations and developing countries' participation could be autonomously negotiated. With issuing multiple types of permits for the participating countries and distributing the permit bundles composed of all types of permits to each country according to the quantity of conventional permits it holds, we can assure the evolution from the conventional permit system to TTPS. Considering the complexity of TTPS, however, an international negotiation on the detailed design principle of TTPS may take longer time than on the conventional permit system.

As a transitional process for the short term, we can design a modified conventional trading system complemented by TTPS: First, each country sets the price of QELROs of other countries. Given those prices, each country chooses its QELRO in the next commitment period, and receive payments from all the other countries for the increase of its own emission reduction commitment. The QELROs of developing countries could be set from their voluntary pledge levels and adjusted through the same process. Our results on TTPS show that this would make all the participating countries better off and facilitate an adjustment towards an efficient level of global emissions. This process creates an incentive for developing countries to participate in the system with a greater amount of permit endowments at the starting point, thus, forming a system of financial transfer. The initial voluntary reduction commitments by developing countries, though it may not be enough for mitigation of global warming, will serve as a starting point for continual improvement and we could expect a notable advantage of deterring carbon leakage effect.

As well as the above-mentioned TTPS and its variations, a centralized financial mechanism could be developed from the concept of TTPS. As an example, an international financial authority, like GEF, could initiate projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of GHGs with the money from the developed countries. Any participating country can provide financial resources in proportion to the emission reduction units accruing from the project activities, but will not attain the property right for the emission reduction credits. That is, each country sets the willingness-to-pay (WTP) level for each unit of emission reduction from the projects and pays the cost of projects according to the amount of emission reductions multiplied by its WTP level. The international financial institution continues to invest in emission reduction projects as long as the sum of WTP levels from all the countries exceeds the cost of the projects. The WTP level from each country plays a role of an individualized price for tagged permits under TTPS. The larger the benefits from the reduction is for a country, the higher its share of the financial contribution to the projects will be. The ongoing process of this financial mechanism facilitates a convergence to a global first-best state.

Most of the developing countries, together with some developed countries, criticize the flexibility measures such as emissions trading, CDM, or JI in view of the environmental effectiveness because those measures do not guarantee an additional reduction of GHGs but promotes only cost-effective transaction between countries. We should note that the flexibility measures under the Kyoto Protocol were introduced to minimize overall reduction cost and not intended to reduce global emissions for environmental effectiveness. The environmental effectiveness is no less important than cost-effectiveness. But we should choose the right policy instrument fit for the objective. To improve environmental effectiveness, TTPS or its variations we discussed are more effective than the conventional emissions trading or other flexibility measures such as CDM and JI.[6]

As a final note, even though our discussion has been mostly on climate change issues, it is believed that the proposed TTPS can be used for other international issues and some domestic pollution control problems, as well as common property resource problems, where the long-term dynamics play a crucial role and where autonomous participation is the key requirement.

Appendix A.

A.1. Proof of Theorem 1

First, we will prove that $\sum_k x_k^*(p^*) < \sum_k x_k^{\mathrm{N}}$, by contradiction. Assume that $\sum_k x_k^{**} < \sum_k x_k^{\mathrm{N}} < \sum_k x_k^*$. Then, from the convexity assumption of damage functions, $D_i'\left(\sum_k x_k^{**}\right) < D_i'\left(\sum_k x_k^{\mathrm{N}}\right) < D_i'\left(\sum_k x_k^*\right)$ for all i. From Eqs. (1) and (3) and the fact that $p_{-i}>0$, we have

$$B_i'(x_i^*) \geq D_i'\left(\sum\nolimits_k x_k^*\right) > D_i'\left(\sum\nolimits_k x_k^{\mathrm{N}}\right) = B_i'\left(x_i^{\mathrm{N}}\right), \text{ for all } i.$$

This implies that $x_i^* < x_i^N$, $\forall i$ (from the concavity of benefit functions) and $\sum_k x_k^* < \sum_k x_k^{\mathrm{N}}$, which is contradiction. Therefore, $\sum_k x_k^* < \sum_k x_k^{\mathrm{N}}$.

Prior to the proof of Pareto superiority, let us show $\sum_{k\neq i} \partial x_k^*/\partial p_i < 0$: a higher price set by a country induces other countries to reduce their emissions. In order to show a contradiction, let us assume $\sum_{k\neq i} \partial x_k^*/\partial p_i \geq 0$. Differentiating Eq. (3) with p_i yields:

$$\frac{\partial x_{-i}^*(p)}{\partial p_i} = -\frac{-B_i''(x_i^*) + D_i''(x^*)}{D_i''(x^*)}\frac{\partial x_i^*(p)}{\partial p_i}, \text{ for all } i.$$

[6] Many representatives in climate change negotiations insist on imposing some constraints on the trading process of the flexibility measures, i. g., discounting the trade ratio, placing a ceiling on the trading, or conservative credit certification. We should, however, be cautious about the negative effect of these constraints, which would deter efficient trading and thus harm the efficiency of the measures.

Since $-B_i''+D_i''>0$, $\sum_{k\neq i}\partial x_k^*/\partial p_i \geq 0$ makes $\partial x_i^*/\partial p_i \leq 0$, and by rearranging the above equation, we see that $\partial x^*/\partial p_i \geq 0$. Differentiating Eq. (3) for player j with p_i yields:

$$-B_j''(x_j^*)\frac{\partial x_j^*}{\partial p_i} + D_j''(x^*)\frac{\partial x^*}{\partial p_i} + 1 = 0, \text{ for all } j \neq i.$$

The above equation says that $\partial x_j^*/\partial p_i < 0$ if $\partial x^*/\partial p_i \geq 0$, that is, $\sum_{k\neq i}\partial x_k^*/\partial p_i < 0$ if $\partial x^*/\partial p_i \geq 0$. This is a contradiction to the assumption of $\sum_{k\neq i}\partial x_k^*/\partial p_i \geq 0$.

Now, we show the Pareto superiority of the outcome. Country i is better off under the TTPS than under the no-intervention case by the amount of

$$\begin{aligned}
&\sum_{k\neq i} p_k^*[x_i^{\mathrm{N}} - x_i^*] - \int_{x_i^*(p^*)}^{x_i^{\mathrm{N}}} B_i'(x_i)\mathrm{d}x_i + \int_{\sum_k x_k^*(p^*)}^{\sum_k x_k^{\mathrm{N}}} D_i'(x)\mathrm{d}x \\
&\quad - p_i^*\sum_{k\neq i}(x_k^{\mathrm{N}} - x_k^*) \\
&\quad = \sum_k p_k^*[x_i^{\mathrm{N}} - x_i^*] - \int_{x_i^*(p^*)}^{x_i^{\mathrm{N}}} B_i'(x_i)\mathrm{d}x_i + \int_{\sum_k x_k^*(p^*)}^{\sum_k x_k^{\mathrm{N}}} D_i'(x)\mathrm{d}x \\
&\qquad - p_i^*\sum_k (x_k^{\mathrm{N}} - x_k^*) \\
&\quad > \left(\sum_k p_k^* - B_i'(x_i^*)\right)[x_i^{\mathrm{N}} - x_i^*] \\
&\qquad + \left(D_i'\left(\sum_k x_k^*\right) - p_i^*\right)\sum_k [x_k^{\mathrm{N}} - x_k^*] \\
&\quad = \left(D_i'\left(\sum_k x_k^*\right) - p_i^*\right)\sum_{k\neq 1}[x_k^{\mathrm{N}} - x_k^*]
\end{aligned} \tag{A1}$$

The last inequality comes from Eq. (3).

We rewrite Eq. (4) as follows:

$$D_i'\left(\sum_k x_k^*(p^*)\right) \leq p_i^* + \sum_{k\neq i}\left(x_k^*(p^*) - x_k^{\mathrm{N}}\right) \Bigg/ \sum_{k\neq i}\frac{\partial x_k^*(p^*)}{\partial p_i}, \text{ for all } i. \tag{A2}$$

Strict inequality holds if the permit price of type i is zero and equality holds otherwise. Due to the fact of $\sum_{k \neq i} \partial x_k^* / \partial p_i < 0$, we can see from Eq. (A2) that $D_i'\left(\sum_k x_k^*(p^*)\right) < p_i^*$ if and only if $\sum_{k \neq i}(x_k^*(p^*) - x_k^{\mathrm{N}}) > 0$, and vice versa. This implies that the last term in Eq. (A1) is greater than or equal to zero and completes the proof.

Table A1
Basic data for analysis

	CO_2 emission (1989, million tons)	GNP (1989, US$ billion)	$-a_i$	$-b_j$	c_i
Canada	134.1	542.4	309.9	3.57	0.0139
Germany	189.7	1321.9	756.5	6.22	0.0174
Italy	110.9	930.5	544.2	7.24	0.0344
Japan	284.6	1775.9	1592.6	8.70	0.0162
UK	155.4	826.3	475.7	4.71	0.0160
US	1361.2	5200.8	2994.3	3.39	0.0013
China	609.6	398.3	188.1	0.52	0.0005
India	147.9	258.4	146.1	1.60	0.0058
Poland	124.5	72.5	40.8	0.54	0.0023
CIS	1067.3	2535.0	1494.1	2.04	0.0010
Total	4185.2	13,862.0	8542.3	38.53	0.1088

Source: Hinchy et al., 1993.

A.2. Proof of Theorem 2

Let $\hat{y}_i(S,\mathrm{x},\mathrm{p})$, $\hat{p}_i(S,\mathrm{x})$ be a strategy profile of country i in an MPE. The optimality condition of $\hat{y}_i$ gives

$$B_i'(\hat{y}_i) - p_{-i} + \delta[W_i^S(\gamma S + \hat{y}, \hat{\mathrm{y}}) + W_i^i(\gamma S + \hat{y}, \hat{\mathrm{y}})] = 0, \tag{B1}$$

where $W_i^S(S,\mathrm{y}) = \partial W_i(S,\mathrm{y})/\partial S$ and $W_i^j(S,\mathrm{y}) = \partial W_i(S,\mathrm{y})/\partial y_j$. The above equation enables us to take $\hat{y}_i = \hat{y}_i(S,\mathrm{p})$. From the optimality of $\hat{p}_i$, we get

$$[\hat{y}_{-i} - x_{-i}] + \sum_{k \neq i} \Big[\hat{p}_i + \delta[W_i^S(\gamma S + \hat{y}, \mathrm{y})$$

$$+ W_i^k(\gamma S + \hat{y}, \hat{\mathrm{y}})]\Big] \frac{\partial y_k}{\partial p_i} = 0 \tag{B2}$$

Let $\overline{S}$, $\overline{p}_i$, and $\overline{y}_i$ be the stock, permit price, and emission quantity at steady states. Then,

$$\overline{S} = \gamma\overline{S} + \overline{y}, \overline{p}_i = \hat{p}_i(\overline{S}, \overline{\mathrm{y}}), \overline{y}_i = \hat{y}_i(\overline{S}, \overline{\mathrm{p}}) \text{ for all } i. \tag{B3}$$

Table A2
Coefficients of equilibrium strategies

	Canada	Germany	Italy	Japan	UK	US	China	India	Poland	CIS	Global
k_i**	122.90	174.33	103.00	263.79	142.08	1244.89	366.70	124.72	84.07	943.35	3569.83
l_i**	−1.7606	−1.4065	−0.7114	−1.5107	−1.5295	−18.8250	−48.9451	−4.2194	−10.6402	−24.4725	−114.0210
k_i^N	128.19	178.29	105.08	267.52	146.58	1280.41	515.37	137.67	117.21	1005.20	3881.52
l_i^N	−0.0675	−0.1315	−0.0468	−0.2968	−0.0894	−6.9544	−1.3798	−0.0771	−0.0550	−4.4014	−13.4998
k_i^0	143.97	181.84	111.10	250.60	157.24	1156.65	546.01	166.51	158.39	967.30	3839.62
k_i^S	1.1227	0.1545	0.3604	−1.4606	0.7163	−11.2156	1.9159	2.2003	3.2479	−3.9544	−6.9126
k_i^1	18.4468	−2.1321	−1.3330	−1.9022	−2.3799	−11.5472	−33.0094	−4.9524	−9.4741	−16.5934	−64.8769
k_i^2	−2.5231	16.4441	−1.2381	−1.7382	−2.2183	−11.2026	−32.7693	−4.6920	−9.1557	−16.2719	−65.3650
k_i^3	−2.0525	−1.5622	10.3660	−1.2977	−1.7832	−10.3153	−32.1544	−4.0013	−8.3255	−15.4461	−66.5723
k_i^4	−2.5785	−2.0266	−1.2682	17.4874	−2.2695	−11.3108	−32.8447	−4.7743	−9.2559	−16.3728	−65.2139
k_i^5	−2.5877	−2.0347	−1.2732	−1.7987	17.1425	−11.3288	−32.8571	−4.7879	−9.2725	−16.3896	−65.1876
k_i^6	−4.1797	−3.4316	−2.1105	−3.3024	−3.7412	34.2353	−35.5278	−7.2781	−12.5486	−19.9721	−57.8568
k_i^7	−4.2316	−3.4854	−2.1235	−3.3981	−3.7892	−15.9975	23.1200	−7.4367	−12.9239	−20.7138	−50.9797
k_i^8	−3.3827	−2.7337	−1.6992	−2.5438	−3.0105	−12.9963	−34.0257	26.4779	−10.7823	−17.9509	−62.6472
k_i^9	−3.9480	−3.2287	−1.9937	−3.0781	−3.5292	−14.4143	−35.0247	−6.8899	31.5236	−19.2873	−59.8702
k_i^{10}	−4.2413	−3.4861	−2.1399	−3.3663	−3.7974	−15.4201	−35.7089	−7.3915	−12.7342	31.5948	−56.6909
l_i^0	5.3198	4.6843	5.7121	3.6058	5.0767	−3.3071	23.5056	5.8095	8.8273	3.2773	62.5113
l_i^S	−0.0636	−0.0200	−0.0491	0.0658	−0.0482	0.2237	−0.0599	−0.0734	−0.0794	0.0673	−0.0369
l_i^1	0.01090	−0.00194	−0.00210	−0.00167	−0.00203	−0.00294	−0.00831	−0.00219	−0.00287	−0.00424	−0.01738
l_i^2	−0.00209	0.01106	−0.00213	−0.00170	−0.00205	−0.00293	−0.00831	−0.00220	−0.00287	−0.00423	−0.01744
l_i^3	−0.00216	−0.00205	0.01116	−0.00178	−0.00213	−0.00293	−0.00832	−0.00224	−0.00288	−0.00423	−0.01755
l_i^4	−0.00208	−0.00195	−0.00211	0.01127	−0.00204	−0.00293	−0.00831	−0.00219	−0.00286	−0.00423	−0.01743
l_i^5	−0.00208	−0.00196	−0.00212	−0.00169	0.01097	−0.00293	−0.00831	−0.00220	−0.00287	−0.00423	−0.01742
l_i^6	−0.00197	−0.00182	−0.00194	−0.00156	−0.00191	0.01073	−0.00822	−0.00218	−0.00295	−0.00433	−0.01615
l_i^7	−0.00195	−0.00180	−0.00192	−0.00154	−0.00189	−0.00294	0.00686	−0.00216	−0.00290	−0.00414	−0.01438
l_i^8	−0.00201	−0.00188	−0.00201	−0.00161	−0.00196	−0.00298	−0.00831	0.01084	−0.00289	−0.00428	−0.01708
l_i^9	−0.00198	−0.00184	−0.00196	−0.00158	−0.00193	−0.00304	−0.00829	−0.00218	0.01056	−0.00433	−0.01657
l_i^{10}	−0.00197	−0.00182	−0.00194	−0.00156	−0.00191	−0.00306	−0.00816	−0.00219	−0.00296	0.00971	−0.01585

Differentiating $W_i(S,\mathrm{x})$ with each argument and applying the envelop theorem yields

$$W_i^S(\overline{S},\overline{\mathrm{x}}) = \frac{D_i'(\overline{S})}{1-\gamma\delta},\ W_i^i(\overline{S},\overline{\mathrm{x}}) = -\overline{p}_{-i},\ \text{and}\ W_i^j(\overline{S},\overline{\mathrm{x}}) = \overline{p}_i,\ \text{for}\ j \neq i, \tag{B4}$$

at steady states. Inserting conditions (B3) and (B4) into the two optimality conditions (Eqs. (B1) and (B2)), gives

$$\frac{\delta \sum_k D_k'(\overline{S})}{1-\delta\gamma} = B_i'(\overline{y}_i),\ \overline{S} = \gamma\overline{S} + \overline{y},\ \overline{p}_i = \frac{\delta D_i'(\overline{S})}{(1-\delta)(1-\gamma\delta)},\ \text{for all}\ i,$$

which implies the first-best condition.

A.3. Data for analysis in Section 5

The coefficients of damage functions are estimated as follows: $D_i(S) = 0.133\cdot\mathrm{GNP}_i(\mu S/3)^2$, where μ is the conversion parameter from emission stock to temperature, set to be 0.0000047 in this analysis so that a doubling of CO_2 concentration results in 3 °C increase of earth temperature.

A.4. Equilibrium strategies in Section 5

Basic forms of linear stationary strategies:

1. Optimal control strategy in first-best solution: $x_i^{**}(S) = k_i^{**} + l_i^{**} S$
2. MPE strategy in no-intervention scenario: $x_i^{\mathrm{N}}(S) = k_i^{\mathrm{N}} + l_i^{\mathrm{N}} S$
3. MPE strategy in TTPS:
   (a) Emission strategy: $\hat{k}_i(S,\mathrm{p}) = k_i^0 + k_i^S S + \sum_{j=1}^{m} k_i^j p_j$
   (b) Pricing strategy: $\hat{p}_i(S,\mathrm{x}) = l_i^0 + l_i^S S + \sum_{j=1}^{m} l_i^j x_j$.

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Note to Table A2:
Coefficients for stock variables, l_i^{**}, l_i^{N}, k_i^S, and l_i^S are multiplied by 10,000.

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