Int Tax Public Finance (2008) 15: 430–459
DOI 10.1007/s10797-008-9074-z

Global trading of carbon dioxide permits with noncompliant polluters

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Abstract An international mechanism intended to curb global carbon dioxide emissions, mirrored after the Kyoto Protocol, is composed of decentralized regulatory and enforcement authorities and two supranational agencies that are in charge of promoting international transfers and imposing punitive fines. Regulatory enforcement is costly and imperfect. Polluting firms located in various sovereign nations may not comply with emission regulations. We show that there is a combination of decentralized emission quotas and centralized income transfers and fines, with decentralized leadership in policy making, which induces regional regulatory authorities to internalize all environmental and pecuniary externalities.

Keywords Carbon dioxide · Permits · Compliance · Enforcement · Pollution

JEL Classification H41 · H77 · K42

1 Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC),[1] which entered into force on February 16, 2005, provides the foundation

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[1] The UNFCCC entered into force on March 21, 1994. It sets an overall framework for intergovernmental efforts to combat climate change and the adverse effects.

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for the development of the first global carbon emission permit market.[2] The industrialized members of the Protocol are to be legally bound to meet their greenhouse gas emission reduction targets over the period of 2008–2012 and will use a mechanism called emissions trading to trade carbon emission permits among them.[3]

The literature on cost efficiency of tradable emission permit programs teaches us that competitive global carbon emission permit markets have the potential of minimizing aggregate abatement costs given a global emission reduction target.[4] However, the literature typically concentrates on cost minimization and ignores the impacts of climate damage on policy formation. After Nordhaus (1991) first combined benefits (avoided climate damage) and costs to estimate the optimal degree of carbon emissions control, scientific papers began to emerge not only on integrated quantitative assessments of both benefits and costs of climate policy,[5] but also on designing Pareto-efficient international climate policy mechanisms for the goal of overall welfare maximization through international emissions trading.

The studies by Chichilnisky and Heal (1994), Chao and Peck (2000), and Manne and Stephan (2005) inform us that, when policy making takes into account nonmarket climate damage (e.g., biodiversity loss) as well as monetary climate damage (e.g., lower crop yields),[6] the Pareto-efficient level of global carbon emissions generally depends on the pattern of income distribution across regions. International income transfers are, therefore, needed for competitive global permit markets to operate Pareto efficiently.[7]

This interrelation of Pareto efficiency and distribution motivates Caplan et al. (2003) to link international emissions trading with a branch of the fiscal federalism literature that studies efficient income redistribution and provision of public goods generating interregional spillovers. They demonstrate that interregional income transfers implemented after regional choices of emission quotas will lead to Pareto-efficient

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[2] The idea of tradable pollution permits is originated in Coase's (1960) idea of creation of property rights for the correction of negative externalities. Dales (1968) first proposed emissions trading in the context of water pollution control. In the United States, the Acid Rain Program under Title IV of the Clean Air Act Amendments of 1990 (CAAA) initiated the first large-scale use of a market-based system for controlling sulfur dioxide emissions. For development and empirical evaluation of the SO_2 emission permit market, see, e.g., Joskow et al. (1998) and Burtraw and Palmer (2003). For earlier US experiences with tradable permits, see Hahn (1989).

[3] The Kyoto Protocol aims to reduce the anthropogenic emissions of six main greenhouse gases: Carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. All other gases are measured in units of carbon dioxide according to their global warming potentials.

[4] See Montgomery (1972) for a rigorous theoretical treatment on cost efficiency of emissions trading.

[5] Great uncertainties are involved in assessing benefits and costs of climate policy, especially climate benefits. For the current state of benefit estimation of climate policy, see Jacoby (2004). For integrated assessment models using cost-benefit analysis, see Nordhaus and Boyer (2000).

[6] In economics of climate change, monetary damages are usually modeled by a production externality, i.e., global carbon emissions enter production functions; nonmarket damages are usually modeled by a consumption externality, i.e., global carbon emissions enter utility functions.

[7] As demonstrated by Chao and Peck (2000), and Manne and Stephan (2005), Pareto efficiency and income distribution are separable if carbon emissions generate production externality only. See Chichilnisky et al. (2000) for discussions on how to allocate a fixed total of carbon emission permits across regions to achieve Pareto-efficient allocations of resources through international emissions trading in the presence of consumption externality.

allocation of global resources because the transfers induce each region to choose a quota that internalizes all environmental externalities caused by its region's carbon emissions.[8] Caplan et al. (2003) envisioned that a supranational authority, such as the Global Environmental Facility (GEF),[9] would implement the necessary interregional income transfers.

A key shortcoming of Caplan et al. (2003) is that in their setting regulatory enforcement is costless. Hence, polluters perfectly comply with environmental regulations. However, due to sovereignty issues, it is not unreasonable to postulate that at the launch of the global market each nation will withhold the right to police market participants located within national boundaries. As monitoring technologies will likely vary substantially across participating nations, so will monitoring costs and compliance rates. One should not, therefore, ignore the possibly perverse effects that decentralized costly enforcement may have on the allocation of resources for the global economy.

Indeed, the available results of the literature on the cost efficiency of tradable permit programs up to date inform us that we should be quite pessimistic. Following Malik (1990), a number of authors have shown that the least cost property of tradable permit systems may not hold when enforcement is imperfect.[10] Some have designed cost-efficient enforcement strategies.[11] None, however, analyzes overall welfare maximization through international emissions trading with costly enforcement in complex institutional settings such as ours.[12] We allow for a diverse number of institutional authorities to play important roles on the allocation of resources for the global economy. These authorities are decentralized (regional) regulatory and enforcement agencies and two centralized, supranational authorities that are in charge of promoting international transfers and imposing punitive fines. Taking both benefits and costs of policy making into account, we examine the optimal assignment

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[8] Silva and Zhu (2008) demonstrate that this result holds irrespective of the type of the environmental externality being considered.

[9] The GEF was established by the World Bank, the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP) in 1991 for financing policy measures dealing with global environmental problems. It is currently operating the financial mechanism of the Kyoto Protocol.

[10] For example, Malik (1992) found that tradable permit systems may require higher enforcement plus abatement costs than uniform emissions standards. Keeler (1991) showed that a tradable permit system can result in greater noncompliance than a system of uniform standards, depending on the shape of the penalty functions.

[11] Stranlund and Dhanda (1999) studied how a budget-constrained enforcement agency aimed at minimizing aggregate noncompliance should distribute monitoring and enforcement efforts among heterogeneous, noncompliant polluting firms in a competitive permit market. Stranlund and Chavez (2000) and Chavez and Stranlund (2003) addressed the problem of designing monitoring and enforcement strategies that generate perfect compliance with minimal abatement and enforcement costs for a perfectly competitive permit system and for one in the presence of market power, respectively.

[12] Our analysis will focus on monitoring and enforcing compliance of private-sector polluters. The problem of enforcing national commitments under the Kyoto Protocol will not arise in our framework. Readers interested in the formation and stability of international environmental agreements could see, e.g., Hoel (1992), Carraro and Siniscalco (1993), Barrett (1994), Weikard et al. (2006) and others; for a survey, see, e.g., Finus (2003). More generally, readers can refer to Sandler (1992, 1997, 1998) for the important issue of collective action in the control of international transboundary pollution and the provision of other global public goods.

of responsibilities over monitoring and enforcement as well as decisions on carbon emission quotas juxtaposed to centralized income transfers, a task that has not been previously undertaken in the literature.

Recognizing that regulatory and enforcement decentralization enhances the chance that a global climate policy scheme will be accepted by sovereign nations, the first question we shall ask is: In the presence of noncompliant polluters, will decentralization of regional emission quotas, inspection efforts, and fines lead to a socially optimal allocation of resources if we allow a supranational authority to implement interregional income transfers after it observes the regional policy commitments of quotas and fines?[13,14] The answer is negative. The regional governments' choices of fines are bounded from above by the noncompliant polluters' profits. Such nonbankruptcy constraints are nevertheless affected by changes in permit prices brought about by changes in any region's policy making. As each regional authority makes its policy choices in full anticipation of the income redistribution policy implemented by a supranational authority, but subject to its single regional nonbankruptcy constraint, each regional authority does not acknowledge the pecuniary external effects that its choices have on every other region's nonbankruptcy constraint. A social planner would be constrained by all regional nonbankruptcy constraints, and hence would certainly account for the pecuniary externalities in solving its constrained maximization problem. Since previous studies did not study the problems associated with decentralized choices of enforcement strategies subject to endogenous nonbankruptcy constraints, the failure of decentralized authorities to internalize pecuniary externalities did not arise.[15]

With inefficiency stemming from decentralized fines, it becomes logical to ask the following question next: If we allow a supranational authority to choose fines and keep all the other features of the model intact, is there an institutional setting whereby the equilibrium allocation of resources is socially efficient?[16] We answer this question by examining three different types of interregional climate policy schemes. It

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[13] Silva and Zhu (2008) show that the GEF's transfer policy does not induce regional regulators to internalize externalities if the transfers are implemented prior to regional policy making. To avoid this inefficiency resulting from the timing of transfers, in this paper, we will assume that the income transfer policy takes place after regional policy making as in Caplan et al. (2003).

[14] We do not assume that enforcement agencies can credibly precommit to probabilities of inspection. As we will discuss later, this enables us to study time consistent choices of inspection efforts.

[15] Scitovsky (1954) demonstrates that pecuniary externalities are not by themselves impediments to efficiency. However, pecuniary externalities have significant, real welfare consequences when there exist distortions in the economy (e.g., from distortionary taxes, technological externalities, incomplete market, incomplete information, etc.), as pointed out by Greenwald and Stiglitz (1986). The pecuniary effects present here are exemplified in Greenwald and Stiglitz (1986), where the self-selection competitive equilibrium is Pareto-inefficient because the self-selection constraints are affected by relative prices.

[16] An example of centralized monetary punishment for carbon emission violation is the uniform fine set by the European Union's Greenhouse Gas Emissions Trading Scheme. The penalty for a firm in violation is EUR 40 for each ton of carbon emission violation during the period 2005–2007 and will be EUR 100 during the period 2008–2012. In our model, we analyze how the centralized authority may determine efficient monetary punishment on private sector polluters for each Kyoto participating nation. The fines, in general, would be differentiated across nations due to differences in the polluters' financial constraints. To facilitate compliance with national emission reduction commitments under the Kyoto Protocol, both monetary and nonmonetary penalties will be imposed on noncompliance. The Enforcement Branch of the Compliance Committee for the Kyoto Protocol, adopted in 2001 Marrakesh Accords, will not only apply

becomes clear then that the answer depends on the timing of choices of fines and quotas. In all three policy schemes, the GEF implements interregional income transfers as the last mover in policy making. When regional regulators set quotas before a centralized authority (say, the UNFCCC) decides on fines, they fully anticipate the impacts of their choices on fines and transfers. They are then induced to choose quotas that maximize global social welfare. In the other two policy schemes, regional regulators move after or simultaneously with the UNFCCC. These two policy schemes yield identical but inefficient allocations of global resources. Each regional regulator fully acknowledges the effects of his choice of regional emission quota on global income, but neglects the effects of his choice on *all* regions' nonbankruptcy constraints.

In this paper, we explicitly consider time consistency problems for the enforcement agencies in the design of enforcement policies. This is a critical departure from the standard approach utilized in the literature (see, e.g., Stranlund and Chavez 2000; Chavez and Stranlund 2003).[17,18] Rather than commit to a probability of inspection, enforcement agencies with rational expectations will adjust inspection efforts to zero in face of perfect compliance of firms, which would then make perfect compliance behavior irrational from the perspective of polluting firms. Hence, a pure strategy equilibrium with perfect compliance of polluters is time inconsistent. We show that the rational expectation equilibrium must involve mixed strategies if fines can be set sufficiently high or enforcement costs are sufficiently low: The enforcement agencies conduct inspections so that firms are indifferent between being compliant or noncompliant because their costs of purchasing permits are equal to their expected penalty for violation.

This paper is organized as follows. Section 2 builds the basic model. Section 3 describes the behavior of the market participants when polluters may choose to be noncompliant. Section 4 characterizes the socially optimal regulations. Section 5 presents four interregional climate policy schemes with different extents of decentralization and different timings of regional policy instruments. We model the policy schemes as games played by the interregional authorities and the regional regulators. Game 1 in Sect. 5.1 describes complete decentralization of regional policy instruments. All three games in Sect. 5.2 feature centralized fines and decentralized regional emission

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a 30% monetary penalty on a Party that fails to meet its emissions target (i.e., for every ton of emissions by which a Party exceeds its target in the current compliance period, 1.3 tons will be deducted from its emissions allocation for the subsequent compliance period), but will also bar the Party from selling permits until it has demonstrated that it will meet the target in the next period. As mentioned in footnote 12, the issue of enforcing national compliance with emission reduction targets does not arise in our framework, where regions decide on their own regional emission quotas in anticipation of redistributive transfers. It will nonetheless be our future work to examine the implications of such stiff monetary and nonmonetary sanctions imposed on nations as part of the compliance regime.

[17] For a classic discussion of time consistency problems, see Kydland and Prescott (1977). See, e.g., Laffont and Tirole (1996a, 1996b) for discussions of the effects of such problems on investment and innovation decisions of compliant polluters trading through permit markets.

[18] In this respect, our analysis is similar to that in Grieson and Singh (1990) and Mookherjee and Png (1995), who consider costly enforcement of regulation of a negative externality. However, in these two papers, the negative externality is only corrected through the use of inspections and fines but not with other policy instruments, e.g., permits. Their framework is insufficient for the design of policy making at interregional and regional levels for efficient international emissions trading. Furthermore, they do not explore the role of the polluters' endogenous wealth constraints in policy design.

quotas. In Sect. 5.2.1, the regional regulators choose quotas prior to the UNFCCC setting fines. In Sect. 5.2.2, the timing for the game is reversed, with the UNFCCC moving first. In Sect. 5.2.3, the UNFCCC and the regional regulators move simultaneously. Section 5.3 discusses our assumptions for the existence of mixed strategy equilibria of the inspection games. Section 6 concludes the paper.

2 Basic model

Imagine a global economy with J politically autonomous regions and governments, $J \geq 2$, indexed by j, $j = 1, \ldots, J$. There are two globally traded consumption goods, an industrial good whose production generates carbon dioxide emissions and an agricultural good whose production is negatively affected by carbon dioxide emissions. Let the agricultural good be taken as numeraire, and let p denote the relative price of the industrial good.

The industrial sector in region j is competitive and is composed of a large number of identical producers. Let N_j be the (fixed) number of industrial producers in region j. Each producer produces $h^j(\bar{x}_j)$ units of the industrial good with $\bar{x}_j$ units of the agricultural good. The production function h^j[19] is assumed to be decreasing and strictly concave in $\bar{x}_j$. Define $\overline{X}_j \equiv N_j \bar{x}_j$ as region j's total demand for the agricultural input in the production of the industrial good. Region j's production function for the industrial good is denoted as $H^j(\overline{X}_j) \equiv N_j h^j(\overline{X}_j / N_j)$. Hence, region j's industrial product is $Y_j = H^j(\overline{X}_j)$.

For simplicity, we assume that the production of one unit of the industrial good generates one unit of the emission of carbon dioxide. Letting E be the global quantity of carbon dioxide emitted into the atmosphere through industrial production, we have $E \equiv \sum_{j=1}^{J} Y_j$.[20]

The agricultural sector in region j is also competitive and has A_j (fixed) identical producers. Agricultural production is harmed by global atmospheric concentration of carbon dioxide emissions. Each producer produces $g^j(\bar{y}_j, E)$ units of the agricultural good with $\bar{y}_j$ units of the industrial good, $\bar{y}_j \leq 0$. g^j is assumed to be decreasing in both $\bar{y}_j$ and E and strictly concave. Define $\overline{Y}_j \equiv A_j \bar{y}_j$ and $G^j(\overline{Y}_j \sum_{i=1}^{J} H^i(\overline{X}_i)) \equiv A_j g^j(\overline{Y}_j / A_j, \sum_{i=1}^{J} H^i(\overline{X}_i))$. Region j's agricultural product is $X_j = G^j(\overline{Y}_j, \sum_{i=1}^{J} H^i(\overline{X}_i))$.

Region j is populated by n_j identical and immobile consumers. Each consumer derives utility from consumption of x_j units of the agricultural good and y_j units of the industrial good: $U^j(x_j, y_j)$.[21] We assume that the utility function is increasing in both arguments, quasi-concave and twice continuously differentiable.

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[19] We use superscripts to index functions throughout the text.

[20] For discussions on the technology of public supply aggregation, see, e.g., Cornes (1993) and Sandler (1992, 1998).

[21] As indicated by Silva and Zhu (2008), our results are not affected if carbon emissions enter the utility function.

All regions participate in a competitive global emission permit market.[22] The regional government in region j, called 'regulator j' hereafter, sets a quota of Q_j units of CO_2 emission permits and distributes the permits equally among the consumers in that region. The industrial producers are required to hold an emission permit for each unit of carbon emissions they release. Denote the global CO_2 emission permit price as s, $s \geq 0$.

To enforce compliance on the part of the industrial producers in region j, I_j random inspections are conducted by a regional enforcement agency who can accurately verify the producers' compliance status. A fine of F_j will be imposed on each unit of emission violations. The fine is determined by regional regulator j or an interregional authority, and is announced prior to any inspection. We assume that there are no costs associated with levying fines. The total costs for the regional enforcement agency of performing I_j inspections are represented by the cost function $C^j(I_j)$, which is assumed to be increasing and strictly convex, with $C^j(0) = C_j'(0) = 0$. The probability that an industrial producer is inspected is $\frac{I_j}{N_j}$. Hence, $\frac{I_j}{N_j} F_j$ represents the marginal expected penalty faced by a typical noncompliant industrial producer in region j. Region j's compliance rate is denoted as α_j, $\alpha_j \in [0, 1]$.

Region j is endowed with X_j^0 units of the agricultural good and Y_j^0 units of the industrial good. Market clearing of these two goods requires $\sum_{j=1}^{J}(n_j x_j - X_j^0 - X_j - \overline{X}_j) = 0$ and $\sum_{j=1}^{J}(n_j y_j - Y_j^0 - Y_j - \overline{Y}_j) = 0$, respectively. The global permit market clears if and only if $\sum_{j=1}^{J} \alpha_j Y_j = \sum_{j=1}^{J} Q_j \equiv Q$.

3 International carbon dioxide emissions trading with noncompliant polluters

Since the design of policies must take into account the responses of producers, consumers and enforcement agencies, this section analyzes how the policy instruments affect their behavior in global markets.

With identical producers and identical enforcement pressure on the producers within each industrial sector, we consider the profit maximization problem for an industrial sector as a whole. The industrial sectors decide whether or not to be compliant by comparing the benefits from these two choices. The profit for the industrial sector in region j to be compliant is: $pH^j(\overline{X}_j) + \overline{X}_j - sH^j(\overline{X}_j)$. The expected profit for the industrial sector if it does not purchase any permit is: $pH^j(\overline{X}_j) + \overline{X}_j - \frac{I_j}{N_j} F_j H^j(\overline{X}_j)$. The compliance rate in region j is:

$$\alpha_j = 0 \quad \text{if } s > \frac{I_j}{N_j} F_j, \tag{1a}$$

$$\alpha_j = 1 \quad \text{if } s < \frac{I_j}{N_j} F_j, \tag{1b}$$

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[22] See Caplan et al. (2003) for the efficiency implications of full participation in international emissions trading.

$$\alpha_j \in [0,1] \quad \text{if } s = \frac{I_j}{N_j} F_j. \tag{1c}$$

All industrial producers in region j choose to be noncompliant whenever the benefits of being noncompliant are greater than the benefits of being compliant, i.e., the permit price is higher than the marginal expected penalty of being found in violation. If the permit price is lower than the marginal expected penalty, all industrial producers purchase the required number of permits. If the permit price equals the marginal expected penalty, α_j can take any value over the interval [0, 1] because the industrial producers are indifferent between being compliant or not.

We assume that the regional enforcement agencies behave opportunistically and that the regional regulators are unable to observe the enforcement agencies' actions. Although the regional regulators face moral hazard problems vis-à-vis the regional enforcers, we assume that they find it desirable to delegate the enforcement activity. This setting is commonly used in three-tier agency models, where we find a principal (i.e., the regional regulator), an enforcer or supervisor (i.e., the regional enforcement agency) and an agent (i.e., the polluter).[23]

Given our assumptions, the enforcement agency in region j chooses $I_j \in [0, N_j]$ to maximize its expected profit $\Pi_E^j = (1-\alpha_j)\frac{I_j}{N_j} F_j Y_j - C^j(I_j)$, taking N_j, F_j, α_j and Y_j as given. The assumption that the regional enforcers' objectives are profit maximization enables us to capture the moral hazard issue, since the objectives of the principal and the enforcer diverge in each region. Divergent objectives should be viewed as the rule rather than the exception in settings where the enforcement activity is delegated. Nonetheless, we show in the Appendix that in equilibrium our realistic setting yields the same qualitative results as those we would obtain in the idealistic setting whereby enforcers are nonopportunistic and polluters perfectly comply with regulations.

The profit maximization problems of the regional enforcement agencies yield the following first order conditions:

$$\begin{aligned} &I_j = 0 \quad \text{iff } (1-\alpha_j)\frac{F_j}{N_j} Y_j \le 0, \\ &(1-\alpha_j)\frac{F_j}{N_j} Y_j = C_j'(I_j) \quad \text{if } N_j > I_j > 0, \\ &I_j = N_j \quad \text{iff } (1-\alpha_j)\frac{F_j}{N_j} Y_j \ge C_j'(N_j), \; j = 1, \ldots, J. \end{aligned} \tag{2}$$

Time consistent choices of inspection efforts imply that there is no pure strategy equilibrium for the inspection game played between each regional enforcement agency and the corresponding regional industrial sector. Without loss of generality, let us assume that $s > 0$, $F_j > s$, and $F_j \ge \frac{N_j C_j'(N_j)}{Y_j}$, $j = 1, \ldots, J$.[24] If $s < \frac{I_j}{N_j} F_j$, $\alpha_j = 1$

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[23] The classical paper in the three-tier agency literature is Tirole (1986). See Silva et al. (2007) for some of the key contributions to this literature.

[24] These assumptions are sufficient, but not necessary for the existence of a mixed strategy equilibrium. For expositional clarity, we focus on mixed strategy equilibrium of the inspection-compliance game in

by (1b). This cannot hold in equilibrium because the enforcement agency would then choose to spend no effort on inspection, i.e., $I_j = 0$ by (2), and $I_j = 0$ implies that $s > \frac{I_j}{N_j} F_j$. According to (1a), $\alpha_j = 0$. Since $F_j \geq \frac{N_j C_j'(N_j)}{Y_i}$, $I_j = N_j$ by (2). Then we have $\frac{I_j}{N_j} F_j = F_j > s$, contradicting $s > \frac{I_j}{N_j} F_j$. In sum, there can only exist mixed strategy equilibria for the inspection games, where

$$\alpha_j \in (0,1), \quad j = 1, \ldots, J, \tag{3a}$$

$$s = \frac{I_j}{N_j} F_j, \quad j = 1, \ldots, J, \tag{3b}$$

$$I_j \in (0, N_j), \quad j = 1, \ldots, J, \tag{3c}$$

$$(1-\alpha_j)\frac{F_j}{N_j} Y_j = C_j'(I_j), \quad j = 1, \ldots, J. \tag{3d}$$

Equations (3d) define the regional enforcement agencies' inspection efforts as implicit functions of α_j, F_j, and Y_j, i.e., $I^j(\alpha_j, F_j Y_j)$, $j = 1, \ldots, J$. Standard envelope theorem arguments imply that $\partial I^j/\partial \alpha_j < 0$, $\partial I^j/\partial F_j > 0$, and $\partial I^j/\partial Y_j > 0$ for all j.

With (3b) holding in equilibrium, we can express the industrial sector's problem in region j as choosing $\overline{X}_j$ to maximize its profit $pH^j(\overline{X}_j) + \overline{X}_j - sH^j(\overline{X}_j)$, subject to $\overline{X}_j \leq 0$, taking p and s as given. Assuming that $p > s$, the industrial sectors maximize profit if and only if

$$-(p-s)H_X^j = 1, \quad j = 1, \ldots, J, \tag{4}$$

that is, in each region, the realized value of the marginal industrial product must be equal to the marginal input cost, which equals one, the price of the agricultural input. Let $r \equiv p - s$. Equations (4) enable us to implicitly define the input demand functions $\overline{X}^j(r)$, $j = 1, \ldots, J$. Hence, the industrial sectors' supply functions of the industrial good are $Y^j(r) \equiv H^j(\overline{X}^j(r))$, $j = 1, \ldots, J$, for which $Y_r^j \equiv dY^j/dr > 0$, $j = 1, \ldots, J$.

Inserting $I^j(\alpha_j, F_j, Y_j)$, $Y^j(r)$, and $r \equiv p - s$, $j = 1, \ldots, J$, into (3b) yields $s = \frac{I^j(\alpha_j, F_j, Y^j(p-s))}{N_j} F_j$, $j = 1, \ldots, J$, which determine the regional compliance rates as $\alpha^j(p, F_j, s)$, $j = 1, \ldots, J$. Equations (3b) can then be rewritten as

$$s = \frac{I^j(\alpha^j(p, F_j, s), F_j, Y^j(p-s))}{N_j} F_j, \quad j = 1, \ldots, J. \tag{3b$'$}$$

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each region. In Sect. 5.3, we will show that our major findings are hardly affected when these assumptions are relaxed.

Differentiating (3b′) with respect to F_j and s, respectively, we have

$$\alpha_s^j = -\frac{C_j'' N_j/F_j + (1-\alpha_j) Y_r^j F_j/N_j}{Y_j F_j/N_j} < 0,$$
$$\alpha_{F_j}^j = \frac{C_j'' N_j s/F_j^2 + (1-\alpha_j) Y_j/N_j}{Y_j F_j/N_j} > 0, \quad j = 1, \ldots, J, \tag{5}$$

where $\alpha_s^j \equiv \partial\alpha^j/\partial s$ and $\alpha_{F_j}^j \equiv \partial\alpha^j/\partial F_j$.

The agricultural sector in region j chooses $\overline{Y}_j$ to maximize its profit $G^j(\overline{Y}_j, E) + p\overline{Y}_j$, subject to $\overline{Y}_j \le 0$, taking p and E as given. The agricultural sector in each region maximizes profit if and only if

$$-G_Y^j = p, \quad j = 1, \ldots, J, \tag{6}$$

that is, in each region, the marginal value of the agricultural product must be equal to the marginal input cost, which equals p, the price of the industrial input. Equations (6) enable us to implicitly define the input demand functions $\overline{Y}^j(p, E)$, $j = 1, \ldots, J$. Hence, the agricultural sectors' supply functions of the agricultural good are $X^j(p, E) \equiv G^j(\overline{Y}^j(p, E), E)$, $j = 1, \ldots, J$.

The total profits of the two production sectors in region j, denoted as Π_s^j, and the profit of the regional enforcement agency, Π_E^j, are allocated equally among region j's consumers. Each consumer also holds an equal share of region j's initial endowments of the agricultural and the industrial goods and the emission permits issued by regulator j.[25] Regional per capita income is composed of the items on the right-hand side of (7):

$$w_j \equiv \frac{X_j^0 + pY_j^0 + \Pi_s^j + \Pi_E^j + sQ_j + T_j}{n_j}, \quad j = 1, \ldots, J, \tag{7}$$

where T_j denotes the amount of income (measured in terms of the agricultural good) received by region j from the Global Environmental Facility (GEF), if positive, or paid to the GEF, if negative.

The budget constraint facing the representative consumer in each region is

$$x_j + py_j = w_j, \quad j = 1, \ldots, J. \tag{8a}$$

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[25] Our results do not depend on the assumption that within any region each individual has identical income, implied by equal shares of regional profits and pollution permits supplied in the region. The results will be qualitatively the same, in terms of their efficiency characteristics, if we allow for unequal shares of profits and pollution permits within regions provided that the transfers implemented by the GEF are made directly to individuals rather than to regional governments. In this generalized framework, the GEF would essentially be able to promote transfers that would lead to the same individual levels of utility as in the simpler case examined in this paper. The same reasoning applies if one considers a setting in which individuals earn shares of profits produced in regions other than their regions of residence. Proofs of these claims are available from the authors upon request.

The representative consumer in region j chooses $\{x_j, y_j\}$ to maximize utility $U^j(x_j, y_j)$, subject to (8a) and $x_j \geq 0$, $y_j \geq 0$, taking p and w_j as given.

Assuming a strictly positive solution to the consumer's problem in each region, optimal consumption satisfies (8a) and the following first order conditions:

$$\frac{U_y^j}{U_x^j} = p, \quad j = 1, \dots, J, \tag{8b}$$

that is, the marginal rate of substitution between the industrial and the agricultural goods in every region must be equal to the (relative) price of the industrial good. Equations (8a) and (8b) enable us to implicitly define the demand functions of the representative consumer in region j as $x^j(p, w_j)$ and $y^j(p, w_j)$. This consumer's indirect utility function is $V^j(p, w_j) \equiv U^j(x^j(p, w_j), y^j(p, w_j))$.

The global permit market clears if and only if the number of emission permits purchased by the compliant industrial producers is equal to the number of permits issued in the global market:

$$\sum_{j=1}^{J} \alpha^j(p, F_j, s) Y^j(p - s) = Q. \tag{9a}$$

Equation (9a) enables us to write the equilibrium permit price s as a function of the price of the industrial good p and the policy instruments Q and $\{F_j\}_{j=1,\dots,J}$, i.e., $s(p, Q, F_1, \dots, F_J)$. Equation (9a) can be reexpressed as:

$$\sum_{j=1}^{J} \alpha^j\big(p, F_j, s(p, Q, F_1, \dots, F_J)\big) Y^j\big(p - s(p, Q, F_1, \dots, F_J)\big) = Q. \tag{9b}$$

Differentiating (9b) with respect to Q and F_j, $j = 1, \dots, J$, respectively, we have the following comparative static responses of s to the policy instruments:

$$s_Q = \frac{1}{\sum_{i=1}^{J} \alpha_s^i Y_i \sum_{i=1}^{J} \alpha_i Y_r^i} < 0, \qquad s_{F_j} = -\frac{\alpha_{F_j}^j Y_j}{\sum_{i=1}^{J} \alpha_s^i Y_i - \sum_{i=1}^{J} \alpha_i Y_r^i} > 0,$$
$$j = 1, \dots, J, \tag{10}$$

where $s_Q \equiv \partial s / \partial Q$ and $s_{F_j} \equiv \partial s / \partial F_j$. Other things being equal, an increase in the number of permits depresses the equilibrium permit price s, while a higher fine leads to a higher s.

Combining (5) and (10), we can find out the marginal impacts of the policy instruments on region j's compliance rate:

$$\alpha_{F_j}^j + \alpha_s^i s_{F_j} > 0, \quad \alpha_s^j s_{F_i} < 0, \quad \text{and} \quad \alpha_s^j s_Q > 0, \quad i \neq j, i, \ j = 1, \dots, J. \tag{11}$$

An increase in region j's fine F_j leads to a higher compliance rate in that region if the equilibrium permit price remains constant. This direct effect of a change in F_j on α_j is represented by $\alpha_{F_j}^j > 0$. The equilibrium permit price, however, does respond to changes in F_j. A higher level of penalty raises the equilibrium permit price, which tends to lower the compliance rate in region j. This indirect effect is represented by $\alpha_s^j s_{F_j} < 0$. The sum of the indirect and direct effects is positive, representing a positive net effect of an increase in F_j on α_j. An increase in region i's fine F_i, $i \neq j$, only has an indirect effect on the compliance rate in region j by lowering α_j through a higher equilibrium permit price, i.e., $\alpha_s^j s_{F_i} < 0$. Finally, $\alpha_s^j s_Q > 0$, an increase in the number of permits leads to a higher compliance rate in region j through a lower equilibrium permit price.

With (3b′) and (9b), the profit of each regional enforcement agency can be expressed as

$$\begin{aligned}\Pi_E^j(p, Q, F_1, \dots, F_J) \equiv \bigl(1 - \alpha^j\bigl(p, F_j, s(p, Q, F_1, \dots, F_J)\bigr)\bigr)& \\ \times s(p, Q, F_1, \dots, F_J) Y^j\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr)& \\ - C^j\left(\frac{N_j s(p, Q, F_1, \dots, F_J)}{F_j}\right), \quad j = 1, \dots, J.& \qquad (12)\end{aligned}$$

The profit of the industrial sector in region j, $j = 1, \dots, J$, can be expressed as

$$\begin{aligned}&pY^j\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr) + \overline{X}^j\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr) \\ &\quad - s(p, Q, F_1, \dots, F_J) Y^j\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr). \qquad (13a)\end{aligned}$$

The profit of the agricultural sector in region j, $j = 1, \dots, J$ can be expressed as

$$\begin{aligned}&X^j\left(p, \sum_{i=1}^J Y^i\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr)\right) \\ &\quad + p\overline{Y}^j\left(p, \sum_{i=1}^J Y^i\bigl(p - s(p, Q, F_1, \dots, F_J)\bigr)\right). \qquad (13b)\end{aligned}$$

The total profits of these two production sectors Π_s^j can be written as $\Pi_s^j(p, Q, F_1, \dots, F_J)$, $j = 1, \dots, J$, which are the sum of (13a) and (13b).

Equations (12) and (13) imply that regional per capita income, excluding the inter-regional income transfer m_j, can be defined as a function of p, Q_j, Q, $F_1, \dots, F_J$:

$$\begin{aligned}&m^j(p, Q_j, Q, F_1, \dots, F_J) \\ &\quad \equiv \frac{X_j^0 + pY_j^0 + \Pi_s^j(p, Q, F_1, \dots, F_J) + \Pi_E^j(p, Q, F_1, \dots, F_J) + s(p, Q, F_1, \dots, F_J) Q_j}{n_j}, \\ &\quad j = 1, \dots, J. \qquad (14)\end{aligned}$$

4 Socially optimal regulation

This section gives a characterization of socially optimal climate policies by assuming that the social planner (e.g., the UNFCCC) has the power to control all policy instruments—interregional income transfers, regional emission quotas, and fines—to maximize global welfare, represented by a weighted sum of regional per capita indirect utilities. The optimality conditions derived in this section allow us to investigate whether there is a more decentralized interregional climate policy scheme that yields the same allocation of resources.

With (14), the indirect utility function of region j's representative consumer can be expressed as

$$\begin{aligned}&V^j\big(p, m^j(p, Q_j, Q, F_1, \dots, F_J) + T_j/n_j\big)\\&\quad\equiv U^j\big(x^j\big(p, m^j(p, Q_j, Q, F_1, \dots, F_J) + T_j/n_j\big),\\&\qquad\quad y^j\big(p, m^j(p, Q_j, Q, F_1, \dots, F_J) + T_j/n_j\big)\big).\end{aligned}\tag{15}$$

The UNFCCC chooses interregional income transfers $\{T_j\}_{j=1,\dots,J}$ and nonnegative $\{Q_j, F_j\}_{j=1,\dots,J}$ to maximize

$$\sum_{j=1}^{J}\theta_j V^j\big(p, m^j(p, Q_j, Q, F_1, \dots, F_J) + T_j/n_j\big),\tag{16}$$

subject to the constraints

$$\sum_{j=1}^{J} T_j = 0,\tag{17a}$$

$$\begin{aligned}&pY^j\big(p - s(p, Q, F_1, \dots, F_J)\big) + \overline{X}^j\big(p - s(p, Q, F_1, \dots, F_J)\big)\\&\quad - F_j Y^j\big(p - s(p, Q, F_1, \dots, F_J)\big) \geq 0, \quad j = 1, \dots, J.\end{aligned}\tag{17b}$$

The parameters θ_j, $j = 1, \dots, J$, are the exogenously determined weights attached to the regions' welfare by the UNFCCC. We assume that each weight $\theta_j > 0$ and $\sum_{j=1}^{J}\theta_j = 1$.

Equation (17a) is the redistribution constraint for the interregional income transfers. Conditions (17b) place the upper bounds for the fines, which cannot be set so high that the industrial firms caught in noncompliance will go bankrupt. From (17b), we can see that a region's choices of emission quota and fine generate pecuniary effects affecting not only the nonbankruptcy constraint in its own region, but the constraints on fines in all other regions in the globe as well.

Forming the Lagrange equation

$$\begin{aligned}\varphi &= \sum_{j=1}^{J}\theta_j V^j\big(p, m^j(p, Q_j, Q, F_1, \dots, F_J) + T_j/n_j\big) - \nu\sum_{j=1}^{J} T_j\\&\quad + \sum_{j=1}^{J}\mu_j\big[pY^j\big(p - s(p, Q, F_1, \dots, F_J)\big) + \overline{X}^j\big(p - s(p, Q, F_1, \dots, F_J)\big)\\&\quad - F_j Y^j\big(p - s(p, Q, F_1, \dots, F_J)\big)\big],\end{aligned}$$

and assuming nonzero interregional income transfers, regional emission quotas and fines, the Kuhn–Tucker conditions for the UNFCCC's global welfare maximization problem are:

$$\frac{\partial \varphi}{\partial T_j} = \frac{\theta_j V_w^j}{n_j} - \nu = 0, \quad j = 1, \ldots, J, \tag{18a}$$

$$\frac{\partial \varphi}{\partial Q_j} = \sum_{i=1}^{J} \theta_i V_w^i \frac{\mathrm{d}m^i}{\mathrm{d}Q_j} + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_Q = 0, \quad j = 1, \ldots, J, \tag{18b}$$

$$\frac{\partial \varphi}{\partial F_j} = \sum_{i=1}^{J} \theta_i V_w^j \frac{\mathrm{d}m^i}{\mathrm{d}F_j} + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_{F_j} - \mu_j Y_j = 0, \quad j = 1, \ldots, J, \tag{18c}$$

$$\frac{\partial \varphi}{\partial \nu} = \sum_{j=1}^{J} T_j = 0, \quad \nu \geq 0, \ \nu \frac{\partial \varphi}{\partial \nu} = 0, \tag{18d}$$

$$\frac{\partial \varphi}{\partial \mu_j} = pY_j + \overline{X}_j - F_j Y_j \geq 0, \quad \mu_j \geq 0, \ \mu_j \frac{\partial \varphi}{\partial \mu_j} = 0, \ j = 1, \ldots, J. \tag{18e}$$

Since each $\theta_j > 0$ and $V_w^j > 0$, we have $\nu > 0$ in the first order conditions (18a), which tell us that the UNFCCC redistributes income across regions so that the marginal social utilities of income are equalized across regions, and are equal to the shadow value of the interregional income transfers.

The first order conditions (18a) also enable us to rewrite (18b) and (18c) as follows:

$$\nu \cdot \frac{\mathrm{d}M}{\mathrm{d}Q_j} + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_Q = 0, \quad j = 1, \ldots, J, \tag{18b$'$}$$

$$\nu \cdot \frac{\mathrm{d}M}{\mathrm{d}F_j} + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_{F_j} - \mu_j Y_j = 0, \quad j = 1, \ldots, J, \tag{18c$'$}$$

where

$$M \equiv \sum_{i=1}^{J} n_i m_i = \sum_{i=1}^{J} n_i w_i. \tag{19}$$

The second equality of (19) comes from the redistribution constraint (17a), which implies that global income is not affected by the interregional income transfers.

Equations (18b$'$) and (18c$'$) clearly inform us that global welfare is maximized if and only if global income M is maximized through the choices of regional emission quotas and fines, taking into account the pecuniary external effects of these choices on all the nonbankruptcy constraints. Adding up the regional incomes implied by (14) and making use of the global permit market clearing condition (9a), global income

M can be defined as a function of $p, Q, F_1, \dots, F_J$:

$$\begin{aligned} M(p, Q, F_1, \dots, F_J) = \sum_{j=1}^{J} \Bigg(& X_j^0 + pY_j^0 + pY^j\big(p - s(p, Q, F_1, \dots, F_J)\big) \\ & + \overline{X}^j\big(p - s(p, Q, F_1, \dots, F_J)\big) \\ & + X^j\left(p, \sum_{i=1}^{J} Y^i\big(p - s(p, Q, F_1, \dots, F_J)\big)\right) \\ & + p\overline{Y}^j\left(p, \sum_{i=1}^{J} Y^j\big(p - s(p, Q, F_1, \dots, F_J)\big)\right) \\ & - C^j\big(N_j s(p, Q, F_1, \dots, F_J)/F_j\big)\Bigg). \end{aligned} \tag{20}$$

Global income M is composed of all regions' initial endowments, industrial profits excluding permit and fine payment (what the industrial producers expect to pay for permits and fines is exactly offset by the expected global permit sales revenue and global enforcement revenue), agricultural profits and costs of inspection.

With (20), first order conditions (18b′) and (18c′) can be written as:

$$\nu\left(-s\sum_{i=1}^{J} Y_r^i s_Q - \sum_{i=1}^{J} \frac{C_i' N_i s_Q}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h s_Q\right) + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_Q = 0, \tag{18b″}$$

$$\begin{aligned} &\nu\left(-s\sum_{i=1}^{J} Y_r^i s_{F_j} - \sum_{i=1}^{J} \frac{C_i' N_i s_{F_j}}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h s_{F_j} + \frac{C_j' N_j s}{F_j^2}\right) \\ &\quad + \sum_{i=1}^{J} \mu_i (F_i - s) Y_r^i s_{F_j} - \mu_j Y_j = 0. \end{aligned} \tag{18c″}$$

As long as Q_j is set optimally according to (18b″), (18c″) can be simplified as

$$\nu \frac{C_j' N_j s}{F_j^2} - \mu_j Y_j = 0, \quad j = 1, \dots, J. \tag{21}$$

Once the UNFCCC has optimized Q_j, an infinitesimal increase in F_j has a beneficial welfare effect of saving on inspection cost, balanced by the shadow cost of this increase.

Equations (21) imply that $\mu_j = \nu \frac{C_j' N_j s}{F_j^2 Y_j} > 0$. According to the Kuhn–Tucker conditions (18e), we have

$$pY^j\big(p - s(p, Q, F_1, \dots, F_J)\big) + \overline{X}^j\big(p - s(p, Q, F_1, \dots, F_J)\big)$$

$$- F_j Y^j \big(p - s(p, Q, F_1, \ldots, F_J)\big) = 0, \quad j = 1, \ldots, J. \tag{22}$$

Substituting (21) into (18b″) shows that

$$\left(-s \sum_{i=1}^{J} Y_r^i - \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h + \sum_{i=1}^{J} \frac{C_i' N_i s}{F_i^2 Y_i} (F_i - s) Y_r^i \right) s_Q = 0, \tag{23a}$$

or

$$s \sum_{i=1}^{J} Y_r^i + \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} = - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h + \sum_{i=1}^{J} \frac{C_i' N_i s}{F_i^2 Y_i} (F_i - s) Y_r^i. \tag{23b}$$

Proposition 1 *Socially optimal interregional income transfers, fines and aggregate permits are given by conditions* (17a), (18a), (22), *and* (23).

Although conditions (17a), (18a), (22), and (23) must hold simultaneously for determining the socially optimal interregional income transfers, fines, and the total number of permits issued in the globe, the welfare evaluation of policy is more transparent if we think of (17a) and (18a) as the policy rule for the socially optimal level of transfers, and of (22) and (23) as the policy rules for the optimal fines and aggregate permits, respectively. Having given an interpretation of the optimal choices of transfers, we discuss the socially efficient choices of fines and quotas now.

Conditions (22) are in the same spirit as an important result usually attributed to Becker (1968) in the economics of law enforcement.[26] When inspections are costly, but levying fines is costless, socially optimal deterrence could be achieved by raising fines to their maximal feasible levels while lowering the probabilities of detection to save inspection costs. In our context, the optimal fine in each region is set so that the nonbankruptcy constraint is binding.

The left-hand side of (23b) represents the marginal benefit of issuing an additional permit and the right-hand side represents the marginal cost, expressed in real income terms. An extra permit lowers the equilibrium permit price s, which raises industrial output and the industrial profits excluding permit and fine payment. This beneficial effect on global welfare is represented by the first term on the left-hand side of (23b). The associated increase in carbon emissions hurts agricultural production. The decrease in agricultural profits is measured by the first term on the right-hand side of (23b). When enforcement is perfect, we have $\alpha_j = 1$, $I_j = 0$, and $C_j'(0) = 0$ for all j. A change in the number of permits only has these two effects. Equation (23b) reduces to $s = -\sum_{i=1}^{J} G_E^i$, i.e., the equilibrium permit price is equal to the aggregate

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[26] Polinsky and Shavell (1991) demonstrate that the optimal fine can be nonmaximal if the wealth of offenders varies and the probability of detection is the same for all individuals; however, the optimal fine could be maximal if the probability of detection is chosen for each level of wealth. In this paper, the profits of the industrial sectors vary across regions, so do inspection efforts. Becker's argument hence applies to the choice of fines in each region. In contrast to the exogenous wealth constraints in Polinsky and Shavell (1991), we investigate the implications of endogenous feasibility constraints on fines for resource allocation. See Polinsky and Shavell (2000) for discussions in the law enforcement literature on the optimality of imposing maximal fines.

marginal damages caused to agricultural production. This is the optimality condition for aggregate permits derived in Caplan et al. (2003) with perfect enforcement.

When enforcement is costly and compliance is incomplete, there are two additional effects of increasing the number of permits. The lower equilibrium permit price s resulting from a higher Q implies smaller inspection efforts are needed in each region since $I_j = \frac{N_j s}{F_j}$ holds in equilibrium according to (3b). Fewer resources are needed for inspection than before and the global income will rise by the amount of $-\sum_{i=1}^{J} C_i N_i s_Q / F_i$.[27] Thus, we have the second term on the left-hand side of (23b). The second term on the right-hand side of (23b) involves the fact that when there is an increase in one region's permits; all regions' nonbankruptcy constraints are tightened through equilibrium permit price changes, which imposes a cost on global welfare. As we will see, this type of pecuniary externality plays a key role in the design of socially efficient interregional climate policy schemes with imperfect enforcement. Whether the equilibrium permit price with imperfect enforcement is higher or lower than that which would internalize the aggregate marginal environmental damages depends on the relative magnitude of these two additional effects. If the net effect is an addition to global income, the equilibrium permit price with imperfect enforcement is lower, implying a higher level of global carbon emissions since $E = \sum_{j=1}^{J} Y^j(p - s)$.

5 Interregional climate policy schemes with noncompliant polluters

Socially optimal regulation serves as a benchmark against which we can examine the efficiency properties of more decentralized interregional climate policy schemes, where the GEF transfers income across regions and the other two regional policy instruments, regional emission quotas and fines, are completely or partially decentralized to the regional regulators. The GEF can be seen as an offspring of the UNFCCC and has the same objective of global welfare maximization. We shall model the interregional policy schemes as games played by the regional regulators and the intergovernmental authorities. Four games will be investigated with different extents of decentralization of regional policy instruments and different timing of moves of the policy makers. We assume that the GEF implements interregional income transfers in the last stage of all four policy games.

5.1 Game 1: complete decentralization of regional emission quotas and fines

We start our investigation of the interregional climate policy schemes with complete decentralization of regional policy instruments. We model this interregional policy scheme as a two-stage game played by the GEF and the regional regulators. In the first stage, the regional regulators set their regional emission quotas and fines simultaneously and noncooperatively to maximize regional welfare. Each regulator faces the nonbankruptcy constraint on the fine in its own region. In the second stage, after observing the regional policy choices, the GEF implements interregional income

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[27] Cremer and Gahvari (2002) study second-best tax design issues with costly monitoring. Their optimal emission tax contains a similar item that takes into account the resource costs of monitoring.

transfers to maximize global welfare. The equilibrium concept for the two-stage game is subgame perfection.[28]

Starting from the second stage of the policy game, given p and $\{Q_j, F_j\}_{j=1,\ldots,J}$, the GEF chooses interregional income transfers $\{T_j\}_{j=1,\ldots,J}$ to maximize global welfare (16), subject to the redistribution constraint (17a). The GEF's problem is equivalent to choosing regional per capita income including the transfers, $\{w_j\}_{j=1,\ldots,J}$, to maximize $\sum_{j=1}^{J} \theta_j V^j(p, w_j)$, subject to the constraint (19), which requires that global income be unaffected by the income redistribution policy.

The first order conditions for the GEF's problem are (19) and

$$\frac{\theta_j V_w^j}{n_j} = \nu^1, \quad j = 1, \ldots, J, \tag{24a}$$

where $\nu^1 > 0$ is the Lagrange multiplier associated with the redistribution constraint (19).[29] Equations (24a) correspond to the socially optimal conditions (18a). Marginal social utilities of income are equalized across regions as a result of the GEF's income redistribution policy.

The first order conditions (19) and (24a) enable us to define w_j as a function of p and M, i.e., $w^j(p, M)$, $j = 1, \ldots, J$. Inserting these functions into (19), we have

$$\sum_{j=1}^{J} n_j w^j(p, M) = M. \tag{24b}$$

Differentiating (24b) with respect to M yields

$$\sum_{j=1}^{J} n_j w_M^j = 1, \tag{24c}$$

where $w_M^j \equiv \partial w^j / \partial M > 0$, $j = 1, \ldots, J$.

At this time, we can see that the GEF's interregional income transfer policy leads the regional per capita incomes to be positively related to global income. We expect that as in Caplan et al. (2003), regional regulators will be motivated by the transfers to choose quotas and fines to maximize global income. However, will they be induced to internalize all the pecuniary externalities caused by their choices associated with the nonbankruptcy constraints on fines? Let's proceed to the first stage of Game 1.

In the first stage, regulator j chooses nonnegative Q_j and F_j to maximize $V^j(p, w^j(p, M(p, Q, F_1, \ldots, F_J)))$, subject to (17b), taking p and Q_k, F_k, $\forall k \neq j$,

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[28] Cornes and Sandler (1984), Cauley et al. (1986), Sandler (1992), and Varian (1994) have investigated public goods contribution games under different behavioral assumptions, including the leader-follower behavior. Varian (1994) provided comparison between simultaneous and sequential games, where the equilibrium concepts employed were Nash equilibrium and subgame perfect equilibrium, respectively.

[29] To avoid confusion, the Lagrange function and multipliers in Game 1 will appear in the text with a superscript "1."

as given. The Lagrange equations for the problems of regional welfare maximization are

$$\begin{aligned}\varphi_j^1 &= V^j\big(p, w^j\big(p, M(p, Q, F_1, \ldots, F_j)\big)\big)\\&\quad + \mu_j^1\big[pY^j\big(p - s(p, Q, F_1, \ldots, F_J)\big) + \overline{X}^j\big(p - s(p, Q, F_1, \ldots, F_J)\big)\\&\quad - F_j Y^j\big(p - s(p, Q, F_1, \ldots, F_J)\big)\big], \quad j = 1, \ldots, J.\end{aligned}$$

Assuming nonzero regional emission quotas and fines, the Kuhn–Tucker conditions for the problems of regional welfare maximization are:

$$\frac{\partial \varphi_j^1}{\partial Q_j} = V_w^j w_M^j \frac{\mathrm{d}M}{\mathrm{d}Q_j} + \mu_j^1 (F_j - s) Y_r^j s_Q = 0, \quad j = 1, \ldots, J, \tag{25a}$$

$$\frac{\partial \varphi_j^1}{\partial F_j} = V_w^j w_M^j \frac{\mathrm{d}M}{\mathrm{d}F_j} + \mu_j^1 (F_j - s) Y_r^j s_{F_j} - \mu_j^1 Y_j = 0, \quad j = 1, \ldots, J, \tag{25b}$$

$$\frac{\partial \varphi_j^1}{\partial \mu_j^1} = pY_j + \overline{X}_j - F_j Y_j \geq 0, \quad \mu_j^1 \geq 0, \ \mu_j^1 \frac{\partial \varphi}{\partial \mu_j^1} = 0, \ j = 1, \ldots, J. \tag{25c}$$

Manipulating (25a) and (25b) in a similar way as we did for (18b′) and (18c′) in Sect. 4, the conditions characterizing the first stage Nash equilibrium are:

$$-s\sum_{i=1}^{J} Y_r^i - \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h + \frac{C_j' N_j s}{F_j^2 Y_j}(F_j - s) Y_r^j = 0, \quad j = 1, \ldots, J, \tag{26}$$

and (22), the binding nonbankruptcy constraints.

The subgame perfect equilibrium for Game 1 is given by conditions (19), (22), (24a), and (26). The above analysis of Game 1 leads to the following proposition:

Proposition 2 *The subgame perfect equilibrium policy choices for Game* 1 *are not socially optimal.*

Proof Equilibrium conditions (26) are different from the socially optimal conditions (23). □

Compared with the socially optimal conditions (23), the first three items on the left-hand side of (26) tell us that the interregional income transfer policy induces the regional regulators to maximize global income through the choices of regional emission quotas. However, the last item on the left-hand side of (26) clearly demonstrates that the transfer policy fails to provide the regional regulators with incentives to account for the quotas' pecuniary effects on the nonbankruptcy constraints on fines in other regions. When issuing an additional permit, regulator j only acknowledges the cost of a tightened nonbankruptcy constraint in region j but ignores the costs of more stringent constraints on fines in all other regions. As a result, the equilibrium permit price is lower and the global carbon emission level is higher in Game 1 relative to the socially efficient levels. The subgame perfect equilibrium policy choices for Game 1 do not lead to socially optimal allocations of global resources.

5.2 Centralized fines and decentralized regional emission quotas

The regional regulators' failure to account for the pecuniary externalities associated with the nonbankruptcy constraints on fines in Game 1 leads us to investigate interregional climate policy schemes whereby fines are centralized by the UNFCCC while the regional regulators are left with the choices of regional carbon emission permit quotas.

Games 2, 3, and 4 are featured by the same assignment of policy instruments, but different timing of the moves between the UNFCCC and the regional regulators. We will pay special attention to Game 2, where the regional regulators play the role of Stackelberg leaders and the interregional climate policy scheme underlying which generates socially efficient allocation of global resources. In Game 3, the UNFCCC precommits to fines, while it moves simultaneously with the regional regulators in Game 4. These two games yield inefficient allocations. By showing why the equilibria for Games 3 and 4 are inefficient, we will be able to highlight the importance of the timing of policy making for the efficient result achieved in Game 2.

5.2.1 Game 2: the regional regulators as Stackelberg leaders

Game 2 is a three-stage game played by the regional regulators, the UNFCCC, and the GEF. In the first stage of this game, the regional regulators simultaneously and noncooperatively choose regional emission permit quotas to maximize regional welfare. In the second stage, after observing the regional quotas, the UNFCCC sets fines for each region to maximize global welfare, subject to all the constraints on fines. In the third stage, the GEF transfers income across regions to maximize global welfare. The equilibrium concept for the three-stage game is subgame perfection.

The analysis of the GEF's interregional income transfer policy in the third stage of Game 2 is the same as the analysis performed in the second stage of Game 1. We will not repeat it here, but go directly to the second stage of Game 2.

In the second stage, the UNFCCC chooses nonnegative $\{F_j\}_{j=1,\dots,J}$ to maximize $\sum_{j=1}^{J} \theta_j V^j(p, w^j(p, M(p, Q, F_1, \dots, F_J)))$, subject to the binding nonbankruptcy constraints (22), taking p and Q as given.[30] The binding constraints (22) implicitly define $F^j(p, Q)$, $j = 1, \dots, J$.

Differentiating (22) with respect to Q, the response of region j's fine to a small change in Q, i.e., $F_Q^j \equiv \partial F^j / \partial Q$, satisfies

$$F_Q^j Y_j = (F_j - s) Y_r^j \left(s_Q + \sum_{i=1}^{J} s_{F_i} F_Q^i \right) = 0, \quad j = 1, \dots, J. \tag{27}$$

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[30] For simplicity, we apply the binding nonbankruptcy constraints (22) to the UNFCCC's problem in Games 2, 3, and 4. The proof that these constraints are binding is similar to the proof in Sects. 4 and 5.1 and is available from the authors upon request.

In the first stage, regulator j chooses nonnegative Q_j to maximize $V^j(p, w^j(p, M(p, Q, F_1, \ldots, F_J)))$, subject to $F_j = F^j(p, Q)$, taking p and Q_k, $\forall k \neq j$, as given. Assuming that the solution to each regional regulator's problem is interior, the first order conditions for the Nash equilibrium in the first stage of Game 2 are:

$$n_j w_M^j \left(-s \sum_{i=1}^{J} Y_r^i - \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h + \sum_{i=1}^{J} \frac{C_i' N_i s}{F_i^2 Y_i} (F_i - s) Y_r^i \right) s_Q = 0,$$
$$j = 1, \ldots, J. \tag{28}$$

Given (24c), we obtain exactly the socially optimal condition (23a) when we add up (28) over all j.

The above results for Game 2 can be summarized as follows:

Proposition 3 *The subgame perfect equilibrium policy choices for Game* 2 *lead to socially optimal allocation of global resources.*

Proof Game 2's subgame perfect equilibrium is given by conditions (19), (22), (23), and (24a). The first order conditions (19) and (24a) for the GEF's problem are equivalent to the socially optimal conditions (17a) and (18a). The equilibrium global quota level and fines are determined by the socially optimal conditions (22) and (23). The equilibrium policy choices correspond to the socially optimal ones and hence generate the same allocations of global resources. □

Given the emission quotas chosen by the regional regulators in the first stage, the UNFCCC sets fines according to (22), the socially efficient conditions for fines. In anticipation that the UNFCCC will adjust fines in all regions in order to keep (22) satisfied, each regional regulator's choice of emission quota incorporates the quota's pecuniary effects on all nonbankruptcy constraints. In addition, because the GEF implements interregional income transfers in the last stage of Game 2, the regional regulators are induced to maximize global income. Since the regional regulators maximize global income, acknowledging all the pecuniary externalities associated with the constraints on fines, they behave exactly like the social planner. The socially desirable level of aggregate permits is achieved through decentralized actions of the regional regulators when they indirectly face the feasibility constraints on fines.

5.2.2 *Game 3*: *the UNFCCC as a Stackelberg leader*

In Game 3, the UNFCCC moves before the regional regulators. The GEF's problem in the third stage is the same as in Games 1 and 2. In the second stage, regulator j chooses nonnegative Q_j to maximize $V^j(p, w^j(p, M(p, Q, F_1, \ldots, F_J)))$, taking p, Q_k, $\forall k \neq j$, and $\{F_j\}_{j=1,\ldots,J}$ as given. Assuming that the solution to each regional regulator's problem is interior, the first order conditions for the Nash equilibrium in the second stage of Game 3 are:

$$n_j w_M^j \left(-s \sum_{i=1}^{J} Y_r^i - \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} - \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h \right) s_Q = 0, \quad j = 1, \ldots, J. \tag{29a}$$

Given (24c), we obtain the following condition by adding up (29a) over all j:

$$s\sum_{i=1}^{J} Y_r^i + \sum_{i=1}^{J} \frac{C_i' N_i}{F_i} + \sum_{i=1}^{J} G_E^i \sum_{h=1}^{J} Y_r^h = 0, \tag{29b}$$

which determines the global quota level as $Q(p, F_1, \ldots, F_J)$.

In the first stage, the UNFCCC chooses nonnegative $\{F_j\}_{j=1,\ldots,J}$ to maximize $\sum_{j=1}^{J} V^j(p, w^j(p, M(p, Q, F_1, \ldots, F_J)))$, subject to the binding constraints (22), and the response function $Q(p, F_1, \ldots, F_J)$, taking p as given. The equilibrium fines are determined by substituting $Q(p, F_1, \ldots, F_J)$ into (22).

The subgame perfect equilibrium for Game 3 is given by conditions (19), (22), (24a), and (29). Compared with the socially optimal condition (23a), the left-hand side of equation (29b) lacks the last item in the bracket on the left-hand side of equation (23a), indicating that the regional regulators neglect *all* regions' nonbankruptcy constraints in their decision making over the quotas. The following proposition is now immediate:

Proposition 4 *The subgame perfect equilibrium policy choices for Game* 3 *are not socially optimal.*

In sharp contrast to Game 2, in Game 3, where the UNFCCC sets fines before the regional regulators choose emission quotas, centralized fines have no effect on motivating the regional regulators to internalize the pecuniary external effects of quotas on any of the constraints on fines. The equilibrium permit price is lower, while the global carbon emission level is higher in Game 3 than the socially optimal levels and those determined in Game 1 by comparing (29b) with (23a) and (26). The equilibrium conditions (26) in Game 1 inform us that the regional regulators take account of the constraints in their own regions anyway when both quotas and fines are decentralized.

5.2.3 Game 4: the UNFCCC and the regional regulators move simultaneously

Game 4 is a two-stage game. The UNFCCC and regional regulators play a noncooperative Nash game in the first stage of Game 4. The GEF implements interregional income transfers in the second stage of Game 4.

As in Games 2 and 3, we skip the analysis of the GEF's interregional income transfer policy in the second stage of Game 4 and focus our discussion on the first stage of the game.

The regional regulators' problems in the first stage of this game are exactly the same as those analyzed in the second stage of Game 3. For the UNFCCC, it chooses nonnegative $\{F_j\}_{j=1,\ldots,J}$ to maximize $\sum_{j=1}^{J} V^j(p, w^j(p, M(p, Q, F_1, \ldots, F_J)))$, subject to (22), taking p and $\{Q_j\}_{j=1,\ldots,J}$ as given. The equilibrium global quota level and fines in Game 4 are given by (29b) and (22), the same conditions determining these policy variables in Game 3. And since the first order conditions of the GEF's problems are (19) and (24a) in both games, the following result is straightforward:

Proposition 5 *The subgame perfect equilibrium for Game* 4 *is identical to the subgame perfect equilibrium for Game* 3.

The difference in the timing of the moves between the UNFCCC and the regional regulators in the two policy schemes underlying Games 3 and 4 does not lead to different equilibrium policy choices. These two policy schemes yield identical suboptimal allocations of global resources.

Since Games 2, 3, and 4 are characterized by the same assignment of policy instruments, the timing of the moves between the UNFCCC and regional regulators is responsible for the efficiency of Game 2. Just as the interregional income transfers must be implemented after the regional choices of emission quotas to align the objective of regional income maximization with the objective of global income maximization, the centralized fines must be set after regional policy making for the regional regulators to take all the nonbankruptcy constraints into consideration when deciding on the regional emission quotas.

5.3 The assumptions for mixed strategy equilibria of the inspection-compliance games

In Sect. 3, we have shown that the assumptions of $s > 0$, $F_j > s$ and $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$, $j = 1, \ldots, J$, are sufficient for the existence of mixed strategy equilibria of the inspection games played by the regional enforcement agencies and the industrial producers. Since s, F_j, and Y_j are all endogenously determined variables, we may have equilibria where these assumptions do not hold, depending on exogenous factors like production and enforcement technologies. For example, the assumption of $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$ is equivalent to $F_j y_j \geq C_j'(N_j)$. It is possible that a country has high inspection costs with $C_j'(N_j)$ exceeding $F_j y_j$. Since fines are constrained by industrial profits, (17b) inform us that $F_j y_j$ cannot exceed $p y_j + \bar{x}_j$. Hence, we can also envision that a country has low industrial profits and high inspection costs so that $F_j y_j \leq p y_j + \bar{x}_j < C_j'(N_j)$.

How is our main result affected? The case of $s = 0$ is trivial. The global permit market and the related enforcement problem vanish. Therefore, we examined cases where $s > 0$, but $F_j \leq s$ or $F_j < \frac{N_j C_j'(N_j)}{Y_j}$ and summarized the findings in the following proposition:

Proposition 6 *An interregional policy scheme organized after Game* 2 *is still socially optimal when* $s > 0$, *but* $F_j \leq s$ *or* $F_j < \frac{N_j C_j'(N_j)}{Y_j}$ *in some regions, as long as there is at least one region where the conditions* $s > 0$, $F_j > s$, *and* $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$ *hold.*

Proof See the Appendix. □

6 Conclusions

Recognizing that competitive international carbon dioxide emissions trading does not generally lead to Pareto-efficient emissions reduction due to the global public bad nature of carbon dioxide emissions, a few recent papers have designed international income transfer policy schemes to recover Pareto efficiency in a global emission permit market. These papers have taken complete compliance of polluters for granted. However, as shown by the literature on the cost-effectiveness of tradable permit systems, monitoring and enforcement issues can have significant consequences on environmental quality and the cost-efficiency property of such systems. Similarly, in the presence of noncompliant polluters, one might naturally question the efficiency properties of the interregional income transfer regimes proposed for Pareto-efficient control of global carbon emissions. For this purpose, we examined several interregional climate policy schemes with different assignment of responsibilities over monitoring and enforcement as well as decisions on carbon emission quotas at regional and interregional levels and with different timing of policy making. Due to the difficulties of imposing centralized decisions on sovereign nations, our approach was to identify the most decentralized compliance regime that yields a socially optimal allocation of resources.

Our analysis demonstrated that complete decentralization of regional emission quotas and fines does not lead to social optimum. Regional regulators neglect the pecuniary externalities of their choices on the nonbankruptcy constraints on fines of all the other regions. Centralized fines and decentralized quotas lead the regional regulators to neglect the constraints of all regions in their decision making, when the UNFCCC moves before or simultaneously with the regional regulators. Socially optimal allocation of global resources can be achieved when the UNFCCC sets fines *after* the regional regulators choose their regional emission quotas. The anticipation of the GEF's interregional income transfer policy and the fines set by the UNFCCC induces the regional governments to maximize global social welfare, acknowledging all pecuniary and environmental externalities caused by their choices.

It should be noted that the analysis in the paper is but a first step in the investigation of socially optimal compliance scheme for the Kyoto Protocol. We have made some idealistic assumptions. For example, the supranational authorities have complete information, the regional governments are all benevolent and maximizing the welfare of their citizens, the enforcement agencies are honest and untouchable, etc. Such simplifications leave plenty of room for future work. Among many others, interesting avenues for future research are policy assignments among a hierarchy of regional and interregional authorities and voluntary release of emission and localized damage information. These are undoubtedly important issues about which the implementers of the Kyoto Protocol will greatly benefit from being fully informed.

Appendix

Proof of Proposition 6 We concentrate on positive permit prices, i.e., $s > 0$. As we demonstrated in Sect. 3, $s < \frac{I_j}{N_j} F_j$, $\alpha_j = 1$, $I_j = 0$ cannot exist in equilibrium. But we may have $s \geq \frac{I_j}{N_j} F_j$ in equilibrium, depending on the relation between F_j and $\{s, \frac{N_j C_j'(N_j)}{Y_j}\}$.

Consider $s > \frac{I_j}{N_j} F_j$. According to (1a), $\alpha_j = 0$. Then by (2), $I_j \in (0, N_j)$, if $F_j < \frac{N_j C_j'(N_j)}{Y_j}$; $I_j = N_j$, if $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$. Hence, we may have the following equilibria:

$$s > \frac{I_j}{N_j} F_j, \qquad F_j < \frac{N_j C_j'(N_j)}{Y_j}, \qquad \alpha_j = 0, \qquad I_j \in (0, N_j), \tag{30}$$

$$s > F_j, \qquad F_j \geq \frac{N_j C_j'(N_j)}{Y_j}, \quad \alpha_j = 0, \qquad I_j = N_j. \tag{31}$$

Now consider $s = \frac{I_j}{N_j} F_j$. According to (1a) and (2), $\alpha_j \in [0, 1)$ with $s > 0$. With similar argument as above, we may have the following equilibria:

$$s = \frac{I_j}{N_j} F_j, \qquad F_j < \frac{N_j C_j'(N_j)}{Y_j}, \qquad \alpha_j \in [0, 1), \qquad I_j \in (0, N_j), \tag{32}$$

$$s = F_j, \qquad F_j \geq \frac{N_j C_j'(N_j)}{(1 - \alpha_j) Y_j}, \qquad \alpha_j \in [0, 1), \qquad I_j = N_j. \tag{33}$$

Equilibrium (32) informs us that with $s > 0$, the assumptions of $F_j > s$ and $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$, $j = 1, \ldots, J$, are sufficient but not necessary for the existence of mixed strategy equilibria of the inspection games.

We cannot exclude zero compliance rate in a region in equilibria characterized by (30)–(33). Zero compliance rates in all regions imply $s = 0$, which contradicts $s > 0$. For a global permit market to be significant, we must have at least one region with strictly positive compliant rate, i.e., $\alpha_j \in (0, 1)$. Therefore, we need at least one region where $s > 0$, $F_j > s$ and $F_j \geq \frac{N_j C_j'(N_j)}{Y_j}$ hold, and we have (3), i.e., $s = \frac{I_j}{N_j} F_j$, $\alpha_j \in (0, 1)$, $I_j \in (0, N_j)$ in that region.

For the proof of Proposition 6, we will next explain why Game 2 still leads to socially optimal allocation of resources when conditions (3) hold in at least one region and the inspection games in other regions are depicted by (30), (31), (32), or (33). We will analyze a situation where the inspection game in region 1 is characterized by a mixed strategy equilibrium while the inspection games of all other regions are characterized by (30). Hence, we consider $F_1 > s$, $F_1 \geq \frac{N_1 C_1'(N_1)}{Y_1}$, $s = \frac{I_1}{N_1} F_1$, $\alpha_1 \in (0, 1)$, $I_1 \in (0, N_1)$; $s > \frac{I_j}{N_j} F_j$, $F_j < \frac{N_j C_j'(N_j)}{Y_j}$, $\alpha_j = 0$, $I_j \in (0, N_j)$, $j = 2, \ldots, J$. The rationale we derive from analyzing the above situation can be applied to demonstrate the optimality of the policy choices in Game 2 under other scenarios where (3) and (31), (32) or (33) hold.

The analysis of the industrial sector and the regional enforcement agency in region 1 remains the same as in Sect. 3. In region j, $j = 2, \ldots, J$, the objective of the industrial sector becomes maximizing $pH^j(\overline{X}_j) + \overline{X}_j - \frac{I_j}{N_j} F_j H^j(\overline{X}_j)$, by choosing

$\overline{X}_j$, subject to $\overline{X}_j \leq 0$, taking p and F_j as given. The industrial sector maximizes profit if and only if

$$-\left(p - \frac{I_j}{N_j} F_j\right) H_X^j = 1, \quad j = 2, \ldots, J, \tag{34}$$

which determines the industrial sector's supply function of the industrial good as $Y^j(p - \frac{I_j}{N_j} F_j) \equiv H^j(\overline{X}^j(p - \frac{I_j}{N_j} F_j))$, $j = 2, \ldots, J$.

The regional enforcement agency's first order condition becomes

$$\frac{F_j}{N_j} Y_j = C_j'(I_j), \quad j = 2, \ldots, J, \tag{35}$$

which together with (34), defines $I^j(p, F_j)$. The nonbankruptcy constraint on the fine in region j can be written as

$$(p - F_j) Y^j \left(p - \frac{I^j(p, F_j)}{N_j}\right) + \overline{X}^j \left(p - \frac{I^j(p, F_j)}{N_j} F_j\right) \geq 0, \quad j = 2, \ldots, J, \tag{36}$$

which is not affected by other regions' policy choices.

The global permit market clearing condition becomes

$$\alpha^1(p, F_1, s) Y^1(p - s) = Q, \tag{37}$$

which defines $s(p, Q, F_1)$.

The nonbankruptcy constraint on the fine in region 1 can be written as

$$(p - F_1) Y^1\big(p - s(p, Q, F_1)\big) + \overline{X}^1\big(p - s(p, Q, F_1)\big) \geq 0, \tag{38}$$

which is affected by other regions' choices of emission quotas.

With interregional income transfers equalizing marginal social utilities of income across regions, global welfare maximization is equivalent to global income maximization subject to the nonbankruptcy constraints (see Sect. 4). The Lagrange function can be written as

$$\begin{aligned}
\varphi^A &= pY^1\big(p - s(p, Q, F_1)\big) + \overline{X}^1\big(p - s(p, Q, F_1)\big) + G^1(p, E) \\
&\quad + p\overline{Y}^1(p, E) - C^1\left(\frac{N_1 s(p, Q, F_1)}{F_1}\right) \\
&\quad + \sum_{j=2}^{J} \left\{ pY^j\left(p - \frac{I^j(p, F_j)}{N_j} F_j\right) + \overline{X}^j\left(p - \frac{I^j(p, F_j)}{N_j} F_j\right) \right. \\
&\quad \left. + G^j(p, E) + p\overline{Y}^j(p, E) - C^j\big(I^j(p, F_j)\big) \right\} \\
&\quad + \mu_1^A\big((p - F_1) Y^1\big(p - s(p, Q, F_1)\big) + \overline{X}^1\big(p - s(p, Q, F_1)\big)\big)
\end{aligned}$$

$$+\sum_{j=2}^{J}\mu_j^A\left((p-F_j)Y^j\left(p-\frac{I^j(p,F_j)}{N_j}F_j\right)\right.$$

$$\left.+\overline{X}^j\left(p-\frac{I^j(p,F_j)}{N_j}F_j\right)\right).^{31} \tag{39}$$

By differentiating the Lagrange function, it is easy to show that at social optimum, region 1's nonbankruptcy constraint (38) is binding and all regions' choices of emission quotas account for the pecuniary externalities associated with (38). Following the analysis in Sect. 5, we can demonstrate that an interregional policy scheme organized after Game 2, with decentralized leadership of quotas followed by centralized fines and interregional income transfers, would induce the regional regulators to internalize all environmental and pecuniary externalities.

A complete characterization of the social optimality conditions and the interregional policy schemes for the above situation, and a complete characterization of all other possible scenarios, are available from the authors upon request. □

Nonopportunistic enforcers and perfect compliance

The industrial producers in region j will purchase the required number of permits if the following condition holds:

$$\frac{I_j}{N_j}F_j \geq s, \quad j=1,\dots,J. \tag{40}$$

The equilibrium clearing condition for the global permit market becomes

$$\sum_{j=1}^{J}Y^j(p-s)=Q, \tag{41}$$

which defines $s(p,Q)$. Regional per capita income now can be written as

$$m^j(p,Q_j,Q)\equiv\frac{X_j^0+pY_j^0+\Pi_s^j(p,Q)+s(p,Q)Q_j-C^j(I_j)}{n_j}. \tag{42}$$

Social optimum is obtained when the UNFCCC chooses interregional income transfers $\{T_j\}_{j=1,\dots,J}$ and nonnegative $\{Q_j,I_j,F_j\}_{j=1,\dots,J}$ to maximize $\sum_{j=1}^{J}\theta_j V^j \times (p, m^j(p,Q_j,Q)+T_j/n_j))$, subject to the constraints (17a), (40), and

$$pY^j\big(p-s(p,Q)\big)+\overline{X}^j\big(p-s(p,Q)\big)-F_jY^j\big(p-s(p,Q)\big)\geq 0, \quad j=1,\dots,J. \tag{43}$$

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[31] The Lagrange function and multipliers in the Appendix appear with a superscript "A."

Socially optimal conditions are given by equations (17a), (18a), (22), (23), and

$$\frac{I_j}{N_j}F_j = s, \quad j = 1, \ldots, J. \tag{44}$$

If the task of inspection is decentralized to the regional enforcement agencies, they will choose I_j to maximize $V^j(p, m^j(p, Q_j, Q) + T_j/n_j)$, subject to the conditions (40) in each region. The enforcement agencies' problems will lead to (44), which allow us to write I_j as $\frac{N_j s(p,Q)}{F_j}$.

Following the same analysis as in Game 2, it is straightforward to derive the socially optimal conditions (17a), (18a), (22), and (23) as the result of the choices made by the GEF, the UNFCCC and the regional regulators in such a policy scheme. Similarly, following the same analysis as in other policy games, we can see that they lead to inefficient results. A complete characterization of the equilibrium conditions of the policy games is available from the authors upon request.

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