A Comparison of Emissions Taxes and Permit Markets For Controlling Correlated Externalities

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Abstract: This paper provides an answer to the question, are emission taxes an efficient and self-enforcing mechanism to control correlated externality problems? By "correlated externalities" we mean multiple pollutants that are jointly produced by a single source but which cause differentiated regional and global externalities. By "self-enforcing" we mean a mechanism that accounts for the endogeneity that exists between competing jurisdictions in the setting of environmental policy within a federation of regions. This mechanism incorporates sequential decision making among the jurisdictions and therefore determines an equilibrium based on the concept of subgame perfection. We find that, unlike joint domestic and international tradable permit markets, joint emissions taxes and a hybrid scheme of permits and taxes are neither efficient nor self-enforcing.

Key Words: Correlated externalities; hybrid scheme; joint emissions taxes; joint permits

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Abstract: This paper provides an answer to the question, are emission taxes an efficient and self-enforcing mechanism to control correlated externality problems? By "correlated externalities" we mean multiple pollutants that are jointly produced by a single source but which cause differentiated regional and global externalities. By "self-enforcing" we mean a mechanism that accounts for the endogeneity that exists between competing jurisdictions in the setting of environmental policy within a federation of regions. This mechanism incorporates sequential decision making among the jurisdictions and therefore determines an equilibrium based on the concept of subgame perfection. We find that, unlike joint domestic and international tradable permit markets, joint emissions taxes and a hybrid scheme of permits and taxes are neither efficient nor self-enforcing.

1. Introduction

In a recent paper, Caplan and Silva (2005a) show that tradable permit markets can be used as an efficient self-enforcing mechanism to control correlated externalities in a global federation with "decentralized leadership", i.e., a federation where regional governmental agencies have the authority to choose initial permit endowments. Their finding, while important for international agreements such as the United Nations Framework Convention on Climate Change, begs an immediate question. Are emissions taxes similarly efficient and self-enforcing? This short paper provides an answer – no, they are not. Therefore, policymakers presently involved in climate-change negotiations might exercise greater caution in pursuing alternatives to an international permit trading scheme, particularly when the correlations between global and localized pollution problems are accounted for.

Correlated externalities are simultaneous localized and global third-party effects caused by a single source.[1] In the case of air pollution, for instance, the burning of fossil fuels creates global externalities through the emissions of carbon dioxide (CO_2), ozone, nitrogen oxide (NO_x), and sulfur dioxide (SO_2), as well as local externalities through emissions of carbon monoxide (CO), volatile organic compounds, and particulate matter (i.e., smog). Abatement technologies typically have joint, or "coarse" effects on these pollutants.[2] For example, jet scrubbers used to remove particulate matter from a gas stream with a dispersed liquid – e.g. in the steel, chemical, and foundry industries – also remove gaseous pollutants (Brauer and Varma 1981; Theodore and Buonicore 1982). Absorption technologies, which create residual molecular forces at the surface of solids to attract molecules of gases and vapors, also provide a good example since they lead to simultaneous removal of particulate matter and mixed gaseous pollutants such as SO_2 , NO_x, hydrogen flouride, and hydrogen chloride (Ibid).

One can therefore think of global warming (i.e. carbon emissions) and smog as a specific context for a correlated externality problem, which, as shown by Caplan and Silva (2005a), can be solved through the use of joint permit markets in a three-stage process. In the first stage, regional authorities establish a collective global permit market for carbon emissions through an international agreement. In the second stage, a global environmental facility (GEF) provides redistributive interregional transfers. Finally, in the third stage, the regional governmental authorities establish separate domestic smog permit markets.[3]

As we show below, when joint emissions taxes are substituted for a joint permit program of this type, the regional governments are *not* induced to simultaneously and endogenously control the local and global externalities at efficient levels. Neither does an efficient allocation of the local and global externalities result when a hybrid scheme is used, where the regions establish separate domestic smog permit markets in the third stage, and taxes to control carbon emissions are chosen by the regional authorities in the initial stage. In effect, we find that while parties to international agreements such as the Kyoto Protocol can benefit by developing separate permit markets to control localized externalities in conjunction with an international permit market to control greenhouse gas emissions, the same cannot be said for joint emissions taxes or a hybrid scheme.

The next section presents the basic correlated externality model with joint emissions taxes and abatement technology, and characterizes the Pareto efficient solution. Section 3 solves the model with joint emissions taxes and shows why this mechanism is inefficient under a decentralized-leadership regime. Section 4 compares this inefficiency result with the efficient result for a joint permit market. Section 5 solves the model with a hybrid permit-emissions tax scheme. Section 6 provides an example of the key results in Section 3 and Section 7 concludes.

2. A Correlated Externality Model

Following Caplan and Silva (2005a), consider a global economy consisting of $J \geq 2$ regions indexed by j, and $I_j > 1$ energy firms indexed by ij in each region j. Assume n_j consumers are located in region j. The utility of a representative consumer in region j is $u^j(x_j, y_j, g_j, e)$, where x_j, y_j, g_j, and $e = \sum_j e_j$ are respectively the quantities consumed of a numeraire good, energy, a localized pollutant (smog), and a global pollutant (carbon).[4] We assume that u^j is strictly quasi-concave, increasing in the first two arguments, and decreasing in the last two arguments. We also invoke the standard Inada Conditions for the consumer's choice variables, i.e., $u^j_x \to \infty$ as $x_j \to 0$ and $u^j_x \to 0$ as $x_j \to \infty$ and similarly $u^j_y \to \infty$ as $y_j \to 0$ and $u^j_y \to 0$ as $y_j \to \infty$ (subscripts on functions henceforth denote the associated partial derivatives).

Let net emissions of carbon in region j be $e_j = \sum_{ij} e_{ij} = \sum_{ij}\left(Y_{ij} - \left(a^e_{ij} + \gamma^e a^g_{ij}\right)\right)$, where Y_{ij} is the total quantity of energy produced by energy firm ij in region j, a^e_{ij} is total amount of abatement of e_{ij} produced by firm ij in region j, a^g_{ij} is the total amount of abatement of g_{ij} produced by firm ij in region j. The term $\gamma^e \in (0,1]$ represents the fraction of firm ij's abatement effort of smog that also reduces e_{ij}. Similarly, net emissions of smog in region j is defined as $g_j = \sum_{ij} g_{ij} = \sum_{ij}\left(Y_{ij} - \left(a^g_{ij} + \gamma^g a^e_{ij}\right)\right)$, where in this case (^{g} □ (0,1] represents the fraction of firm ij's abatement effort of carbon that also reduces $g_{ij.}$

The price of the numeraire good is normalized to one, and r_j represents the competitively-determined price of energy in region j. Region j's total income is represented by

$$w_j = x^0_j + \sum_i \pi^{ij} + \tau_j, \ \square \, j \ \square \ J \tag{1}$$

where x^0_j is an initial endowment of the numeraire good, B^{ij} is energy firm ij's profit (defined below), and ϑ_j is the GEF's budget-balanced transfer remitted to region j (if positive) or sent from region j (if negative), $\sum_j \tau_j = 0$.

Since residents are identical within each region, each consumer in region j faces a budget constraint,

$$x_j + r_j y_j = \frac{w_j}{n_j}, \ \square \, j \ \square \ J. \tag{2}$$

The representative consumer's problem is therefore to maximize u^j by choosing $\{x_j,y_j\}$ subject to (2), taking r_j, g_j, and e as given. This results in (2) and

$$\frac{u^j_y}{u^j_x} = r_j, \ \square \, j \ \square \ J \tag{3}$$

i.e., the standard consumer-maximization result where the marginal rate of substitution is set equal to the inverse price ratio. Equations (2) and (3) implicitly define the consumer's demand functions $x_j \equiv x_j\left(r_j, w_j, g_j, e\right)$ and $y_j \equiv y_j\left(r_j, w_j, g_j, e\right)$.

Firm ij's profit from energy production is defined as

$\pi^{ij} = r_j Y_{ij} - c^{ij}\left(Y_{ij}, a^g_{ij}, a^e_{ij}\right) - t^e_j e_{ij} - t^g_j g_{ij}$, where total cost c^{ij} is strictly increasing and convex in each term, t_j^e equals the uniform tax rate per unit of carbon emissions in region j, and t_j^g equals the uniform tax rate per unit of smog in region j.

Energy firm ij's problem is therefore to maximize B^{ij} by choosing $\{Y_{ij}, a_{ij}^g, a_{ij}^e\}$, taking t_j^e, t_j^g and all energy prices as given, resulting in

$$t_j^e + t_j^g = r_j - c_Y^{ij}, \square\ ij \square\ I_j; \square\ j \square\ J \tag{4a}$$

$$\gamma^e t_j^e + t_j^g = c_{a^g}^{ij}, \square\ ij \square\ I_j; \square\ j \square\ J \tag{4b}$$

$$t_j^e + \gamma^g t_j^g = c_{a^e}^{ij}, \square\ ij \square\ I_j; \square\ j \square\ J \tag{4c}$$

which is the standard profit-maximization result associated with the choices of energy output and abatement of smog and carbon.[5] Equations (4a) – (4c) implicitly define energy firm ij's respective supply functions (r_j, γ^g, and γ^e suppressed) $Y_{ij} = Y_{ij}\left(t_j^e, t_j^g\right)$, $a_{ij}^g = a_{ij}^g\left(t_j^e, t_j^g\right)$, $a_{ij}^e = a_{ij}^e\left(t_j^e, t_j^g\right)$, $g_{ij} = g_{ij}\left(t_j^e, t_j^g\right) \Rightarrow g_j = g_j\left(t_j^e, t_j^g\right)$, $e_{ij} = e_{ij}\left(t_j^e, t_j^g\right) \Rightarrow e_j = e_j\left(t_j^e, t_j^g\right) \Rightarrow e = e\left(t_1^e, ..., t_J^e, t_1^g, ..., t_J^g\right)$, and $\pi^{ij} = \pi^{ij}\left(t_j^e, t_j^g\right)$, $\square$ ij $\square$ I_j; $\square$ j $\square$ J.

Equilibrium in the regional energy markets occurs where,

$$n_j y_j\left(r_j, w_j, g_j, e\right) = \sum_{ij} Y_{ij}\left(t_j^e, t_j^g\right), \square\ j \square\ J. \tag{5}$$

The J equations represented by (5) therefore define (n_j suppressed)

$r_j \equiv r_j\left(w_1,\ldots,w_J,t_1^e,\ldots,t_J^e,t_1^g,\ldots,t_J^g\right) \forall\, j \in J$. Similar to the representative consumers, the regional governments and the GEF take $\left\{r_j\right\}_j$ as given.[6]

For a fixed set of social welfare weights $\theta = \{\theta_j \mid 0 < \theta_j < 1, j = 1,\ldots J, \sum_j \theta_j = 1\}$ the conditions that characterize an interior Pareto efficient allocation are (2), (3),

$$\frac{\theta_j u_x^j}{n_j} = \frac{\theta_k u_x^k}{n_k},\ \forall\, j,k \in J,\ j \neq k \tag{6}$$

and for all $j \in J$ and $ij \in I_j$

$$\frac{n_j u_g^j}{u_x^j} + \sum_j \frac{n_j u_e^j}{u_x^j} + \frac{u_y^j}{u_x^j} - c_Y^{ij} = 0 \tag{7}$$

$$\frac{n_j u_g^j}{u_x^j} + \gamma^e \sum_j \frac{n_j u_e^j}{u_x^j} + c_{a^g}^{ij} = 0 \tag{8}$$

$$\frac{\gamma^g n_j u_g^j}{u_x^j} + \sum_j \frac{n_j u_e^j}{u_x^j} + c_{a^e}^{ij} = 0. \tag{9}$$

Equation (6) shows that the marginal utilities of the numeraire good (normalized by the welfare weights and population sizes) are equated across all regions. Equations (7) – (9) are modified Samuelson conditions for an impure public good, equating the marginal social benefits of an additional unit of the economic activity with its associated social marginal cost. The equality in (7) pertains to the choice of firm ij's energy output, while the equalities in (8) and (9) pertain to the choices of firm ij's abatement efforts of smog and carbon, respectively.

As Caplan and Silva (2005a) demonstrate for a wide class of preferences, a joint permit market equilibrates the incentives of the regional governmental agencies and the

GEF, thus inducing the regions to voluntarily allocate their resources according to conditions (6) – (9). This is due to the fact that with permit markets, rather than emissions taxes, firm ij's profit function is written as

$\pi^{ij} = r_j Y_{ij} - c^{ij}\left(Y_{ij}, a^g_{ij}, a^e_{ij}\right) + p\left(\bar{e}_{ij} - e_{ij}\right) + v_j\left(\bar{g}_{ij} - g_{ij}\right)$, where p equals the competitively determined price of a carbon emissions permit, v_j equals the competitively determined price of a smog permit in region j, and the quantities $\bar{e}_{ij}$ and $\bar{g}_{ij}$ are the aggregate endowments of carbon emissions permits and smog permits, respectively, initially allocated by the regional authority to the energy firms.[7] As a result of the firms facing permit prices rather than emissions taxes, equations (4a) – (4c) are rewritten as

$$p = r_j - v_j - c^{ij}_Y = c^{ij}_{a^e} - \gamma^g v_j = \frac{c^{ij}_{a^g} - v_j}{\gamma^e}, \; \square \text{ ij } \square \text{ } I_j; \square \text{ j } \square \text{ J.} \qquad (4')$$

The sub-game perfect equilibrium of the three-stage game described in Section 1 then results in $p = -\sum_j \frac{n_j u^j_e}{u^j_x}$ from first-stage "play", condition (6) from the second stage, and $v_j = -\frac{n_j u^j_g}{u^j_x}$, $\square$ j $\square$ J in the final stage. Combining these results with (1) - (4') results in conditions (6) – (9). A joint permit market therefore results in an efficient allocation of smog and carbon emissions as well as the numeraire good.

3. Joint Emissions Taxes

Although a "harmonized" set of Pareto-efficient emissions taxes can always be chosen *exogenously* (i.e. without the guarantee of self-enforcement) by the regions to simultaneously control for the global and localized externalities, the more important question of whether these taxes can be determined *endogenously* (i.e. with the guarantee of self-enforcement as a result of being consistent with a subgame perfect equilibrium) has yet to be answered.

For example, it is easy to see that if the regional governmental agencies in charge of controlling carbon emissions (henceforth the "carbon agencies") independently and exogenously agree to set

$$t_j^e = t^e = -\sum_j \frac{n_j u_e^j}{u_x^j}, \forall j \in J, \tag{10}$$

and each of the regional agencies in charge of controlling smog (henceforth the "smog agencies") independently and exogenously set

$$t_j^g = -\frac{n_j u_g^j}{u_x^j}, \forall j \in J \tag{11}$$

then, using the representative consumer's and energy firms' corresponding optimality conditions (3) and (4a) – (4c), respectively, the modified Samuelson conditions (7) – (9) are obtained.[8] Indeed, given (3) and (4a) – (4c), (10) and (11) are the *unique* tax rules that result in conditions (7) – (9), similar in nature to the tax rules derived in Hoel (1992) and Michaelis (1992). However, as Chichilnisky, et al. (2000) have shown, exogenously determined tax rules are absent of a mechanism to satisfy condition (6). Thus, the Pareto efficient allocation itself is not obtained. Moreover, nothing ensures that each region j will in fact find it desirable to implement (10) and (11) on its own as an equilibrium strategy.

The problem with joint emissions taxes unfortunately does not stop there. Endogenizing the tax instruments in a decentralized mechanism, such as in the three-stage game described in Section 1 (and in greater detail below), does not restore Pareto efficiency. The mechanism provides incorrect incentives to each region with respect to their choices of the tax rules, and therefore does not engender the regions' respective Lindahl prices (i.e. conditions (10) and (11) are not satisfied). Thus, the allocations of carbon and smog across regions are inefficient. The allocation of the numeraire good is similarly inefficient. To show these inefficiency results, we consider below the following multi-stage mechanism, or Stackleberg game, played between the regions and the GEF.

Stage 0: Each region decides (on behalf of its smog and carbon agencies) whether or not to participate in the game, taking each other's decision as given. The regions play the three-stage game below if they choose to participate. Otherwise, the game ends before it starts and the non-participating region(s) consequently resort to purely decentralized play.

Stage 1: Taking r_j and $\left\{t^g_{-j}, t^e_{-j}\right\}_{-j}$ as given (where subscript –j represents "not j"), region j's carbon agency chooses non-negative t^e_j to maximize $u^j(x_j,y_j,g_j,e)$ s.t. (i) conditions (1) and (2), (ii) its representative consumer's demands for x_j and y_j derived from (3), (iii) firm ij's factor output supplies of Y_{ij}, a^g_{ij}, and a^e_{ij} derived from (4a) – (4c) $\square$ ij $\square$ I_j, and (iv) region j's smog agency's smog-tax response function with respect to t^e_j (i.e., $t^g_j\left(t^e_j\right)$, which is described in detail below) $\square$ j $\square$ J.

Stage 2: Having observed $\left\{t^g_j\right\}_j$, the GEF chooses $\left\{\tau_j\right\}_j$ to maximize a weighted utilitarian welfare function (described in detail below) s.t. (i) conditions (1) and (2), (ii) $\sum_j \tau_j = 0$, (iii) $\left\{x_j, y_j, \left\{Y_{ij}, a^g_{ij}, a^e_{ij}\right\}_{ij}, t^e_j\right\}_j$, and (iv) the respective regions' smog agencies' smog-tax response functions with respect to τ_j (i.e., $\left\{t^g_j\left(\tau_j\right)\right\}_j$).

Stage 3: Taking $r_j, \left\{t^g_{-j}\right\}_{-j}$ as given, region j's smog agency chooses non-negative t^g_j to maximize $u^j(x_j,y_j,g_j,e)$ s.t. (i) conditions (1) and (2), and (ii) $\left\{x_j, y_j, \left\{Y_{ij}, a^g_{ij}, a^e_{ij}\right\}_{ij}, t^e_j\right\}_j$.

Stage 0 is a "pre-game" where the regional authorities decide (either simultaneously or sequentially) whether to participate in the ensuing three-stage game in full knowledge of their own potential gains from participation. With only two regions in the global economy, if one of the two chooses in stage 0 not to participate in the ensuing three-stage game, the game is not played. In cases with more than two regions, any possible permutation of two or more regions could potentially agree in stage 0 to play among themselves, resulting in any number of possible equilibrium outcomes from the three-stage game.[9]

Assuming J > 1 regions agree to participate in stage 0, region j's carbon agency next decides in stage 1 on its uniform carbon tax rate across all firms ij, $ij \in I_j$, taking as given the price of energy and the other regional governments' decisions. Having observed the regional governments' decisions concerning their carbon tax rates, the GEF decides in stage 2 on the levels of the interregional income transfers. In the third and final stage, region j's smog agency decides on its uniform smog tax rate across all firms ij, $ij \in I_j$, taking as given the price of energy and the other regional governments' decisions. The equilibrium concept used for the game is sub-game perfection.

It is important to note that since the GEF and the regional governmental authorities take as given the decisions of the consumers and energy firms in each region, equations (1) – (5) are naturally obtained in this game's equilibrium. Further, we assume that all tax revenue from smog ($t_j^g g_j$) and carbon ($t_j^e e_j$) emissions in region j are returned lump sum to that region's representative consumer via exogenous redistribution mechanisms T_j^g and T_j^e, respectively. These lump-sum tax-revenue rebates redefine the consumer's income constraint as

$$w_j = x_j^0 + \sum_i \pi^{ij} + \tau_j + T_j^g + T_j^e, \ \square j \square J. \qquad (1')$$

<u>The Third Stage of the Game</u>

Through backward induction, we start at the last stage of the game. In this stage, the smog agency in region j solves the problem,

$$\underset{\{t_j^g\}}{\text{Max}} \ u^j(x_j, y_j, g_j, e),$$

subject to budget constraint (2), where w_j is defined according to (1'). This results in the set of Kuhn-Tucker first-order optimality conditions,

$$\frac{u_x^j g_j}{n_j} \geq 0, \ t_j^g \left[\frac{u_x^j g_j}{n_j}\right] = 0, \ \square j \square J. \qquad (12)$$

At an interior solution the smog agency in region j therefore sets t_j^g such that $g_j = 0$.[10] We note that this tax rate is not unique. Any t_j^g satisfying (12) with equality is optimal from the smog agency's perspective. Having chosen in Stage 0 to participate in the game, the incentive for region j's smog agency is to set t_j^g high enough to drive smog emissions to zero.

Comparing (12) with (11) shows that the smog agencies in each region are unable to simultaneously choose their respective socially efficient tax rules for smog, implying an inefficient allocation of smog emissions for the federation irrespective of what choices the carbon agencies and GEF have made in the preceding stages. The smog agencies set their tax rates too high, resulting in inefficiently low levels of smog emissions regionally. Section 4 discusses why this inefficiency result for emissions taxes is avoided in the case of transferable permit markets.

Assuming an interior solution, equations (12) can be used to define the smog agencies' respective smog-tax response functions $t_j^g\left(t_j^e, \tau_j\right)$, $\square\, j \,\square\, J$. These response functions are derived by totally differentiating (12) with respect to t_j^e and τ_j, which results in,

$$\frac{\partial t_j^g}{\partial t_j^e} = -e_j \frac{\partial t_j^g}{\partial \tau_j} = -\frac{e_j}{g_j} < 0, \square\, j \,\square\, J \tag{13}$$

According to (13), the smog agency's response to its region's transfer τ_j is positive, yet inversely proportional to the level of smog. Thus, a reduction in (or negative) τ_j induces region j's smog agency to reduce t_j^g. The smog-tax reduction is larger in magnitude the lower is the level of smog. To the contrary, the smog agency's response to its region's carbon tax t_j^e is negative and proportional to the ratio of smog and carbon emissions. Thus, an increase in t_j^e induces the smog agency to reduce t_j^g. The smog-tax reduction is larger in magnitude the larger is the ratio of smog and carbon emissions. It is important to note that although the smog agency's choice of t_j^g is responsive to the choices of τ_j and t_j^e, in equilibrium t_j^g is never set such that $g_j > 0$, □ j □ J.

In a subgame perfect equilibrium, the smog agency's response functions are endogenized (i.e., "correctly guessed") by the other players (i.e. the GEF and the carbon agency) in the earlier stages of the game. We now proceed to the second stage of the game to show why the GEF is similarly unable to satisfy its optimality condition (6).

The Second Stage of the Game

In this stage, we assume that the GEF's objective function is a weighted global welfare function as follows:

$$W\left(\left\{u^j\right\}_j\right) = \sum_j \theta_j u^j\left(x_j, y_j, g_j, e\right).$$

that is, the same objective function as in the Pareto efficiency problem described above. The GEF takes $\left\{r_j, x_j, y_j, Y_{ij}, a_{ij}^g, a_{ij}^e, t_j^e\right\}_j$ as given and chooses the set $\left\{\tau_j\right\}_j$ to maximize $W(\{u^j\}_j)$ subject to (1'), (2), (13), $\sum_j \tau_j = 0$, and

$$u^j\left(x_j, y_j, g_j, e\right) \geq \bar{u}^j, \text{ □ } j \text{ □ } J,$$

(14)

where the set of variables $\left\{x_j, y_j, g_j, e\right\}_j$ in (14) is evaluated at the game's equilibrium. Caplan and Silva (2005a) have shown that for an efficient solution to this type of game there exists a range $\{2_j\}_j$ for which the participation constraints (14) are satisfied slack for each region. Therefore, the game is potentially implementable.

The first-order conditions for this problem result in

$$\lambda = 0 \tag{15}$$

where λ represents the shadow price, or multiplier attached to the budget-balance constraint $\sum_j \tau_j = 0$. Equation (15) implies that the marginal value to the GEF of making an additional transfer to any region j in equilibrium is zero *regardless of the transfer levels themselves*. Thus, unlike the case of a joint permit market, the GEF has no a priori incentive to provide interregional transfers. This result is consistent with the fact that in the subsequent stage the smog agencies over-tax smog emissions.

Ironically, if the GEF ignores (13) in its decision problem, its optimality rule is then (6) rather than (15). However, this decision would also result in a sub-optimal redistribution of income across regions given the smog agencies' decisions in the third stage of the game.

By following optimality rule (15) the GEF's transfer response functions $\tau_j\left(t_1^e,\ldots,t_J^e\right)$ are necessarily equal to zero, i.e.,

$$\frac{\partial \tau_j}{\partial t_j^e} = 0, \square\, j \,\square\, J. \tag{16}$$

As will now be shown, the smog agency's choice in the third stage not only renders the GEF's decision ineffectual, it similarly "unravels" the carbon agency's problem.

<u>The First Stage of the Game</u>

In this stage, region j's carbon agency chooses t_j^e to maximize its regional welfare. In doing so, the carbon agency correctly guesses the GEF's transfer-response function for its region, as well as the smog agency's smog-tax response function. Formally stated, its problem is,

$$\underset{\left\{t_j^e\right\}}{\text{Max}} \quad u^j\left(x_j, y_j, g_j, e\right),$$

subject to (1'), (2), (13), and (16). As shown in Appendix A, the carbon agency's first-order conditions imply the optimal tax rule,

$$t_j^e = 0, \forall j \in J. \tag{17}$$

In other words, the effect of the smog agency's decision in the third stage "carries backward" to the first stage, inducing the region's carbon agency to choose an inefficient carbon tax rate. Specifically, it becomes optimal for the carbon agency not to levy a carbon tax at all!

The following proposition summarizes the overall results for this game.

Proposition 1: The subgame perfect equilibrium for joint emissions taxes is inefficient. This inefficiency emanates from the smog agencies' choices of sub-optimal smog tax rates in the third stage of the game. As a result, both the GEF's and the carbon agencies' preceding choices of transfers and carbon tax rates are rendered ineffectual.

Proposition 1 stands in stark contrast to the efficiency result for joint permit markets obtained in Caplan and Silva (2005a) under a similar three-stage game. Recall that for the joint-permit game, the same decision framework was adopted, i.e. the carbon agencies "moved" in the first stage, followed by the GEF in the second stage, and then the smog agencies in the third stage. Further, it was assumed that the agencies and the GEF had well-defined informational limits, i.e. they took as given all prices as well as the decision rules followed by the representative consumers and energy firms. Under these circumstances, joint permit markets resulted in socially efficient allocations of smog, carbon, and income, i.e. the game satisfied the Pareto efficiency conditions (6) – (9). To better understand why joint emissions taxes do not similarly result in the socially efficient outcome, we now turn to a comparison of the two policy instruments.

4. What Went Wrong with Joint Emission Taxes?

As pointed out in Proposition 1, the inefficiency associated with joint emissions taxes emanates from the smog agency's choice of the smog tax rate in the third stage of the game, rather than the choice of an aggregate endowment of smog across its energy firms, as it would be able to make in a joint-permit game. To better understand what went wrong in this stage, we can compare this outcome with what went right in the third stage of the joint-permit game in Caplan and Silva (2005a).

In the third stage of the joint-permit game, region j's smog agency chooses an aggregate endowment of smog permits, rather than a smog tax rate, to maximize its regional welfare. The resulting first-order conditions show that each smog agency chooses the level of smog up to the point where the price of a permit just equals the value of the region's aggregate welfare loss associated with an additional unit of smog. Thus, the equilibrium price of a permit reflects the social marginal damage associated with an additional unit of smog in each respective region.

What drives this result is the simple fact that in a joint-permit game the smog agency's choice variable, $\overline{g}_j$, appears directly in the representative agent's utility function as well as in the firms' profit functions via the added revenue associated with holding a net endowment of permits. As a result, each smog agency has no better alternative than to choose the socially efficient endowment of smog permits, precisely because it can do so directly, as opposed to indirectly through the setting of a tax rate on the energy firms. Put another way, the derivation of the smog agency's optimal tax rule (equation (12)) in the joint-emissions game does not include a (direct) accounting of the value of the marginal damages suffered by the consumer (i.e., u_g^j). Thus, although the smog agency is able to directly determine with its tax rule the energy firm's smog emissions, it is unable to do this in a way that directly accounts for the marginal value of the damages suffered by the consumer (i.e., the consumer's Lindahl prices), and thus the smog agency is generally unable to induce the energy firms to choose the socially efficient level of smog emissions.

Given the smog agency's optimal choice of smog permits in stage three of the joint-permit game, the GEF is induced to follow (6) – the optimal decision rule for transfers – irrespective of the smog agency's permit response functions. Furthermore, by endogenizing these permit response functions, the GEF chooses to align its own transfer response functions with the carbon permit price that is established in the first stage of the game. Together, the smog agencies' optimal choices of aggregate smog-permit endowments and the GEF's alignment of its transfer responses to the carbon permit price, induce the respective carbon agencies to simultaneously choose the optimal aggregate endowment of carbon permits. Caplan and Silva (2005a) show that this occurs where the equilibrium price of a [carbon] permit just equals the value of the *global* welfare loss associated with an additional unit of carbon, which is also consistent with the GEF's transfer policy.

To reiterate, the inefficiency of the joint emissions taxes relates back to the fact that by choosing a smog tax rate rather than an endowment of smog permits in the third stage of the game, the smog agencies do not have a choice variable that appears directly in the representative consumers' preferences. As a result, each smog agency is effectively precluded from determining the socially efficient smog tax rate that would just equal the value of the region's aggregate welfare loss associated with an additional unit of smog. In other words, the subgame perfect equilibrium for this game cannot endogenously support the smog tax rate as represented by (11). Instead, the smog agencies over-tax the firms and thus render both the GEF and the carbon agencies ineffectual in their choices of interregional transfers and carbon tax rates, respectively.

5. A Hybrid Scheme

Introducing domestic smog permit markets into the model requires the following modifications. First, firm ij's profit function is redefined as

$\pi^{ij} = r_j Y_{ij} - c^{ij}\left(Y_{ij}, a_{ij}^{g}, a_{ij}^{e}\right) - t_j^e e_{ij} + v_j\left(\bar{g}_{ij} - g_{ij}\right)$, where v_j and $\bar{g}_{ij}$ are as defined above in Section 2. Second, the consumer's income constraint is redefined as

$$w_j = x_j^0 + \sum_i \pi^{ij} + \tau_j + T_j^e, \ \square\, j \,\square\, J. \tag{1''}$$

Third, equations (4b) and (4c) must be rewritten as

$$\gamma^e t_j^e + v_j = c_{a^g}^{ij}, \ \square\, ij \,\square\, I_j; \ \square\, j \,\square\, J \tag{4b'}$$

$$t_j^e + \gamma^g v_j = c_{a^e}^{ij}, \ \square\, ij \,\square\, I_j; \ \square\, j \,\square\, J. \tag{4c'}$$

Finally, a smog-permit market clearing condition must be added to the model,

$$\sum_i g_{ij}\left(r_j, t_j^e, v_j\right) = \bar{g}_j, \ \square\, j \,\square\, J. \tag{5a}$$

As in the joint-emission tax scenario, each carbon agency decides in the first stage its uniform carbon tax rate across all firms ij, ij □ I_j, taking as given the price of energy and each other regional government's decisions. Having observed the regional governments' decisions concerning their carbon tax rates, the GEF decides in the second stage of the game the levels of the interregional income transfers. In the third and final stage, each smog agency decides its region's total endowment of smog permits, taking as given the price of energy, each other regional government's decision, and the smog market permit price, v_j. The equilibrium concept used for this game is again sub-game perfection, which is solved for through backward induction.

In stage three, region j's smog agency chooses $\bar{g}_j$ to maximize its regional welfare. Formally stated, its problem is,

$$\underset{\{\bar{g}_j\}}{\text{Max}} \quad u^j\left(x_j, y_j, \bar{g}_j, e\right),$$

subject to the budget constraint (2) and income defined according to (1"). This results in the set of first-order optimality conditions

$$v_j = -\frac{n_j u_g^j}{u_x^j}, \square\, j \,\square\, J. \tag{18}$$

Equations (18) reveal that each smog agency chooses the level of smog up to the point where the price of a permit just equals the value of the region's aggregate welfare loss associated with an additional unit of smog. The regional markets for smog therefore work as they should – the equilibrium price of a permit reflects the social marginal damage associated with an additional unit of smog in each respective region. Furthermore, equations (18) define the smog agencies' respective smog-endowment response functions $\bar{g}_j = \bar{g}_j\left(\tau_j, t_j^e\right), \square\, j \,\square\, J$. These response functions are derived by totally differentiating (18) with respect to τ_j and t_j^e, resulting in,

$$\frac{\partial \bar{g}_j}{\partial t_j^e} = -e_j \frac{\partial \bar{g}_j}{\partial \tau_j} = e_j \frac{\Gamma_{t^e}^j}{\Omega_g^j}, \square\, j \,\square\, J \tag{19}$$

where $\Gamma^j_{t^e} = \dfrac{v_j u^j_{xx}}{n_j} + u^j_{gx}$ and $\Omega^j_g = \dfrac{v_j^2 u^j_{xx}}{n_j} + 2v_j u^j_{xg} + n_j u^j_{gg} \le 0$.

In stage 2, the GEF solves the same type of second-stage problem as in Section 3 for joint emissions taxes (with (1") replacing (1') and excluding (13)), resulting in the first-order conditions, $\dfrac{\theta_j u^j_x}{n_j} + \dfrac{\theta_j u^j_x v_j}{n_j}\dfrac{\partial \bar{g}_j}{\partial \tau_j} + \theta_j u^j_g \dfrac{\partial \bar{g}_j}{\partial \tau_j} = \lambda$ $\square$ j $\square$ J, which, after applying (18), results in (6). Thus, the GEF endogenously chooses its transfers such that the marginal utilities of the numeraire good (normalized by the welfare weights and populations) are equated across all regions.

It is interesting to note that given (4a), (4b'), and (4c'), the results from stages 2 and 3 indicate that (10) must be satisfied as a result of the regions' first-stage problems in order for the hybrid scheme to mimic the efficiency conditions (6) – (9). We now show that this generally will not be the case.

As shown in Appendix B, total differentiation of equations (6) result in the GEF's transfer response functions $\tau_j\left(t^e_1,\ldots,t^e_J\right)$, $\square$ j $\square$ J, which are endogenized in the carbon agencies' respective first-stage maximization problems,

$$\underset{\left\{t^e_j\right\}}{\text{Max}} \quad u^j\left(x_j, y_j, \bar{g}_j\left(\tau_j\left(t^e_1,\ldots,t^e_J\right), t^e_j\right), e\right),$$

subject to (1"), (2), (19), and $\tau_j\left(t^e_1,\ldots,t^e_J\right)$. The first-order conditions for this problem are,

$$\frac{u^j_x\left(v_j\left(\dfrac{\partial \bar{g}_j}{\partial t^e_j} + \dfrac{\partial \bar{g}_j}{\partial \tau_j}\dfrac{\partial \tau_j}{\partial t^e_j}\right) - e_j + \dfrac{\partial \tau_j}{\partial t^e_j}\right)}{n_j} + u^j_g\left(\frac{\partial \bar{g}_j}{\partial t^e_j} + \frac{\partial \bar{g}_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial t^e_j}\right) = 0, \square\ j \square\ J,$$

which, after applying conditions (18) result in,

$$\frac{u_x^j\left(\frac{\partial \tau_j}{\partial t_j^e} - e_j\right)}{n_j} = 0, \square\, j \,\square\, J.$$

(20)

Given the results in Appendix B for $\partial\tau_j/\partial t_j^e \,\square\, j \,\square\, J$, we see that the carbon agencies generally do not abide by (10) in setting their respective carbon taxes. Rather, according to (20) they set t_j^e such that

$$\frac{\partial \tau_j}{\partial t_j^e} = e_j, \square\, j \,\square\, J \tag{21}$$

which leads to our second proposition.

Proposition 2: The subgame perfect equilibrium for the hybrid scheme is inefficient. This inefficiency emanates from the carbon agencies' choices of sub-optimal carbon tax rates in the first stage of the game. This occurs in spite of the fact that both the GEF's and the carbon agencies' succeeding choices of transfers and carbon tax rates are correctly aligned with the Pareto-efficient conditions.

Thus, although the hybrid scheme induces the GEF and the smog agencies to align their choices with the Pareto efficiency conditions (6) – (9), the carbon agencies do not share this incentive. The reason for this lack of incentive equivalence is similar to that for joint emission taxes. In this case, however, the inefficiency relates back to the fact that by choosing a carbon tax rate rather than an endowment of carbon permits, the carbon agencies do not have a choice variable that appears directly in the representative consumers' preferences. As a result, each carbon agency is effectively precluded from choosing the optimal carbon tax rate that would just equal the value of the global welfare loss associated with an additional unit of carbon emissions.

6. An Example

In this section we use a simple Cobb-Douglas specification of preferences to show that a joint permit market satisfies Pareto efficiency, but that joint taxation does not (as discussed in Section 3).

6.1. Joint Permit Market

Assume a simple three-region, I_j-firm world. The representative consumer in region j, j=1,2,3, is characterized by the Cobb-Douglas utility function,

$$u_j = x_j^{\sigma_j} y_j^{\delta_j} \bar{g}_j^{\alpha_j} \bar{e}^{\beta_j},$$

and income and budget constraints (1) and (2), respectively, where $0 < \Phi_j > 0$, $0 < *_j < 1$, $\forall_j < 0$, and $\exists_j < 0$. The consumer's utility maximization problem therefore results in,

$$\frac{\delta_j x_j}{\sigma_j y_j} = r_j, \ \text{j=1,2,3.} \qquad (3')$$

Profit for firm i, inclusive of its specified joint cost function, is defined as

$$\pi^{ij} = \begin{cases} r_j Y_{ij} - \left(Y_{ij}^2 + \dfrac{\left(a_{ij}^g\right)^2}{2} + \dfrac{\left(a_{ij}^e\right)^2}{2} \right) & \text{if Pareto efficient solution} \\ r_j Y_{ij} - \left(Y_{ij}^2 + \dfrac{\left(a_{ij}^g\right)^2}{2} + \dfrac{\left(a_{ij}^e\right)^2}{2} \right) + v_j\left(\bar{g}_{ij} - g_{ij}\right) + p\left(\bar{e}_{ij} - e_{ij}\right) & \text{if mechanism with joint permits} \end{cases}$$

The firm's profit maximization problem results in,

$$p = r_j - v_j - 2Y_{ij} = a_{ij}^e - \gamma^g v_j = \frac{a_{ij}^g - v_j}{\gamma^e}, \ \square\ i \in I_j;\ j = 1,2,3.$$

(4")

Together, the representative consumers' utility functions and the firms' profit functions define concave programming problems under both the Pareto-efficient and pollution-permit mechanisms. It is now straightforward to show that the Pareto efficient solution satisfies the following conditions,

$$\frac{\sigma_1\theta_1 u_1}{n_1 x_1} = \frac{\sigma_2\theta_2 u_2}{n_2 x_2} = \frac{\sigma_3\theta_3 u_3}{n_3 x_3} \tag{6'}$$

$$\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j} + \sum_{j=1}^{3} \frac{\beta_j n_j x_j}{\sigma_j \bar{e}} = -\left(r_j - 2Y_{ij}\right),\ \square\ i \in I_j \text{ and } j=1,2,3 \tag{7'}$$

$$\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j} + \gamma_j^e \sum_{j=1}^{3} \frac{\beta_j n_j x_j}{\sigma_j \bar{e}} = -a_{ij}^g,\ \square\ i \in I_j \text{ and } j=1,2,3 \tag{8'}$$

$$\frac{\gamma_j^g \alpha_j n_j x_j}{\sigma_j \bar{g}_j} + \sum_{j=1}^{3} \frac{\beta_j n_j x_j}{\sigma_j \bar{e}} = -a_{ij}^e,\ \square\ i \in I_j \text{ and } j=1,2,3. \tag{9'}$$

For the three-stage joint-permit market game, note that conditions (1), (2), (3'), (4''), all hold, as well as appropriate energy, smog permit, and carbon permit market clearing conditions (see Caplan and Silva (2005a) for further details). Following the procedure for stage 3 described in Section 2, the smog agencies' problems result in $v_j = -\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j}$, j=1,2,3. Letting $\sum_{j=1}^{3} \tau_j = 0 \Rightarrow \tau_2 = \tau_1 - \tau_3$, total differentiation of $v_j = -\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j}$, j=1,2,3 results in $\frac{\partial \bar{g}_j}{\partial \bar{e}_j} = p\frac{\partial \bar{g}_j}{\partial \tau_j}$ for j = 1 and 3 and $\frac{\partial \bar{g}_2}{\partial \bar{e}_2} = -p\frac{\partial \bar{g}_2}{\partial \tau_1} = -p\frac{\partial \bar{g}_2}{\partial \tau_3}$ for j = 2.

In the second stage, the central government chooses $\{\tau_j\}_{j=1,2,3}$ to maximize $\sum_{j=1}^{3} \theta_j u^j = \sum_{j=1}^{3} \theta_j x_j^{\sigma_j} y_j^{\delta_j} \bar{g}_j\left(\tau_j\right)^{\alpha_j} \bar{e}^{\beta_j}$, subject to (1), (2), and $\sum_{j=1}^{3} \tau_j = 0 \Rightarrow \tau_2 = -\tau_1 - \tau_3$. We note that $\bar{g}_j\left(\tau_j\right)$ accounts for the fact that in a subgame perfect equilibrium the central government endogenizes the effect of its choice of τ_j on the smog agency's choice of $\bar{g}_j$ in the succeeding stage. This problem results in,

$$\frac{\theta_1\sigma_1 u^1}{n_1 x_1} + \theta_1\left(\frac{\sigma_1 v_1 u^1}{n_1 x_1} + \frac{\alpha_1 u^1}{\bar{g}_1}\right)\frac{\partial \bar{g}_1}{\partial \tau_1} = \frac{\theta_2\sigma_2 u^2}{n_2 x_2} + \theta_2\left(\frac{\sigma_2 v_2 u^2}{n_2 x_2} + \frac{\alpha_2 u^2}{\bar{g}_2}\right)\frac{\partial \bar{g}_2}{\partial \tau_1}, \text{ and}$$

$$\frac{\theta_3\sigma_3 u^3}{n_3 x_3} + \theta_3\left(\frac{\sigma_3 v_3 u^3}{n_3 x_3} + \frac{\alpha_3 u^3}{\bar{g}_3}\right)\frac{\partial \bar{g}_3}{\partial \tau_3} = \frac{\theta_2\sigma_2 u^2}{n_2 x_2} + \theta_2\left(\frac{\sigma_2 v_2 u^2}{n_2 x_2} + \frac{\alpha_2 u^2}{\bar{g}_2}\right)\frac{\partial \bar{g}_2}{\partial \tau_3}.$$

Applying $v_j = -\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j}$ to these equations results in (6'). It is now straightforward, albeit algebraically messy, to show that totally differentiating the first equality in (6') with respect to $\vartheta_1, \bar{e}_1$, and $\bar{e}_2$, and the second equality by $\vartheta_3, \bar{e}_3$, and $\bar{e}_2$ results in

$$\frac{\partial \tau_1}{\partial \bar{e}_2} - \frac{\partial \tau_1}{\partial \bar{e}_1} = \frac{\partial \tau_3}{\partial \bar{e}_2} - \frac{\partial \tau_3}{\partial \bar{e}_3} = p.$$

Following the procedure for stage 1 described in Section 2, the carbon agencies' problems result in,

$$\frac{\sigma_j u_j\left(v_j\left(\frac{\partial \bar{g}_j}{\partial \bar{e}_j} + \frac{\partial \bar{g}_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial \bar{e}_j}\right) + p + \frac{\partial \tau_j}{\partial \bar{e}_j}\right)}{n_j x_j} + \frac{\alpha_j u_j\left(\frac{\partial \bar{g}_j}{\partial \bar{e}_j} + \frac{\partial \bar{g}_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial \bar{e}_j}\right)}{\bar{g}_j} + \frac{\beta_j u_j}{\bar{e}} = 0, \quad j = 1,2,3.$$

Applying $v_j = -\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j}$ to these equations results in $p + \frac{\partial \tau_j}{\partial \bar{e}_j} = -\frac{\beta_j n_j x_j}{\sigma_j \bar{e}}$ for j = 1 and 3, and

$p - \left(\frac{\partial \tau_1}{\partial \bar{e}_2} + \frac{\partial \tau_3}{\partial \bar{e}_2}\right) = -\frac{\beta_2 n_2 x_2}{\sigma_2 \bar{e}}$ for j = 2. Summing these last two equations and applying

$\frac{\partial \tau_1}{\partial \bar{e}_2} - \frac{\partial \tau_1}{\partial \bar{e}_1} = \frac{\partial \tau_3}{\partial \bar{e}_2} - \frac{\partial \tau_3}{\partial \bar{e}_3} = p$ results in $p = -\sum_{j=1}^{3}\frac{\beta_j n_j x_j}{\sigma_j \bar{e}}$. Finally, substituting $v_j = -\frac{\alpha_j n_j x_j}{\sigma_j \bar{g}_j}$ and

$p = -\sum_{j=1}^{3}\frac{\beta_j n_j x_j}{\sigma_j \bar{e}}$ recursively into the three equalities of equations (4') for each of the three regions results in equations (7$'$) – (9$'$). Therefore, each of the necessary and sufficient conditions for a Pareto efficient solution is satisfied in a joint permit market.

6.2. Joint Taxation

For the case of joint taxation, we first note that – as in the joint permit market – the consumers' utility maximization problems result in (3'). However, firm i's profit is now defined as, $\pi^{ij} = r_j Y_{ij} - \left(Y_{ij}^2 + \frac{\left(a_{ij}^g\right)^2}{2} + \frac{\left(a_{ij}^e\right)^2}{2} \right) - t_j^e\left(Y_{ij} - a_{ij}^g - \gamma^g a_{ij}^e\right) - t_j^g\left(Y_{ij} - a_{ij}^e - \gamma^e a_{ij}^g\right)$, resulting in the profit maximizing conditions,

$$t_j^e + t_j^g = r_j - 2Y_{ij},\ \square\ ij\ \square\ I_j;\ j = 1,2,3 \tag{4a'}$$

$$\gamma^e t_j^e + t_j^g = a_{ij}^g,\ \square\ ij\ \square\ I_j;\ j = 1,2,3$$

(4b')

$$t_j^e + \gamma^g t_j^g = a_{ij}^e,\ \square\ ij\ \square\ I_j;\ j = 1,2,3.$$

(4c')

For the three-stage joint-taxation game, note that conditions (1'), (2), (3$'$), (4a') – (4c'), and (5) all hold. Following the procedure described in Section 3, the smog agency's interior problem in stage 3 results in,

$$\frac{\sigma_j x_j^{\sigma_j - 1} y_j^{\delta_j} g_j^{\alpha_j + 1} e_j^{\beta_j}}{n_j} = 0,\ \ j = 1,2,3 \tag{12'}$$

and (13). Thus, t_j^g is set by the smog agency such that $g_j = 0$, j = 1,2,3.

The GEF's problem in stage 2 results in the first-order condition,

$$\frac{\theta_j \sigma_j x_j^{\sigma_j - 1} y_j^{\delta_j} g_j^{\alpha_j} e_j^{\beta_j}}{n_j} - \frac{\theta_j \sigma_j x_j^{\sigma_j - 1} y_j^{\delta_j} g_j^{\alpha_j + 1} e_j^{\beta_j}}{n_j} \frac{\partial t_j^g}{\partial \tau_j} = \lambda,\ \ j = 1,2,3$$

which, after applying (13), results in (15) and (16).

Finally, in stage 1 the carbon agency chooses t_j^e to maximize regional welfare subject to (1'), (2), (13), and (16). This results in the first-order condition,

$$\frac{\theta_j \sigma_j x_j^{\sigma_j-1} y_j^{\delta_j} g_j^{\alpha_j} e_j^{\beta_j}}{n_j} \frac{\partial \tau_j}{\partial t_j^e} - \frac{\theta_j \sigma_j x_j^{\sigma_j-1} y_j^{\delta_j} g_j^{\alpha_j+1} e_j^{\beta_j}}{n_j} \frac{\partial t_j^g}{\partial t_j^e} - \frac{\theta_j \sigma_j x_j^{\sigma_j-1} y_j^{\delta_j} g_j^{\alpha_j} e_j^{\beta_j+1}}{n_j} = 0$$

which, after applying (13) and (16), results in (17).

7. Conclusions

This paper represents an initial step toward characterizing the relative effectiveness of joint emissions taxes and a hybrid permit-tax scheme in controlling correlated externalities with joint abatement technology when control over the relevant policy instruments is shared by a hierarchy of independent governments and governmental agencies. We have shown that, unlike with joint permit markets, joint emissions taxes and the hybrid scheme do not result in efficient allocations of the local and global externalities when applied under an identical decision framework.

The emissions taxes "fail" in the third and final round of a decentralized leadership game played between the regional agencies charged with setting the regions' global and local pollution policies and a central government charged with determining an interregional transfer policy. In the final round, the agency in charge of setting local pollution policies sets its emission tax too high in an effort to compensate for the fact that it cannot directly control the level of the externality as it appears in the representative consumer's preference function. As a result, the game unravels in the preceding rounds – the central government's transfers are rendered ineffectual, as are the carbon emission tax rates set by the agency in charge of controlling its region's contribution to the global externality. The hybrid scheme fails in the initial stage of the game, when the carbon agencies choose their emission tax rates. Although the smog permit market is able to efficiently allocate smog emissions, and the GEF is able to satisfy the Pareto efficiency condition for income distribution, carbon emissions are inefficiently allocated across the regions.

These results denote yet another difference between price and quantity instruments in their effectiveness at controlling pollution problems. Beginning with Lerner (1971), Weitzman (1974, 1978), Roberts and Spence (1976), and Laffont (1977), who demonstrate that emission fees and marketable permits can have markedly different effects when control costs are unobserved by the regulator, to Milliman and Prince (1989), who show that emission fees provide greater incentive for firms to innovate and diffuse cleaner technologies, the list of differences between these two instruments has grown steadily over time. Now we add a stark difference between marketable permits and emission fees in the context of a self-enforcing mechanism to control correlated externality problems.

Future research should focus in two areas. First, it would be interesting to know how much additional information the regional agencies and the central government would need in order for joint emissions taxes and the hybrid scheme to induce efficient allocations of the local and global externalities. For instance, the current model is built on the assumption that the agencies and the central government know neither how energy prices nor the firm and consumer decisions are affected by their respective policy decisions. It is therefore of interest to know if endogenizing these effects would lead to an efficient outcome. Second, we have not thoroughly explored the issue of implementability in this paper. It would likewise be of interest to characterize the specific conditions (i.e. the various game frameworks) under which a joint emissions tax approach and a hybrid scheme would be implementable given that they are efficient. We have avoided this issue in this paper primarily because joint emissions taxes and the hybrid scheme have been shown to be an inefficient control mechanism. If a framework can eventually be developed within which joint emissions taxes and the hybrid scheme are shown to be efficient, the framework's implementability will then be of great practical importance.

Notes

[1] Correlated externality is not to be confused with "correlated uncertainty" that may exist between the costs and benefits associated with controlling a single externality (either localized or global). For examples of how correlated uncertainty can affect the choice of policy instruments see Shrestha (2001) and Stavins (1996).

[2] "Fine" abatement technologies would single out these factors, enabling the controlling sources to deal with each factor separately.

[3] This pattern of decision-making seems to best reflect how separate domestic policies might ideally be linked across a hierarchy of governmental agencies with global policies regarding transfers and control of the global pollutant. The global policies are set initially and then based on these policy outcomes the domestic authorities enact their policies to control the more localized externalities. Of course, in order to engage this three-stage process, an initial "pre-game" stage must be "played" by the regions to elicit their participation in the three-stage game itself. This process is outlined in detail in Section 3.

[4]In keeping with the extant literature, we identify regions with superscripts on functions and subscripts on variables.

[5] We further assume that $c^{ij}_{YY}(c^{ij}_{a^g a^g} + c^{ij}_{a^e a^e}) - \left(c^{j}_{Ya^g} + c^{j}_{Ya^e}\right)^2 > 0$, which along with the quasi-concavity condition for the representative agents' utility functions ensures concave programming problems for each of the ensuing games analyzed below.

[6] Given the implicit relationships characterizing the firm's choices and the market determination of energy prices, the consumers' implicit demands can be re-written as (r_j, γ^g,and γ^e suppressed) $x_j\left(w_j, t_1^e,\dots,t_J^e, t_1^g,\dots,t_J^g\right)$ and $y_j\left(w_j, t_1^e,\dots,t_J^e, t_1^g,\dots,t_J^g\right)$, □ j □ J.

[7] Note that in this case $\sum_i \bar{e}_{ij} = \bar{e}_j$, $\sum_j \bar{e}_j = \bar{e}$, and $\sum_i \bar{g}_{ij} = \bar{g}_j$. Also, additional market-clearing conditions are added for the smog and carbon permits.

[8] Note that the smog and carbon agencies need not be separate agencies within any given region. They are assumed so here strictly for expository purposes.

[9] As shown in Caplan and Silva (2005a), because the joint permit game is Pareto efficient there is incentive for all regions to agree to play in Stage 0. Although outside the scope of this paper, there is a burgeoning literature dealing with the issues of coalition size and stability and implementability of international agreements. For examples, see Barrett (1994), Carraro and Siniscalco (1993), Finus, et al. (2004), and Finus (2004) on the design of cooperative international environmental agreements. Caplan and Silva (2005b) explore the issue of implementability in the context of a "proportional equity" scheme.

[10] In the context of this model, a non-interior solution (i.e., $t_j^g = 0$ for any $j \in J$) implies that that particular region has chosen in stage 0 not to participate in the game. According to (11), this would also imply an inefficient allocation of smog across the regions. We further note that the smog agency is unable to satisfy (12) with equality by choosing a t_j^g such that $u_x^j = 0$, since u_x^j only approaches zero as $x_j \to \infty$.

Appendix A

The first-order condition for this first-stage problem is,

$$-\frac{u_x^j e_j}{n_j} - \frac{u_x^j g_j}{n_j}\left(\frac{\partial t_j^g}{\partial t_j^e}\right) + \frac{u_x^j}{n_j}\left(\frac{\partial \tau_j}{\partial t_j^e}\right) - \frac{u_x^j g_j}{n_j}\left(\frac{\partial t_j^g}{\partial \tau_j}\right)\left(\frac{\partial \tau_j}{\partial t_j^e}\right) = 0 \tag{A1}$$

Applying (13) and (16) to (A1) results in an undefined solution, meaning that any t_j^e is a potential optimal solution. Without loss of generality, we can therefore assume that the carbon agency chooses to abide by (17).

Appendix B

Without loss of generality assume two regions (regions 1 and 2). Totally differentiating (6) for this problem therefore results in,

$$\Phi_{\tau_1} d\tau_1 + \Phi_{t_1} dt_1^e + \Phi_{t_2} dt_2^e = 0, \tag{B1}$$

where $\Phi_{\tau_1} = \frac{\theta_1 n_2 u_{xx}^1}{n_1} + \left(\frac{v_1\theta_1 n_2 u_{xx}^1}{n_1} + \theta_1 n_2 u_{xg}^1\right)\frac{\partial \overline{g}_1}{\partial \tau_1}$,

$\Phi_{t_1} = -\frac{\theta_1 n_2 u_{xx}^1 e_1}{n_1} + \left(\frac{v_1\theta_1 n_2 u_{xx}^1}{n_1} + \theta_1 n_2 u_{xg}^1\right)\frac{\partial \overline{g}_1}{\partial t_1^e}$, and

$\Phi_{t_2} = \frac{\theta_2 n_1 u_{xx}^2 e_2}{n_2} - \left(\frac{v_2\theta_2 n_1 u_{xx}^2}{n_2} + \theta_2 n_1 u_{xg}^2\right)\frac{\partial \overline{g}_2}{\partial t_2^e}$. Conditions (19) can be applied to these expressions and (B1) can then be rearranged to derive specific expressions for $\frac{\partial \tau_1}{\partial t_1^e}$ and $\frac{\partial \tau_1}{\partial t_2^e}$.

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