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The Simple Analytics of Carbon

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This paper analyzes atmospheric carbon accumulation in a simple non-cooperative game model with two sets of participants: developed countries and less-developed countries (LDCs). Both sets are shown to contribute to global warming through different combinations of activities. Developed countries primarily add carbon through the burning of fossil fuels and CFC emissions, while the LDCs add through deforestation, animal wastes, agriculture, and burning fossil fuels. Unlike earlier papers, our game representation stresses joint productys of a nation-specific and global variety. The following issues are explored: (1) the desirability of unilateral action; (2) the efficacy of treaties among a subset of nations; (3) the effectiveness of income redistribution policies between coalitions; and (4) the self-enforceability of agreements. In the joint product scenario, some of our results are more hopeful and differ from anything in the literature.

THE SIMPLE ANALYTICS OF CARBON

Executive Summary

A number of global commons problems are interrelated and involve the atmospheric accumulation of carbon, which, in turn, absorbs and traps heat, thus leading to the warming of the atmosphere. These global commons difficulties include deforestation, ozone depletion, and global warming. Although each problem derives from different economic and natural causes, each is interdependent. The atmospheric heating problem provides challenges to the economic modeller. First, the interdependency among the contributing commons problems must be taken into account. Second, the strategic interactions among nations worldwide must be included. Standard policy prescriptions, such as corrective taxes or bargaining, for externalities (i.e., noncompensated interdependencies among economic agents) will not work if transnational interactions are ignored. Hence, a carbon tax on a barrel of oil imposed at the national level may have no ameliorating influence when other nations react in an optimizing fashion. Third, cooperative supranational pacts and agreements that involve a subset of nations must be judged in light of the responses from nations outside the pact. Fourth, both nation-specific benefits and transnational public benefits must be included when assessing the international distribution of costs and benefits that arise from activities leading to global warming. That is, joint products or multiple outputs are often involved.

This paper devises a simple game theoretic representation of the carbon accumulation problem that includes the following: the interdependencies among contributing commons problems, interactions among nations, and the presence of joint products. This framework is used to investigate the outcome of unilateral action and/or cooperative pacts among a subset of nations. The paper also identifies some pitfalls that inhibit the achievement of meaningful supranational agreements.

If allocative decisions involve the provision of a pure public good (e.g., sequestering carbon in fast-growing tree plantations), then unilateral action will impose unequal costs on those nations that seek to set a good example. (A good is purely public if its benefits cannot be withheld from anyone and if benefits do not change with group size.) In the case of pure public goods, redistributive income policies is prone to failure; aid receipts will increase provision by the amount that aid donors will cut back provision. For carbon accumulation, joint products are present and these derived outputs may be country-specific or globally public. The existence of these joint products yields some interesting results. First, a role for redistributive policy can exist. Second, the degree of suboptimality may be attenuated as compared with the pure public good scenario. Third a rich set of different cases exists, including that in which unilateral action can be beneficial to all involved. Fourth, treaties can be designed to be self-enforcing.

In the presence of joint products, a role for aid is present. A simple principle applies: aid must flow so that aid-assisted increases in carbon in the recipient nation is less than the reduction in carbon in the donor nations as real resources are transferred. Suppose that the developed nations transfer resources to the LDCs to preserve tropical forests. These resources will go to support development in the LDCs and, in so doing, will increase industrial emissions of carbon in the recipients. One form of carbon emission will be substituted for another. Will the world be better off? If the public goods of biodiversity and existence value are equal or greater in value to the foregone economic activities in the donor countries, then a welfare improvement will be achieved even if the overall level of carbon is unchanged. The inclusion of <u>all</u> joint products may justify an action that would otherwise be viewed as ineffective. Donors would be wise to insist that such aid be used in energy efficient processes.

THE SIMPLE ANALYTICS OF CARBON*

1. Introduction

Many of the world's most precious assets are owned in common by all nations and, as such, are borderless. Examples include the stratospheric ozone shield, the oceans (beyond 200 miles from coastlines), and the troposphere. Other assets, while providing benefits to current and future generations worldwide, are located within political borders. The moist tropical forests and their vast biodiversity are apt examples. The first class of assets is associated with global commons problems, in which open access often results in a tragedy of the commons[1] as the resource or asset is overexploited by users who do not consider the costs that their actions impose on others. The second class of assets may also be inefficiently exploited if the nation hosting the resource does not account for transnational public benefits derived from the resource. If, for example, the host nation only includes private and public benefits received within its own territory when making allocative decisions, inefficiency will result at the global level. Rapidly expanding populations and technology have increased the range of interactions among nations. When these interactions are uncompensated and no mechanism for compensation exists, a transnational externality exists.

A number of global commons problems are interrelated and involve the atmospheric accumulation of carbon, which, in turn, absorbs and traps heat, thus leading to the warming of the atmosphere. These global commons difficulties include deforestation, ozone depletion, and global warming. Although each problem derives from different economic and natural causes, each is interdependent. The atmospheric heating problem provides challenges to the economic modeler. First, the interdependency among the contributing commons

problems must be taken into account. Second, the strategic interactions among nations worldwide must be included. Standard prescriptions, such as Pigovian taxes or Coase bargaining, for externalities will not work if transnational strategic interactions are ignored. Hence, a carbon tax on a barrel of oil imposed at the national level may have no ameliorating influence when other nations react in an optimizing fashion. Third, cooperative supranational pacts and agreements that involve a subset of nations must be judged in light of the responses from nations outside the pact. Finally, both nation-specific benefits (outputs) and transnational public benefits (outputs) must be included when assessing the international distribution of costs and benefits that arise from activities leading to global warming. That is, joint products are often involved and must be included in the model.

The purpose of this paper is to devise a simple game theory representation of the carbon accumulation problem that includes the following: the interdependencies among contributing commons problems, interactions among nations, and the presence of joint products. The framework presented is designed to be tractable yet sufficiently flexible to analyze a host of different transnational common property scenarios. A second purpose is to employ the framework to investigate the outcome of unilateral action and/or cooperative pacts among a subset of nations. A third purpose is to identify pitfalls that inhibit the achievement of meaningful supranational agreements. A final purpose is to develop some policy recommendations.

The model presented consists of a simultaneous-play, noncooperative game between two classes or coalitions of nations: developed (aid donors) and less developed (aid recipients). In the pursuit of country-specific (private) benefits, each set of countries engages in activities that either give off atmospheric carbon or some (carbon-indexed) greenhouse gas as a jointly

produced output. This framework proves sufficiently tractable to study the issues posed above. Most important, it can identify a number of pitfalls of policy, while explaining the maneuvering taking place in reaction to the Earth Summit in Rio during June 1992. In addition, our framework can be generalized in future work to account for intertemporal aspects of carbon accumulation.[2]

The body of the paper contains five sections. Background material on carbon accumulation and its relationship to ozone depletion, deforestation and greenhouse gases is provided in section 2. A pure public good model is presented in section 3, and a joint product model of carbon accumulation is put forth in section 4. Contrasts between the two models are also drawn. Section 5 applies the analysis to other global commons problems including arms races and acid rain. Concluding remarks are contained in section 6.

2. Background on Carbon Accumulation

Global warming occurs when gases trapped in the earth's atmosphere let sunlight through but absorb and trap infrared radiation. The resulting greenhouse effect raises mean air temperature. Gases with this heat-trapping property are called greenhouse gases (GHGs) and include carbon dioxide, methane, chlorofluorocarbons (CFCs), tropospheric ozone, nitrous oxide, and water vapor. Neither oxygen nor nitrogen, which comprises the bulk of the earth's atmosphere, acts as a GHG. Using atmospheric concentrations of GHGs during the mid 1980s, the World Resources Institute (1990, p.14) attributed the following heat-trapping activities to accumulated GHGs: 50 percent for carbon dioxide, 20 percent for CFCs, 16 percent for methane, 8 percent for ozone, and 6 percent for nitrous oxide. Two of the most efficient GHGs in terms of their heat-trapping property are CFCs and methane; CFCs trap 20,000 times as much heat as an equivalent amount of carbon dioxide, whereas methane

traps over 20 times as much heat as an equivalent amount of carbon dioxide. Carbon dioxide is derived from the burning of fossil fuels and the production of cement; CFCs are used in air conditioning, refrigeration, aerosols, insulating foams, and the cleansing of circuit boards; methane comes from municipal solid wastes, livestock, hard-coal mining, natural gas, agriculture, and deforestation; tropospheric ozone is derived from automobile emissions; and nitrous oxide is emitted by burning fossil fuels and applying nitrogen fertilizers.

Atmospheric concentrations of selected GHGs are growing as follows: carbon dioxide by 0.4 percent per year; methane by 1 percent per year, and CFCs by 5 percent per year.[3] Carbon dioxide and methane have large natural sources and sinks that include the oceans, forests, grasslands, and wetlands. Approximately half of all human emissions of carbon dioxide is absorbed by these sinks without increasing atmospheric carbon; while over 80 percent of methane emissions is absorbed. At its current rate of increase, atmospheric levels of carbon dioxide will double from preindustrial levels by the year 2075.

Although much uncertainty exists with respect to the influence that the accumulation of GHGs has on global warming, rainfall, the levels of the seas, and climate, scientists agree on some findings. Most notably, they concur that the buildup of GHGs heats the atmosphere. The exact quantitative relationship is yet to be discovered owing to many intervening variables. Though estimates vary widely, unabated accumulation of GHGs can raise mean temperatures between 2 and 5°C during the next century.[4] The National Aeronautics and Space Administration's Goddard Institute estimates that mean global temperature has risen between 0.5° and 0.7°C since 1860 (Houghton and Woodwell, 1989). Scientists believe that atmospheric concentrations of carbon

dioxide have increased by about 20 percent from 1880 to 1989 (White, 1990, p.37). Much of the impact of global warming is expected to be felt at the higher latitudes. More favorable agricultural conditions are expected to occur in these latitudes as growing seasons lengthen and rainfall increases.

Much recent concern about global warming has stemmed from the observation that six of the warmest years on record are, in decreasing order, 1988, 1987, 1983, 1981, 1989, and 1980. Since many years of observations are needed before a true trend can be extracted, caution must be exercised before drawing dire forecasts. Concern is, however, warranted when the growth of GHGs are projected into the next century based on current trends.

Global warming is a complex collective action problem and includes more than the problem of burning fossil fuels, which accounts for approximately half of atmospheric heating. At least, three other global commons problems are related; each possesses its own distribution of costs and benefits (Sandler, 1992). First the preservation of the ozone shield comes into play, since CFCs, which deplete ultraviolet-shielding ozone, are GHGs. Treaties to limit CFCs (e.g., the Montreal Protocol on Substances, 1987) have an important by-product of limiting the accumulation of GHGs, provided that CFCs' substitutes are less efficient GHGs. In 1987, the major emitters of CFCs (in descending order) were the U.S., the U.S.S.R., Japan, West Germany, Italy, the U.K., and France.[5] These seven nations accounted for two-thirds of all CFC emissions. Second, population growth leads to food demands, fuel needs, and wastes that put methane into the atmosphere. The largest emitters of methane are the U.S., India, China, the U.S.S.R., Canada, and Brazil, accounting for over half of all emissions. Unlike the primary CFC emitters, which include only developed countries, key emitters of methane involve both developed and less developed nations. Developed countries, such as the U.S. and Canada,

grow crops for less developed nations; hence, these latter nation's derived food demand is, in part, behind some developed countries' output of methane. Third, moist and dry tropical forests are disappearing at an alarming rate. Recent estimates indicate that 20.4 million hectares of tropical forests are cleared annually (World Resources Institute, 1990, ch.7). The world's forests are an important sink for carbon, storing approximately 450 billion metric tons. In fact, deforestation may now account for upwards of one-third of the (equivalent) accumulation of atmospheric carbon. Unlike the methane and CFC problems, deforestation is almost entirely taking place in less developed countries. Temperate forests are now increasing in area. Deforestation is a major problem in Brazil, India, Indonesia, Colombia, Myanmar, Mexico, Cote d'Ivoire, Sudan, and Thailand.[6] Tropical forests are valued globally not only for their carbon storage abilities, but also for the biodiversity that they house. More than half of the world's species live in the moist tropical forests. These forests provide existence value,[7] including undiscovered medicines, for current and future generations worldwide. For the purpose of this study, we are primarily concerned with the carbon storing benefits as they relate to global warming.

Tropical deforestation is rooted in a number of causes,[8] including rapid population growth and the associated demands for settlement and fuel. Fuel demands are especially damaging for the dry tropical forests of Africa and Southeast Asia. Tropical deforestation has also resulted from rent seeking on behalf of government officials, entrusted with managing public forests. These officials have, too often, sold concessions to logging interests at a fraction of the forest's true value (Repetto, 1988, 1990). Short-term contracts that do not provide incentives to logging interests to manage the resource in a renewable fashion have also been responsible for waste. Land tenure policies,

requiring forest lands to be "improved," have motivated individuals to clear forests. In Brazil, public policies have subsidized alternative agricultural uses, such as raising livestock, that would have been unprofitable otherwise (Browder, 1988). Many of these shortsighted policies could be reversed if those in charge could be made to gain from forest preservation.

Table 1 provides a summary of the four sources of global warming in 1987. The influences of land use changes (including deforestation), methane, and CFCs on global warming have been converted to an equivalent carbon dioxide heating index for comparability purposes. The top half of the table lists seven regions of the world, where Asia and Europe excludes the U.S.S.R. In the right-most column, each region's percentage of the world total is given. The bottom portion of the table lists some selected countries' contributions to the atmospheric carbon heating index. When the various sources of GHGs are taken into account, GHG emitters include both developed and less developed countries. The underlying sources of global warming, of course, differ between the haves and the have-nots. The greatest growth in carbon dioxide emissions (not shown in Table 1) has occurred since 1950 in the less developed world, the U.S.S.R., and Eastern Europe (White, 1990). When global warming treaties are considered, developed countries will want to emphasize that its agreed-upon ban on CFCs by the year 2000 will have a dramatic impact on global warming, while tropical countries will want to argue that deforestation not be part of any agreement. The stakes are large. Nordhaus (1991, p.148) has conservatively estimated that a 50 percent reduction in GHG emissions will cost about $200 billion a year or approximately one percent of world output. Is the world willing to pay this price? Obviously, the cost of global warming must also be known before the optimal level of GHGs can be found by equating the relevant margins.

1a

Table 1. Greenhouse Heating: Net Additions in Terms of an Equivalent Carbon Dioxide Index,[a] 1987

REGIONS	FOSSIL FUEL & CEMENT[a]	ANNUAL LAND USE CHANGE[a]	METHANE[b]	CFCs USED[b]	NET TOTAL ATMOSPHERIC INCREASE[a]	PERCENT OF WORLD TOTAL[c]
Africa	75,000	170,000	57,000	42,000	340,000	6
No. & Cen. America	630,000	39,000	190,000	400,000	1,300,000	22
South America	64,000	640,000	54,000	34,000	800,000	14
Asia	610,000	380,000	340,000	190,000	1,500,000	25
Europe	520,000	nil	85,000	480,000	1,100,000	19
U.S.S.R.	450,000	nil	60,000	180,000	690,000	12
Oceania	32,000	1,200	19,000	25,000	76,000	1
World	2,500,000	1,200,000	800,000	1,400,000	5,900,000	
Selected Countries						
U.S.A.	530,000	2,600	130,000	350,000	1,000,000	17
Brazil	23,000	540,000	28,000	16,000	610,000	10
China	260,000	nil	90,000	32,000	380,000	6.6
India	67,000	61,000	98,000	700	230,000	3.9
Japan	110,000	nil	12,000	100,000	220,000	3.7
W. Germany	79,000	nil	8,000	75,000	160,000	2.7
U.K.	69,000	nil	14,000	71,000	150,000	2.5
France	41,000	nil	13,000	69,000	120,000	2.0
Italy	45,000	nil	5,800	71,000	120,000	2.0

Source: World Resources Institute (1990, Table 24.2, 348-49). Percentages are the author's own calculations.

Notes: [a]Attributed atmospheric carbon concentration in thousands of metric tons.

[b]Equivalent carbon dioxide heating effect in thousands of metric tons of carbon.

[c]Does not add to 100% owing to rounding.

3. Pure Public Good Model

To show the importance of joint products in the case of global warming, it is instructive first to consider the pure public good model. This model can correspond to a scenario where nations can remove transfrontier pollution from a commons or shared ecosystem. Examples include raising the pH levels of a shared lake, whose acidity has risen owing to acid rain, or eliminating pollution along a shared waterway. If the technology could be devised, the replenishment of stratospheric ozone would represent another example.

The model includes two coalitions of countries: the developed countries (D) and the less developed countries (L). Each coalition is treated as a unified actor, whose utility is derived from a private numéraire good, y, and a pure public good, Z. The latter denotes pollution removal and equals aggregate pollution removal:

$$Z = z^D + z^L, \tag{1}$$

where z^i, $i = D, L$, denotes the respective coalition's pollution reduction. Each coalition's preference or taste is represented by a quasi-concave, strictly increasing utility function:

$$U^i = U^i(y^i, Z), \qquad i = D, L. \tag{2}$$

The coalition's budget or resource constraint is[9]

$$I^i = y^i + pz^i, \qquad i = D, L, \tag{3}$$

where I^i is the coalition's income endowment, p is the per-unit price of pollution removal, and unity is the per-unit price of the numéraire. Each coalition chooses y^i and z^i to

$$\text{maximize } \{U^i(y^i, z^i + z^j) \mid I^i = y^i + pz^i\}, \tag{4}$$

where z^j is treated as j's best response and is viewed as fixed (exogenous) to coalition i.

For the developed-nations coalition, the first-order conditions (FOCs) associated with (4) require the following equality:

$$MRS^{D}_{Zy} = p, \tag{5}$$

in which MRS^{D}_{Zy} is the coalition's marginal rate of substitution between pollution removal and the private good, and, as such, denotes the marginal benefit from the public good. The MRS consists of a ratio of marginal utilities with each evaluated at the best response or optimizing level of z^L. An analogous FOC characterizes the less-developed-nations coalition. A Nash equilibrium is attained for the two coalitions when a vector of pollution removal amounts, (z^D_N, z^L_N), is achieved that simultaneously satisfies the FOCs. The subscript N denotes a Nash equilibrium.

The resulting Nash equilibrium is Pareto suboptimal since benefits conferred on another coalition by a coalition's action are not taken into account. Pareto optimality requires each coalition to remove pollution until

$$MRS^{D}_{Zy} + MRS^{L}_{Zy} = p \tag{6}$$

is satisfied.[10]

To illustrate the suboptimality of the Nash equilibrium and other results, we employ a graphical apparatus introduced by Cornes and Sandler (1984, 1985, 1986).[11] From (4), budget-constrained utility for coalition D can be written as

$$\begin{aligned} U^D &= U^D(I^D - pz^D,\ z^D + z^L) \\ &= U^D(z^D,\ z^L;\ I^D,\ p). \end{aligned} \tag{7}$$

Given income and relative prices, equation (7) indicates that utility can be depicted in terms of pollution removal levels in the two coalitions. The set of points weakly preferred by coalition D to any reference allocation must be a convex set, since it is itself the intersection of two convex sets: points

on or below the budget constraint, and points on or above an indifference curve. Monotonicity ensures that a higher level of z^L, for given y^D and z^D, must imply a greater level of utility.

In Figure 1, curves II and I'I' depict two budget-constrained iso-utility curves for coalition D, where z^L is measured on the vertical axis and z^D on the horizontal axis. Iso-utility curve I'I' denotes a higher level of utility than II, since for a given z^D, the amount of coalition L's pollution removal is greater. By the implicit function rule applied to (7), the slope of the iso-utility curve is

$$dz^L/dz^D = -1 + (p/MRS^D_{Zy}). \tag{8}$$

When this slope is zero, the FOC in (5) is obtained for a given level of pollution removal in coalition L. A Nash reaction path is derived by joining the zero-sloped points of the iso-utility curves for different levels of z^L. Path R_D denotes the path for coalition D. If all goods are normal with positive income elasticities less than one, then the slope of the reaction path must be negative and greater than one in absolute value (Cornes and Sandler, 1986, pp.74-75).[12]

An analogous procedure can be used to display coalition L's budget-constrained iso-utility curves in Figure 1. Two of these curves--ii and i'i' --are depicted. These curves are U-shaped oriented to the vertical axis, and have slopes equal to the reciprocal of $[-1 + (p/MRS^L_{Zy})]$. The Nash reaction path for coalition L is R_L in Figure 1. If all goods are normal, then the slope of R_L must be negative and less than one in absolute value. The unique Nash equilibrium is at point N where both coalitions' Nash FOCs are mutually satisfied; hence, neither coalition has an incentive to alter its provision of the public good. This Nash equilibrium is Pareto-inferior to points in the cross-hatched region, formed by the iso-utility curves through N, since both

10a

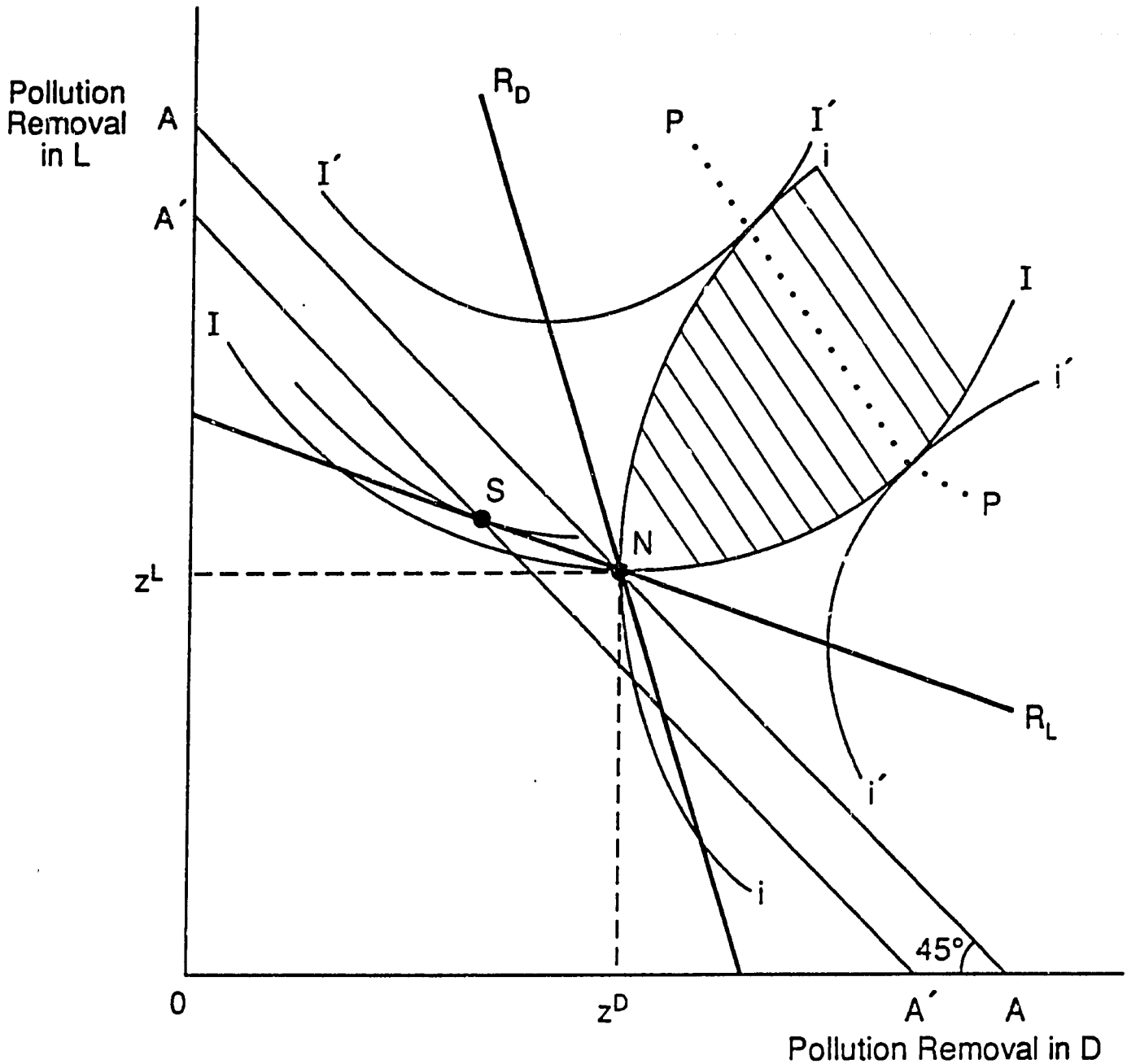

Figure 1: Nash Equilibrium and Pareto Path

coalitions' utility would increase in this region. The Pareto-optimal path corresponds to the tangencies between the coalitions' iso-utility curves, where $\Sigma MRS^{i}_{Zy} = p$ is satisfied. In Figure 1, this path is the dotted line PP, a portion of which goes through the cross-hatched region. The position of point N vis-à-vis path PP establishes the suboptimality of the Nash equilibrium.

To show the total amount of pollution removed at the Nash equilibrium, draw line AA with slope − 1 through point N, so that this line makes a 45° angle with the two axes. Distance OA along either axis then measures the total pollution removed by the two coalitions.

If one coalition were to move first as a Stackelberg leader, and the other were to follow, then the leader would gain an advantage, while the total amount of pollution removed would decline. Suppose that coalition D is the leader and coalition L is the follower. Coalition D maximizes its utility subject to its budget constraint and to the reaction path of the follower. In Figure 1, this equilibrium corresponds to point S, where coalition D's iso-utility curve is tangent to R_L. By inspection, we see that the leader's (follower's) utility is greater (smaller) at point S than at point N. There is an advantage to assuming a Stackelberg leadership role. The 45° line A'A' indicates that total pollution removal has fallen.

Is it in a coalition's (or nation's) interest to set a "good example" by <u>unilaterally</u> instituting pollution abatement or removal actions beyond those associated with a Nash equilibrium when a global pollution problem is confronted? Should a nation act prior to an enforceable agreement? To answer this question, we suppose that the coalition unilaterally subsidizes pollution removal with a per-unit subsidy, t, that is financed by a lump-sum tax of T. This corresponds to coalition D choosing z^D and y^D to

$$\text{maximize } \{U^D(y^D, z^D + z^L) \mid I^D - T = y^D + (p - t)z^D\}, \tag{9}$$

where z^L is coalition L's best-response. The FOC is now

$$MRS^D_{Zy} = p - t, \tag{10}$$

which implies (owing to quasi-concave utility) a greater amount of pollution removal for each level of z^L. This result is illustrated in Figure 2, where point N is the Nash equilibrium, prior to the subsidization scheme. Once in place, the unilateral subsidization scheme shifts coalition D's reaction path rightward to R'_D. The latter curve connects positively sloped points on the iso-utility curve where (10) is satisfied.

At the new equilibrium M, total pollution control has increased from OA to OB; however, the efforts of coalition L have diminished in relation to the original Nash equilibrium. Coalition L has taken advantage of coalition D's augmented efforts, and this results in coalition D being worse off at M than at N since L'I' is a lower level of welfare than II. In the case of a global pure public good, unilateral action does not pay.[13] Cooperative agreements that also raise R_L could make both coalitions better off.

Another interesting, and much discussed, case concerns the developed countries financing pollution reduction in the less developed countries. The so-called neutrality theorem,[14] associated with pure public good provision, may nullify the desired influence of pollution aid flowing from the developed countries to the less developed countries when a <u>global</u> pollution cleanup is involved. The neutrality theorem indicates that the Nash-equilibrium provision level for a pure public good is invariant to income redistributions among an unchanged set of providers. This follows because the aid donors' cutback on pollution removal matches the aid recipients' increased removal. Strategic interactions may undo well-intentioned policies. If, however, the redistribution of income is sufficiently large to alter the set of public good

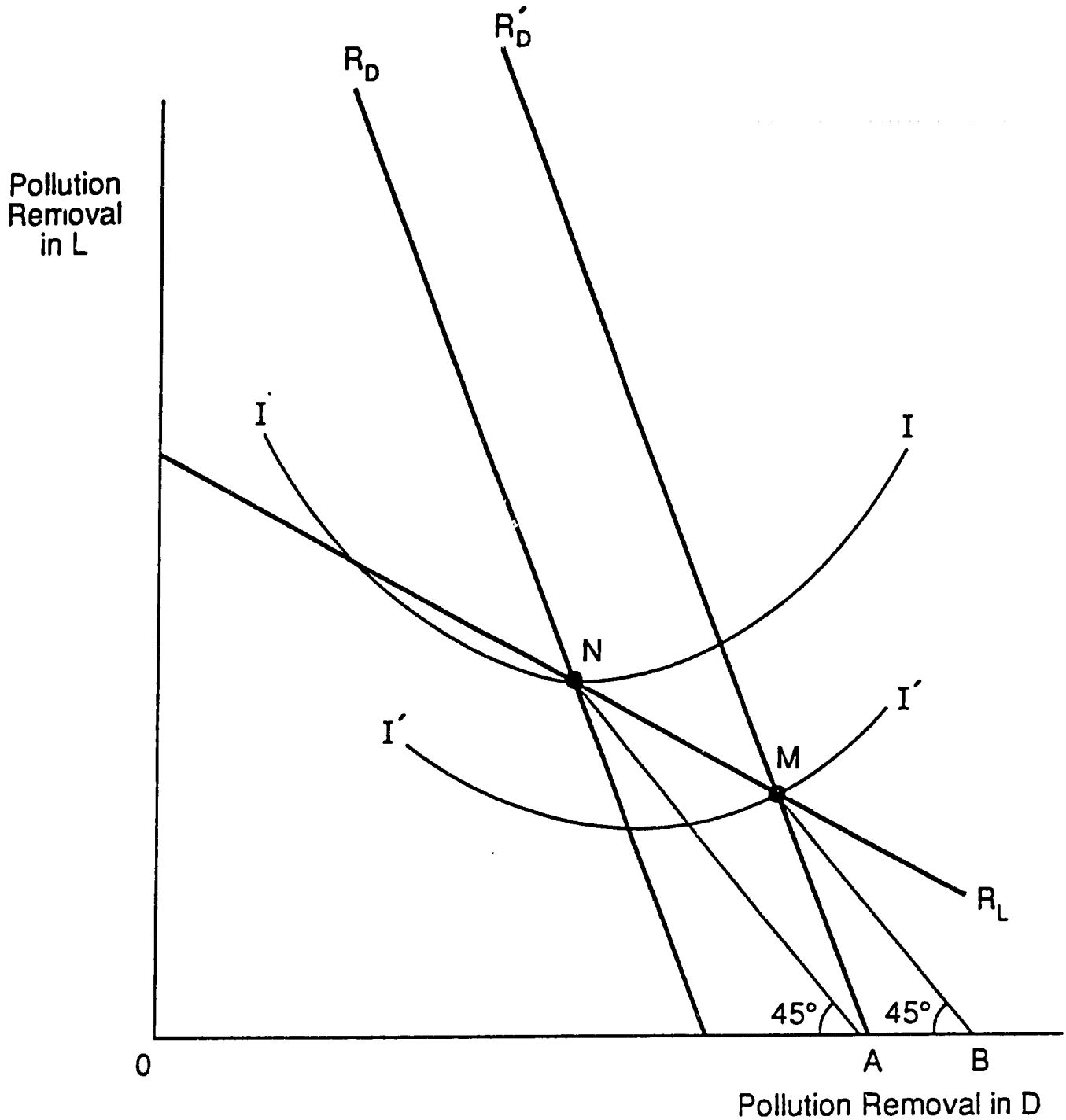

Figure 2: Unilateral Action

providers, then neutrality does not apply and policy can engineer changes in the overall level of pollution removal (Bergstrom, Blume, and Varian, 1986). Other influences, including different comparative advantages in removing pollution among providers, may also nullify neutrality (Sandler and Posnett, 1991).

The more-interesting model concerns global commons problems that are not purely public among participants. For impure public goods, results are much richer and findings less extreme. An impure public good model of joint products is most appropriate for global warming problems to which we now turn.

4. Joint Product Models of Carbon Accumulation

Table 1 indicated that both developed and undeveloped countries engage in activities that lead to global warming. In terms of an equivalent atmospheric carbon dioxide (or carbon accumulation) index, culpability for global warming is fairly evenly divided between the two sets of countries even though the activities producing atmospheric carbon or heating differ. To capture the essential elements of carbon accumulation in a tractable model,[15] I allow a coalition-specific activity, q^i, to yield a coalition-specific private good, x^i, and atmospheric carbon, z^i. The latter gives rise to global warming, C, which is a global public bad. As before, two coalitions are assumed: developed and less developed nations.

Fixed proportions are assumed to characterize the production of the joint products. For the private (coalition-specific) output, the joint product relationship is

$$x^i = \alpha^i q^i, \qquad i = D, L, \tag{11}$$

where α^is are positive, and x^D and x^L can denote completely different outputs. Similarly, activity q can differ between the coalitions; hence, q^L can refer

to deforestation, while q^D can refer to the burning of fossil fuels or the emission of CFCs. Carbon results from activity q^i as follows:

$$z^i = \beta^i q^i, \qquad i = D, L, \tag{12}$$

where β^is are positive. Global heating depends on accumulated carbon, so that

$$C = C(\beta^D q^D + \beta^L q^L), \tag{13}$$

which is, henceforth, written as the identity map,

$$C = \beta^D q^D + \beta^L q^L = Q, \tag{14}$$

where the right-hand side denotes the overall increase in the carbon index.

The coalition's strictly quasi-concave utility function is

$$U^i = U^i(y^i, \alpha^i q^i, Q), \qquad i = D, L, \tag{15}$$

in which $\partial U^i/\partial y^i > 0$, $\partial U^i/\partial(\alpha^i q^i) > 0$, and $\partial U^i/\partial Q < 0$. The coalition's budget is divided between the private numéraire and the joint-product activity,

$$I^i = y^i + r^i q^i, \qquad i = D, L, \tag{16}$$

where r^i is the per-unit price of the activity.

Each coalition chooses y^i and q^i to maximize utility in (15) subject to its budget constraint and the best response level of q in the other coalition. For a Nash equilibrium, the FOCs can be written as

$$\alpha^i MRS^i_{xy} + \beta^i MRS^i_{Qy} = r^i, \qquad i = D, L, \tag{17}$$

in which the weighted MRSs are set equal to the relative price of the activity. Since MRS^i_{Qy} is negative, the activity will not take place unless the first term on the left-hand side of (17) is greater than the second in absolute value. A Nash equilibrium corresponds to a vector (q^D_N, q^L_N) that simultaneously satisfies (17) for both coalitions. As in the pure public good case, the Nash equilibrium does not correspond to a Pareto optimum, which for, say, coalition D requires the following equality,

$$\alpha^D MRS^D_{xy} + \beta^D MRS^D_{Qy} + \beta^L MRS^L_{Qy} = r^D, \tag{18}$$

for an interior solution with $q^D > 0$. In contrast to the public good case, too much of the activity occurs in the Nash equilibrium as compared with the Pareto optimum, since the negative externality imposed on others is ignored.

We now intend to use the Cornes-Sandler diagrammatic apparatus to display the case of joint products. The budget-constrained iso-utility function for coalition D is

$$\begin{aligned} U^D &= U^D(I^D - r^D q^D,\ \alpha^D q^D,\ \beta^D q^D + \beta^L q^L) \\ &= U^D(q^D,\ q^L;\ \alpha^D,\ \beta^D,\ \beta^L,\ r^D,\ I^D), \end{aligned} \tag{19}$$

which can be displayed in (q^D, q^L) space for fixed production coefficients, income, and prices.[16] Since the utility function in (15) is strictly quasi-concave, and since activities and final outputs are related in a linear fashion, budget-constrained utility in (19) must also be quasi-concave, so that the set of points (q^D, q^L) that are weakly preferred to any given allocation is convex. An increase in q^L, for a given level of q^D, implies a lower utility level as q^L gives forth more global carbon but no benefits for coalition D. In Figure 3, two of coalition D's iso-utility curves are displayed, where the cross-hatched region indicates preferred points. The slope of the iso-utility curve is

$$\frac{dq^L}{dq^D} = \frac{r^D - \alpha^D MRS^D_{xy} - \beta^D MRS^D_{Qy}}{\beta^L MRS^D_{Qy}} . \tag{20}$$

When this slope is zero, the FOCs for a Nash equilibrium are satisfied at a given level of q^L. The Nash reaction path connects the points of zero slope. In Figure 3, the Nash reaction path is drawn negatively sloped; but this is only one possibility. In the case of joint products, income and substitution effects are more complex than in the previous public good model, since the interrelationship of the three consumption activities must be taken into account. For coalition L, the iso-utility curves are hill-shaped contours

15a)

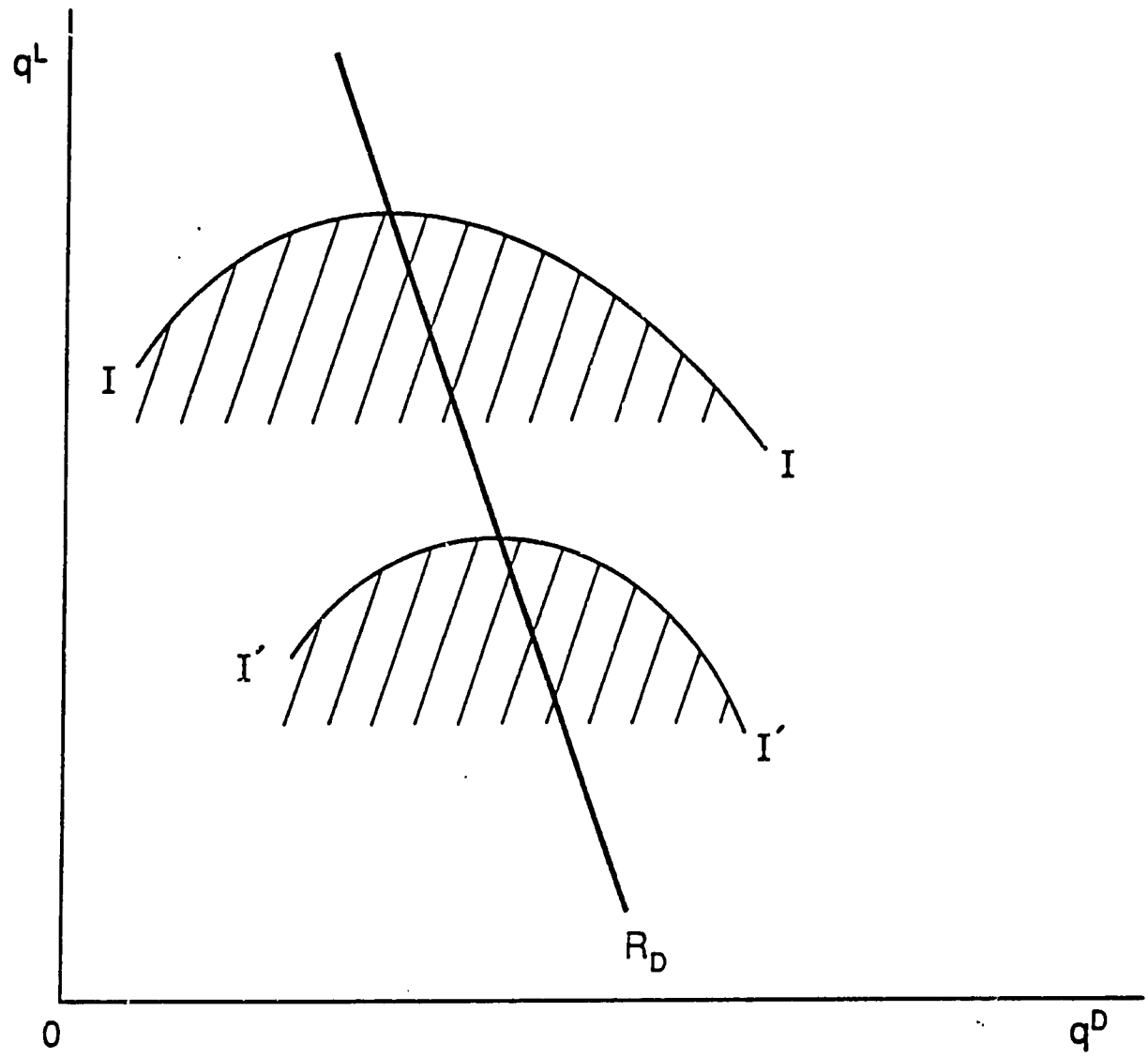

Figure 3: Iso-utility Curves for Joint Products

oriented to the vertical axis.

Slope of the reaction path

We demonstrate below that the influence of unilateral action, leader-follower behavior, tax policies, and treaties hinges on the slope of the reaction path. Unlike the analysis of global public goods, the presence of joint products can make unilateral action as well as tax policies beneficial to a subset of nations. This result contrasts with that of Hoel (1991) and Carraro and Siniscalco (1992).

To derive a general expression for the slope of the reaction path, we follow the procedure presented in Cornes and Sandler (1986, pp. 118-20). Restricted cost functions, e.g.,

$$y^D(x^D, Q, u^D) = \underset{y^D}{\text{minimize}} \{y^D | U(y^D, x^D, Q) \geq u^D\}, \tag{21}$$

are defined in terms of the Nash equilibrating values of x^D, Q, and u^D. The partial derivatives of $y^D(\cdot)$ with respect to x^D and Q yield compensated inverse demand functions that express the coalition's MRSs as

$$-\partial y^D/\partial x^D = MRS^D_{xy} = \pi^D_x(x^D, Q, u^D), \tag{22}$$

$$-\partial y^D/\partial Q = MRS^D_{Qy} = \pi^D_Q(x^D, Q, u^D). \tag{23}$$

These relationships can be substituted into (17) for the MRS expressions. By taking a total differential and rearranging, we get the slope of the reaction path:[17]

$$\frac{dq^D}{dq^L} = \left[\frac{\beta^L(\alpha^D\pi^D_{xQ} + \beta^D\pi^D_{QQ})}{\Omega}\right] + \left[\frac{\alpha^D\pi^D_{xu} + \beta^D\pi^D_{Qu}}{\Omega}\right]\frac{du^D}{dq^L}, \tag{24}$$

where $\pi^D_{xQ} = \partial\pi^D_x/\partial Q$, $\pi^D_{QQ} = \partial\pi^D_Q/\partial Q$, etc. In (24), the denominator of the bracketed term is

$$\Omega = -(\alpha^D \;\; \beta^D) \begin{bmatrix} \pi^D_{xx} & \pi^D_{xQ} \\ \pi^D_{Qx} & \pi^D_{QQ} \end{bmatrix} \begin{pmatrix} \alpha^D \\ \beta^D \end{pmatrix} \geq 0. \tag{25}$$

Its sign follows from the strict quasi-concavity of utility. Henceforth, we ignore the zero values and assume that Ω and its subcomponents are nonzero.

The first right-hand expression in (24) is an income-compensated substitution effect, while the second expression is an income effect. The sign of the substitution effect is ambiguous, because π^D_{xQ} may be of either sign, depending on the consumption relationship of the jointly produced goods. If, for example, x^D and Q are Hicksian q-substitutes or independent outputs ($\pi^D_{xQ} < 0$ or $= 0$), then the substitution effect must be negative, since π^D_{QQ} is negative by strict quasi-concavity. For Hicksian q-complements, the substitution effect is positive when $\alpha^D\pi^D_{xQ} > |\beta^D\pi^D_{QQ}|$.

The income effect is also ambiguous since both a good and a bad is derived from q^D. The multiplicative factor du^D/dq^L is negative, but π^D_{xu} is positive while π^D_{Qu} is negative. A negative income effect results when $\alpha^D\pi^D_{xu} > |\beta^D\pi^D_{Qu}|$, so that the willingness to pay for x as real income increases is greater than the willingness to pay to avoid more Q or carbon. If, however, wealth is associated with a greater income elasticity for the environment, then the income effect may be positive. Apparently, the slope of the reaction path depends on a host of factors and may be negative or positive. In the absence of income effects, substitute joint products are unequivalently associated with negatively sloped reaction paths, while complement joint products are a necessary, but not sufficient, condition for positively sloped reaction paths. The likelihood for a positive slope is enhanced in the case of complements when environmental concern increases with wealth. If joint products are substitutes or independent of one another, and environmental

concern weakens with income, then negatively sloped reaction paths are expected.

Case 1: Negative Sloped Reaction Paths

When the reaction paths are negatively sloped, the behavior of the Nash equilibrium contains many, but not all, of the features associated with the equilibrium of the pure public good model. In Figure 4, the joint output producing activities q^D and q^L are measured on the horizontal and vertical axes, respectively. The initial Nash reaction paths are R_D and R_L, and the Nash equilibrium is N. This equilibrium implies a Pareto-inferior position as indicated by the Pareto-superior cross-hatched region defined by the iso-utility curves through N. The Pareto path, PP, connects the tangencies of the iso-utility curves. If unilateral action on behalf of one coalition, say D, is performed to decrease q^D for each level of q^L, then D's reaction path shifts leftward to R_D' and the new equilibrium is N'. Coalition D becomes worse off, while coalition L becomes better off. Given the shapes of the reaction paths, coalition L increases its q^L activity, and thus its output of carbon, in response to the unilateral decrease in coalition D's output of carbon. A 45° line through N' and N (not shown) would indicate that unilateral action leads to a drop in the overall level of Q and, hence, in carbon.

This unilateral action can arise under a number of scenarios. First, a coalition of nations can institute a carbon tax on its members so as to tax the jointly produced global bad of carbon emissions. Such a tax has been recently proposed by the European Community. Second, a single nation or group of nations can impose a standard or limit to its emissions. Some of the Scandinavian countries (e.g., Norway) have been considering this option. Third, a subset of nations can sign a treaty to limit or curb its level of

18a

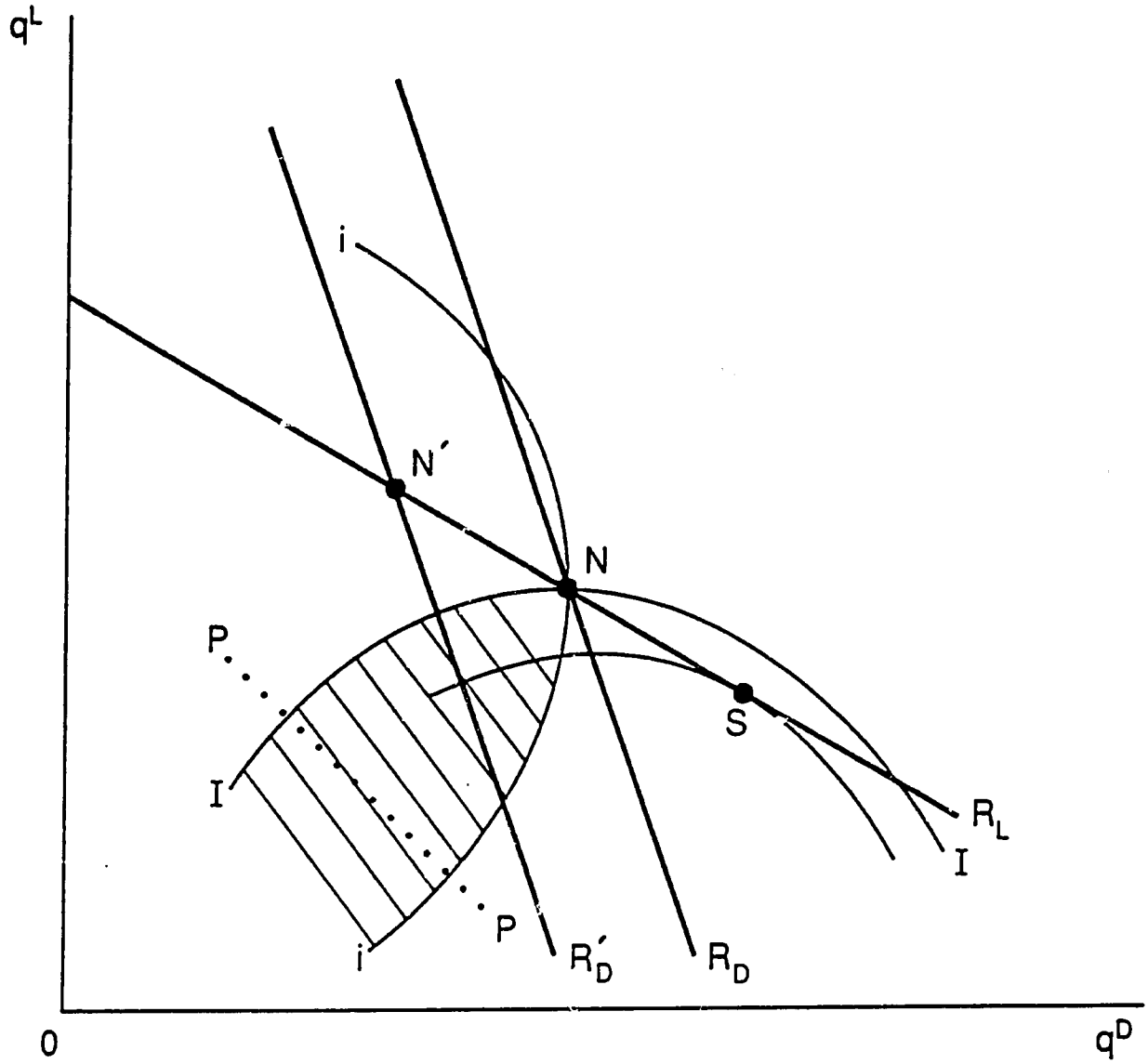

Figure 4: Joint Products and Downward Sloping Reaction Paths

activity q. In the treaty's absence, reaction path R_D applies, while with the treaty, path R_D' applies. Treaties among only a subset of nations to curb emissions can impoverish its well-intentioned members as shown by Figure 4.

In Figure 4, leader-follower behavior is seen to increase the overall level of Q and, hence, carbon. If coalition D is the leader, while coalition L is the follower, then the leader-follower equilibrium occurs at S. Despite coalition L's cutback on q, the overall level of Q increases as compared with N.

A major difference between the public good and the joint product model concerns the neutrality theorem. Neutrality does not apply in the presence of joint products,[18] because the existence of a private, coalition- or nation-specific jointly derived output allows the distribution of income to have an impact on the overall level of Q. Thus, a role for aid is now present. A simple principle applies: aid must flow so that aid-assisted increases in carbon in the recipient nations is less than the reduction in carbon in the donor nations as real resources are transferred if other public outputs are ignored. Suppose that the developed nations transfer resources to the LDCs to preserve tropical forests. These resources will go to support development in the LDCs and, in so doing, will increase industrial emissions of carbon dioxide. One form of carbon emission will be substituted for another. Will the world be better off? If the public goods of biodiversity and existence value are equal or greater in value to the foregone economic activities in the donor countries, then a Pareto improvement will be achieved even if the overall level of carbon is unchanged. Hence, the inclusion of all joint products, both negative and positive, may justify an action that would otherwise be viewed as ineffective. If, moreover, the donors insist that the aid be used in energy efficient processes, then carbon levels may actually

fall via the resource transfer, thus providing additional benefits to the policy. Once multiple public joint products are included, the diagrams lose their usefulness.

Case 2: Positively Sloped Reaction Paths

The effects of unilateral action, treaties, and first-mover actions are much more favorable to all concerned when reaction paths are positively sloped and the Nash equilibrium is stable as displayed in Figure 5. Strong complementarity among the jointly produced outputs may give rise to positively sloped reaction paths. If, for example, increased emissions of carbon create an increased demand for the jointly produced private output, then a complementarity exists. Increased global warming may, for instance, augment the demand for refrigerants such as CFCs, which, in turn, creates more global warming.

In Figure 5, the initial Nash equilibrium is at point N. The cross-hatched region is the Pareto-superior points to N. Since a portion of R_L lies within this region, unilateral action on the part of coalition D can be Pareto improving; hence, a shift from R_D to R_D' leads to a new equilibrium at the intersection of R_D' and R_L where both coalitions are better off. Additional action on behalf of coalition L to curb q^L and, hence, emissions of carbon would shift R_L to R_L' and further improve everyone's welfare at the new equilibrium T. An assurance game applies, since once one player cooperates it is still in the interests of the other players to cooperate [see Runge (1986, 1990) and Sandler (1992, ch. 2) on assurance games].

Leader-follower behavior would also improve the welfare of both of the coalitions, since the equilibrium would be between F and N when coalition D is the leader, or between F′ and N when coalition L is the leader. At the

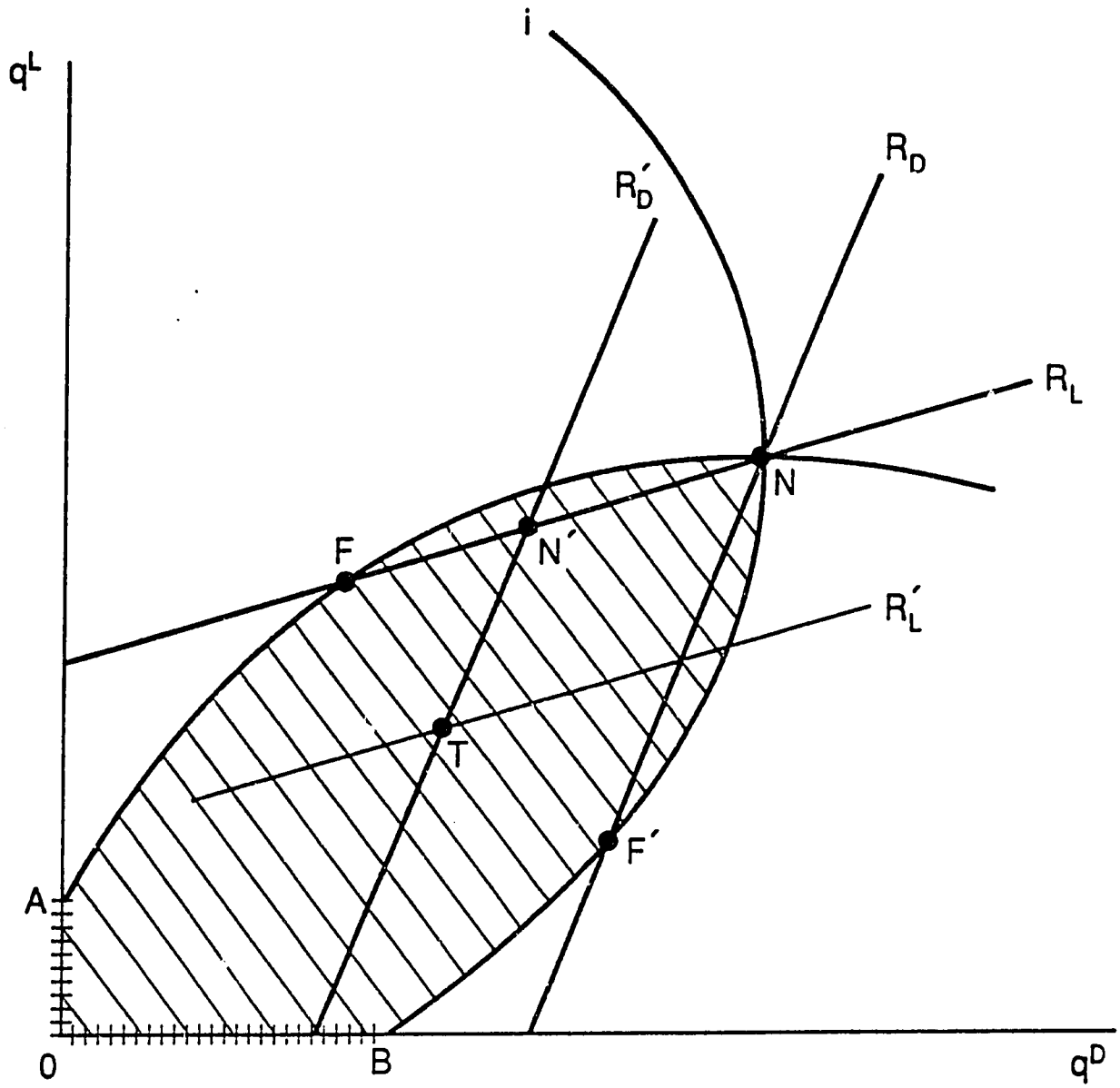

Figure 5: Joint Products and Upward Sloping Reaction Paths

leader-follower equilibrium (not shown), both coalitions reduce their levels of q, so that the overall level of Q falls. The follower is apt to make the greatest reduction.

The Pareto path is AOB, and does not consist of tangencies.[19] Along this path, one coalition's welfare increases as the other's welfare decreases. Cooperation is much more likely with positively sloped reaction paths, since reductions in q, and emissions, are copied to some extent by the other coalition. In summary, a global commons problem may prosper from unilateral action under some circumstances.

5. Other Global Problems

The analysis here can be applied to other commons problems. For example, arms race interactions may give rise to positively sloped reaction paths and an analysis along the lines of the last subsection where unilateral action might be desirable. This kind of interaction may have occurred recently between the U.S. and the Commonwealth of Independent States regarding arms reduction. Other less optimistic arms race scenarios are also possible.

A problem like acid rain that involves a unidirectional externality is likely to have a corner solution in which the polluter transfers the problem to nations downwind by building smoke stacks sufficiently high. If, however, the polluter values the trees and lakes downwind beyond its borders, then a jointly produced public bad is experienced by its actions. This jointly produced public bad might motivate the nation to curb its transferring activity somewhat. In the case of reciprocal transnational externalities, nations receiving the acid rain may be able to induce the polluter to curb emissions in return for the acid rain recipient's own reduction of some other form of pollutant. In effect, positively sloped reaction paths would apply.

Another global commons problem involves the pollution of the oceans and waterways. Outer space is another commons that can be polluted with space debris, spent satellites, and satellites in useless orbits. The orbital band of geostationary space is, for example, quite limited, but open access is allowed.

6. Concluding Remarks

In many ways, transfrontier commons problems share many of the features of the classic problem of the voluntary provision of a public good. Nevertheless, important distinctions exist and must be drawn in the theoretical model. In particular, joint products tend to be associated with transfrontier pollution, and often involve a private nation-specific output and a global public bad. Additional public goods and bads may also be included. The existence of these joint products yields some interesting results. First, a role for redistributive policy can exist, since the neutrality theorem, which inhibits income policy in the case of pure public goods, does not apply. Second, the degree of suboptimality may be attenuated as compared with the pure public good scenario. Third, a rich set of different cases exists, including that in which unilateral action and leader-follower behavior can be self-enforcing and beneficial to all involved. Moreover, treaties may be self-enforcing due to an underlying assurance game structure.

The next logical step is to extend the analysis from noncooperative to cooperative games. Since the no-agreement payoffs revert to the Nash equilibrium of the noncooperative game, the noncooperative game analysis here is a necessary first step. Any realistic investigation of cooperation needs to incorporate transaction cost considerations, which are almost always left out.

Footnotes

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1. Common property ownership is not a sufficient condition for overexploitation. Tribal and/or local common ownership has been frequently associated with efficient exploitation, especially if the tribes have a concern about future generations. Inefficiency is, instead, associated with an open access commons. Furthermore, ownership assignment is not sufficient for efficiency. In some countries when the ownership to the moist tropical forests was assigned to the governments, shortsighted officials increased the rate of exploitation while seeking their own gains (Repetto, 1988; Sedjo, 1991).

2. Intertemporal models include Nordhaus (1991) and Ko, Lapan, and Sandler (1992).

3. The facts from this paragraph come from the World Resources Institute (1990, pp. 12, 345).

4. On global warming, see Schneider (1989), Nordhaus (1991), Schelling (1992), Morrisette and Plantinga (1991), Morgenstern (1991), Houghton and Woodwell (1989) and White (1990).

5. The facts from this paragraph are derived for Table 24.2 in World Resources Institute (1990, p. 348-49).

6. This list is derived from the World Resources Institute (1990, pp. 292-93) Table 19.1. Countries are ordered in the text based on the number of hectares cleared in 1987.

7. On existence value and forests, see Strang (1983), Hartman (1976), and Hultkrantz (1992).

8. Deforestation, its causes and cures, are analyzed by Gillis (1988), Gillis and Repetto (1988), Hyde and Newman (1991), Repetto (1988, 1990), and Sedjo (1992).

9. A nonlinear convex constraint could also be used to allow marginal costs to vary with pollution abatement.

10. The underlying problem is

$$\underset{y^D, y^L, z^D, z^L}{\text{maximize}} \quad \{U^D(y^D, Z) \mid U^L(y^L, Z) \geq \bar{u}^L,\ Y + pZ = I\},$$

where $\bar{u}^L$ is a given level of utility for coalition L, $Y = y^D + y^L$, and $I = I^D + I^L$.

11. The reader should consult Cornes and Sandler (1985, 1986) and Sandler (1992) for a more in-depth description of the graphical apparatus.

12. This follows from the comparative static derivative,

$$\partial z_N^D/\partial z^L = p\partial z_N^D/\partial I^D - 1,$$

which indicates the effect of a change in z^L on the Nash equilibrium level of z^D. The two right-hand expressions are an income effect and a substitution effect. The latter is equal to -1, since pollution removal is a perfect substitute regardless of which coalition performs the cleanup.

13. Hoel (1991) uses a similar, but different, model to demonstrate that unilateral action may reduce the well-being of the activist nation. He also uses the Cornes-Sandler diagram. Also see Carraro and Siniscalco (1992).

14. The neutrality theorem is discussed in Warr (1983), Cornes and Sandler (1984, 1986) and Sandler (1992, pp. 77-79).

15. Additional joint products of a public or private nature could be

included to account for such things as biodiversity or existence value. For the purposes of this paper, we focus on carbon.

16. If the βs were normalized to equal one, the joint product relationship in (11)-(12) would allow the graph to be displayed in carbon space--i.e., in terms of (z^D, z^L). If, however, the βs are not normalized, we could still choose to display everything in terms of (z^D, z^L) via (11)-(12). This translation of axes requires a number of algebraic manipulations, which we choose to ignore. Another alternative is to use a three-dimensional representation in terms of the three characteristics (y, x, C)--see Cornes and Sandler (1992) for a three-dimensional approach.

17. See Cornes and Sandler (1992) for a different decomposition of the slope of the reaction path and an analysis of other comparative static changes.

18. This result was first established in Cornes and Sandler (1984). Also see Andreoni (1989), Sandler and Posnett (1991), and Cornes and Sandler (1992).

19. In a pure public good model of opposing alliances, this type of Pareto contract curve was first noted by Bruce (1990).

References

Andreoni, James, "Impure Altruism and Donations to Public Goods: A Theory of Warm-Glow Giving," Economic Journal, 100, June 1990, 464-477.

Bergstrom, Theodore C.; Lawrence Blume; and Hal Varian, "On the Private Provision of Public Goods," Journal of Public Economics, 29, February 1986, 25-49.

Browder, John O., "Public Policy and Deforestation in the Brazilian Amazon," in Robert Repetto and Malcolm Gillis (eds) Public Policies and the Misuse of Forest Resources, New York: Cambridge University Press, 1988, 247-297.

Bruce, Neil, "Defense Expenditures by Countries in Allied and Adversarial Relationships," Defence Economics, 1, May 1990, 179-195.

Carraro, Carlo and Domenico Siniscalco, "The International Dimension of Environmental Policy," European Economic Review, 36, April 1992, 379-387.

Cornes, Richard and Todd Sandler, "Easy Riders, Joint Production, and Public Goods," Economic Journal, 94, September 1984, 580-598.

Cornes, Richard and Todd Sandler, "The Simple Analytics of Pure Public Good Provision," Economica, 52, February 1985, 103-116.

Cornes, Richard and Todd Sandler, The Theory of Externalities, Public Goods, and Club Goods, New York: Cambridge University Press, 1986.

Cornes, Richard and Todd Sandler, "The Comparative Static Properties of the Impure Public Good Model," unpublished manuscript, Canberra: Australian National University, 1992.

Gillis, Malcolm and Robert Repetto, "Conclusion: Findings and Policy Implications," in Robert Repetto and Malcolm Gillis (eds) Public Policies and the Misuse of Forest Resources, New York: Cambridge

University Press, 1988, 385-410.

Gillis, Malcolm, "West Africa: Resource Management Policies and the Tropical Forest," in Robert Repetto and Malcolm Gillis (eds), Public Policies and the Misuse of Forest Resources, New York: Cambridge University Press, 1988, 299-351.

Hartman, Richard, "The Harvesting Decision When a Standing Forest Has Value," Economic Inquiry, 14, March 1976, 52-58.

Hoel, Michael, "Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country," Journal of Environmental Economics and Management, 20, January 1991, 55-70.

Houghton, Richard A. and George M. Woodwell, "Global Climate Change," Scientific American, 260, April 1989, 36-44.

Hultkrantz, Lars, "Forestry and the Bequest Motive," Journal of Environmental Economics, 22, March 1992, 164-177.

Hyde, William and David Newman, "Forest Economics and Policy Analysis: An Overview," World Bank Discussion Paper 134, Washington, DC: The World Bank, 1991.

Ko, Il-Dong; Harvey E. Lapan; and Todd Sandler, "Controlling Stock Externalities: Flexible Versus Inflexible Pigouvian Corrections," European Economic Review, 36, August 1992, 1263-1276.

Morgenstern, Richard D., "Towards a Comprehensive Approach to Global Climate Change Mitigation," American Economic Review Papers and Proceedings, 81, May 1991, 140-145.

Morrisette, Peter M. and Andrew J. Plantinga," The Global Warming Issue: Viewpoints of Different Countries," Resources, No. 103, Spring 1991, 2-6

Nordhaus, William D., "A Sketch of the Economics of the Greenhouse Effect," American Economic Review Papers and Proceedings, 81, May 1991, 146-150.

Repetto, Robert, "Overview," in Robert Repetto and Malcolm Gillis (eds), Public Policies and the Misuse of Forest Resources, New York: Cambridge University Press, 1988, pp. 1-41.

Repetto, Robert, "Deforestation in the Tropics," Scientific American, 262, April 1990, 36-42.

Runge, Carlisle Ford, "Common Property and Collective Action in Economic Development," World Development, 14, No. 5, 1986, 623-635.

Runge, Carlisle Ford, "Common Property Resources in a Global Context," Staff Paper P90-27, St. Paul, MN: University of Minnesota, April 1990.

Sandler, Todd and John Posnett, "Private Provision of Public Goods: A Perspective on Neutrality," Public Finance Quarterly, 19, January 1991, 22-42.

Sandler, Todd, Collective Action: Theory and Applications, Ann Arbor, MI: University of Michigan Press, 1992.

Schelling, Thomas, "Some Economics of Global Warming," American Economic Review, 82, March 1992, 1-14.

Schneider, Stephen H., "The Changing Climate," Scientific American, 261, September 1989, 70-79.

Sedjo, Roger A., "Tropical Forests, Property Rights, and Environmental Values: Economic Concepts and Real World Complexities," unpublished manuscript, Washington, DC: Resources for the Future, 1992.

Strang, William J., "On the Optimal Forest Harvesting Decision," Economic Inquiry, 21, October 1983, 576-583.

Warr, Peter G., "The Private Provision of a Public Good Is Independent of the Distribution of Income," Economics Letters, 13, 1983, 207-211.

White, Robert M., "The Great Climate Debate," Scientific American, 263, July 1990, 36-43.

World Resources Institute, World Resources 1990-91: A Guide to the Global Environment, New York: Oxford University Press, 1990.