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SPECIAL ISSUE ARTICLE

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Population growth and technological change in a global warming model

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Abstract Global warming (GW) is now recognized as a significant threat to sustainable development on an international scale. After providing some introductory background material, we introduce a benchmark dynamic game within which to study the GW problem. The model allows for population growth and is subsequently generalized to allow for changes in technology. In each case, a benchmark "Business as Usual" (BAU) equilibrium is analyzed and contrasted with the efficient solution. Furthermore, a complete characterization is provided in the benchmark model of the entire subgame perfect equilibrium value correspondence.

Keywords Global warming · Population growth · Dynamic game · Subgame perfect equilibrium

JEL Classification Q54 · D99 · O12

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1 Introduction

Here are four facts related to global warming (GW):

1. Average global surface temperatures have risen by 0.6°C in the last 140 years.
2. Every one of the 10 warmest years in recorded history have occurred since 1990, including each year since 1997.
3. The intergovernmental panel on climate change (IPCC) predicts that if we go on as we are, by 2100 global sea levels will probably have risen by 9–88 cm and average temperatures by between 1.5 and 5.5°C.
   The most frequently cited cause for this warming is the greenhouse effect – the increase in greenhouse gases (GHGs), especially CO_2, generated through the burning of fossil fuels.[1] Note,
4. Before the Industrial Revolution, atmospheric CO_2 concentrations were about 270–280 parts per million (ppm). They now stand at almost 380 ppm, and have been rising at about 1.5 ppm annually.[2]

The dramatic rise of the world's population in the last three centuries, coupled with an even more dramatic acceleration of economic development in some parts of the world, has led to a transformation of the natural environment by humans that is unprecedented in its scale. In particular, on account of the greenhouse effect, the threat of GW has emerged as a serious world-wide problem.

The present paper is part of an ongoing research project in which we have addressed certain elements of the GW problem from a strategic and economic perspective. In particular, our focus is on the economic costs of warming and the countervailing benefits foregone in containing the greenhouse effect. Our research is also the first to take a fully strategic approach to the problem. The strategic approach is necessary in our view because the problem is a transnational one and, in the absence of a global government, the only implementable treaties are likely to be agreements that are incentive-compatible for the signatories. (For other studies in the current project, see Dutta and Radner (2004a,b,c). For other studies that take a strategic, though static, view of global warming, see Barrett (2003) and Finus (2001).)

The present paper has three main parts:

1. Background material on the GW problem and a general discussion of the theoretical issues that need to be faced in the analysis of the control of GW. (Section 2). In turn that leads us to formulate a bench-mark model (Section 3); this model allows population growth and in doing that generalizes a model analyzed in detail elsewhere (Dutta and Radner 2004a).
2. In the benchmark model we establish a series of results on the tragedy of the common and the population effects on emissions. We also provide a complete characterization of the entire set of subgame perfect equilibria (SPE) of the model (Section 3).

[1] "Carbon dioxide and [certain] trace gases (methane, CFCs, nitrous oxide, ozone) are transparent to incoming shortwave solar radiation but opaque to outgoing longwave (infrared) radiation from the earth. Their natural levels raise the earth's average temperature by some 33°C. (from −18 to +15°) (Cline 1992, p. 4)."

[2] These facts are derived from IPCC reports. An immediate reference is "Climate Change: Uncharted Waters," a BBC Science report by Alex Kirby, December 5, 2004 and available on the web at http://news.bbc.co.uk/2/hi/science/nature/4061871.stm.

3. We then study the implications of the arrival of new technology for the reduction of emissions (Section 4).

2 Background and theoretical issues

2.1 Global warming: a background

Carbon dioxide (CO_2) is by far the most important of the "GHGs". It is produced by the metabolism of living organisms, and by other activities of humans. Currently, the burning of fossil fuels accounts for most of the carbon emissions actually produced by humans. On the other hand, CO_2 is broken down by photosynthesis in plants. However, the destruction of forests and other changes in land use have reduced the rate of global photosynthesis. Also, as the concentration of CO_2 in the atmosphere increases, the oceans recapture some of it, but very slowly. The net result of these activities is a net emission rate of CO_2. Fossil-fuel use currently accounts for more than two-thirds of the (net) emissions, with changes in forest and land use accounting for most of the rest.

Almost all of the burning of fossil fuels is done for the purpose of producing energy. North America currently produces about 27% of such emissions, with the bulk of this coming from the US. The current share of Asia (not including Japan) is double its cumulative share since 1800, reflecting its recent spurt in economic development; Asia currently ranks second amongst the various regions. Furthermore, given the large population of Asia, and its rate of population growth, if per capita carbon emissions in Asia were to increase to North American and Western European levels, the total emissions from Asia would increase enormously.

Over time technology changes and typically this leads to a progressive "decarbonization" of energy production. For example this has coincided with the movement from coal to oil and natural gas. Another technological change - and source of decarbonization – is increased efficiency in the utilization of energy.

The costs and benefits of GW are subject to considerable uncertainty and debate. Roughly speaking, the costs and benefits of GW are themselves the results of two primary effects: (1) a rise in the sea level, and (2) climate changes. The rise in the sea level is caused by melting of glacial ice, especially at the poles, and to some extent by the thermal expansion of the sea water. The rise in the sea level would damage, and even eliminate, many coastlines, and would be particularly costly to low-lying areas, such as Bangladesh, The Netherlands, and the eastern seaboard of the US. (for example). Climate changes are more complex. In some parts of the world, like the northern latitudes of North America, the warming would be accompanied by higher rainfall. This, with the lengthening of the summer growing period, would increase the agricultural productivity of such areas, benefiting Canada, the U.S., and Russia. Other parts of the world, such as Sub-Saharan Africa, would probably become more arid and less productive agriculturally. Other effects would include:

(a) Increased energy requirements for air-conditioning, only partially offset by reduced heating costs.
(b) Lesser runoff in water basins, curtailing water supplies.
(c) Increased urban air pollution (tropospheric ozone).
(d) Increased hurricane and fire damage.

Damages are likely to be nonlinear in the amount of warming. For example, "in the initial range, the Antarctic does not contribute to sea-level rise, because temperature is in a low range where increased melting is more than offset by increased snow carried by air with more moisture. On the scale of 10 degrees warming, however, the Antarctic would likely become a major source of sea-level rise, especially if the West Antarctic ice shelf should disintegrate (Cline 1992, p. 6)."

The efforts to avoid GW will, of course, be costly as well. Immediate costs would be incurred if economies were forced to substitute more expensive but less carbon intensive technologies for producing energy. Cutbacks in energy use would also be costly in terms of lower levels of output of goods and services, including "amenities" such as household cooling.[3] Perhaps most important, significant long-term reductions or even stabilization of carbon emissions would require significant research and development efforts, whose outcomes would also be uncertain.

Estimates of the net benefit of actions taken to prevent or abate GW depend heavily on the cost-benefit methodology that is used. For one thing, the long time period involved in the calculations makes the choice of a discount rate (or rates) important. Second, as is typical in the case of most environmental issues, it is important to include all of the (sometimes hidden) costs and benefits, and to get the prices right, which is especially difficult for goods and services for which markets are imperfect or nonexistent (see Dasgupta and Mitra 1999; Weitzman unpublished).

2.2 Theoretical problems

The problem of GW poses interesting theoretical challenges for several reasons:

1. It is international is scope, and will require international, or at least transnational, cooperation for its solution;
2. Its dynamics are long-lasting, and reversibility, even if possible, is very slow;
3. Because of significant international differences in population, rates of population growth, levels of economic development, and cultural attitudes, issues of international equity are also significant; and
4. Although the scientific basis of GW is qualitatively established, there is considerable quantitative uncertainty (and disagreement) about its dynamics and its consequences.

National and transnational issues - We should distinguish between issues that are national from those that are transnational. Even for small countries, some environmental issues such as depletion of cheap energy sources, exhaustion of arable land, smog and other local air pollution, and pollution of water supplies will typically be national issues. For national issues, one can imagine that the national government can pass laws and/or issue regulations that determine the "rules of the game" for participants (e.g., individuals, corporations, local governments), and enforce these rules. Here we have a standard mechanism design situation.

[3] On the other hand: "...The engineering tradition cites several avenues (such as compact fluorescent lights) by which energy needs may be reduced at zero or even negative cost. Market imperfections such as utility pricing rules that do not reward energy saved may contribute to this situation.... [S]tudies by the U.S. National Academy of Sciences and others suggest that this initial tranche of zero-cost energy reduction may be on the order of 20% (Cline 1992, p. 7)."

For transnational issues, such as GW, there is no capability for higher-level enforcement, e.g., no world government to enforce the rules of a game. In this case, the “rules of the game” are determined by the powers of the individual governments and the laws of Nature. If there is more than one Nash Equilibrium (NE) of this game, then the problem of mechanism design is replaced by the problem of identifying the best equilibria, according to some global criterion.

To the extent that the evolution of GW depends on global (i.e., total world) emissions of GHGs, the situation is formally analogous to the “problem of the commons,” as in the cases of fishing from a common population, or grazing on a common pasture. Thus we might expect to learn something about the structure of the set of NEs from the literature on the problem of the commons. It is well known that such games typically have many NEs, some of which are Pareto superior to others. The situation here is analogous to the simpler case of “repeated games,” but richer because of the presence of state variables that evolve through time, and hence the results of the theory of repeated games cannot be blindly applied to such dynamic games (Benhabib and Radner 1992; Dutta and Sundaram 1998; Radner 1991) We may interpret the negotiation of a treaty or other (nonbinding) transnational agreement as the process of moving to a new NE. And that is indeed the perspective that we take in this paper.

Intertemporal and distributional preferences - Issues in sustainable development usually (but not always) concern significant and persistent costs and benefits in the fairly distant future, say 50–200 years from now. It is therefore important to give a good deal of thought to the representation of the intertemporal preferences of the relevant players. Here we can observe an apparent paradox. On the one hand, if future benefits are discounted at plausible “market” rates, their present value at relevant time horizons will be very small, and the net present value of environmental projects will typically be negative. For example, if the discount rate is 8%, the discounted present value of one dollar 50 years from now is less than 2 cents.

Environmental projects also have diverse distributional consequences, among as well as within, nations and regions. Citizens and governments reveal by their actions that they are not entirely insensitive to these distributional issues, although this sensitivity may decrease with greater geographical and/or cultural remoteness. At a national level, richer citizens of many countries are willing to be taxed progressively in order to provide poorer citizens (of the same country) with food, medical care, housing, and education. It is more difficult, however, to persuade these richer citizens to provide comparable benefits to the poorer citizens of other countries. At an international level, countries may be more willing to aid ”culturally similar” countries than ”culturally distant” ones.

3 A generalized model with exogenous population change

In this section we generalize the simplified “global warming game” studied in detail in Dutta and Radner (2004a). We present a model in which the global stock of GHG evolves endogenously whilst the population in each country changes exogenously over time. For simplicity, we assume that each population evolves according to a linear first-order difference equation, although models with other autonomous dynamics would also be tractable. (The population growth element is the generalization studied in this paper.) The players in the game are countries, and it is assumed that each country has the authority and political will to control its own rate of emission of GHGs. In the model, each country can control its emissions essentially by controlling its level of economic activity.

For this model, we derive a bench-mark equilibrium termed the Business as usual (BAU) equilibrium, and the Pareto optimal solutions. We shall see that the BU emission rate for each country is higher than it is in any global Pareto optimum (GPO). We further report a full characterization of the set of SPE of the game. We also derive results that explore the connection between the size of population and equilibrium emissions.

It should be noted, that, though we focus on exogenously growing populations, a very similar analysis can be done for exogenously growing capital stocks – or any other such variable.

3.1 The model

There are I countries. The emission of (a scalar index of) GHGs during period t by country i is denoted by $a_i(t)$. (Time is discrete, with $t = 0, 1, 2, ...,$ ad inf., and the $a_i(t)$ are nonnegative.) Let $A(t)$ denote the global (total) emission during period t;

$$A(t) = \sum_{i=1}^{I} a_i(t). \tag{1}$$

The total (global) stock of GHGs at the beginning of period t is denoted by $g(t)+g_0$, where g_0 is what the "normal" steady-state stock of GHGs would be if there were negligible emissions from human sources (e.g., the level of GHGs in the year 1800). We might call $g(t)$ the *excess GHG*, but we shall usually suppress the word "excess." The law of motion for the GHG is

$$g(t+1) = A(t) + \sigma g(t), \tag{2}$$

where σ is a given parameter ($0 < \sigma < 1$). We may interpret $(1-\sigma)$ as the fraction of the beginning-of-period stock of GHG that is dissipated from the atmosphere during the period. The "surviving" stock, $\sigma g(t)$, is augmented by the quantity of global emissions, $A(t)$, during the same period. (Note: A realistic model of GHG dynamics would be more complicated; see Thomson 1997).

Let $P_i(t)$ denote the population of country i at the beginning of period t, and let $P(t)$ be the vector with coordinates $P_i(t)$. We assume that the population in country i evolves according to the linear difference equation

$$P_i(t+1) = \ell_i P_i(t) + (1-\ell_i)S_i, \tag{3}$$

where the parameter ℓ_i satisfies $0 < \ell_i < 1$. The solution of this difference equation is

$$P_i(t) = \ell_i^t P_i(0) + (1-\ell_i^t)S_i. \tag{4}$$

Thus the population in country i converges monotonically to the steady state S_i. Suppose that the utility of country i in period t is

$$v_i(t) = h_i[a_i(t), P_i(t)] - c_i P_i(t) g(t). \tag{5}$$

The function h_i represents, for example, what country i's gross national product would be at different levels of its own emissions and population, holding the global level of GHG constant. This function reflects the costs and benefits of producing and using energy from alternative sources, including fossil fuels. For a given population there will be an optimal level of energy use, and hence an optimal level of emissions, *not taking account of the costs of the stock of GHG*; call this the *myopically optimal* level of emissions. It therefore seems natural to assume that for each value of P_i, h_i is a strictly concave C^2 function of the variable a_i that reaches a maximum at a finite level of emissions and then decreases thereafter. The parameter $c_i > 0$ represents the marginal cost to the country of increasing the global stock of GHG. Of course, it is not the stock of GHG itself that is costly, but the associated climatic conditions. In a more general model, the cost would be nonlinear. Note that the marginal cost coefficient of increasing the level of GHG is now proportional to the population of the country. (The results of this section can be extended to cover cases in which this coefficient is some nonlinear function of the population, but we omit the details.) The total payoff (utility) for country i is

$$v_i = \sum_{t=0}^{\infty} \delta^t v_i(t)\mathrm{d}t. \tag{6}$$

For the sake of simplicity, we have taken the discount factor, δ, to be the same for all countries.

The *state of the system at the beginning of period t* is now the pair $[g(t), P(t)]$ where $P = (P_1, \ldots P_I)$ is the population vector. A Markov strategy for country i is a function that maps the current state, (g, P) into a current action, a_i. A *strategy* for a country determines for each period the country's emission level as a function of the entire past history of the system, including the past states and actions of all the countries. A *stationary strategy* for country i is a function that maps the current state, g, into a current action, a_i. As usual, a NE is a profile of strategies such that no individual country can increase its payoff by *unilaterally* changing its strategy. A *Markov–Nash equilibrium* is a NE in which every country's strategy is stationary. A SPE is a profile of strategies, not necessarily stationary, that constitutes a NE after every history.

3.2 The BAU equilibrium

We first derive a simple MPE called BAU; it is characterized by the following two features. First, country i's emission is *independent* of the GHG stock g. Second, whilst it depends on the population level, it *only depends* on own-population level, P_i.

In what follows, let h_{i1} denote the first partial derivative of the function h_i with respect to the variable a_i.

Theorem 1 (BAU Equilibrium) *Let g be the initial stock of GHG, and let P be the vector of initial populations. For each i, let country i use the Markovian strategy* $a_i{*} = \alpha_i{*}(P_i)$ *determined by*

$$h_{i1}(a_i{*}, P_i) = \delta w_i(P_i'), \tag{7}$$

$$w_i(P_i) = c_i\left(\frac{S_i}{1-\delta\sigma} - \frac{S_i - P_i}{1-\delta\sigma\ell_i}\right); \tag{8}$$

then this strategy profile is a MPE, and country i's corresponding payoff is

$$V_i{*}(g, P) = u_i{*}(P) - w_i(P_i)g, \tag{9}$$

where the function $u_i{*}$ is bounded, continuous and separable in its arguments, i.e., there exist bounded, continuous functions $u_i^i{*}\,(P_i)$ and $u_i^j{*}(P_i, P_j)$ such that they solve the functional equations

$$u_i^{i*}(P_i) = h_i[\alpha_i{*}(P_i), P_i] + \delta[u_i^{i*}(P_i') - w_i(P_i')a_i^*(P_i)], \tag{10}$$

$$u_i^{j*}(P_i, P_j) = -\delta w_i(P_i')a_j^*(P_j) + \delta u_i^{j*}(P_i', P_j'), \tag{11}$$

$$P' \equiv (P_i'),$$

$$P_i' \equiv \ell_i P_i + (1-\ell_i)S_i.$$

Proof That the value associated with the strategies given by equation (7) is bounded, continuous and separable and of the form given in equations (9–10) is established by way of a bootstrapping argument and the Bellman equation. Presuming that the value function is of that form, we write the Bellman equation as:

$$u_i^{i*}(P_i) + \sum_{j\neq 1}^{I} u_i^{j*}(P_i, P_j) = \max_{a_i}\left[h_i(\alpha_i, P_i) + \delta[u_i^{i*}(P_i') - w_i(P_i')a_i\right]$$
$$+\delta\sum_{j\neq 1}^{I}\left[-w_i(P_i')a_j^*(P_j) + u_i^{j*}(P_i', P_j')\right]$$

It is seen that the Bellman equation preserves all three properties. Standard arguments then show that the space of bounded, continuous, separable functions is a complete, separable metric space. The Bellman equation is a contraction and hence it has a fixed point, i.e., the value function. The characterization of the BAU emissions follows immediately from the first-order conditions of the maximization above. The first-order condition is that, for each i,

$$h_{i1}(a_i, P_i) - \delta w_i(P_i') = 0.$$

Hence the optimal emission is independent of g, and is given by equation (7). The value of $w_i(P_i)$ is now determined by the cost equation

$$w_i(P_i)g = c_i P_i g + \delta w_i(P_i')\sigma g,$$

The theorem is proved. □

Remarks

1. To repeat, what makes the BAU-equilibrium strategy of country i simple is that the current action depends only on the country's own current population. Own value u_i^i is also affected only by own population P_i.

2. For *any* profile of stationary strategies with property that a country's current action depends only on its own current population, the value function of country i has the separable form of given by equation (10), with w_i given by (8).
3. The functions w_i are strictly positive. To see this, note that

$$\frac{S_i}{1-\delta\sigma} > \frac{S_i}{1-\delta\sigma\ell_i} > \frac{S_i - P_i}{1-\delta\sigma\ell_i},$$

and use (8).

3.3 Global pareto optima

Let $x = (x_i)$ be a vector of positive numbers, one for each country. A GPO corresponding to x is a profile of strategies that maximizes the weighted sum of country payoffs,

$$v = \sum_i x_i v_i, \tag{12}$$

which we shall call the *global welfare*. Without loss of generality, we may take the weights, x_i, to sum to I. We now characterize the GPO. The proof is omitted, since the method is similar to that used in the previous theorem.

Theorem 2 (GPO) *Given strictly positive welfare weights (x_i), let $\hat{V}(g, P)$ be the maximum attainable global welfare starting with an initial GHG stock equal to g and initial populations P; then*

$$\hat{V}(g) = u(P) - w(P)g, \tag{13}$$

where

$$w(P) = \sum_j x_j w_j(P_j), \tag{14}$$

$$u(P) = \sum_j x_j u_j(P), \tag{15}$$

where the functions w_j are given by (8), and the functions u_j are bounded and continuous, and the solution of the functional equation

$$u_i(P) = h_i[\alpha_i(P_i), P_i] + \delta\left[u_i(P') - w_i(P')\sum_j \alpha_j(P_j)\right],$$

and $\alpha_i(P_i)$ is determined by

$$x_i h_{i1}[\alpha_i(P_i), P_i] = \delta w(P'). \tag{16}$$

(It is assumed that this last equation has a solution.) Furthermore, country i's GPO strategy is the Markovian strategy determined by the function α_i. Notice that the GPO emission rates are again independent of the stock of GHG.

3.4 Comparison of BAU and GPO emission rates

Comparing the BAU and GPO strategies, we have:

$$\begin{aligned} BAU: &\quad h_{i1}[\alpha_i{*}(P_i), P_i] = \delta w_i(P_i), \\ GPO: &\quad h_{i1}[\alpha_i(P_i), P_i] = \delta\left(\tfrac{1}{x_i}\right)\textstyle\sum_j x_j w_j(P_j). \end{aligned} \tag{17}$$

By Remark 3 above, the functions w_i are strictly positive, and hence so are the right-hand-sides in the second equation above. Therefore, since the function h_i is strictly concave, the BAU emission rates will exceed the GPO emission rates if and only if

$$\delta w_i(P_i) < \delta\left(\frac{1}{x_i}\right)\sum_j x_j w_j(P_j),$$

or equivalently,

$$x_i w_i(P_i) < \sum_j x_j w_j(P_j),$$

which is true because all the terms are positive. Hence, *for all* P, i, *and vectors* (x_i),

$$\alpha_i{*}(P_i) > \alpha_i(P_i), \tag{18}$$

i.e., the BAU emission rates will exceed the GPO emission rates. Note that this inequality holds for all vectors of strictly positive weights (x_i). (We conjecture that this inequality would hold in a variety of models. Indeed, one can show in a quite general model that a GPO cannot be a BAU, or even that, starting from a GPO, each country will want to increase it emissions unilaterally by a small amount. However, to get the inequality (18) one probably needs more specific concavity assumptions.)

It follows from these results that there is an open set of strictly positive weights (x_i) such that the corresponding GPO is strictly Pareto superior to the BAU. We are therefore led to search for (non-Markovian) Nash equilibria of the dynamic game that sustain a GPO, or at least are superior to the BAU – and that we shall do two sub-sections from this one.

3.5 A special case: constant population

Consider the special case where population remains constant over time, i.e., $P_i(t) = P_i(0) = P_i$ for all t. This is the case studied in Dutta and Radner (2004a). It immediately follows from the results above that the BAU emission is given by a constant emission level that solves

$$h_i'(a_i{*}) = \delta w_i,$$

where

$$w_i = \frac{c_i}{1 - \delta\sigma}.$$

On the other hand, the GPO, while also a constant, is determined by

$$x_i h_i'(\hat{a}_i) = \delta w,$$

where the permanent cost coefficient w is given by

$$w = \frac{1}{1 - \delta\sigma} \sum_i x_i c_i,$$

and the comparison of the two emissions – along with the concavity of h_i – yields

$$a_i{*} > \hat{a}_i.$$

3.6 Effects of population size on emission levels

In this subsection we investigate how the BAU and GPO emission levels vary with population. Note that the BAU emission level for country i only depends on its own population. It will be seen that the crucial determinant is the cross-partial derivative of the net welfare function, $h_i(a_i, P_i) - \delta w_i(P_i)a_i$.

In what follows, let h_{i12} denote the cross-partial derivative of the GDP function h_i. In particular, if $h_{i12} > 0$ then the marginal product of GDP with respect to emissions, h_{i1}, is increasing in the population size – and this would be the case for a Cobb–Douglas specification–and vice-versa if $h_{i12} < 0$.

Theorem 3 (Population effect on BAU) *Suppose that*

$$h_{i12} - \frac{\delta c_i l_i}{1 - \delta\sigma\ell_i} > 0.$$

then the BAU emission level, $\alpha_i{*}(.)$, *is an increasing function of population size* P_i*, i.e., the larger the population the greater is the size of emissions. Conversely, suppose that*

$$h_{i12} - \frac{\delta c_i l_i}{1 - \delta\sigma\ell_i} < 0$$

(and a sufficient condition for that is $h_{i12} < 0$*). Then, the BAU emission level,* $\alpha_i{*}(.)$, *is a decreasing function of population size* P_i*, i.e., the larger the population, the lower the size of emissions.*[4]

Proof Consider two different population levels, P_i and $\widetilde{P}_i$ and suppose that $P_i > \widetilde{P}_i$. Denote the corresponding BAU levels α_i^* and $\widetilde{\alpha}_i^*$ (and, without loss, $\alpha_i^* \neq \widetilde{\alpha}_i^*$). Since both emission levels are feasible choices at the two population sizes, it follows from the Bellman equation for population P_i that

$$h_i(\alpha_i^*, P_i) + \delta[u_i^{i*}(P_i') - w_i(P_i)\alpha_i^*] > h_i(\widetilde{\alpha}_i^*, P_i) + \delta[u_i^{i*}(P_i') - w_i(P_i)\widetilde{\alpha}_i^*]$$

Similarly, the Bellman equation for population $\widetilde{P}_i$ yields

$$h_i(\widetilde{\alpha}_i^*, \widetilde{P}_i) + \delta[u_i^{i*}(\widetilde{P}_i') - w_i(\widetilde{P}_i)\widetilde{\alpha}_i^*] > h_i(\alpha_i^*, \widetilde{P}_i) + \delta[u_i^{i*}(\widetilde{P}_i') - w_i(\widetilde{P}_i)\alpha_i^*]$$

[4] Please note that *decreasing* means "weakly decreasing," (versus *strictly decreasing*).

A simple re-arrangement, substitution for the form of $w_i(.)$ and cancellation of common terms yields

$$h_i(\alpha_i^*, P_i) - h_i(\alpha_i^*, \widetilde{P}_i) - \frac{\delta c_i l_i (P_i - \widetilde{P}_i)}{1 - \delta\sigma\ell_i}\alpha_i^*$$
$$> h_i(\widetilde{\alpha}_i^*, P_i) - h_i(\widetilde{\alpha}_i^*, \widetilde{P}_i) - \frac{\delta c_i l_i (P_i - \widetilde{P}_i)}{1 - \delta\sigma\ell_i}\widetilde{\alpha}_i^*$$

Note that

$$h_i(\alpha_i, P_i) - \frac{\delta c_i l_i P_i}{1 - \delta\sigma\ell_i}\alpha_i$$

has a cross-partial derivative equal to

$$h_{i12} - \frac{\delta c_i l_i}{1 - \delta\sigma\ell_i}.$$

From that observation, the theorem follows.

An identical result can be proved for the GPO emission levels. Since the proof is almost identical to that for the BAU, we state the result without proof. □

Theorem 4 (Population effect on GPO) *Consider two population levels, P_i and $\widetilde{P}_i$ for country i – $P_i > \widetilde{P}_i$ – and suppose $P_j = \widetilde{P}_j$ for all $j \neq i$. Suppose that*

$$h_{i12} - \frac{\delta c_i l_i}{1 - \delta\sigma\ell_i} > 0.$$

Then, the respective GPO emission levels satisfy $\alpha_i(P_i, P_{-i}) > \alpha_i(\widetilde{P}_i, P_{-i})$. Conversely, suppose that

$$h_{i12} - \frac{\delta c_i l_i}{1 - \delta\sigma\ell_i} < 0$$

(and a sufficient condition for that is $h_{i12} < 0$). Then, $\alpha_i(P_i, P_{-i}) < \alpha_i(\widetilde{P}_i, P_{-i})$.

3.7 All SPE in the generalized model

In this subsection, we characterize the entire SPE correspondence of the model with population change. Of the two state variables, GHG level g and population size P, the effect of GHG stock, g, is felt through a linear (present discounted value of costs) function which affects all equilibria from a given population level identically. As we will see, no matter which SPE we consider, if the current GHG level is g and the current population is P_i, then *every* equilibrium value will have, as one of its component terms, the magnitude $-w_i(P_i)g$.

Additionally, the value of an SPE will depend on the population vector P and will do so through a correspondence that is separable in own-population and each of the other-population levels. In particular, we have the following theorem.

Theorem 5 *The equilibrium payoff correspondence* Ξ *depends on the size of GHG* g *and the population vector* $\dot{P}$. *The effect of* g *is linear. The effect of* P *can be separated out into own-population and other-population effects. In particular, letting* $\wp(\Re)$ *denote the set of subsets of* $\Re$, *there is a compact and convex-valued, upper hemi-continuous correspondence*

$$U_i^i(P_i) : [0, S_i] \to \wp(\Re)$$

and compact-valued, upper hemi-continuous correspondences

$$U_i^j(P_i, P_j) : [0, S_i]^2 \to \wp(\Re), \; for every \; j \neq i,$$

such that for every initial GHG state g *and population vector* P,

$$\Xi_i(P, g) = U_i^i(P_i) + \sum_{j \neq i} U_i^j(P_i, P_j) - \{w_i(P_i)g\}$$

where

$$w_i(P_i) = c_i \left(\frac{S_i}{1 - \delta\sigma} - \frac{S_i - P_i}{1 - \delta\sigma\ell_i} \right), \quad i = 1, \ldots, I.$$

In particular, consider any SPE, any period t *and any history of play up until* t. *Then the payoff vector for country* i *from the continuation strategies must necessarily be of the form*

$$u_i^i + \sum_{j \neq i} u_i^j - w_i(P_i)g_t,$$

where $u_i^i \in U_i^i(P_i)$, $u_i^j \in U_i^j(P_i, P_j)$, *and* g_t *is the state at period* t. *Furthermore, associated with those values there must be period* t *emissions* $\widetilde{a}_i$ *and continuation values* $\widetilde{u}_i^i \in U_i^i(P_i')$, $\widetilde{u}_i^j \in U_i^j(P_i', P_j')$, $\underline{u}_i^i \equiv \min\{u_i^i \in U_i^i(P_i')\}$, *such that*[5]

$$\begin{aligned} u_i^i &= h_i(\widetilde{a}_i, P_i) + \delta[\widetilde{u}_i^i - w_i(P_i^{'})\widetilde{a}_i] \geq h_i(a_i, P_i) + \delta[\underline{u}_i^i - w_i(P_i^{'})a_i], \; \forall a_i, \\ u_i^j &= -\delta w_i(P_i)\widetilde{a}_j + \delta\widetilde{u}_i^j. \end{aligned}$$

Proof Consider a correspondence, $V : [0, S_i]^I \dashrightarrow \wp(\Re^I)$ that is separable of the form above - $V_i(P) = V_i^i(P_i) + \sum_{j \neq i} V_i^j(P_i, P_j)$ where V_i^i is compact and convex valued and V_i^j is compact (but not necessarily convex) valued. Now define the Abreu–Pearce–Stachetti operator, TV, for each component of the correspondence, as follows:

$$\begin{aligned} TV_i^i(P_i) = \{&v_i^i : \exists\, \widetilde{a}_i \;\&\; \widetilde{v}_i^i \in V_i^i(P_i'), \; \underline{v}_i^i \equiv \min\{v_i^i \in V_i^i(P_i')\}, \; s.t. \\ &v_i^i = h_i(a_i, P_i) + \delta[\widetilde{v}_i^i - w_i(P_i^{'})a_i] \geq h_i(a_i, P_i) + \delta[\underline{v}_i^i - w_i(P_i^{'})a_i], \; \forall a_i, \end{aligned}$$

[5] As above, P_i' refers to the population of country i in period $t + 1$.

and

$$\begin{aligned} TV_i^j(P_i, P_j) = \{v_i^j : \exists\, v_j^j,\ \widetilde{a}_j \ \&\ \widetilde{v}_j^j \in V_j^j(P_j'), \\ \underline{v}_j^j \equiv \min\{v_j^j \in V_j^j(P_j')\},\ \widetilde{v}_i^j \in V_i^j(P_i')\ s.t. \\ v_j^j = h_j(a_j, P_j) + \delta[\widetilde{v}_j^j - w_j(P_j^{'})a_j] \\ \geq h_j(a_j, P_j) + \delta[\underline{v}_j^j - w_j(P_j^{'})a_j],\ \forall a_j, \\ v_i^j = -\delta w_i(P_i^{'})\widetilde{a}_j + \delta \widetilde{v}_i^j \end{aligned}$$

and define the correspondence inclusive of the terms involving the GHG level g as follows:

$$T[V_i(P) - \{w_i(P_i)g\}] = TV_i^i(P_i) + \sum_{j \neq i} TV_i^j(P_i, P_j) - \{c_i(P_i)g + \delta\sigma w_i(P_i^{'})g\}.$$

Matching the terms involving g we get

$$w_i(P_i) = c_i(P_i) + \delta\sigma w_i(P_i') = c_i(P_i) + \delta\sigma w_i(\ell_i P_i + (1 - \ell_i)S_i),$$

whose solution is

$$w_i(P_i) = c_i\left(\frac{S_i}{1 - \delta\sigma} - \frac{S_i - P_i}{1 - \delta\sigma\ell_i}\right).$$

Hence, the correspondence preserves the posited linear structure with respect to g. We therefore focus instead on the terms involving the population levels and show that they too have the advertized structure.

Note that each component of the correspondence defined above is non-empty. This is because one element of the correspondence $TV_i^i(P_i)$ is always the BAU value $u_i^{i*}(P_i)$ (generated by offering as continuation the BAU value $u_i^{i*}(P_i')$ from the next period onwards and requiring the BAU emission $\alpha_i{*}(P_i)$ in the current period).

Furthermore, a standard argument, invoking the continuity and finite maximand of the payoff function h_i, shows that the correspondences $TV_i^i(P_i)$ and $TV_i^j(P_i, P_j)$ are both compact-valued. Similar arguments, but using joint continuity of the function as well as the Maximum Theorem, show that the correspondences are also upper hemi-continuous.

To see that $TV_i^i(P_i)$ is a convex set, consider the following argument. Suppose that $v_i^i(1)$ and $v_i^i(2)$ are both elements of $TV_i^i(P_i)$ – and they are because each is generated through corresponding emission levels $\widetilde{a}_i(k)$ and continuation values $\widetilde{v}_i^i(k)$, $k = 1, 2$. We need to show that $v_i^i(3) \equiv \lambda v_i^i(1) + (1 - \lambda)v_i^i(2)$ is also an element of $TV_i^i(P_i)$. The first point to recall is that $h_i(a_i, P_i) - \delta w_i(P_i')a_i$ is a strictly concave function with an argmax at $\alpha_i{*}(P_i)$. It follows then that there is $\widetilde{a}_i(3)$ with the property that

$$\begin{aligned} h_i(\widetilde{a}_i(3), P_i) - \delta w_i(P_i')\widetilde{a}_i(3) = \lambda[h_i(\widetilde{a}_i(1), P_i) - \delta w_i(P_i')\widetilde{a}_i(1)] \\ +(1 - \lambda)h_i(\widetilde{a}_i(2), P_i) - \delta w_i(P_i')\widetilde{a}_i(2) \end{aligned}$$

Furthermore, let $\widetilde{v}_i^i(3) \equiv \lambda\widetilde{v}_i^i(1) + (1-\lambda)\widetilde{v}_i^i(2)$ - this will serve as the continuation payoff to ensure that the emission level $\widetilde{a}_i(3)$ is implemented. Since $V_i^i(P_i)$ is convex by hypothesis, it follows that $\widetilde{v}_i^i(3) \in V_i^i(P_i)$. We can then note that

$$\begin{aligned} v_i^i(3) &= h_i(\widetilde{a}_i(3), P_i) + \delta[\widetilde{v}_i^i(3) - w_i(P_i')a_i] \\ &= \lambda\{h_i(\widetilde{a}_i(1), P_i) + \delta[\widetilde{v}_i^i(1) - w_i(P_i')\widetilde{a}_i(1)]\} + (1-\lambda)\{h_i(\widetilde{a}_i(2), P_i) \\ &\quad +\delta[\widetilde{v}_i^i(2) - w_i(P_i')\widetilde{a}_i(2)]\} \\ &\geq h_i(\alpha_i, P_i) + \delta[\underline{v}_i^i - w_i(P_i')a_i],\ \forall a_i \end{aligned}$$

Hence, we have shown that $v_i^i(3) \in TV_i^i(P_i)$, i.e., that set is convex. So the operator T maps a correspondence that is separable, compact-valued in each component and convex-valued in own-population back into the space of correspondences with those exact same properties.

Now we shall argue that this correspondence has a fixed point. To see this note that the correspondence is monotone in a set-inclusion sense: if $V' \supset V$, then $TV' \supseteq TV$. So start with the "largest" correspondence – for example, the one that includes all possible feasible payoffs to the game. Define iteratively, $V_{n+1} \equiv TV_n$. That gives us a sequence of correspondences which have a progressively smaller range but each of which is compact-valued. Hence, for every P_i and P_j, $V_{in}^i(P_i)$ and $V_{in}^j(P_i, P_j)$ have non-empty limits. Call the associated limit correspondences $V_i^i(P_i)$ and $V_i^j(P_i, P_j)$. Standard arguments show that these are nothing but the SPE value correspondences $U_i^i(P_i)$ and $U_i^j(P_i, P_j)$, $i, j = 1, \ldots, I$. □

4 Effects of reducing emission factors

It is generally agreed that it will not be possible to achieve an acceptable level of global emissions of GHG without considerable research and development effort. If one expands the strategy spaces of the countries to include research and development, and technology transfers among countries, it may be possible to improve the BAU itself. Technological innovations may reduce the attraction of increased emissions. If the costs to advanced countries of developing such innovations, and transferring them to other (presumably poorer), countries are not too high, it may be part of a BAU in such an "expanded" game for such activities to take place, thus moving the global economy along a path of declining emissions.

We shall illustrate this point in the context of a special case. Suppose that the emission of GHG is entirely caused by the production and consumption of energy (which is, of course, an exaggeration). Imagine that energy is an input in the production function of each country, along with other inputs like capital, labor, etc. Assume that, as a function of the input of energy, e_i in country i, it's net output in a given period is $Y_i(e_i, P_i)$ where P_i is, as in the previous section, the population of country i. Assume further that the country's emission of GHG during the period is proportional to the input of energy, say

$$a_i = f_i e_i. \tag{19}$$

We shall call the coefficient f_i the *emission factor* of country i. Thus the one-period GDP function is given by

$$h_i(a_i, P_i; f_i) \equiv Y_i\left(\frac{a_i}{f_i}, P_i\right), \tag{20}$$

and the total period welfare is

$$h_i(a_i, P_i; f_i) - c_i P_i g.$$

Note that P_i grows over time according to the dynamics identified in the preceding section, whereas the emission factor f_i remains fixed.

4.1 Characterization of the BAU with emission factor as a parameter

In this subsection we characterize the BAU allowing the emission factors to enter explicitly as parameters. Thereafter, we explore the question: if emission factors were to change, how would it effect the size of emissions and payoff values?

Instead of directly applying Theorem 1 to characterize the BAU, it is slightly more transparent to take the energy inputs as the control variables. In this case, the law of motion becomes:

$$\begin{aligned} g(t+1) &= A(t) + \sigma g(t), \\ A(t) &\equiv \textstyle\sum_i f_i e_i(t). \end{aligned} \tag{21}$$

Note that $A(t)$ is a linear function of the energy inputs of the several countries, with coefficients equal to their respective emission factors. The BAU energy inputs, $e_i{*}$, can then be shown to be the solutions of the equations:

$$\begin{aligned} Y_{i1}(e_i{*}, P_i) &= f_i \delta w_i(P_i'), \\ w_i(P_i') &= c_i\left(\tfrac{S_i}{1-\delta\sigma} - \tfrac{l_i(S_i-P_i)}{1-\delta\sigma\ell_i}\right). \end{aligned} \tag{22}$$

where Y_{i1} refers to the first derivative of the function Y_i. By a direct application of the theorem in the previous section, the value function for country i is seen to be separable in own population and emission factors on the one hand and others' population and emission factors on the other hand:

Theorem 6 (BAU Equilibrium) *Let g be the initial stock of GHG, and let P be the vector of initial populations. For each i, let country i use the Markovian energy strategy $e_i{*} = e_i{*}(P_i; f_i)$ determined by equation (22) above. Then this strategy profile is a MPE, and country i's corresponding payoff is*

$$V_i{*}(g, P; f) = u_i{*}(P; f) - w_i(P_i)g, \tag{23}$$

where the function $u_i{*}$ is bounded, continuous and separable in its arguments, i.e., there exist bounded, continuous functions $u_i^i{*}\ (P_i; f_i)$ and $u_i^j{*}(P_i, P_j; f_j)$ such that they solve the functional equations

$$u_i^{i*}(P_i; f_i) = Y_i[e_i{*}(P_i; f_i), P_i] + \delta[u_i^{i*}(P_i'; f_i) - w_i(P_i') f_i e_i^*(P_i; f_i)], \tag{24}$$

$$u_i^{j*}(P_i, P_j; f_j) = -\delta w_i(P_i') f_j e_j^*(P_j; f_j) + \delta u_i^{j*}(P_i', P_j'; f_j), \tag{25}$$

$$P' \equiv (P_i'),$$

$$P_i' \equiv \ell_i P_i + (1-\ell_i) S_i.$$

Research and development that "decarbonizes" energy inputs without increasing the price of energy would have the effect of decreasing the emission factors. Somewhat paradoxically, *this need not lead to a decrease in emissions for that country*.[6] From equation (19),

$$\frac{\partial a_i{*}}{\partial f_i} = e_i{*} + f_i \frac{\partial e_i{*}}{\partial f_i}. \tag{26}$$

Of course, if the energy input were held constant, then a decrease in the emission factor would result in a decrease in the emissions. However, from equation (22) and the strict concavity of the function Y_i, it is clear that

$$\frac{\partial e_i{*}}{\partial f_i} < 0. \tag{27}$$

Hence a *decrease* in the emission factor for a given country would result in an *increase* in its BAU energy input, thus having the effect of *increasing* its emissions. Hence,

$$\frac{\partial a_i{*}}{\partial f_i} > 0 \tag{28}$$

if and only if

$$\left(\frac{\partial \log e_i{*}}{\partial \log f_i}\right) = \left(\frac{\partial e_i{*}}{\partial f_i}\right)\left(\frac{f_i}{e_i}\right) > -1. \tag{29}$$

Note that the absolute value of the left-hand-side of the equation above is what economists call the *elasticity* of $e_i{*}$ with respect to f_i (see also the discussion below for a special case).

On the other hand, the country's welfare in the BAU will nevertheless be increased with a decrease in its own emission factor.

Theorem 7 *For all g and i,*

$V_i{*}(g)$ is decreasing in the emission factor f_i of country i.

Proof Note that the only effect of f_i on country i's value is through the own effect value function $u_i^{i*}(P_i;\, f_i)$. Further, this function is a fixed point of the Bellman equation, $u_i^{i*} = Tu_i^{i*}$, where the operator is defined as

$$Tu_i^i(P_i;\, f_i) = \max_{e_i}\; Y_i[e_i, P_i] + \delta[u_i^i(P_i';\, f_i) - w_i(P_i')f_i e_i].$$

Suppose that $u_i^i(P_i;\, f_i)$ is decreasing in f_i for every population level. Evidently then the operator maintains that property, i.e., Tu_i^i is also decreasing in f_i. Hence so must the unique fixed point of that operator. The theorem is proved. □

[6] In the discussion that follows, we will suppress reference to the population level P_i. Alternatively, imagine that the discussion applies population level by population level.

The effect on one country's BAU welfare of a change in another country's emission factor is not so unambiguous. Note from the Bellman equation that

$$u_i^{j*}(P_i, P_j; f_j) = -\delta w_i(P_i') f_j e_j^*(P_j; f_j) + \delta u_i^{j*}(P_i', P_j'; f_j)..$$

Since another country's emissions, $f_j e_j^*(P_j; f_j)$, is ambiguously related to its emission factor, in turn the effect on country $i's$ welfare is also ambiguous. If the elasticity condition discussed above is met, then country $j's$ emissions decrease with a reduction in its emission factor and that is value improving for country i. It follows that, if the cost of the R&D were sufficiently small, it might pay for a small group of advanced countries, or even a single advanced country, to develop a technology for reducing emission factors and transfer that technology to other countries, provided that the elasticity condition, equation (29), were satisfied for enough of the latter countries. A formal analysis of such situations is beyond the scope of this paper.

4.2 An example

We illustrate these results with a special case of the "production function" Y_i:

$$Y_i(e_i, P_i) = \pi_i e_i^{\theta_i} P_i^{\Lambda_i} - p_i e_i \ , \tag{30}$$

where π_i, Λ_i and θ_i are positive parameters, with Λ_i and $\theta_i < 1$, and p_i is the price of energy for country i, also a positive parameter. Such a formulation is consistent with a "Cobb–Douglas" production function in which population is fixed exogenously (but grows), and the other inputs (e.g., capital, but excluding energy) are optimized accordingly (see below for a further discussion of this point).

In this special case, the BAU energy inputs are given by

$$e_i{*}(P_i; f_i) = \left(\frac{\theta_i \pi_i P_i^{\Lambda_i}}{p_i + f_i \delta w_i(P_i')} \right)^{1/(1-\theta_i)} . \tag{31}$$

Note that

$$w_i(P_i') = c_i \left(\frac{S_i}{1-\delta\sigma} - \frac{l_i(S_i - P_i)}{1 - \delta\sigma\ell_i} \right),$$

and hence is really a function of P_i alone.

It turns out that in this Cobb–Douglas model the net effect on emissions depends on the size of the emission factor. It is straightforward to verify that

$$\frac{\partial a_i{*}}{\partial f_i} > 0 \text{ iff } f_i < \left(\frac{1-\theta_i}{\theta_i} \right) \left(\frac{p_i}{\delta w_i(P_i')} \right) . \tag{32}$$

Thus *if the emission factor is sufficiently large, a decrease in it will result in an increase in BAU emissions for that country.* Moreover, the cut-off emission factor for which such an increase in emission levels takes place is negatively related to the population level. When population gets to be very large – i.e., $w_i(P_i')$ is very large, then for large subsets of emission factors $\frac{\partial a_i{*}}{\partial f_i} < 0$.

We now take a closer look at the "production function" model in equation (30). Suppose that there are three factors of production, say capital, labor (proportional to population and with re-scaling set equal to it), and energy, and that the (net) output of a country in any period is determined by a "Cobb–Douglas" production (to simplify the notation, we temporarily suppress the country subscript):

$$Y = \phi K^k P^\lambda e^\in - rK - pe, \tag{33}$$

where K, P, and e denote the inputs of capital, labor, and energy, respectively, and $\phi, k, \lambda, \in, r$, and p are positive parameters. Capital and energy are to be chosen optimally by the country (in the BAU), whereas labor is given exogenously. We assume constant returns to scale:

$$k + \lambda + \in = 1. \tag{34}$$

The amount of capital has no effect on emissions, so it will be chosen to maximize Y. It is straightforward to verify that the optimal input of capital is:

$$K = \left(\frac{k\phi}{r}\right)^{\left(\frac{1}{1-k}\right)} P^\Lambda e^\theta, \tag{35}$$

$$\Lambda \equiv \left(\frac{\lambda}{\lambda + \in}\right), \quad \theta \equiv \left(\frac{\in}{\lambda + \in}\right). \tag{36}$$

The corresponding output is:

$$Y = \pi P^\Lambda e^\theta - pe, \tag{37}$$

$$\pi \equiv \phi^{\left(\frac{1}{1-k}\right)} \left(\frac{k}{r}\right)^{\left(\frac{k}{1-k}\right)} (1-k).$$

Of course, π should have a country subscript i, as it does in equation (30) above, and as should all of the parameters and variables.

One can also examine the effect on a GPO of changing the emission factors of one or more countries. One obtains similar results, using arguments similar to those above, but we omit the details.

In the discussion thus far the emission factor is taken as given. In Dutta and Radner (2004c) we extend the model in the direction of making the emission factor choice endogenous. Whilst that is, of course, a richer formulation it still preserves the conclusion that emission levels may or may not decrease when emission factors are lowered.

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