Preliminary and incomplete

SHARING THE BURDEN OF SAVING THE PLANET: GLOBAL SOCIAL JUSTICE FOR SUSTAINABLE DEVELOPMENT

Lessons from the Theory of Public Finance

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There is, by now, a global consensus that global warming/climate change is real and that strong actions need to be taken to ensure that the world does not face excessive risk from an increase in the atmospheric concentration of greenhouse gases. This is my point of departure.

There are five other points of consensus that form the background for this paper:

(a) Global warming is a global problem and needs to be addressed globally. Unless all countries participate, there is a danger of leakage; reductions in one country may be more than offset by increases elsewhere.[2]
(b) Global warming is a long-run problem. We are concerned not so much with the level of emissions in any particular year, as with the long run levels of atmospheric concentrations of greenhouse gases.
(c) The costs of reducing the level of emissions (limiting the increases in atmospheric concentration of greenhouse gases) will be much lower if it is done efficiently. Efficiency implies *comprehensiveness*—we need to address all sources of emissions and explore all ways of reducing atmospheric carbon concentrations, including carbon storage and carbon sequestration.
(d) There is considerable uncertainty, both about the level of "tolerable" increases in greenhouse gas concentrations and the impact of particular policy interventions.
(e) Global warming is a public good problem, so there is a risk of *free riding*. This means that there will have to be some system of credible enforcement.

There are four important corollaries of these points of consensus:

(a) We need a global agreement, and a global agreement will require equitable burden sharing. Much of this paper is concerned with exploring what this entails.
(b) The shadow price of carbon should be approximately the same *in all uses, in all countries, and at all dates.* Current arrangements deviate in important ways from this principle. The (shadow) price of carbon in those countries that have signed on to the

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[2] Nicholas Stern, 2007. *The Economics of Climate Change: The Stern Review.* Cambridge, UK: Cambridge University Press.

Kyoto protocol is higher than in other countries. The (shadow) price of carbon associated with deforestation is lower than in other uses. In many countries, the price of carbon associated with renewables, and especially ethanol, is higher than in other uses.

(c) The fact that this is a long-run problem with considerable uncertainty means that whether we work through emission targets or prices, there will need to be adjustments over time. In an emission targets system, we will have to adjust the targets. In a carbon tax, we will have to adjust the tax. Thus, the standard argument that, in the face of certain types of uncertainties, quantity targets are preferable to price interventions is of limited relevance.

(d) We need to differentiate between "systemic risk" and risk faced by market participants. Uncertainties—and differences in beliefs about the nature of the risks—in fact provides an argument for mixed instruments, such as the safety valve, where, in the short run, there is a cap on the price. Market participants are risk averse, and there is a cost to imposing risk on them. Intertemporal adjustments allow firm and individual risks to be spread out over time, and this greatly mitigates those risks. The fact that what matters is the long run atmospheric concentrations means that the environmental costs of any limited temporary deviations from pre-specified targets is likely to be small.

There are two more introductory remarks. The problem we are discussing has many of the features of classical public finance. There is a global public good, global warming.[3] It has to be financed. Standard theories of public finance provide clear formulations concerning equitable and efficient taxation.

Alternatively, we can think of carbon emissions as generating a global externality, and again, standard public finance theories discuss efficient and equitable ways of controlling the externality generating activity—including the relative merits of corrective taxation and regulatory interventions.[4] Much of the literature has focused on the equivalence of the two systems of interventions, under certain conditions, and much of our analysis will make use of that equivalence. We will analyze tax interventions, because in doing so, the efficiency and equity implications become more transparent. We will then provide the interpretation for quantity interventions.

Secondly, policy in this area—even more than in many other areas of economics—is a matter of the *economics of the second best*. We cannot even measure emissions perfectly. Even governments that are committed to reducing emissions have limited control. Emissions are the by-product of every economic activity. Emissions are not just a matter of industrialization: The methane produced by animals is a major contributor to emissions. We have increasingly become concerned with deforestation, which contributes 20% of the world's emissions. But moving to other building materials may not help: 5% of the world's emissions comes from the production of cement.

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[3] The concept of global or international public goods was first articulated in J. E. Stiglitz, "The Theory of International Public Goods and the Architecture of International Organizations," Background Paper No. 7, Third Meeting, High Level Group on Development Strategy and Management of the Market Economy, UNU/WIDER, Helsinki, Finland, July 8-10, 1995.

[4] As we have noted, there is one standard misapplication of this theory, focusing on uncertainty, which has failed to make note of the long run nature of this problem.

There is a second important second-best consideration. There are, in fact, two important unpriced (or imperfectly priced) resources, (clean, fresh) water, and (carbon in the) air. Many of the reform proposals involve, implicitly or explicitly, putting a price on carbon. But this may increase the importance of the other distortion.

Bio-fuels provide an illustration of what is at issue. One of the responses in many parts of the world to the threat of global warming is to increase the production of bio-fuels, the production of which, in some parts of the world, makes extensive use of already very limited supplies of water.[5] At the very least, we need to be aware of this distortion. Moreover, the increase in bio-fuels has contributed to the increase in the price of food. In this case, the *incidence* of the (hidden and implicit) tax on carbon is borne disproportionately by the poor in the world, since they spend a larger fraction of their income on food, while the rich bio-fuel producers and corn producers in the U.S. are actually better off. Global warming would have disproportionately affected the poor in the world, but this response puts the burden of adjustment disproportionately on the poor.

One of the reasons that the economics of the second best is especially important in this context is that enforcing a global carbon regime will not be easy. Imagine the difficulties of enforcing a global income tax. Tax evasion would be rife. Whether we have a global carbon tax or a system of emission permits, carbon will have a price, and there will be incentives to avoid paying that price. Over the years, we have come to understand how better to enforce taxes; we will need to transfer some of these lessons to controlling carbon emissions. Because the *design* of the system will itself have distributive consequences, we need to discuss this issue before we turn to the issue that is at the center of our concern, how to share the burden.

II. Implementation

In a world with perfect competition, it makes little difference whether we impose a tax on producers or consumers. The incidence of the tax is the same, and the general equilibrium which emerges is the same. Public discussions, however, typically make a great deal of the difference, partly because markets are not perfectly competitive and partly because transitions from one equilibrium to another are not instantaneous; how the tax is levied can make a great deal of difference in the transition.

In the case of carbon, the focus has been totally on production. China is being “credited” with exceeding the U.S. in emissions (though its carbon emissions per capita are still markedly smaller), but many of the goods that are produced in China, and which account for considerable amounts of its emissions, are consumed in the U.S. In terms of “consumption” accounting, America is still in the lead.

[5] It may be more accurate to see that certain corporate interests in the United States have taken advantage of global warming concerns to increase the magnitude of their subsidies.

Whether one uses a consumption or production based accounting makes a great deal of difference in the case of carbon, for two reasons. If one levies a tax (or imposes a system which is equivalent to a tax), how the tax is levied can have large distributional consequences. If a tax is levied on consumption, revenues are generated at the point of consumption; if levied on production, at the point of production. In a closed economy, it makes no difference.

Secondly, if some countries are more effective in enforcement—or impose a lower tax—then production, particularly of carbon intensive goods, will gravitate to where it is, in effect, taxed less. In the case of carbon, this is of particular concern, because the objective of imposing the tax (restriction) is a *global* reduction. As we noted earlier, with such "evasion" total carbon emissions could actually increase, as production shifts from high tax locales to low taxed locales, if the latter are less carbon efficient.

In the design of tax systems, problems of enforcement have taken on first order importance. The argument for the V.A.T. in the advanced industrial countries is that the system is self-enforcing, and thus there is greater compliance. Collection efforts can be focused on large firms which generate a large fraction of value added. Each firm in the production chain has an incentive to claim a deduction for goods purchased from others, which helps ensure that they reveal their income.

(At the same time, the difficulties of enforcing the V.A.T. uniformly in developing countries has provided one of the strongest criticisms for its adoption there. While with full enforcement, such a tax is efficient, in practice, it is highly distortionary—moving resources out of the "formal sector," the very sector that most developing countries wish to encourage.[6])

A *carbon added tax (CAT),* levied at each stage of production, would have some of the same advantages that a value added consumption tax has. Each producer would have to show receipts for the carbon tax paid on inputs into its production. (We frame the discussion in terms of a carbon tax; later, we will reframe the discussion in terms of a regime of emission permits.) The taxes levied at each stage of production would be passed on to consumers. It is *as if* the tax were imposed on consumers; but the problem with levying a tax directly on consumers is that there may be many ways of producing a good. We cannot look at a good and infer how much carbon was used in its production. A carbon value added tax will both discourage production in more carbon intensive ways and discourage the consumption of carbon intensive goods.

If a firm could not produce receipts for carbon taxes on inputs, then a tax would be levied on the input assuming it was made in the least carbon efficient way. This would provide strong incentives for each firm to make sure that its suppliers complied with the carbon tax regime.

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[6] See Shahe Emran and J. E. Stiglitz, "On Selective Indirect Tax Reform in Developing Countries" *Journal of Public Economics*, April 2005, Pages 599-623.

It would be easy to incorporate countries that failed to go along with the international regime. Producers in those countries would not be able to show carbon tax receipts. We could imagine two alternative regimes. One would follow the procedure just described: a tax would be imposed on the input on the assumption that it was produced in the most carbon intensive way possible. This by itself would provide a strong incentive for the country to impose a carbon tax at least on exports. The cost to outside buyers would be the same, but the producing country government would garner the revenue.

Since most firms are unlikely to have two production lines—one for exports, one for domestic consumption—the tax would provide an incentive for reducing carbon emissions. But if exports are a small fraction of total production, the incentive is limited.

This suggests a more aggressive approach, with a compensatory tax on the input designed to make up for the failure to impose the tax on output that is not exported.

Under a CAT, it would, presumably, pay the oil and coal exporters to impose a carbon tax—a tax in addition to the market price. But if all countries imposed the tax, then *that* would be the market price. The point is that, when the government owns the natural resource, it is hard to distinguish the "tax" from the "rent" charged on extraction—a distinction which is clear when the oil is owned and produced by a private company. Thus, while it might seem administratively simpler to impose the tax at the point of production of coal, oil, or gas, or at the cutting of the forest, etc., any carbon tax system will have to focus on usage, i.e. imposing the tax on the *use* of carbon (oil, coal, gas) at each stage of production.[7]

Thus, there would be a charge imposed on the use of carbon in the production of electricity—a charge which would be passed on in the price of electricity. But there would not be a separate charge for the use of electricity.

Emission permits.

The same logic can easily be extended to emission permits. Permits would be granted for producers at each stage of production. They would be responsible for verifying that those from whom they bought inputs did so "legally," i.e. holding the requisite carbon permits. If the supplier did not have valid permits, then the firm would be "charged' for using carbon on the assumption that the most carbon intensive method of production had been used.

Both systems have the advantage of decentralized enforcement.

[7] Indeed, as we shall argue below, since we are concerned about long run concentrations, we will almost surely want to keep large amounts of fossil fuels beneath the ground—with the optimal tax, rents will be zero (negative). It is not surprising that owners of large amounts of fossil fuels are unhappy about this outcome. And most of the interventions, discussed below, do not focus on ensuring that they are fully compensated. There is, I suspect, widespread sentiment that it was luck that resulted in their wealth—the good luck of being borne on land under which there was oil—and it is similarly luck, the bad luck of the reality of global warming, that it now taking that wealth away from them. Without this oil wealth, they may, of course, need assistance.

III. Terrestrial carbon and the basic carbon conservation equation

Terrestrial carbon provides a particularly difficult challenge, both conceptually and in terms of implementation. Conceptually, it forces us to think through clearly stock/flow distinctions. Much of the discussion focuses on emissions, the flow of carbon into the atmosphere. But, of course, what is of concern is the stock of carbon in the atmosphere. To a first order approximation, we can think of the stock of carbon being fixed, and

(1) $C_A + C_F + C_S + C_T + C_O = C^*$

The world's stock of carbon is either in the atmosphere (which is what we are worried about), under the ground, either in the form of fossil fuels or in storage, stored on earth (as terrestrial carbon) or in the ocean. Our concern is to keep C_A under control. Most of the discussion has centered around limiting the amount of fossil carbon put into the atmosphere. Some scientists are hoping that the development of carbon storage technology will allow fossil fuels to be burned and the resulting carbon to be returned back below the ground.

It is hard to monitor deforestation. It occurs at millions of points on the globe. Moreover, only part of the wood from a tree that has been harvested will be used as fuel, and therefore contributes directly to amounts of carbon in the atmosphere. Wood used for furniture or construction enters the atmosphere only slowly, through decay. At the same time, cutting down a forest may lead to far more carbon entering the atmosphere than the carbon from the burning itself; carbon can be released from the soil (from the roots). Those using wood as fuel should be charged for these indirect releases of carbon into the atmosphere; those using wood for long-lasting construction should be given some credit for the carbon storage.

It may be useful to think about how one might design a system if one could have perfect monitoring. When a tree is cut down, a charge would be made for the indirect emissions into the atmosphere. When the wood is burned, a charge would be made for the carbon entering the atmosphere. And when wood is used for construction, a charge would be imposed as the wood rots and the carbon enters the atmosphere.

In other words, given that our focus is on carbon *in the atmosphere,* a "toll" would be imposed every time a carbon molecule enters the atmosphere on the individual who is responsible for it entering—whose action "accounts" for the entry. (The charge would take account of the expected duration of the carbon in the atmosphere—which is sufficiently long that it may be approximated by infinity.[8])

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[8] That is, a carbon molecule can be thought of as renting space in the atmosphere. If the rent per unit time were c, and there were a decay rate of μ, and the interest rate is ρ, then the entry charge would be $c/\mu + \rho$. Of course, we don't care about how long any particular molecule stays in the atmosphere; we don't have to track each. We care about the average. If zero (a molecule never leaves), then the entry charge is c/ρ.

It should be clear that this "ideal" monitoring is impossible. We will be looking for second best approximations. One approximation that may do well—at least in the long run—focuses on the steady state, making use of the fact that forests are renewable. A forest (with a particular tree, cut down in a regular way after T years) takes out carbon from the atmosphere and stores it (not only in the tree itself, but in the root system). In steady state, the tree (and its products) are decaying at the same rate that carbon is being taken out of the atmosphere. We give the forest "credit" for the carbon which it has stored (carbon that is *not* in the atmosphere)—including carbon that is stored in post-cutting uses (construction, furniture). Denote by V_i the volume of carbon stored in a particular forest ($C_T = \Sigma_i V_i$, terrestrial carbon is the sum of the carbon stored in all the forests[9])

(2) $dC_A/dt = - dV_i/dt = e_i - s_i$,

the increase in atmospheric concentration of carbon (from this forest) are the emissions *minus* the absorption (storage) of carbon. In steady state,

(2) $dV_i/dt = 0$,

or

(2a) $e_i = s_i$,

emissions are equal to the amount stored. There is no net contribution.

Were all of this carbon to be transported into the atmosphere, there would be a charge of cV, where c is the price of carbon and V is the amount. The flow value of not being transported into the atmosphere is thus rcV. In terms of economic incentives, it makes no difference whether we charge someone cV for transporting V units into the atmosphere, or pay him rcV every period for not transporting it into the atmosphere. If he never transported it into the atmosphere, he would receive cV.

Of course, from a property rights perspective, these outcomes are quite different: one implicitly assigns the right to the owner of the forest to pollute and pays him not to pollute; the other gives him no rights to pollute and forces him to compensate the atmosphere should he pollute.

Land should be used in the most efficient way possible. Assume that there is a flow of lumber of L, and $\alpha_1 L$ is used for energy, with a value of $\alpha_1 p_1 L$. And α_2 is used for furniture (or other decaying uses) with a value of $\alpha_2 p_2 L$. Thus, this particular use of land generates a (flow) value of

(4) $rcV + \alpha_1 p_1 L + \alpha_2 p_2 L - z$

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[9] Plus the carbon stored in wood cut down from the forest.

where z is the (non-energy, non-carbon) cost of maintaining the forest, and r is the real interest rate.[10]

Note that in this formulation, we do not charge for burning wood, because in steady state, exactly the same amount of carbon will be (was) taken out of the atmosphere.[11]

It should be clear that increasing carbon payments (c) increases the return to forest usage with high storage. A higher price of energy shifts production towards uses that result in more 'bio-fuels.' Higher prices of lumber shifts production towards uses that result in more lumber out. Better preservatives increase the longevity of carbon stored in furniture, so increase V (and presumably p_2, the price paid for lumber).

There is some controversy about whether land should be devoted to forests with the highest V or the highest growth rates. Some forests with tall trees (and thus high V) are slow growing and thus take out little carbon from the atmosphere. A fast growing forest, by contrast, may take out much more carbon from the atmosphere per unit time. Equations (3) and (4) provide an easy resolution of this controversy—and suggest neither view is quite right. In steady state, the amount of carbon taken out is equal to the amount of emissions, so the pace of storage is not directly relevant. (It is only that we typically do not fully measure all of the decay.)

On the other hand, the rate of growth may be relevant for another reason. Assume that the amount of Lumber (biomass) that we can take out (per acre) from a forest is related to the stock of carbon by the growth rate:

(5) $L = gkV$

Some forests have a higher growth rate, g, than others, where we assume that the flow of lumber L is proportion to the rate of growth and the volume V, i.e. $L = gkV$. Then

(6) $rcV + \alpha_1 p_1 gkV + \alpha_2 p_2 gkV - z$

Other things being equal, a forest with a higher growth rate will generate more energy and usable lumber and thus be more valuable. But, of course, typically, things are not equal. (6) makes clear that we have to evaluate each plot of land for the carbon that can be stored on it, for its generation of energy, and for its generation of other lumber products (as well as for the cost of maintenance).

But (6) also makes clear that it may be a mistake to cut down a tropical forest (with a high V), to be replaced by sugar cane, even if sugar cane grows more quickly.

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[10] The energy used in the production of energy from the forest is netted out in α_1.

[11] And nothing was paid to the forest as it was taken out. There are some issues of timing (present discount values). We assume that the interest rate is sufficiently small that these can be ignored in this first order approximation. Alternatively, they can be thought of as subsumed in our αp.

Note that if the price of fossil fuels rises (as Hotelling's formula predicts), then more and more land will shift towards forests with a higher renewable energy usage. In a general equilibrium model, the effect will be mitigated by the reduced output of grain, which will raise the price of grain.

What is critical, however, is that in changing land usage, the carbon cost is correctly included. Let π_i denote the private returns to land usage (per hectare).

(7) $\pi_i = \alpha_{1i} \; L_i \; p_1 + \alpha_{2i} L_i p_2 - z_i$

where, in this generalized formulation

z_i are the costs from activity i

$\alpha_{1i} \; L_i$ are the non energy outputs, valued at p_1
and

$\alpha_{2i} L_i$ are the energy outputs, valued at p_2.

Then, the net social returns are

(8) $S_i = rcV_i + \pi_i$

A change in land usage from i to j induces a change in social profit of

(9) $\Delta S_{ij} = rc\Delta V_{ij} + \Delta\pi_{ij}$

$= rc \int \delta V_{ijt} + \Delta\pi_{ij}$

where the change in the level of carbon storage in moving from one steady state (i) to the other (j) is just equal to the integral of the flows into or out of carbon storage, denoted by δV_{ijt}.

(10) $\int \delta V_{ijt} = \Delta V_{ij}$

The problem with current bio-fuel policies is that, while recognizing that we are failing to take account of the cost of carbon in fossil fuels and the advantages of bio-fuels, we fail to take account of the carbon opportunity costs, which we have represented by ΔV_{ij}, and we therefore do not obtain socially efficient resource allocations.

Limit

Controlling climate change entails controlling the limiting value of C_A at or below some level C_A*. To simplify, let us ignore the amounts of carbon that can be absorbed into the ocean or re-injected through carbon storage into the earth. Then, from (1), we can solve for

(1') $C_F^* = C^* - C_A^* - C_T^*$.

This means that in long run equilibrium (ignoring technological change), all energy needs are met by renewables, and the rents associated with the carbon remaining under ground are zero. (1') has some other (obvious) implications. The more carbon sequestered in forests (the greater C_T^*) the less carbon needs to remain in fossil fuels, i.e. the higher the level of extraction of fossil fuels. If extraction costs for fossil fuels are low, this means that the lower costs for energy (in the intermediate run—in the long run, we will still have to rely on renewables).

Since costs of extraction increase the more fossil fuel that is extracted, the tax (per unit of equivalent energy) on fossil fuel must be t*, such that

(11) $p_1^* = t^* + \xi(C_F^*)$

where $\xi(C_F^*)$ is the marginal cost of extraction when C_F^* fossil fuel is left in the ground. Letting C_T^* be the equilibrium terrestrial carbon ($= \Sigma V_i$), a function of the prices for energy, non-energy uses of "lumber," and the carbon charge t, and noting that efficiency implies c = t*, then, from (6), if each parcel of land is allocated to its best use, i.e. the use for which[12]

$$rt^*V_i + \alpha_1 p_{1*} g_i kV_i + \alpha_2 p_2 g_i kV_i - z_i$$

is maximized, then we can solve

(12a) $C_T^* = \Sigma V_i = \chi(p_1, t)$

And

(12b) $D(p_1^*) = \Sigma_i g_i \alpha_i V_i = \varsigma(p_1^*, p_2^*, t^*,..)$

Where ς is the aggregate supply of energy, a function of prices and taxes. In the long run, all of the demand for energy must be met by renewables. For simplicity, we take p_2 (and other prices) in the long run as given.

Substituting (12a) into (1'), we obtain

(1") $\xi^{-1}(p_1^* - t^*) = C^* - C_A^* - \chi(p_{1*}, t^*)$.

[12] The full dynamic equation is somewhat more complicated than this, since there cannot be an instantaneous shift from one land use to another, and since trees are long term investments. Hence, at each moment of time, a decision has to be made, say, about terminating its current use (based on the current rate of growth of existing trees) and switching to an alternative use, based on projections on future prices (including prices for carbon storage) and taxes (and future interest rates).

(12b) and (1") are two equations in two unknowns, p^*_1 and t^*: we can solve simultaneously for the long-run equilibrium price of energy and the equilibrium carbon tax.

This analysis assumes that there are static demand and supply functions. If, over time, the demand for energy increases, it would imply that (if p_2 and other prices remained unchanged) p_1 would increase, which would shift land use to more energy production and less carbon sequestration (as well as less non-energy uses). For the carbon equilibrium condition (1) to continue to be satisfied, there would have to be an offsetting increase in t^*.[13]

Knowing the long run value of p^*_1 and t^*, we can solve backwards for prices of energy and the equilibrium carbon tax at each moment of time. Consider the simplest case where there are zero extraction costs, and where we normalize our units so the price of fossil fuels is per unit energy, p_1. Then at each date τ,

(13) $p_1(\tau) = t(\tau)$.

In the long run, there can be no rents to fossil fuels, and that means that at every date, there can be no rents (otherwise, there would be an incentive to extract all the oil at the moments when it had positive rents). Equilibrium is described by a rent function and a price function $\{t(\tau), p_1(\tau)\}$ such that (as before, we take p_2 and other prices as given; it is an easy matter to expand the analysis to incorporate the simultaneous solution for these as well), given $\{t(\tau), p_1(\tau)\}$:[14]

(a) optimal land usage generates a supply of terrestrial energy ς_τ (..).
(b) the optimal tax (subsidy) is increasing at the rate of interest, r: $d\ln t/d\tau = r$.
(c) at each date, demand for energy equals the sum of terrestrial energy plus fossil fuel energy

(14) $D(p_1(\tau))) = \varsigma_\tau(\ldots) + \kappa c_F$

where κc_F is the fossil fuel energy, and c_F is the addition to atmospheric carbon from burning fossil fuel:

(15) $dC_F/dt = c_F$

and

(d) the sum over time of fossil fuel energy equals that required by the carbon conservation equation

[13] In the general equilibrium, the reduced supply of non-energy outputs would lead to an increase in p_2 as well.
[14] These results can be derived more formally from an intertemporal maximization problem, using a standard Hamiltonian formulation. We assume that there is no short-run impact of climate change.

(16) $\int c_F(\tau)\, d\tau = C_F^* - C_F(0)$

Over time, land is switched from its current production patterns (which pay no attention to carbon storage) to patterns which recognize the social value of carbon storage. Simultaneously, this entails an increase in the price of energy and the tax on carbon. More and more land is switched into uses that do better in carbon sequestration, and less reliance is placed on fossil fuels for energy production.

Notice that in this formulation, setting a tighter atmospheric target entails no difference in the steady state value of relevant variables. It simply means that we switch from fossil fuels to renewables more rapidly. This in turn enables us to calculate the upper bound of the cost: An amount of energy, equal to $\kappa\Delta C_F$ would have been produced at zero social costs (zero extraction costs). Now this energy will be produced at a cost of $p_1(\tau) + \nu t(\tau)$, where ν is the implicit renewable subsidy per unit energy produced. Hence, the upper bound of the cost is just

$$\int [p_1(\tau) + \nu t(\tau)]c_F(\tau)\exp\{-\int r\, dz\}\, d\tau$$

over the period during which fossil fuels would have been used under the looser regime, and not under the tighter regime.

In the more general case, the marginal fossil fuel extracted, C_F^*, generates a rent of zero asymptotically; but this means that it must generate a rent of zero (more precisely, non-negative rent) at each moment of time, i.e.

$$p_1(\tau) - t(\tau) = \xi(C_F^*)$$

for all τ. Low extraction fossil fuels are extracted first and then higher extraction fuels. For a fossil fuel with extraction costs ξ, rents are

$$p - t - \xi$$

and the rate of increase of rents is

$$dp_1/d\tau - dt/d\tau / p - t - \xi$$

At date τ, fossil fuels with extraction costs $\xi(C_F)$ will be extracted, where

$$[dp_1/d\tau - dt/d\tau]/ [p - t - \xi] = r(\tau)$$

where r is the rate of interest. From the pricing and emissions tax functions, we can solve for the carbon utilization (and fossil energy supply) time profiles.

The patterns we have just described do not, of course, accord with observed patterns of fossil fuel usage. We should be extracting oil first from Saudi Arabia (low extraction costs) before we turn to higher extraction cost oil (say from Alaska). The fact that we do not do so reflects in part the complexity of the oil industry—the risk that we associate, for instance, with reliance solely on the low cost provider; the fact that Saudi Arabia may feel that investments not inside its boundaries are risky—and hence has an incentive to keep some of its assets below ground. It reflects, too, the uncertainty associated with discovery. The latter uncertainty would remain, even if we resolved the other political risks. It would mean, for instance, that should a low cost supply of oil be discovered some time in the future, we would want to make use of it. If we are to do that—and to obey our carbon conservation equation—it means that we have to anticipate that we will want to extract some fossil fuels in the future, i.e. given our prior beliefs about the discovery of oil of different extraction costs, we set a reservation extraction costs, ξ_R, such that we only extract oil whose extraction costs are lower than that level. Assume we believed, for instance, that we believe that we will be able to continue to discover an amount of oil every period $c_f(\xi_R)$ for the next hundred years, after which there will be no more (cheap) oil to be discovered. Then, we adjust our "intermediate" target C_F* to reflect the fact that we will add an additional amount of carbon $\int c_f$ over the next hundred years, but that during this interim period, we will continue to use fossil fuels in the amount $c_f(\xi_R)$.

III. Equitable burden sharing

The key problem today in reaching an agreement is not the science: as we have noted, there is a growing consensus about the minimum that needs to be done—and consensus that that minimum is much greater than what the world is doing today. The problem is how to share the burden of adjustment—and adjustment costs are likely to be large.

A scarce resource—carbon in the atmosphere—has been treated as if it were a free good. The market equilibrium which has emerged is, as a result, greatly distorted. Many of the key decisions that affect carbon emissions are long run—power plants, housing, transportation systems. Many of the decisions themselves are not totally market driven—land usage patterns are affected by zoning.

It is, of course, not just a matter of adjustment costs. Charging the social cost for something that has been treated as free will change relative prices. There will be winners and losers. The losers will want to be compensated; the winners will be reluctant to do so. In a sense, any change in the scarcity value of any factor of production has similar consequences; when these changes in relative prices are driven by market forces, we come to accept them—though those hurt are again more demanding of help than those who benefit are willing to share their new found gains. But this seems somehow different, for it is a political decision (though no less than the enclosure of common land or common knowledge is a political decision).

If we succeed in ensuring that fossil fuels remain below the ground, then those who otherwise would have sold those fuels are clearly worse off. With a credible program on global warming, the owners of oil and coal reserves will see the value of their assets diminish—regardless of the design of the program. The wealth of the oil exporters will also diminish. To be sure, there may be limited sympathy—they have done very well in the last few years, and unlike wealth that is the result of hard work, ingenuity, or savings, it appears to be largely the result of luck. We should expect that countries with large endowments of these resources will do everything they can to make sure that there is no agreement.

The same thing is true, of course, not just of countries but of companies—though companies have more of a choice. An important part of their asset base is their skills and knowledge. BP, with its slogan *Beyond Petroleum,* has suggested that a company can transform itself from an oil producer to an energy producer that is not dependent on fossil fuels. Still, responding to global warming will result in a decrease in the value of certain assets (just as *not* responding to global warming will result in the decrease in the value of other assets).

It is worth bearing in mind these *within* country distributive effects, because they play an important role in determining policies. America's response to global warming may be more determined by impacts on its oil companies and its automobile industry, which has been geared towards high oil consuming vehicles, than by a more balanced consideration of the country's national interest. As a major oil importer, America would benefit from the lower price of oil that a global agreement would bring about.

Still, for most of this lecture, as important as these within country distributive effects are for political economy, I shall focus my attention on the cross-country distributive effects.

Much attention has been placed on the inefficiencies in energy usage in developing countries. Increasing energy efficiency will, it is widely believed, reduce emissions. This is presented as a win-win situation: the global environment benefits at the same time that the developing country saves on scarce resources. But whether increases in energy efficiency lead to an overall increase or decrease in emissions depends on whether achieving "economic" energy efficiency leads to an increase or decrease in the use of carbon (an unpriced resource) in the production of energy, and on whether the demand for energy has an elasticity that is greater or less than unity. While most economically more efficient technologies will be less carbon emitting, at the margin, it pays to emit more to save on costs. And more energy efficiency will lead to the price of energy falling; if the demand for energy is price elastic, then there will be a more than proportionate increase in energy usage so that emission levels will increase. Achieving energy efficiency is desirable, but it will not suffice.

Global societal costs associated with reducing energy emissions can be minimized by the imposition of a global carbon tax. The current price of carbon is zero. Assume that the efficient carbon tax (needed to achieve the agreed-upon reductions in global emissions) is t^*. Then, the expenditure function for country j, giving the minimum level of income required to attain a given level of utility, provides a money-metric for assessing the impact of the tax. Let $\Pi(t, p(t))$ be aggregate producer profits when the carbon tax is t and the vector of prices is p. Let B(t*) denote the cost of the tax

(17) $B(t^*) = E(\mathbf{p}(t^*), t^*, U_o, G(t^*)) + \Pi(t, \mathbf{p(t)}, G(t)) - [E(\mathbf{p}(0), 0, U_o, G(0)) + \Pi(0, p(0), G(0))]$

where **p(t)** is the general equilibrium price vector that emerges when the price of carbon is t, U_o is the initial level of utility, and G(t) is the "climate" associated with carbon tax t—a global public good.[15] Clearly, different countries will be affected differently, both as consumers and producers. We are seeing a glimmer of these general equilibrium effects today, with higher fuel and food prices. There is one difference, which is that oil producers are large beneficiaries of today's high oil prices but would be large losers under a carbon tax.

There is one important aspect of the analysis that we have not discussed: the disposition of the revenue. Denote the revenue raised by the carbon tax by T(t). Assume country i gets T_i, with $\Sigma_i T_i = T$. Then (under the assumption that it is desirable to have some carbon tax), for t*, there exists an allocation such that

(18) $B_i(t^*) + T_i(t^*) > 0$.

Indeed, there are many allocations of the tax revenues which can make every country better off, and much of the fight going on can be viewed as how to allocated the *typically implicit* tax revenues.

Thus, a system of carbon trading, based on, say 1990 levels of emissions, gives emission tax revenues in proportion to 1990 levels of emissions. That means that the US not only gets the single largest allocation but gets the largest allocation on a per capita basis.

(19) $T_i(t) = tE_{1990}(1 - \eta)$

where η is the agreed upon reduction from 1990 levels.

There is no ethical basis for such an allocation. Indeed, developing countries argue that since the North contributed disproportionately to the current buildup of greenhouse gases, their future allocations should be commensurately reduced.

The developing countries say that they should be fully compensated for the extra production costs associated with using more carbon efficient technologies. The discussion so far has not shifted to the broader issue of compensation for the implied changes in consumption prices, e.g. for food. And it typically takes no account of the benefits from reduced global warming. Such considerations argue that, at a minimum,

[15] This analysis simplifies in a key way: the impacts of changes in emission levels will be (mostly) felt only over the long run. We thus need a more complete dynamic model.

$$(20) \quad T_i(t) \geq \Pi(0, p(0), G(0)) - \Pi(t, \mathbf{p(t)}, G(0))$$

With the new focus on terrestrial carbon, it is argued that, in addition, they should be compensated for maintaining their forests

$$(21) \quad T_i(t) \geq \Pi_i (0, p(0), G(0))] - \Pi_i (t, \mathbf{p(t)}, G(0)) + rtV_i$$

where now V_i stands for the amount of carbon stored in their forests and $c(t)V = rtV$ now stands for the compensation for maintaining a forest with carbon storage V when the price of carbon is t.

In this view, global warming is a global public good, and given the large disparities between the rich and the poor countries, all (or at least most) of the costs of providing this public good should be borne by rich countries. Developing countries should be compensated for providing the valuable environmental services they provide—carbon storage—and for the additional costs of reducing carbon—of going beyond energy efficiency to carbon efficiency.

Note that once countries are charged for carbon, improvements in carbon efficiency again do not necessarily reduce carbon emissions; because they lower the price of the product, they increase the demand, and if the demand elasticity is high enough, overall carbon emissions are increased. Overall impacts on carbon emissions are even more difficult to ascertain, because demand for substitutes is reduced and complements increased. If the carbon content of substitutes is low and that of complements is high, again total emissions may increase. Such increases in carbon efficiency are still desirable; they increase the overall efficiency of the economy system.

An agreed upon carbon tax.

One proposal that has received some attention is that the countries of the world agree upon a carbon tax level—a level which would achieve the desired level of reduction in emissions. Each country would then keep the revenue for itself. In effect, a carbon tax would substitute for taxes on work and savings; and under the principle that it is better to tax bad things than good things, such taxes yield a double dividend.

Denoting the emissions generated in the country with the price vector **p** (t) and tax t, $e(\mathbf{p}(t), t)$, then

$$(22) \quad T_i (t) = t\, e(\mathbf{p} (t),t)$$

The appendix explains why, for most countries, we should expect this to suffice to provide adequate compensation—so that all countries are better off. In a sense, the distributional impacts are likely to be small. The "cost" of the carbon tax is the *difference* between the dead weight loss of the carbon tax and the alternative tax (say a wage tax). This number is likely to be small. But the *differential* incidence is the difference in this difference across countries—a number that is likely to be even smaller.

In short, the advantage of the common carbon tax is that distributive consequences can be shunted aside.

Emission permits

This is not true of the system of carbon permits. We have already discussed the implicit—and unacceptable—allocation of the Kyoto protocol. The question of the allocation of emission permits is, of course, isomorphic to the question of the allocation of tax revenues.

One philosophically widely accepted principle is equal emission permits per capita—i.e. distributing the revenues equally among all the citizens of the world. But most theories of social justice argue for a more progressive distribution of the revenues generated from the "sale" of a global natural resource, the right to emit carbon in the atmosphere. Arguing that those who polluted more in the past have the right to pollute more in the future is, to say the least, perverse; and since past levels of pollution are related to income, such a rule is clearly highly regressive.

The question can be viewed another way, from a more Coasian perspective: how should property rights in the atmosphere be allocated? Coase, of course, argued that it didn't matter how one assigned property rights; all that mattered for economic efficiency was that there was a clear assignment. Though that proposition has come to be questioned, to achieve a global agreement among all the countries will require that the developing countries believe that the implicit assignment of property rights is, in some sense, fair, or at least acceptable.

Within democratic developing countries today, acceptance of a property rights allocation that gives their citizens any less than a proportionate claim is not likely to be acceptable.

The "problem" with this rule is that it is feared it will lead to high levels of payments from developed to developing countries—at least for the foreseeable future. To be sure, as developing countries develop, differences in per capita emissions will be reduced, and so the scope for transfers will be reduced. A slow enough pacing in of emission reductions might hold out the possibility that transfers could be kept to a moderate level. But projections made on the basis of current rates of increases in emissions, say in China, may be misleading, for at least two reasons: (a) Rapid paces of technological adaptation may lead to rapid increases in energy efficiency—the government is committed to making these changes; and (b) China has been (and will, for some time, continue to do so) going through a resource intensive phase of its development—focused on expanding housings and cars. But it will eventually follow the pattern of other countries, shifting to the less resource intensive service sector. Already, it is discouraging output in energy intensive sectors, particularly energy intensive exports (this, in turn, may in part be due to the system of attribution, which "credits" China with emissions for products consumed elsewhere.)

There is another problem with most systems of emission permits within countries: any system in which the government allocates permits (which is equivalent to allocating money) is subject to corruption, either overt corruption, or the more subtle form, campaign contributions to induce the political process to adopt a "rule" that benefits particular parties.

There is an alternative, auctioning off emission permits. If the auction is held internationally, the system is identical to a system of global taxation in which the revenues are pooled together—and the international community must then decide on the allocation of revenues (see the discussion above.) If the auction is held at the national level, it is equivalent to the system of an agreed upon tax level, with revenues retained by each country.

Of course, the auction undoes one of the reasons given for the permit system: the possibility of receiving large amounts of money (or the protection that it provides that mitigation will not make one worse off) has provided political support for (or reduced opposition to) taking actions to reduce emissions. But these political economy arguments *for* tradable emission permits are, at the same time, the main arguments against, for allocating a disproportionate number of permits to those currently engaged in polluting is the very reason that the poor, who are not currently polluting (as much, on a per capita basis), will oppose it.

(There are other arguments for not granting emission permits on the basis of past levels of emissions, besides the obvious one that it rewards those with bad behavior, going precisely against the "polluter pay" presumption. In dynamic competitive markets, it *overrewards* these past polluters; new firms, entering the market, will, for instance, not have these permits. It is their marginal costs—including the costs of buying the requisite pollution permits-- that will determine market price. Prices will rise to reflect the marginal cost of pollution, so *efficient* firms are fully compensated in equilibrium. Thus, granting them pollution permits on the basis of past levels of pollution overcompensates them. This may help explain the active support for these initiatives by these firms.)

V. Distortionary approaches to mitigation

So far, we have considered two alternative, efficient ways of reducing emissions: a global carbon tax and a system of tradable emission permits. Both guarantee that there will be a single price of carbon, in all uses, in all countries. In fact, almost every country has deviated from this general principle, by introducing, for instance regulations on minimal usage of ethanol (U.S.), minimum fuel efficiency standards (U.S.), or providing subsidies to renewables (many developed countries.)

How can these deviations be justified—particularly in the U.S., by an administration seemingly committed to free market principles? There are two bases for arguing for these distortionary interventions.

(a) Distributive concerns

The first focuses on distributive concerns, a worry about the magnitude of price changes (say induced by the carbon tax) required to elicit the requisite behavioral responses. When there are low demand or supply elasticities, large price changes may be required. A high enough price of carbon would lead to a high enough price of energy which, in turn, would lead to the requisite changes in carbon emissions; but the effect on the poor could be devastating. To be sure, one could offset these adverse effects, using, for instance, revenues raised by the carbon tax or the auctioning of emission permits. But it is never possible to target perfectly, and many may be hurt in the process. And if the revenues have been committed to "buying" off politically powerful potential opponents of emission reductions (for instance, by providing emission permits on the basis of past levels of emissions), to compensate those hurt indirectly additional taxes will have to be levied; and there is a deadweight loss to these taxes.

(The problems may be exacerbated if monetary authorities subscribe to simplistic rules of inflation targeting; for the large increases in energy prices then induce large increases in interest rates, which in turn leads to a slowing down of the economy and an underutilization of resources, with especially adverse effects on the poor.)

Regulatory approaches may be able to achieve large reductions in emissions, with much smaller changes in equilibrium prices, and accordingly, with much smaller distributive impacts.

Part of the argument (for and against) these regulatory approaches may be that the impacts are less transparent. Requiring the use of renewables increases costs of production, and leads to higher consumer prices; but it may be harder to link directly the price increase with the regulation than in the case of a tax.

(b) Market failures

The other argument is that markets, by themselves, are not efficient, and government intervention is required to achieve efficiency. There may, for instance, be a coordination failure: builders do not install energy efficient light bulbs as standard equipment, because they know that consumers will be unhappy, since they cannot easily replace them in local stores. And local stores do not stock these light bulbs, because there simply isn't the demand. A government regulation requiring all new buildings to have energy efficient light bulbs solves the coordination problem. Stores will quickly perceive the demand, and will stock them.

Innovation is based not only on prices today, but on beliefs about future prices. Market expectations may not be rational. Each market participant may believe that there will be a technological breakthrough that will allow the economy to achieve its emission reductions with a low carbon tax. With a low carbon tax in the future, it does not pay most firms to invest a lot in carbon reducing innovation. (It is clear that American automobile manufacturers misjudged the probability distribution of gasoline. Shareholders have borne some of the costs of this mistake—but so too does the rest of society, when, as a result, there is excessive emissions. Of course, if they had to pay the full costs—though a carbon tax—society would have been compensated. But when a whole industry makes a correlated mistake, it may be too big to fail, and not only will there be a reluctance of impose the full carbon costs, there may even by a bail-out.)

Of course, innovation almost always entails externalities—there are learning spill-overs, so that without government support or government mandates, there may be insufficient incentives to innovate.

Standard welfare theory begins with the *assumption* of exogenous preferences. Yet we know that preferences themselves are endogenous, affected, for instance, by advertising and social processes. Government policies can help shape the evolution of preferences, and certainly their expression.

Not only is there a need for more public transportation, but cities need to be redesigned and zones to allow for greater reliance on public transportation. This is an example where market mechanisms by themselves will not suffice: there is a need for collective action. But changes in the design of cities can, themselves, lead to changes in preferences. There were changes in life styles (and almost surely preferences) in America in the 1950s, following the construction of the superhighways; but more recently, there has been another change in life style—an increased preference for urban living. Reducing emissions will require changes in the way we live and work—including where we live and work and the structures in which we live and work. And government policies may facilitate such changes.

VI. Access to Technology

Efficient utilization of knowledge requires that it be made freely available. Knowledge is a quintessential global public good. But, of course, the patent system tries to restrict the usage of knowledge, as one way of compensating innovators.

The deficiencies in the patent system (especially as currently designed in the U.S.) are becoming increasingly recognized: not only does it lead to an underutilization of knowledge, it may even have adverse effects on the pace of innovation.[16] Here, however, we are concerned with another aspect—the distributive impact. The refusal of the U.S. to transfer technology to developing countries may have large distributive consequences.

If developing countries sign on to a convention requiring them to reduce their emissions by a certain amount, by a certain date, they are committing themselves thereby to an

[16] See, for instance, J. E. Stiglitz, *Making Globalization Work,* Chapter 4. The adverse effects arise from several sources: (a) the patent system gives rise to monopoly power, which lowers levels of production, reducing incentives to innovate; (b) the patent system increases the cost of the most important input into innovation—knowledge; (c) the patent system gives rise to a high risk of patent litigation, especially in the context of the patent thicket—where there is some probability that any innovation will trespass on others' intellectual property.

increase in demand for emission reduction innovations. If certain countries have a comparative advantage in the production of these innovations, such a convention can induce large transfers from developing countries to developed countries—and it is understandable that they would object.

Assume, for instance, that with existing technologies, emission per unit of output is e_o. Assume the country signed an agreement to reduce emissions below the level of E*, that the international agreement has sufficient sanctions that the country will comply, and that in the absence of commitment, it would have produced an output of Q_o and emissions of Q_oe_o. To comply with its commitment, the country would have to restrict output to E^*/e_o. If the new technology lowers emissions per unit of output to e_1, sufficient that at Q_o the country can meet its obligations, then the owner of the new technology can extract a rent up to $[Q_o - E^*/e_o]$.

With the developing countries feeling that they have repeatedly been shortchanged, not just be colonialism, but also by international agreements (the poorest countries were actually made worse off by the Uruguay round), it is not surprising that they feel reluctant to sign on to an agreement that might result in large transfers from the developing countries to the developed.

Any equitable approach to global warming and to the financing of technological innovations which will succeed in reducing emissions requires that the financial burden rest on the developed countries. The developed countries have made a commitment to provide assistant to poorer countries of .7% of their GDP. To date, most countries have fallen far short of that commitment. Perhaps developed countries should be credited with some part of the costs of technology transfer.

There are, of course, several alternative ways to finance and facilitate the requisite innovations: (a) public financing and public production; (b) public financing and private production, e.g. through a prize system; (c) private production and private financing, with developed country governments paying the cost of technology transfer. Almost surely, there will be some combination (though, again almost surely, universities and government research laboratories will play a central role.)

VII. National Security, Energy Independence, and Emission Reductions

The analysis so far has focused on conventional economic goods. Energy, however, is so important that many countries—including the United States-- have expressed a concern about energy independence. A cutoff of supplies of energy would have a disastrous effect on the country. Countries can take actions to ensure that there is no cut off of supplies within their boundaries, but there is little they can do to protect themselves against external shocks. These concerns are not just a matter of the imaginations of security experts, entrusted with thinking though worse-case scenarios. There have been oil boycotts in the past. Sea lanes for shipping oil are vulnerable. In a world in which a country can, with impunity, violate international level, and invade another, countries rightly worry about their vulnerability.

The problem is that different kinds of energy are not quickly substitutable. China and India have large coal stocks, but must import oil and gas. Developing an economy that relies on imported oil and gas leaves the country vulnerable. Restrictions on emissions (or a global carbon tax) can impose a particularly large burden on such countries. We capture this in our model by positing another public good, S, security; the costs of attaining S can be very dependent on t:

$B(t^*) = E(\mathbf{p}(t^*), t^*, U_o, G(t^*), S(t^*) + \Pi(t, \mathbf{p(t)}, G(t)) - [E(\mathbf{p}(0), 0, U_o, G(0), S(0)) + \Pi(0, p(0), G(0))]$

It will be much easier to reach a global agreement on global warming, if we can make progress in achieving greater international security.

VIII. **Concluding Remarks**

The world is engaged in a risky experiment, increasing to dangerous levels atmospheric concentrations of greenhouse gases. Though we may not yet know the full consequences of this experiment, the risks are sufficiently great that there is a growing consensus that there must be marked reductions in the level of emissions. And given developing countries aspirations of growth—and increasing evidence that many of these aspirations will be realized—the reductions within the developed countries will have to be all the greater. The total costs of meeting the requisite reductions will depend, to a large extent, on advances in technology. For the last two hundred years, much of the innovation in the west has been directed at saving labor; little has been directed at reducing emissions. And why should it have been: with the atmosphere treated as if it were a free good, there were no incentives in place. This suggests that there may be ample opportunities for technological advances.

But the pace of innovation is uncertain, and it would be foolhardy to rely on such advances. It is imperative that the West change, as well, patterns of consumption—patterns that regrettably are all too often emulated in the developing world. There is a need for the development of a new economic model, one which centers less on the production of emission intensive goods and more on other things which individuals and societies value. Changes in relative prices, reflecting the scarcity value of air and water, will help facilitate these changes, but so too will other government policies.

This paper has focused on one question which is critical to reaching a global agreement on emissions reductions: how the burden of saving the planet should be shared, between rich countries and poor. There is no question that there will have to be *global* reductions. That is not the question. The question is upon whom should the incidence of the cost of adjustment be imposed? Avoiding global warming is a global public good. Standard public finance theory provides clear guidance, both about how to achieve such reductions in the most efficient way, and how the burden should be shared. Clearly, the brunt of the burden (under virtually any welfare criterion) should lay with the advanced industrial countries. Indeed, these standard ideas suggest that even the approach often taken by developing countries—that there should be equal emissions permits per capita—puts an excessive burden on developing countries.

One of the advantages of an agreed upon common tax rate (with each country keeping its tax revenues) is that it reduces the scope for redistributive deadlock; most countries will, in fact, be better off moving from labor or savings taxes to a carbon tax—and the differences in the welfare costs are likely to be small.

Appendix A

A Simple Model Illustrating the Double Dividend

With the warming up of the debate about global warming, and with attention shifting from the Kyoto approach of agreed up target levels for reduction to agreed upon levels of taxation for emissions (see, e.g. Stiglitz [2006a]), the debate over the "double dividend" has arisen once again. (See, e.g. critique of Stiglitz [2006b]). Several political leaders, on both sides of the political spectrum, have argued that it makes more sense to tax bads, like pollution, than goods, like work and savings. The double dividend argument holds that not only will pollution be reduced, but there is an additional dividend from the reduced burden of taxation from other sources.

The issue has sometimes been incorrectly framed: the claim is not that *measured* GDP would actually increase, but that there is a welfare gain in the reduced burden of taxation. Whether there is this additional benefit, of course, it is still the case that corrective taxation is desirable; it is part of an optimal tax structure. (See Sandmo [ ], Stiglitz [ ].) The discussion over the double dividend is really a debate about the *interpretation* of the welfare benefits associated with positive taxation of, say, carbon.

In this appendix, I construct a simple but general model which demonstrates the existence of *both* the direct benefit from the reduction in pollution and the indirect benefit from the lowering of a distortionary income tax—so long as labor is elastically supplied (so that the wage tax is in fact distortionary.) To highlight the issues, we use a model and notation which is somewhat different from that of the text of the paper.

We assume an aggregate production function of the usual form, where output is a function of labor, L_Q and energy, E:

1) $Q = F(L_Q, E)$

Energy output is a function of labor input, L_E and environmental degradation, z:

2) $E = G(L_E, z)$

Firms maximize profits. If we choose output as the numeraire, w is the (real) wage, and p is the price of energy, this means

3) $F_L = w$
4) $F_E = p$
5) $pG_L = w$

Initially, no charges are imposed for environmental degradation, so

6) $G_z = 0$

The representative individual has a utility function of the form

7) $U(Q, L, z)$

where L is the total labor supply, so in equilibrium

8) $L = L_E + L_Q$

Individuals maximize their utility, and we assume that initially there is a tax on labor at the rate t, so that

9) $U_Q w(1-t) + U_L = 0.$

We can solve the above set of equations for the equilibrium outputs {Q, L, z}, prices {w, p} and labor allocations $\{L_E, L_Q\}$.

We now wish to calculate the effect on utility of a tax on environmental degradation, at the rate of τ. To do this, we substitute into (7) to obtain

$U = U(F(L- L_E, G(L_E, z), L, z)$

$dU/d\tau = U_1\{ -F_L + F_E G_L\} dL_E/d\tau$

$+ \{U_1 F_E G_z + U_z\} dz/d\tau$

$+ \{U_1 F_L + U_L\} dL/d\tau$

$= U_z dz/d\tau$ the direct environmental impact
$+ [U_1 \tau F_L + U_L] dL/d\tau$ the double dividend effect

$= U_z dz/d\tau$
$+ U_1 tF_L dL/d\tau$ by Eq. 9

using equations (1) to (8). The first term, $U_1\{ -F_L + F_E G_L\}$drops out because of the envelope theorem. $G_z = 0$ by (6).

In short, so long as the supply curve of labor is upward sloping[17], there is a benefit to introducing a pollution tax that goes beyond the reduction in pollution itself, from the

[17] Actually, what is required is somewhat more complex: the total derivative of labor with respect to the tax rate is given by

$$dL/d\tau = \underset{+}{(\partial L/\partial w)}\ [\underset{+/-}{(1-t)\ dw/d\tau} - \underset{+}{w\ dt/d\tau}\ ] + \underset{-}{(\partial L/\partial z)}\ (dz/d\tau).$$

reduction in the level of distortionary taxation. This is so even given the maxim about not taxing intermediate goods. But pollution is both an input into an intermediate good and something that is "consumed" as a final good.

The first term is the standard supply elasticity, which we assume is positive. The second and third term reflects general equilibrium effects; the increase in the pollution tax has general equilibrium effects on the level of pollution (it is designed to reduce it) and on wages. Labor supply is obviously sensitive to the level of wages, less so to the level of pollution. Our analysis simply requires that

$$(\partial L/\partial w)\,[(1-t)\, dw/d\tau \; - w\, dt/d\tau\,] + (\partial L/\partial z)\,(dz/d\tau) \geq 0.$$

Ignoring for the moment the effect of the environment (or assuming that an improvement in the environment leads to an increase in labor supply), this means that if the real wage falls, the magnitude of the fall is limited. This might not be the case if the pollution tax leads (as expected) to a reduction in the production of energy, and the reduced input of energy has an enormously negative effect on the marginal product of labor. But if, for instance, the effect of the pollution tax is that more labor is spent on pollution control, and if labor and energy are substitutes in production, then it is impossible for the after tax wage to fall. For if the after tax wage were to fall, both the reduced labor input into production and the reduced energy input would lead to an increase in the marginal product of labor:)

$$dw = \underset{-}{F_{LL}}\, \underset{-}{d(L - L_E)} + \underset{+}{F_{LG}}\, \underset{-}{dG} > 0,$$

contrary to the hypothesis that the wage went down. While it is clear that there may be circumstances in which the double dividend does not appear, these would appear to be unusual. Of course, when the "double dividend" term is negative, it simply means that the optimal tax on pollution is less than it otherwise would have been. The general point is that one does have to pay attention to effects of the reduced tax on labor; it is only that the combination of a tax on pollution and a reduced tax on labor could, perversely, somehow lead to a reduction in the labor supply so that revenue that was previously generated by the income tax is reduced.