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Policy Options

Tradable emission quotas, technical progress and climate change*

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ABSTRACT. The paper reviews two alternative rules for allocation of property rights in a global greenhouse-gas emissions budget, assuming implementation of a tradable-quota arrangement. These are the per capita rule and no-regrets-for-the-South (NRFTS) rule. The operation of a quota market under these alternative regimes is simulated on a spreadsheet, using 1990–1 data from 125 countries. A significant result is that once the South has secured a quota allocation based on the per capita principle, it stands collectively to lose from progress in abatement technology because of the strong link from technical progress to the world market price of quota. The more restricted NRFTS rule gives the South smaller gains from the quota system, but enables it to retain some of the rents from its own technical progress. Some implications for the South's position in future negotiations are noted.

1. Introduction

An appropriate policy response to climate change could be an agreement requiring each country to acquire and hold some portfolio of internationally issued emission quota instruments sufficient to match its ongoing annual flow contributions to atmospheric concentrations of greenhouse gases (GHGs). Economic efficiency requires that such quotas be tradable, in order to allocate a limited global emissions budget to the highest-valued uses, and to allow the secondary market to establish a uniform world shadow price of marginal emissions (Grubb, 1989; Barrett, 1992; Bertram, 1992a; Bohm, 1992; Kosobud *et al.*, 1994; Larsen and Shah, 1994; Stavins, 1995). The market price of quota, in turn, would provide a uniform global incentive for efficient abatement.

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Tradability implies that countries or regions holding surplus quota would be net sellers (exporters) of quota, and hence net recipients of financial transfers from quota-deficit countries. These transfers would constitute both a reward for current restraint on emissions, and an incentive for future restraint including adoption of emission-abating technologies. There is, however, a catch in this incentive mechanism. The financial reward for each country's abatement effort will be related directly to (i) the amount of physical abatement achieved relative to that country's allocated quota, but also (ii) the market valuation of marginal abatement, which sets the price at which surplus quota can be sold to deficit countries. The greater each individual country's abatement effort relative to the rest, the greater its exportable surplus of quota will be. But the greater the world's overall abatement effort, the lower will be the market value of quota.

The rents obtainable from technological progress in emission abatement will therefore tend to be high when the relevant technology is held by only a few countries, but low when it is shared by all. This issue is familiar from growth theory, where it is often used as an argument for patents and other monopoly devices which may slow down the rate of diffusion of new technologies but increase the incentive to develop them (Schumpeter, 1934; Barro and Sala-i-Martin, 1995, ch. 8). In the context of global climate change, raising the cost of acquiring abatement technology is undesirable, yet increasing the reward for technological advance is desirable.

One possible solution would be to target a particular world quota price and make the quantity of global quota endogenous. In a manner analogous to monetary policy, a global quota agreement could be designed not to enforce pre-set quantitative limits on emissions year by year, but rather to vary the total emission budget so as to maintain the market value of quota, and hence the reward to innovation. Technical progress in emission abatement would then lead to a tightening of the global emission budget rather than a falling quota price. The effect would be both to protect low-emission countries' revenues in the face of global technical progress, and to accelerate the pace of global adjustment towards climatic sustainability.

This paper uses comparative-static spreadsheet simulations of a global emissions-quota market to explore the impact of a one-off technological change on the market value of quota, and hence on the balance of payments of quota-exporting countries. For reasons outlined below, in the initial stages of a tradable-quota regime it is expected that the poor countries of the South will be the exporters of quota, and the rich countries of the North will be the importers. The South's terms of trade will then rise and fall with the market price of quota. The effects of technological progress on the South's total revenues from quota exports will then depend on the behaviour of the global budgeting agency, and on the elasticities in the quota market.

The analysis in this paper assumes an exogenously fixed global emissions budget, and simulates only the comparative-static impact of changes in the quota price. Simulating dynamic feedbacks to technology and simulating general-equilibrium effects would be worthwhile exercises, but are not feasible with the simple spreadsheet model used for this paper. Abatement benefits are not explicitly modelled, but are assumed sufficient to persuade world leaders that a tradable-quota regime would be a Pareto improvement.

2. Allocation rules in a world tradable quota market

Three themes which emerge from the literature on tradable quota schemes are:

- the initial allocation of scarce quota is of fundamental importance in determining the effect of quota trading on the world distribution of income and wealth (Barrett, 1992; Bertram, 1992b);
- the time-path followed by the quota price depends heavily on the nature of the property right created and the constraints imposed, as well as on the dynamics of technical change (Kosobud *et al.*, 1994);
- transaction costs are the main potential source of distortions in a national quota-trading regime (Sandler and Sargent, 1995; Stavins, 1995), although such costs should be less of a burden in a thick, highly competitive global quota market.

Figure 1 shows the operation of such a market with transaction costs assumed away (cf. Bohm, 1992, fig. 2). The length of the horizontal axis between O^N and O^S represents the global emission budget, and two simple linear marginal-abatement-cost schedules are drawn, for the 'North' and 'South' respectively. The North's marginal abatement cost (MAC_N) is

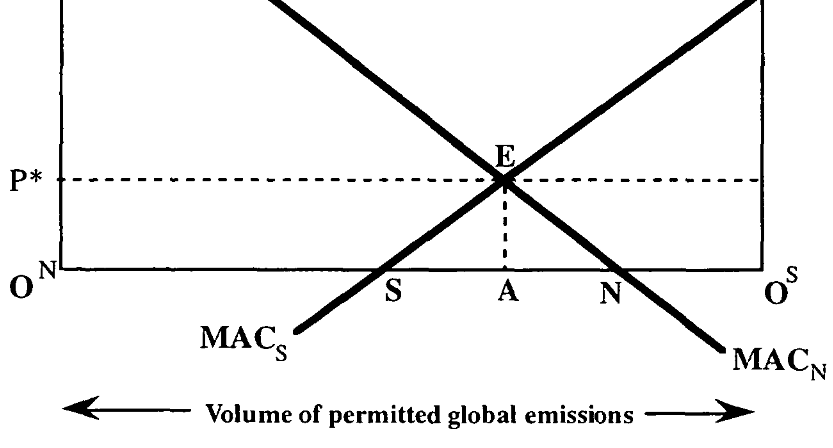

Figure 1. *Optimal abatement to meet a global emissions limit.*

drawn sloping up to the left from origin N, and shows that lower volumes of emissions from the North are associated with higher marginal costs of abatement in the North. 'Business as usual' emissions (zero abatement) would locate the North at N with emissions $O^N N$. Similarly, in the absence of abatement the South's emissions are $O^S S$.

Total business-as-usual emissions ($O^N N + O^S S$) would violate the global emission limit $O^N O^S$. Economic instruments (a carbon tax or a tradable quota system) work by pushing both parties back up their MAC curves until the global constraint is met at least cost. This brings them to point E in Figure 1 with a shadow price on emissions of P^*, which is made explicit to individual economic agents as a corresponding carbon tax or quota price.

Faced with this world shadow price of emissions, economic agents have an incentive to optimize their activities so as to eliminate all carbon emissions which are worth less to them than the quota price. This means implementation of cost-effective abatement programmes sufficient to enable the world economy to meet its targets for emissions and/or atmospheric concentrations of GHGs at least overall cost. At the same time, research and development effort would be directed towards the invention and development of sustainable energy-supply technologies which are economic at the abatement-cost threshold.

Because the world economy starts out with very unequally distributed purchasing power, it is important to ensure that the initial allocation of quotas does not lead to abatement behaviour being dictated by financial rather than technical constraints, and also to organize the allocation of quota on a basis which can secure the agreement of all countries to participate. In practice, this means that quotas would be allocated disproportionately to poorer countries with relatively low per capita emissions, so that the onus to buy-in emission rights would lie with rich countries which possess the means to pay. There is general agreement in the literature that simply 'grandfathering' emission quotas on the basis of current emissions, or on the basis of present GDP, could not provide the basis of a workable international agreement, because it would impose heavy costs on non-OECD countries, while enabling OECD countries to capture rents from the shortage of atmospheric carbon storage capacity for which they themselves have been responsible through high past emissions (Barrett, 1992; Bertram, 1992b; Edmonds *et al.*, 1993; Larsen and Shah, 1994; Hourcade *et al.*, 1996).

As Barrett (1992: 86) has observed,

> Since accession to a treaty is voluntary, and since the rich countries have a particular interest in having the poor participate in a treaty, the rich have an incentive to offer the poor countries a treaty proposal that makes them better off.

Two particular quota-allocation principles have emerged which could be the basis for a sustainable agreement. The first, based on a simple and universally intelligible ethical principle, is the per capita approach, which allocates quotas at the outset in proportion to the population of each country (Bertram, 1992b). The principle is that the global atmosphere is a common, in which all individual members of the world community have equal stakes. The usual argument against per capita allocation has been pragmatic: that the resulting financial transfers from North to South would be greater than the North's willingness to pay, and above the South's reserve price for cooperating.

The second option is to 'grandfather' quotas to the countries of the South to cover their business-as-usual emissions, with the North receiving the residual quota. The South is then no worse off with the agreement than without it, while the North (which values the abatement to be achieved through the quota system) has the option of undertaking its own abatement programmes to meet the constraint, or buying-in quota from the South and thereby creating financial transfers from North to South (Edmonds *et al.*, 1993; Larsen and Shah, 1994).

Figure 2 shows the two cases. With the global emission budget fixed as the length of the horizontal axis, the per capita rule would allocate the North O^NB of quota, while the South would receive O^SB. The North would then abate to point E and buy-in BA of quota from the South, in the process paying the South the sum BDEA.

Under the NRFTS rule, the South would be allocated O^SS of quotas and the North would receive the remainder, O^NS. Quota trading would then transfer AS of the global quota to the North, for a payment of SFEA < BDEA.

If we assume that the South has no willingness to pay for global abate-

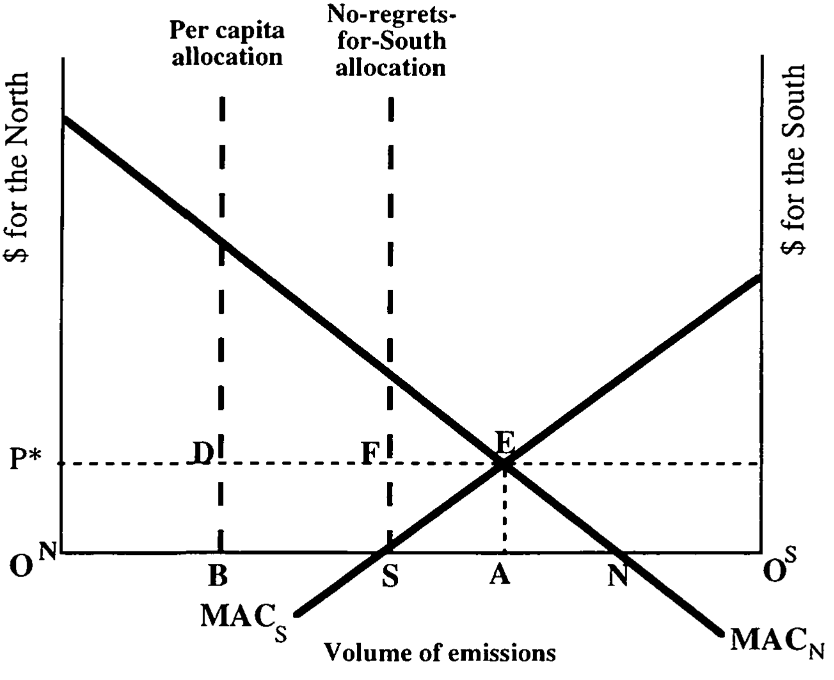

Figure 2. *Two possible quota allocation rules.*

ment, so that the NRFTS rule is the minimum requirement for agreement to be reached,[1] then the quest for economic efficiency alone would point to this allocation rule. A per capita rule would apply if egalitarian ethical considerations were predominant.

With given technology, the abatement incentives to the two regional parties are theoretically the same under either allocation, but the per capita rule obviously increases the total volume of rents which the South (as a whole) secures from its low-emissions status, and might thereby be expected to accelerate technical progress in the South. The per capita rule also has the operational advantage that the objective criterion used (population) can be readily and unambiguously measured, and is (to a first approximation) invariant to abatement effort, whereas actual emissions are hard to measure with precision,[2] and become endogenous once abatement gets underway.

3. Simulating a quota market: a simple model

The linear MAC curves in Figure 2 are attractive from a modelling point of view, although intuition suggests that their real-world counterparts are likely to be non-linear. This section constructs a simple simulation model in which the MAC curve for each individual country is linear, but in which aggregation across countries in the 'North' and 'South' of the world economy yields non-linear MAC curves for the two regional blocs, or for any other regional groupings that might be considered.

For each country we assume a quadratic proportional loss function showing the percentage sacrifice of GDP required to achieve any required percentage reduction of emissions:[3]

$$c_i = c_{0i} + \beta_i a^2_i \qquad 0 < a_i < 1 \tag{1}$$

where c_i is the proportional loss of GDP incurred by country *i* as the cost of abatement, a_i is the proportional reduction in country *i*'s 'business-as-usual' emissions E_i^B due to abatement effort A_i measured in tonnes of reduced carbon emissions, so that $a_i = A_i/E_i^B$, and c_0 is a constant.

Multiplying through Equation (1) by real GDP, Y_i, gives each country's total cost of abatement,

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[1] Obviously, if the South considers global abatement to be beneficial (i.e. in its own interest), then a less generous allocation rule could be acceptable. Estimating the benefits from global abatement, however, is an exercise fraught with difficulty, despite the substantial literature following the pioneering work of Nordhaus, because of fundamental disagreements over the valuation of damage from global warming. By focusing purely on abatement costs, the present paper avoids any need to estimate a damage function.

[2] Problems are well known. Are land-use changes to be included? Are other GHGs such as methane included? Are emissions measured on a net or a gross basis? What conversion factors are used to bring GHGs to a common unit of measurement?

[3] This corresponds to the form in which the results from compatible general equilibrium (CGE) modelling exercises are usually reported: the percentage change in the level of GDP associated with achievement of a target percentage reduction of emissions relative to their business-as-usual path. Cf. Grubb *et al.* (1993).

$$TC_i^A = (c_{0i} + \beta_i \frac{A_i^2}{E_i^{B2}})Y_i,$$

and differentiating with respect to A_i gives the marginal cost of abatement over the range $0 \leq A_i \leq E_i^B$:

$$MC_i^A = \frac{TC_i^A}{A_i} = \frac{2\beta_i Y_i}{E_i^{B2}} A_i = \frac{2\beta_i}{e_i E_i^B} A_i \tag{2}$$

where $e_i = E_i^B / Y_i$ is the country's business-as-usual emission intensity of GDP.

In a world market for abatement, each country supplies the amount of abatement that is profitable to its producers at the world price of quotas in \$ per tonne of emission quota, P^*, so that

$$MC_i^A = P^*. \tag{3}$$

Substituting Equation (3) into Equation (2) and rearranging gives the abatement supply curve for each country:

$$A_i = \frac{e_i E_i^B}{2\beta_i} P^*. \tag{4}$$

Summing across countries gives the world abatement supply curve:

$$A_W = P^* \sum_{i=1}^{n} \frac{e_i E_i^B}{2\beta_i} . \tag{5}$$

To fit numbers into this equation, and hence estimate orders of magnitude for emission trading and the resulting financial flows, we use the World Resources Institute's (1994) recently published 1991 emission data for 125 countries, together with Penn World Tables estimates of purchasing-power-parity per capita real GDP and population for the same countries at about 1990. For each country in the data set we then have the value of e_i and E_i^B at about 1991, so by inserting values of β_i for each country we can model the quota price for any required level of world abatement with 1991 technology. Technical change is simulated as a one-off rightward shift of the abatement supply curve, so that

$$A_i = \frac{e_i E_i^B}{2\beta_i} P^* + \lambda E_i^B \tag{4a}$$

where λ is the proportion of business-as-usual emissions abated at zero cost due to technical progress.

The lack of detailed abatement cost data is the main constraint on simulating the model. Only for the main GHG, carbon dioxide, is there a reasonable international abatement-cost database. The remainder of the analysis in this paper will therefore be limited to CO_2 emissions originating in the burning of fossil fuels and manufacture of cement. Even for this subset of GHGs, there are few estimates of β_i available for individual countries. However, loss functions for CO_2 emissions from fossil fuels and cement manufacture are assembled in Grubb *et al.* (1993) and Hourcade *et al.* (1996), and seem consistent with preliminary estimates of $\beta = 0.062$ for the USA and $\beta = 0.25$ for OECD countries other than the USA, taken as a whole. These numbers are intuitively consistent with the observation that the non-US OECD countries have had higher energy prices in the past, and hence now have less scope for further reductions in their emission intensities, than the USA. Canada is provisionally classed with the USA. The rest of the world has been assumed to be closer to the USA than to the rest of the OECD in terms of feasible reductions in emission intensity, and an assumed figure of $\beta = 0.1$ has been used for the simulations below. Fortunately, sensitivity tests (see section 8 below) show the simulation results to be robust across the likely range of values of β.

With these rough guesses for β_i and using the actual 1990–1 data for population, real GDP, and GHG emissions, it is possible to simulate the operation of a quota market by solving Equation (5) for P^* at different levels of required global abatement A_w. Figure 3 shows the simulated MAC curves for the North (defined here as OECD, Eastern Europe and the former USSR), the South (rest of the world) and the world as a whole. Once a global emission quota is set, the corresponding quota price can be obtained from the world MAC curve, and the allocation of abatement effort between North and South (and across individual countries) is then given by the detailed MAC schedules.

Specification of a rule for the initial allocation of emission rights for the period considered then enables each country's purchases or sales of quota, and the resulting financial flows, to be calculated. All of these computations are readily performed on a spreadsheet. Table 1 shows a sample calculation of the outcomes that would result from a tradable quota system applied to the world of 1991 but with a global quota for fossil-fuel CO_2 set 20% below the actual level of emissions. Quota is assumed to be allocated using the NRFTS rule.

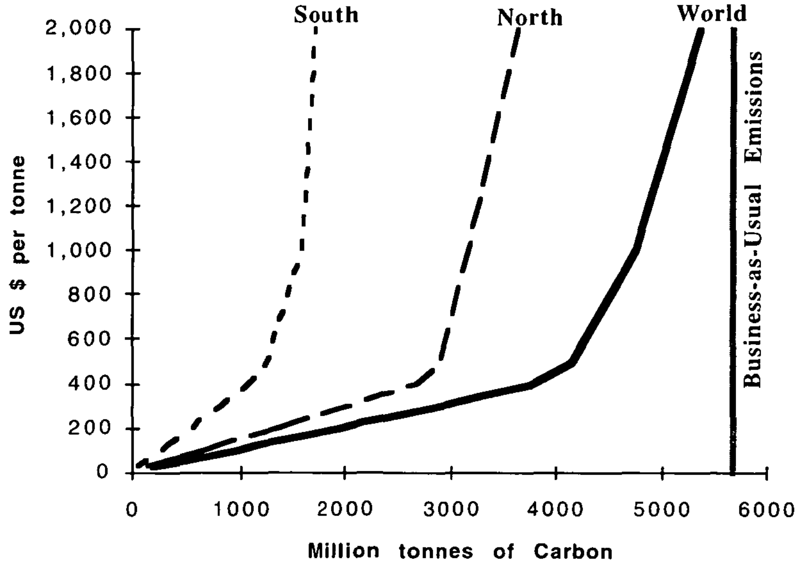

Figure 3. *Simulated 1991 abatement supply curves.*

Table 1. *Fossil-fuel CO_2 emissions and hypothetical trading data: 1990–1 baseline with 20% abatement imposed. Quota price = \$117.35 per tonne of carbon; $\lambda = 0$*

Country	*Actual 1991 emissions (million tC)*	*Hypothetical quota allocation (million tC)*	*Emissions with price-induced abatement (million tC)*	*Quota sales (million tC)*	*Quota sale revenue (\$m)*	*Sale revenue minus abatement cost (\$m)*
Algeria	15.08	15.08	13.17	1.91	224.16	112.08
Angola	1.31	1.31	1.16	0.15	17.53	8.77
Benin	0.15	0.15	0.15	0.00	0.35	0.17
Botswana	0.59	0.59	0.51	0.07	8.78	4.39
Burkina Faso	0.15	0.15	0.15	0.00	0.33	0.16
Burundi	0.06	0.06	0.06	0.00	0.08	0.04
Cameroon	0.53	0.53	0.51	0.01	1.44	0.72
Central African Republic	0.06	0.06	0.06	0.00	0.13	0.07
Chad	0.07	0.07	0.07	0.00	0.13	0.07
Congo	0.55	0.55	0.55	0.00	0.54	0.27
Côte d'Ivoire	1.74	1.74	1.62	0.12	14.61	7.31
Djibouti	0.10	0.10	0.09	0.01	1.49	0.74
Egypt	22.31	22.31	19.46	2.85	334.30	167.15
Ethiopia	0.77	0.77	0.75	0.03	2.93	1.47
Gabon	1.64	1.64	1.27	0.36	42.68	21.34
Gambia, The	0.05	0.05	0.05	0.00	0.29	0.14
Ghana	0.94	0.94	0.91	0.04	4.37	2.19
Guinea	0.28	0.28	0.27	0.01	1.21	0.60
Guinea-Bissau	0.06	0.06	0.05	0.00	0.36	0.18
Kenya	1.32	1.32	1.28	0.05	5.35	2.68
Liberia	0.08	0.08	0.07	0.00	0.22	0.11
Madagascar	0.29	0.29	0.29	0.01	0.77	0.39
Malawi	0.17	0.17	0.17	0.00	0.42	0.21
Mali	0.12	0.12	0.12	0.00	0.23	0.11
Mauritania	0.74	0.74	0.54	0.20	23.14	11.57
Mauritius	0.33	0.33	0.32	0.01	1.17	0.59
Morocco	6.61	6.61	6.17	0.45	52.32	26.16
Mozambique	0.28	0.28	0.28	0.00	0.46	0.23
Niger	0.28	0.28	0.27	0.01	1.45	0.73
Nigeria	25.12	25.12	21.52	3.60	421.95	210.97
Rwanda	0.12	0.12	0.12	0.00	0.18	0.09
Senegal	0.76	0.76	0.72	0.04	4.72	2.36
Sierra Leone	0.19	0.19	0.18	0.01	0.62	0.31
Somalia	0.14	0.14	0.14	0.00	0.24	0.12
South Africa	76.15	76.15	48.67	27.48	3,224.57	1,612.28
Sudan	0.93	0.93	0.90	0.03	3.13	1.57
Swaziland	0.09	0.09	0.09	0.00	0.29	0.14
Tanzania	0.59	0.59	0.57	0.02	1.95	0.97
Togo	0.20	0.20	0.19	0.01	1.16	0.58
Tunisia	4.05	4.05	3.65	0.40	46.66	23.33
Uganda	0.25	0.25	0.25	0.00	0.45	0.22
Zaire	1.16	1.16	1.11	0.05	6.01	3.01
Zambia	0.66	0.66	0.62	0.04	5.21	2.61
Zimbabwe	4.64	4.64	3.64	1.00	117.85	58.93
Africa total	**171.71**	**171.71**	**132.72**	**39.00**	**4,576.25**	**2,288.12**

Country	*Actual 1991 emissions (million tC)*	*Hypothetical quota allocation (million tC)*	*Emissions with price-induced abatement (million tC)*	*Quota sales (million tC)*	*Quota sale revenue ($m)*	*Sale revenue minus abatement cost ($m)*
Belize	0.07	0.07	0.07	0.00	0.48	0.24
Costa Rica	0.89	0.89	0.84	0.04	5.14	2.57
Dominican Republic	1.71	1.71	1.60	0.11	13.27	6.63
El Salvador	0.69	0.69	0.66	0.03	3.37	1.68
Guatemala	1.11	1.11	1.08	0.04	4.19	2.09
Haiti	0.20	0.20	0.20	0.00	0.52	0.26
Honduras	0.53	0.53	0.51	0.02	2.71	1.36
Jamaica	1.28	1.28	1.11	0.16	19.35	9.68
Nicaragua	0.57	0.57	0.53	0.04	4.65	2.32
Mexico	92.86	92.86	82.77	10.09	1,184.25	592.13
Panama	0.98	0.98	0.91	0.07	8.68	4.34
Trinidad and Tobago	5.04	5.04	3.59	1.44	169.07	84.53
Non-OECD N & C America total	**105.93**	**105.93**	**93.87**	**12.06**	**1,415.68**	**707.84**
Canada	112.19	63.50	85.54	−22.04	−2,586.25	−4,150.32
United States	1,347.44	587.72	960.97	−373.25	−43,799.46	−66,474.58
OECD N America total	**1,459.63**	**651.22**	**1,046.51**	**−395.25**	**−46,385.71**	**−70,624.90**
Argentina	31.65	31.65	27.79	3.86	453.49	226.74
Bolivia	1.60	1.60	1.48	0.12	14.14	7.07
Brazil	58.91	58.91	55.55	3.36	393.75	196.87
Chile	8.89	8.89	8.58	0.31	36.43	18.21
Colombia	15.71	15.71	12.43	3.28	385.08	192.54
Ecuador	4.86	4.86	4.41	0.45	53.19	26.59
Guyana	0.23	0.23	0.20	0.04	4.25	2.13
Paraguay	0.49	0.49	0.47	0.01	1.73	0.86
Peru	5.23	5.23	4.90	0.34	39.60	19.80
Suriname	0.55	0.55	0.39	0.17	19.45	9.72
Uruguay	1.22	1.22	1.16	0.06	6.89	3.45
Venezuela	33.23	33.23	28.28	4.94	580.14	290.07
S America total	**162.56**	**162.56**	**145.62**	**16.94**	**1,988.13**	**994.06**
Bangladesh	4.22	4.22	4.16	0.06	7.52	3.76
Bhutan	0.03	0.03	0.03	0.00	0.10	0.05
China	694.91	694.91	516.05	178.87	20,989.16	10,494.58
India	192.23	192.23	172.23	20.00	2,346.95	1,173.48
Indonesia	46.58	46.58	43.14	3.43	403.03	201.51
Japan	298.13	288.22	286.86	1.37	160.32	−500.91
Korea, Republic of	72.31	72.31	62.53	9.78	1,147.38	573.69
Lao People's Democratic Republic	0.07	0.07	0.07	0.00	0.06	0.03

Country	*Actual 1991 emissions (million tC)*	*Hypothetical quota allocation (million tC)*	*Emissions with price-induced abatement (million tC)*	*Quota sales (million tC)*	*Quota sale revenue ($m)*	*Sale revenue minus abatement cost ($m)*
Malaysia	16.72	16.72	15.11	1.61	188.54	94.27
Mongolia	2.68	2.68	1.64	1.05	122.94	61.47
Myanmar	1.36	1.36	1.31	0.04	5.07	2.54
Nepal	0.25	0.25	0.25	0.00	0.27	0.13
Pakistan	18.71	18.71	17.44	1.27	149.29	74.64
Philippines	12.18	12.18	11.37	0.82	95.66	47.83
Singapore	11.28	11.28	9.07	2.21	259.48	129.74
Sri Lanka	1.14	1.14	1.12	0.02	2.37	1.19
Thailand	27.57	27.57	25.49	2.08	243.75	121.87
S & E Asia total	**1,400.37**	**1,390.46**	**1,167.86**	**222.61**	**26,121.89**	**12,479.87**
Iran, Islamic Rep	60.75	60.75	50.20	10.56	1,239.03	619.52
Israel	9.72	9.72	8.54	1.18	138.02	69.01
Jordan	2.73	2.73	2.28	0.46	53.82	26.91
Kuwait	3.24	3.24	2.93	0.31	36.16	18.08
Oman	3.20	3.20	2.66	0.54	63.18	31.59
Saudi Arabia	58.72	58.72	38.36	20.36	2,388.74	1,194.37
Syrian Arab Republic	8.13	8.13	7.36	0.78	91.00	45.50
Turkey	38.95	38.95	34.71	4.24	497.00	248.50
Yemen	2.72	2.72	2.52	0.20	23.55	11.78
Middle East total	**188.16**	**188.16**	**149.55**	**38.61**	**4,530.51**	**2,265.25**
Austria	16.48	18.20	15.85	2.35	275.26	238.04
Belgium	27.89	23.26	26.53	–3.27	–383.49	–463.37
Bulgaria	15.48	20.87	12.50	8.37	982.56	807.51
Czechoslovakia	52.28	36.43	27.28	9.15	1,073.88	–393.34
Denmark	17.23	11.99	16.26	–4.28	–501.77	–558.35
Finland	14.22	11.70	13.48	–1.78	–208.69	–252.42
France	102.22	132.69	99.12	33.57	3,939.37	3,757.55
Germany	264.93	173.41	248.98	–75.58	–8,868.54	–9,804.06
Greece	19.91	24.03	18.58	5.45	638.95	561.06
Hungary	17.37	24.06	13.91	10.15	1,190.85	987.88
Iceland	0.49	0.60	0.48	0.12	14.56	13.58
Ireland	8.81	8.19	8.26	–0.07	–7.71	–40.00
Italy	109.98	134.35	106.08	28.27	3,317.81	3,089.01
Netherlands	37.98	35.04	36.27	–1.23	–144.77	–244.66
Norway	16.03	9.91	15.09	–5.18	–607.53	–662.71
Poland	84.20	88.95	54.90	34.05	3,996.10	2,277.04
Portugal	11.42	22.95	11.00	11.95	1,402.01	1,377.68
Romania	37.71	53.85	20.07	33.78	3,963.70	2,928.61
Spain	60.08	90.77	57.85	32.91	3,862.20	3,731.84
Sweden	14.62	20.08	14.21	5.87	688.96	665.24
Switzerland	11.43	15.79	11.15	4.64	544.54	528.23
United Kingdom	157.69	133.89	149.78	–15.90	–1,865.48	–2,329.55
Yugoslavia	23.83	55.38	20.75	34.62	4,062.74	3,882.18
Europe total	**1,122.27**	**1,146.38**	**998.39**	**147.99**	**17,365.50**	**10,097.00**
USSR	**978.46**	**668.99**	**726.18**	**–57.19**	**–6,710.74**	**–21,513.07**

Country	*Actual 1991 emissions (million tC)*	*Hypothetical quota allocation (million tC)*	*Emissions with price-induced abatement (million tC)*	*Quota sales (million tC)*	*Quota sale revenue ($m)*	*Sale revenue minus abatement cost ($m)*
Australia	71.53	40.22	66.66	–26.44	–3,103.11	–3,388.95
Fiji	0.19	0.19	0.18	0.01	0.83	0.42
New Zealand	6.51	7.92	6.25	1.67	196.23	180.71
Papua New Guinea	0.62	0.62	0.58	0.04	4.34	2.17
Solomon Islands	0.04	0.04	0.04	0.00	0.21	0.11
Oceania total	**78.90**	**48.99**	**73.72**	**–24.73**	**–2,901.50**	**–3,205.55**
South	1,731.45	1,731.45	1,403.56	327.90	38,478	19,239
North	3,936.55	2,802.95	3,130.85	–327.90	–38,478	–85,750
World total	5,668.00	4,534.40	4,534.40	0.00	0	–66,511

4. Dynamic issues and technical change

It is important not to confuse the simulations reported in this paper with the results from full-scale global CGE models of the sort used by Dean and Hoeller (1992) and Edmonds *et al.* (1993). Forward-looking simulations with the present model would require the 1991 MAC curves to be shifted by economic growth and technical change over time, which has not been attempted here. The simulations reported in this paper are performed on a world economy 'frozen' at 1991 GDP and emissions.

Bringing in dynamic elements, obviously, will be an essential step in designing actual economic instruments. Two dynamic issues which stand out are the optimal time-path for global abatement, and the rate of technical progress.

The abatement time-path sets the size of the global budget for each period (that is, the distance O^NO^S in Figure 1). In the long run, the aim of abatement policy is to stabilize not annual emission flows but the stock of GHGs in the global atmosphere. As several authors have pointed out, this means that, in principle, abatement effort can be distributed over time in such a way as to minimize the long-run cost. Kosobud *et al.* (1994) have shown that for the world economy as a whole, a time-path with initially low abatement effort but with a rising shadow price over time, leading to progressively increased abatement effort, could be expected to generate better outcomes than a 'big bang' focus on early abatement at high cost.

Pindyck and Dixit (1994) have argued that abatement costs will fall as technology progresses, and this may be one reason for deferring abatement effort.[4]

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[4] Pindyck and Dixit's argument for deferring investment, however, is flawed by their failure to recognize that uncertainty about future damage from emissions is just as serious as uncertainty over future abatement costs. Deferring investment involves purchasing not just an option to abate later at possibly lower cost, but also an offsetting option to suffer greater-than-expected future damage. Weighing the overall value of the two options could well lead to a case for bringing abatement investment forward rather than deferring it, especially if damages follow (say) a Poisson process rather than the Brownian process assumed by Pindyck and Dixit.

This argument relies on their implicit assumption that technical change is exogenous, so that 'waiting' is the only way to gain access to low-cost abatement technologies. Under this assumption, the effect of economic incentives to abate is limited to moving the world economy up a global abatement cost curve which is given for each period, independently of the quota price. The issue of the optimal path of a carbon tax is discussed also by Sinclair (1994) and Ulph and Ulph (1994).

If in fact technological breakthroughs are stimulated by a high quota price or by the credible expectation of a high price, then a complex and unpredictable interaction between the quota price and the rate of technical progress would occur, with the quota price rising in periods when technical progress slows, but falling when induced technical progress occurs, for a given time-path of the global emission quota. The present paper does not pursue this line of enquiry. The next section explores only a single aspect of technical progress: the within-period comparative static effect of technical progress on the distribution of quota rents across countries.

5. Technical progress and the distribution of rents

It was shown above that a tradable quota system would be likely to generate large financial transfers from North to South, which would be in accordance with the polluter-pays principle. However, by making the South a net supplier of emission rights, such a system would link the South's income from quota rents directly to the level of global emissions, which could make the South a net loser from its own progress in abatement technology.

Consider, for example, Figure 4 in which a technological breakthrough is assumed to shift the South's MAC curve downwards to MAC'_s, under an NRFTS quota allocation rule based on the original MAC_s curve. Technical progress in the North is assumed zero to simplify the analysis.[5]

With the global quota allocation fixed at O^NO^S, the quota price falls to P′, with the South now selling SF of quotas for revenue of IGFS, while lowering its abatement expenditure by the difference between the triangle AES (the South's abatement expenditure before the technical change) and the triangle FGH (the South's abatement expenditure after the change).

It can be seen that the downward shift of the South's MAC curve has three effects which are relevant to the region's gains and losses from technical progress for a given global emissions budget:

- abatement cost in the South has fallen, which frees up resources for other uses;
- the volume of quota sold by the South to the North has increased;
- the world price of quota has fallen.

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[5] This assumption does not affect the validity of the results. The reader is invited to check from inspection of Figure 4 that as a permit exporter in a world with a given emissions budget, the South must be a net loser either from technical progress in the North alone or from technical progress spread equally across the world economy. The case on which our simulations focus is that in which the South is the leader in technical progress, so that MAC_s shifts down more rapidly than MAC_n. The simplest way to model this is to hold the North's MAC unchanged while shifting the South's MAC.

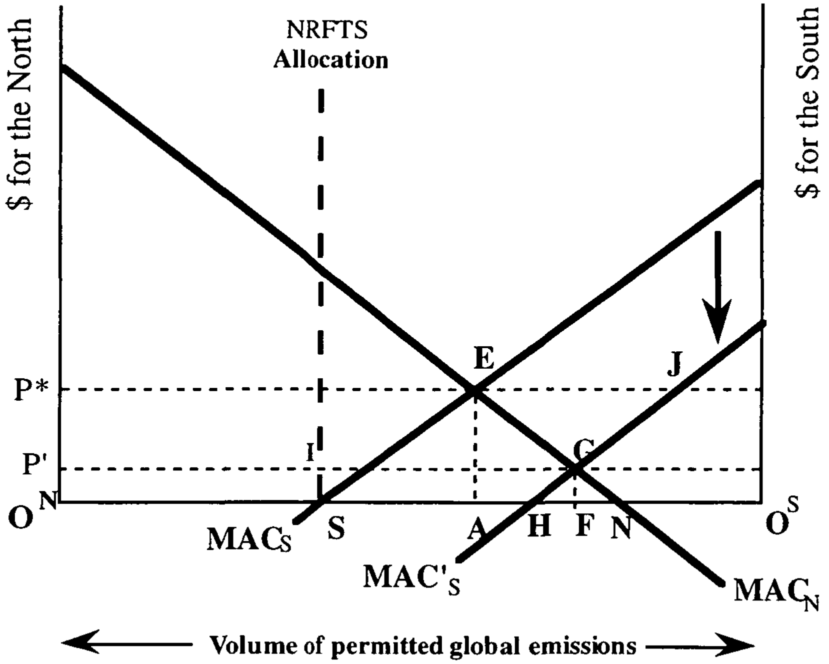

Figure 4. *Technical progress in the South.*

The first two effects represent gains for the South, while the third represents a loss. The outcome depends on the slopes of the MAC curves combined with the rule used to allocate quota. If the North's MAC curve is sufficiently steep over the relevant range, then the fall in the quota price will mean a fall in revenue for the South, and if this is sufficient to outweigh the reduction in the South's abatement costs then the South will lose overall from its own technical progress.

Inspection of Figure 4 and comparison with Figure 2 shows that the more favourable to the South the initial quota allocation, the less is the probability that the South will benefit collectively from its own technical progress. This is because of the larger revenue loss caused by a given price reduction across a larger volume of quota sold. Write $E_N^* = E_N^*(P^*)$ for the equilibrium quantity of emissions in the North, determined by the intersection of MAC_N and MAC_S, and write Q_N^r for the North's quota allocation under rule r. Then the North's demand for quota sold by the South will be

$$Q_N^d = E_N^* (P^*) - Q_N^r \tag{5}$$

and the North's elasticity of demand for quota will be

$$\epsilon_N^d = \frac{dQ_N^d}{dP^*}\,\frac{P^*}{E_N^* - Q_N^r} = \frac{dE_N^* P^*}{dP^* E_N^* - dP^* Q_N^r} \tag{6}$$

which states that the elasticity of demand for the South's quota exports varies positively with the size of the quota allocated to the North. In other words, the more generous to the South is the initial allocation rule, the lower will be the elasticity of world demand for its excess quota, and vice versa. This has obvious implications for the choice of a rule for allocating quota. The per capita rule, which is very favourable to the South in terms of initial quota allocation, is more likely to deprive the South of any subsequent benefit from technical progress than is the case with the NRFTS rule. In fact, the simulations below give the result that if the NRFTS rule is used (as in Figure 4) the South secures a net gain from its own technical progress, whereas under the per capita rule the South loses from technical progress unless the global abatement target is set extremely tightly (over a 30% reduction from 1991 emission levels).

6. Simulating the effects of technical progress in the South

The simulation model developed in section 3 of this paper can be used to provide some indicative orders of magnitude for the distribution of benefits from technical progress in the South. This section presents results from such an exercise.

Table 1 above simulated a quota trading regime based on 1991 technology and baseline emissions, with 20% global abatement imposed as the quota constraint and with quota allocated by the NRFTS rule. Table 2 shows the results of the same experiment with one-off technical progress in the South along the lines of Figure 4, and also shows what the results would be under a per capita rule for allocation of quota.[6]

The simulations reported in Table 2 model technical progress by assuming that 10% of South emissions are abated at zero cost while no matching progress occurs in the North. The downward shift of the South's MAC curve reduces the world price of quota to $99.42 per tonne of carbon from the $117.35 per tonne of Table 1, while reducing the abatement effort required in the North to achieve the global abatement target of 20%. In the Table 1 experiment without technical change, the South sold 328 million tonnes of quota at $117.35/tonne. for total revenue of $38.5 billion. In the Table 2 experiment with technical change under the NRFTS rule, the South sells 451 million tonnes of quota at $99.41 for revenue of $44.8 billion. The implied demand elasticity for Southern quota is 2.45, and North and South share the rents from the South's technical progress.

Contrasting results are found in the second part of Table 2, which conducts the same experiment for a world which has allocated quotas under the per capita rule. Again 10% technical progress in the South lowers the world price of quota to $99.42, but this time the South loses heavily from the price change because of its higher pre-existing revenues from quota sales. The fall in price raises the South's quota exports from 2,066 million tonnes to 2,189 million tonnes (the same 123 million tonne absolute increase as under NRFTS, but a much lower percentage gain), but reduces revenue from $242.4 billion to $217.6 billion. The implied demand elasticity in this case is only 0.4.

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[6] Individual country results are not given in Table 2, to save space. The full table, and similar tables for alternative assumptions, are available from the author.

Table 2. *Distribution of gains from 10% technical progress in abatement in the South*

Region	*Abatement costs without technical change ($m)*	*Abatement costs with technical change ($m)*	*Impact of technical change on abatement costs ($m)*	*Quota sale revenue without technical change ($m)*	*Quota sale revenue with technical change ($m)*	*Impact of technical change on quota sale revenues ($m)*	*Net gain (+) or loss (−) due to technical change ($m)*
			NRFTS quota allocation rule				
Africa	2,288.1	1,642.5	−645.59	4,576.2	4,992.3	416.0	1,061.6
C. America	707.8	508.1	−199.72	1,415.7	2,069.4	653.7	853.5
US–Canada	24,239.2	5,921.6	−18,317.62	−46,385.7	−45,574.4	811.3	19,129.0
S. America	994.1	713.6	−280.47	1,988.1	3,043.4	1,055.3	1,335.8
Asia	13,642.0	11,456.1	−2,185.93	26,121.9	29,559.9	3,438.0	5,624.0
Middle East	2,265.3	1,626.1	−639.14	4,530.5	5,122.9	592.4	1,231.6
Europe	7,268.5	6,318.8	−949.75	17,365.5	12,831.9	−4,533.6	−3,583.9
USSR	14,802.3	3,124.3	−11,678.02	−6,710.7	−9,516.9	−2,806.1	8,871.9
Oceania	304.1	152.7	−151.36	−2,901.5	−2,528.6	372.9	524.3
South	**19,239**	**13,811**	**−5,428**	**38,478**	**44,836**	**6,358**	**11,786**
North	**47,273**	**17,653**	**−29,619**	**−38,478**	**−44,836**	**−6,358**	**23,261**
World	**66,511**	**31,464**	**−35,048**	**0**	**0**	**0**	**35,048**
			Per capita quota allocation rule				
Africa	2,288.1	1,642.5	−645.59	50,321.4	43,750.4	−6,571.1	−5,925.5
C. America	707.8	508.1	−199.72	2,457.2	2,951.8	494.7	694.4
US–Canada	24,239.2	5,921.6	−18,317.62	−93,761.3	−85,713.8	8,047.4	26,365.1
S. America	994.1	713.6	−280.47	13,938.7	13,168.6	−770.0	−489.5
Asia	13,642.0	11,456.1	−2,185.93	154,911.6	138,678.4	−16,233.2	−14,047.3
Middle East	2,265.3	1,626.1	−639.14	−470.0	886.2	1,356.2	1,995.3
Europe	7,268.5	6,318.8	−949.75	−66,032.9	−57,828.3	8,204.6	9,154.3
USSR	14,802.3	3,124.3	−11,678.02	−55,379.4	−50,751.9	4,627.51	6,305.5
Oceania	304.1	152.7	−151.36	−5,985.2	−5,141.3	843.9	995.3
South	**19,239**	**13,811**	**−5,428**	**242,390**	**217,603**	**−24,787**	**−19,359**
North	**47,273**	**17,653**	**−29,619**	**−242,390**	**−217,603**	**24,787**	**54,407**
World	**66,511**	**31,464**	**−35,048**	**0**	**0**	**0**	**35,048**

Under the per capita rule, therefore, Southern governments would have no general collective incentive to promote technical progress. On the contrary, their collective incentive would be to obstruct such progress in their own region, although individual South countries could still benefit from their own technical progress to the extent that they acted alone as price-takers. Under the NRFTS rule, in contrast, the South's collective incentives are aligned with the incentives of individual countries and with the world interest in advancing abatement technology.

Even if we abstract from possible collective strategic behaviour by South governments, the general point would remain that with an exogenously set global budget allocated by the per capita rule with a consequent large redistribution of global permanent income towards the South, inhabitants of the South would lose from technical progress wherever in the world it takes place. This conclusion must of course be viewed in context. First, we have assumed zero abatement benefit to the South; relaxing this assumption could enable us to appeal to such benefits as compensation for the South's collective net loss on quota revenues plus abatement cost savings. Abatement benefits, however, are ill-defined and very long-run in nature, while the losses identified in Table 2 are tangible and immediate.

Second, the choice of counterfactual is important. As the next section will show, the total net benefit to the South from joining a tradable quota regime, measured against the benchmark of business as usual (policy-off), shows higher gains from the per capita rule than from the NRFTS rule over a wide range of scenarios (though not all). It could therefore be rational for the South to negotiate collectively for such an allocation rule. At the margin, however, where the relevant benchmark for measuring the effect of technical progress is the tradable quota regime without technical progress, the marginal benefits to the South from technical progress are negative over a wide range of scenarios (again, not all).

An implication for policy design which could follow from Table 2 is that the more generous to the South the quota allocation rule is, the stronger the South's collective incentive to support arrangements which maintain the market price of quota in the face of technical progress, thus enabling rents from technical progress to be captured where the technical progress itself is achieved.

7. Some explorations with the model

This section presents simulation outcomes for the South over a range of scenarios. Table 3 gives model results under the two quota allocation rules for global abatement targets ranging from 10% to 40% and South technical change ranging from zero to 30%, with β_i set at 0.1 for all South countries. The global cost of abatement is 0.08% of GDP for 10% abatement, 0.3% for 20% abatement, 0.7% for 30% abatement and 1.2% for 40% abatement. For all cases, the tradable-quota arrangement makes the South better off compared with the policy-off benchmark, with a substantial difference between the two allocation rules. At 20% global abatement, for example, the South's net gain from implementation of the regime is 3% of GDP with per capita quota allocation, but only 0.3% of GDP with NRFTS.

The North, of course, shows negative net gains in Table 3, but it must be remembered that this is the outcome of a calculation which has abstracted from abatement benefits. The underlying assumption at the outset of this analysis was that abatement benefits for the North are positive and sufficiently large to motivate negotiation of the international tradable-quota treaty in the first place. The negative net gain figures in Table 3 refer only to the direct financial implications of the policy regime and thus serve to indicate the minimum level of expected abatement benefits that would be sufficient to attract support from North governments.

Table 4 arrays figures for the net benefit to the South (quota revenue minus abatement cost) from a tradable-quota regime across a range of 56 scenarios of global abatement targets and technical progress in the South. The results are plotted in Figure 5, which shows the net direct gain to the South from the quota regime, compared with the policy-off benchmark. The South's quota revenues net of abatement costs for the per capita allocation rule are plotted as solid lines, while those under NRFTS are plotted

Table 3. *Quota trading simulation results*

	North		*South*		*World*	
	Per capita rule	*NRFTS rule*	*Per capita rule*	*NRFTS rule*	*Per capita rule*	*NRFTS rule*
(a) 10% global abatement target						
Quota price ($/tC)	58.67	58.67	58.67	58.67	58.67	58.67
Emissions (million tC)	3,534	3,534	1,568	1,568	5,101	5,101
Abatement (%)	10.2	10.2	9.5	9.5	10.0	10.0
Cost of abatement ($b)	11.8	11.8	4.8	4.8	16.6	16.6
Quota sale revenue ($b)	–137.02	–9.62	137.02	9.62	0.00	0.00
Net gain ($b)	–148.84	–21.44	132.21	4.81	–16.63	–16.63
Net gain as % of GDP	–1.03	–0.15	1.77	0.06	–0.08	–0.08
(b) 20% global abatement target						
Quota price ($/tC)	117.35	117.35	117.35	117.35	117.35	117.35
Emissions (million tC)	3,131	3,131	1,404	1,404	4,534	4,534
Abatement (%)	20.5	20.5	18.9	18.9	20.0	20.0
Cost of abatement ($b)	47.3	47.3	19.2	19.2	66.5	66.5
Quota sale revenue ($b)	–242.39	–38.48	242.39	38.48	0.00	0.00
Net gain ($b)	–289.66	–85.75	223.14	19.24	–66.51	–66.51
Net gain as % of GDP	–2.01	–0.59	2.98	0.26	–0.30	–0.30
(c) 30% global abatement target						
Quota price ($/tC)	176.02	176.02	176.02	176.02	176.02	176.02
Emissions (million tC)	2,728	2,728	1,240	1,240	3,968	3,968
Abatement (%)	30.7	30.7	28.4	28.4	30.0	30.0
Cost of abatement ($b)	106.4	106.4	43.3	43.3	149.7	149.7
Quota sale revenue ($b)	–316.11	–86.57	316.11	86.57	0.00	0.00
Net gain ($b)	–422.48	–192.94	272.83	43.29	–149.65	–149.65
Net gain as % of GDP	–2.93	–1.34	3.64	0.58	–0.68	–0.68
(d) 40% global abatement target						
Quota price ($/tC)	234.69	234.69	234.69	234.69	234.69	234.69
Emissions million (tC)	2,325	2,325	1,076	1,076	3,401	3,401
Abatement (%)	40.9	40.9	37.9	37.9	40.0	40.0
Cost of abatement ($b)	189.1	189.1	77.0	77.0	266.0	266.0
Quota sale revenue ($b)	–358.19	–153.91	358.19	153.91	0.00	0.00
Net gain ($b)	–547.28	–343.0	281.24	76.96	–266.05	–266.05
Net gain as % of GDP	–3.79	–2.38	3.76	1.03	–1.21	–1.21

as dotted lines. Compared with per capita allocation, the NRFTS allocation rule gives the South smaller gains from the introduction of tradable quotas, but avoids the perverse incentive of falling net gains as technical progress occurs, at least for low to moderate levels of technical progress in the South.

The top row of Table 4 provides a policy-on, zero-technical-progress benchmark against which marginal effects of technical change can be plotted. Figure 6 shows this marginal gain from technical progress, calculated by reading down each column of Table 4 and observing how total simulated net benefit changes, as the amount of assumed technical progress increases. If net benefit increases with technical progress, then marginal benefit is positive; if net benefit falls with technical progress, then marginal benefit is negative.

Table 4. *Net benefit to South (% of GDP) from introduction of a tradable quota regime, for seven technical change scenarios, four abatement target scenarios, and two quota allocation rules*

	Global abatement target							
	10%		*20%*		*30%*		*40%*	
Technical progress in South (%)	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*
0	1.77	0.06	2.98	0.26	3.64	0.58	3.76	1.03
5	1.55	0.19	2.86	0.34	3.62	0.71	3.84	1.21
10	1.31	0.13	2.72	0.41	3.59	0.83	3.90	1.38
15	1.05	0.13	2.57	0.47	3.53	0.93	3.94	1.53
20	0.78	0.12	2.39	0.50	3.46	1.02	3.97	1.66
25	0.49	0.08	2.20	0.52	3.37	1.08	3.98	1.77
30	0.18	0.03	1.99	0.52	3.26	1.13	3.97	1.87

Figure 6 shows that over the range of scenarios reported here, the NRFTS rule gives positive marginal benefit in most but not all cases, and the per capita rule gives negative values in most but not all cases. Generally, the lower the global abatement target and the greater the amount of technical progress in the South, the more likely the marginal benefit is to be negative. Because the quota revenues for the South with zero technical progress are so much smaller under NRFTS than under per capita allocation, it follows that the marginal effect of technical progress

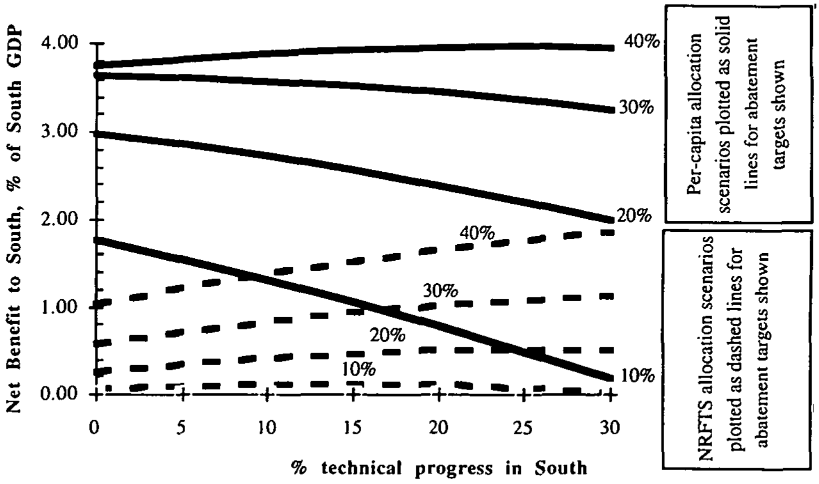

Figure 5. *Scenarios of total net benefit to South from a tradable quota regime for various levels of global abatement and South technical progress: two allocation rules compared.*

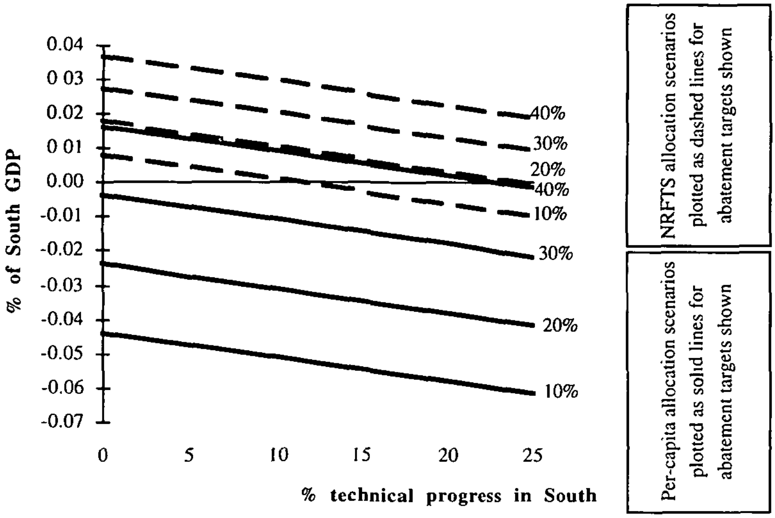

Figure 6. *Marginal net gain to South from technical progress for various levels of global abatement: two allocation rules compared.*

(measured against the zero-technical-progress, policy-on benchmark) is more likely to be positive under the less generous allocation rule.

8. Sensitivity test: alternative values of β_i

It was noted earlier that the available data on abatement costs is scarce and subject to a wide range of uncertainty. Consequently, in implementing the simulation model used in this paper, only three values for β_i were used. A value of $\beta_i = 0.062$ was inserted for the USA and Canada, based loosely on the considerable number of computable-general-equilibrium model estimates of abatement cost for the USA. A value of $\beta_i = 0.25$ was assumed for the remaining OECD countries, similarly based on the available CGE results. The rest of the world was modelled using a blanket value of $\beta_i = 0.1$. This section shows that the simulation results reported above are not sensitive to this arbitrary choice of β_i values for the South.

To test sensitivity, the simulations reported in Table 4 were re-run with (uniform) values of β_i for the South ranging from 0.05 to 0.25. The higher is the South's overall β_i, the lower is the simulated world price of quota for each abatement level, and the more abatement effort is required in the North, as would be expected on an intuitive basis. The qualitative pattern of results obtained in previous sections of the paper, however, remains unchanged. Table 5 shows re-runs of the Table 4 results for $\beta_{South} = 0.05$ and $\beta_{South} = 0.25$. Figure 7 shows as grey bars the sensitivity range for the results in the 10% and 40% abatement target scenarios under the per capita and NRFTS allocation rules, with the Table 4 results plotted as a heavy line in each case. The conclusion is that the general results of the paper are robust across the likely range of β_i values.

Table 5. *Sensitivity test: scenarios from Table 4 repeated with alternative values for South's* β

	Global abatement target							
	10%		*20%*		*30%*		*40%*	
Technical progress in South (%)	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*	*Per capita allocation*	*NRFTS allocation*
(a) $\beta_{South} = 0.05$								
0	1.13	0.05	1.92	0.20	2.40	0.46	2.57	0.83
5	0.98	0.07	1.84	0.25	2.37	0.54	2.60	0.93
10	0.83	0.08	1.75	0.29	2.34	0.60	2.62	1.02
15	0.67	0.08	1.65	0.32	2.30	0.66	2.63	1.10
20	0.49	0.07	1.53	0.34	2.24	0.70	2.63	1.17
25	0.31	0.05	1.41	0.34	2.18	0.74	2.62	1.23
30	0.11	0.02	1.27	0.34	2.10	0.76	2.61	1.28
(b) $\beta_{South} = 0.25$								
0	2.68	0.06	4.44	0.24	5.27	0.55	5.17	0.97
5	2.35	0.13	4.27	0.40	5.27	0.79	5.34	1.30
10	1.99	0.17	4.08	0.53	5.24	1.00	5.48	1.60
15	1.61	0.19	3.86	0.63	5.19	1.19	5.59	1.87
20	1.19	0.17	3.61	0.70	5.10	1.35	5.67	2.11
25	0.75	0.13	3.33	0.74	4.99	1.47	5.72	2.33
30	0.27	0.05	3.02	0.75	4.85	1.57	5.75	2.51

9. Conclusion

This paper has used a simple spreadsheet model to simulate a global tradable quota market, using 1990–1 data for 125 countries, and running scenarios on a world economy 'frozen' at its early 1990s emissions, population and GDP except for specified exogenous technical progress in emission abatement. The numerical analysis was limited to fossil-fuel and cement-derived CO_2 only.

The simulations suggest that if an exogenously set global emission budget is allocated on a per capita basis, giving full effect to the polluter-pays principle, the resulting market in tradable quotas could give the South a vested interest in continued high emissions by the countries of the North. Technical progress in emission abatement would then reduce rather than increase the South's net gain from the policy regime, even when the technical progress occurs entirely within the South itself. In the simulations, the falling quota price transfers all rents from South technical progress to the North by reducing the total expenditure required to purchase the North's imports of quota. This tendency for the South to lose from technical progress is reversed only if the global emissions budget is quite tight (over 30% abatement from 1991 global emissions).

The more hard-nosed NRFTS rule for allocating property rights in a global emission budget is less favourable to the South in terms of the baseline revenue to be obtained from quota sales to the North; but technical progress in the South gains a positive return at the margin under this regime. Nevertheless, in this case also some rents from South technical

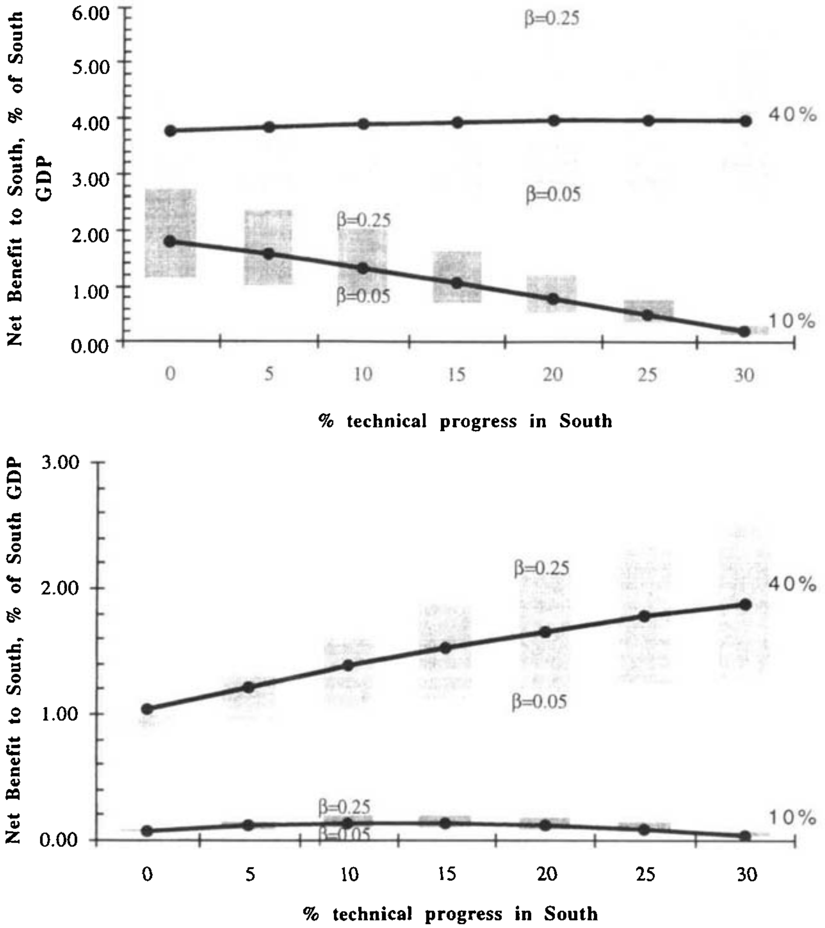

Figure 7. *10% and 40% abatement cases from Figure 5: sensitivity to changes in* β_{South} *for the range* $0.05 < \beta_{South} < 0.25$. *(a) Per capita quota allocation. (b) NRFTS quota allocation.*

progress are captured by the North through changes in the world market value of quota.

The most effective way to prevent leakage of the rents from technical progress in abatement from quota exporters towards quota importers would be to tighten the global emission budget in response to any fall in the world value of quota. This policy rule need not be symmetric, since the issues canvassed in this paper give no grounds for relaxing the global budget constraint in response to an increase in the market price of quota. To protect technology rents from leakage, the primary requirement is just a quota price floor. Both collectively and individually, South governments would seem to have an incentive to press for such an arrangement.

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