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Unilateral emission reductions when there are cross-country technology spillovers[a]

Rolf Golombek[b] and Michael Hoel[c]

Abstract

With limited participation in an international climate agreement, standard economic analysis suggests that a unilateral action taken by a group of countries in order to reduce its emissions is likely to be undermined by increases in emissions from other countries (carbon leakage). While analyses of carbon leakage typically have regarded the technology in each country as given, abatement technologies are endogenous, and thus technology development may be affected by environmental policies. We demonstrate that with endogenous technologies and technology diffusion between countries, it is no longer obvious that reduced emissions in some countries will increase emissions in other countries. We identify cases in which reduced emissions in some countries might reduce emissions also in other countries.

Keywords: transboundary pollution, unilateral environmental action, R&D expenditures, technology spillovers.

JEL classification: O30; Q54; Q59

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1. Introduction

With transboundary environmental pollution it is necessary to have some kind of coordination of policies among the involved countries in order to achieve a first-best efficient outcome. However, at least if the number of involved countries is large, it is well known that the free-rider incentives of each country may undermine the possibility of reaching a collectively good outcome, see e.g. Barrett (2003). It therefore seems unlikely that an efficient cooperative outcome will be achieved in the near future for important transboundary environmental problems such as the climate problem.

At the time of this writing, it is not clear whether the Kyoto agreement will enter into force. If Russia ratifies the agreement, it is likely to enter into force. The Kyoto agreement will, however, cover less than a third of global greenhouse gas emissions. Even if emissions are cooperatively allocated among the countries ratifying the Kyoto agreement, emissions from the Kyoto group as a whole and from other large emitters such as the US will be decided in a non-coordinated manner.

In a situation with less than full cooperation among the countries involved, the effect of a unilateral action taken by one country (or a group of countries) in order to reduce its emissions is a crucial issue. Standard economic analysis suggests that such a unilateral emissions reduction is likely to be undermined by increases in emissions from other countries. There are several reasons for such a response from other countries. One reason given in Hoel (1991) is that the environmental damage cost functions are strictly convex in the sum of emissions from all countries. For given emissions from other countries, it is individually rational for each country to equate its marginal abatement cost with its marginal environmental cost. If emissions are reduced in a particular country (e.g. due to a change in the environmental concern in that country), marginal environmental costs will go down in all other countries. Each country will therefore adjust its emissions upwards, so that marginal abatement costs again are equal to their marginal environmental damage costs.

In the context of the climate problem, increased emissions from other countries as a response to an emissions reduction in one country is often called carbon leakage. In addition to the reason given above, there are several other reasons for carbon leakage: The most obvious way carbon emissions in a country may be affected by abatement policies in another country is through the prices of fossil fuels. If a country reduces its demand for fossil fuels by introducing a carbon tax, international fuel prices will decline. Lower fuel prices will increase fuel demand in other countries, and thus increase their CO_2 emissions. A second mechanism of carbon leakage is via the prices of energy intensive tradable goods: if the use of fossil fuels is reduced through a carbon tax in the sectors producing energy intensive tradable goods, production of these goods will be reduced in the country which introduces the carbon tax, thereby resulting in reduced CO_2 emissions from this country. However, the reduced supply of energy intensive tradable goods in this country will increase the international price of these goods, thus increasing the supply in other countries. Emissions from other countries therefore increase.

Issues related to carbon leakage have been studied in e.g. Bohm (1993), Golombek et al. (1995), Hoel (1994, 1996, 2001), Rauscher (1997; Section 5.8), Gurtzgen and Rauscher (2000) and Mathiesen and Mæstad (2004). This literature discusses how policies introduced in one country, or in a group of countries, with the aim of reducing carbon emissions may increase carbon emissions in other countries, thus weakening the effect of the policies. Numerical simulations quantifying the importance of carbon leakage include Pezzey (1992), who concludes that the carbon leakage might be quite strong, while e.g. Golombek and Bråten (1994), Felder and Rutherford (1993), and Perroni and Rutherford (1993) give numerical simulations indicating that the effects are modest.

In all of the literature referred to above, the technology in each country is regarded as given. However, abatement technologies are in reality endogenous, and technology development may be affected by environmental policies and other policies. Several recent articles have studied interactions between endogenous technological change and environmental policy, see e.g. Jaffe *et al.* (2002) and Löschel (2002) for overviews. With endogenous technologies, it is no longer obvious that reduced emissions in one country will increase emissions in other countries. Assume e.g. that a country that becomes more concerned about the environment (modeled as a positive shift in its environmental damage function) increases its R&D expenditures in order to reduce its abatement costs. If there are cross-country technology spillovers, this will also reduce abatement costs in other countries. Even if the environmental concern in other countries is unchanged, this cost reduction may induce other countries to reduce their emissions.

The present paper gives a formal analysis of the argument above. To do this, we present a simple static two-country model in Section 2. Countries are identical except for their environmental concern. In each country the technology level depends both on R&D expenditures domestically and in the other country. We model this technology spillover by a “standard” linear equation, which we generalize in Section 7. Since our model is static, there is no time lag between R&D expenditures and the effects on technology levels. Uncertainty related to the effects of R&D expenditures on technology levels are also ignored.

Sections 2 and 3 present the model and the initial equilibrium. In Section 4 we consider the case where countries initially are identical, and where R&D expenditures are positive in both countries. Starting from this symmetric equilibrium, preferences change in one of the countries. We show that abatement and R&D expenditure increase in this country, whereas abatement and R&D expenditures decline in the other country.

In Sections 5 and 6 we assume that countries are different. In the “dirty” country, environmental concern is so low that R&D expenditures are zero, while these expenditures are positive in the “clean” country. We show that the effects of increased environmental concern in one country depend on in which country this preference change takes place. A shift in the environmental damage function of the dirty country increases abatement in the dirty country, whereas abatement and R&D expenditures are not increased in the clean country. On the other hand, a shift in the environmental damage function of the clean country increases abatement and R&D expenditures in the clean country, whereas the effect on abatement in the dirty country is ambiguous.

In Section 7 we consider a more general equation determining technology spillovers than in the previous sections. We show that the results in Sections 5 and 6 are not sensitive to the properties of technology spillovers, whereas some of the results in Section 4 are sensitive. In particular, abatement and R&D expenditures may increase in the country where preferences do not change.

Section 8 examines welfare effects. We show that when the concern for the environment increases in one country, welfare increases in the other country, whereas the welfare effect in the first country is in general ambiguous. Finally, Section 9 concludes.

2. The model

We consider a model with two countries, "home" and "foreign". We use small letters for home country variables, and capital letters for foreign country variables. The abatement cost functions of the two countries are identical and continuous, and are given by $\Omega(a,y)$ and $\Omega(A,Y)$, where *a* and *A* are abatement levels and *y* and *Y* are technology levels. We assume that $\Omega(0,y)=0$ for all y, and that (for $a>0$) $\Omega_a = \partial\Omega/\partial a > 0$, $\Omega_{aa}>0$, $\Omega_y<0$, $\Omega_{yy}>0$, $\Omega_{ay}<0$ and $\Omega_{aa}\Omega_{yy}-(\Omega_{ay})^2>0$ (i.e. the Ω-function is strictly convex). We also assume that $\Omega_a(0,y)=0$ for any *y*. This assumption implies that both countries will have positive abatement levels as long as they have *some* concern for the environment.

The technology level in the home country depends on R&D in the home country, *x*, and in the foreign country, *X*. However, technology diffusion is not perfect: Only part ($\gamma<1$) of the R&D expenditures undertaken in the foreign country is beneficial for the home country (and vice versa).[1] The technology levels of the home and foreign countries are thus given by

$$y = x + \gamma X \qquad (1)$$
$$Y = X + \gamma x \qquad (2)$$

[1] In our model γ is assumed to be exogenous. We thus disregard the possibility that the country developing a new technology may actively prevent other countries from using this technology through intellectual property rights.

In (1) and (2) we have assumed an additive structure of technology spillovers, that is, the technology level of a country depends on the sum of R&D expenditures undertaken in all countries, corrected by the technology diffusion parameter γ. This way of modeling spillovers can be found in a wide range of theoretical and empirical contributions analyzing spillovers within countries, and goes back at least to Spence (1984). It is also used in most of the literature on climate policy in the context of interactions between countries and endogenous technology development, see e.g. van der Ploeg and de Zeeuw (1994), Xepapadeas (1995), Rosendahl (2002), Ben Youssef (2003), Buonanno et al. (2003) and Buchner and Carraro (2004).

Although spillovers often are modeled as in (1) and (2), it is not obvious that this is the best way of modeling technology spillovers between firms and countries. Cohen and Levinthal (1989) have argued that the ability of a firm to learn from other firms may depend on its own R&D effort. Graevenitz (2002) discusses the policy implications of whether one models spillovers additively as in (1) or in a similar way as Cohen and Levinthal suggest. We shall return to alternative ways of modeling technology spillovers in Section 7.

Business as usual (BAU) emissions are identical in the two countries, and normalized to 1. Net emissions are thus $1-a$ in the home country and $1-A$ in the foreign country.

Each country is faced by three types of costs; abatement costs, R&D expenditures and environmental damage costs. The sum of the first two costs is $\Omega(a,y)+x$ for the home country and $\Omega(A,Y)+X$ for the foreign country. In both countries environmental damage costs depend on the sum of emissions, which we denote σ ($=2-a-A$). In the home country environmental damage costs are $e(\sigma)+f\sigma$, where *f* is a shift parameter that is equal to zero in the initial equilibrium. In the foreign country environmental damage costs are $E(\sigma)$. Throughout, we assume that the functions *e* and *E* are increasing and strictly convex, but we will also comment on the special case of linear damage functions.

3. Equilibrium

In the non-cooperative equilibrium, each country chooses its abatement level and R&D expenditures in order to minimize its own total costs, taking the abatement level and R&D expenditures in the other country as given. Hence, the home county minimizes $\Omega(a,y)+x+e(2-a-A)+f\cdot(2-a-A)$, taking *A* and *X* as given, where *y* is given by (1). The foreign country solves a similar minimization problem.

Below we distinguish between two cases. In the first case countries are identical, and there exists an interior equilibrium (*x* and *X* are positive) given by:

$$\Omega_a(a,y) = e'(2-a-A) + f \quad (3)$$

$$-\Omega_y(a,y) = 1 \quad (4)$$

$$\Omega_A(A,Y) = E'(2-a-A) \quad (5)$$

$$-\Omega_Y(A,Y) = 1 \quad (6)$$

where $f = 0$ initially. The six equations (1)-(6) determine the equilibrium values of our six endogenous variables *a, A, x, X, y, Y*.

In the second case environmental damage functions differ between the countries. With different countries we shall refer to one country as the dirty country, that is, the country with the lowest valuation of environmental damage, and the other country as the clean country. Moreover, we assume that in the dirty country the equilibrium value of e' (or E') is so low that instead of the interior equilibrium condition (4) we get a corner solution given by $x = 0$ (or $X = 0$) and $-\Omega_y(a,\gamma X) \leq 1$[2].

The case of identical countries is examined in Section 4. We shall call the country in which the shift takes place for the home country, and the other country is called the foreign country. We then study effects of increased valuation of the environment when countries differ. First, we study effects of increased valuation in the dirty country (Section 5) and then in the clean country (Section 6). Again, in both sections we shall call the country in which the shift takes place for the home country, and the other country is called the foreign country. Hence, in Section 5 we assume that the home country is dirty, whereas the home country is clean in Section 6.

4. Identical countries

In the present section we assume that countries are identical initially, and we also assume positive R&D expenditures in both countries initially. Below we investigate the effects of increased concern for the environment in one country, denoted the home country.

For the case in which the environmental damage cost functions are linear, we immediately see from (5) and (6) that the foreign county wants the same abatement level and same technology level as prior to the preference change in the home country. However, since the home country wants a higher technology level (and more abatement) after the shift, R&D expenditures in the foreign country must go

[2] For any given positive pair (A, X) it is not possible to find a non-negative pair (a, x) satisfying the interior equilibrium conditions (1)-(4) when e' is sufficiently low.

down in order to keep the technology level in the foreign country unchanged.[3] In the case of increasing marginal environmental costs, the foreign country wants to abate less when the home country abates more. This reduces the incentives for R&D expenditures in the foreign country even more, that is, R&D expenditures decline in the foreign country.

The reasoning above is confirmed by a formal derivation given in the Appendix. We thus have the following proposition:

Proposition 1: With linear technology spillovers and identical countries, increased concern for the environment in the home country raises abatement and R&D expenditures in that country, whereas R&D expenditures in the foreign country decline. If the damage functions are linear, abatement in the foreign country is unchanged. Otherwise (i.e. with a strictly convex damage function in the clean country) abatement in the foreign country decreases.

5. Increased environmental concern in the dirty country

With linear technology the initial equilibrium is given by (3), (5) and (6) (with $y = \gamma X$ and $Y = X$) when the home country is dirty. Assume now that the environmental damage function of the dirty country (that is, the home country) shifts. Differentiation of (3), (5) and (6) with respect to f ($f = 0$ initially) yields

$$\frac{da}{df} = \frac{-(\Omega_{AA} + E'')\dfrac{\Omega_{YY}}{\Omega_{YA}} + \Omega_{AY}}{N} > 0 \tag{7}$$

$$\frac{dA}{df} = \frac{\dfrac{\Omega_{YY}}{\Omega_{YA}} E''}{N} < 0 \tag{8}$$

$$\frac{dX}{df} = \frac{-E''}{N} < 0 \tag{9}$$

where N is positive.[4] A shift in the environmental damage function of the dirty country will increase abatement in that country. Increased abatement in the dirty country will reduce marginal costs of environment in the clean country, and thus abatement will be reduced in the clean country. Lower abatement in the clean

[3] In a dynamic model with irreversible R&D investments, increased environmental concern in the home country would leave the foreign country with a better technology than it would have chosen had it known of this preference change at the time of the R&D investment.

[4] $N = \Omega_{aa}[(E'' + \Omega_{AA})\dfrac{-\Omega_{YY}}{\Omega_{YA}} + \Omega_{AY}] - E''\Omega_{ay}\gamma + e''(\dfrac{\Omega_{AA}\Omega_{YY}}{-\Omega_{YA}} + \Omega_{AY}) > 0$

country makes investments in R&D less profitable in the clean country, that is, R&D expenditures are reduced.

If the environmental damage function in the clean country is linear[5], increased abatement in the dirty country does not change marginal environmental costs of the clean country. Hence, in the clean country abatement and R&D expenditures do not change, see (8) and (9) for $E''=0$. We have thus shown:

Proposition 2: With linear technology spillovers and no R&D expenditures in the dirty country, a shift in the environmental damage function of the dirty country increases abatement in the dirty country. If the damage function in the clean country is linear, neither abatement nor R&D expenditures in the clean country change. Otherwise, abatement and R&D expenditures are reduced in the clean country.

6. Increased environmental concern in the clean country

In the previous section we studied effects of increased environmental concern in the dirty country if there is no R&D expenditure in that country. We now turn to the case where the home country is clean, and study effects of increased environmental concern in the clean country. Like in the previous section there is no R&D expenditure in the dirty country. The initial equilibrium is given by (3), (4) and (5) (with $y=x$ and $Y=\gamma x$). Differentiating the system w.r.t. f gives (initially $f=0$)

$$\frac{da}{df}=\frac{\frac{\Omega_{yy}}{-\Omega_{ya}}(\Omega_{AA}+E'')}{N}>0 \tag{10}$$

$$\frac{dx}{df}=\frac{\Omega_{AA}+E''}{N}>0 \tag{11}$$

$$\frac{dA}{df}=\frac{-(\gamma\,\Omega_{AY}+E''\frac{\Omega_{yy}}{-\Omega_{ya}})}{N} \tag{12}$$

where $N>0$, see footnote 4. A shift in the environmental damage function of the clean country raises abatement in that country. Because increased abatement raises the profitability of R&D expenditures, the clean country undertakes more investments. Increased R&D expenditures in the clean country raises the technology level of the dirty country through spillovers, which tends to increase abatement in

[5] The damage function in the dirty country could be linear or strictly convex.

the dirty country ($\frac{-\gamma\,\Omega_{AY}}{N} > 0$ in (12)) because costs of abatement have decreased in the dirty country. However, increased abatement in the clean country lowers marginal environmental damage in the dirty country, which tends to decrease abatement in that country ($\frac{E''\frac{\Omega_{yy}}{\Omega_{ya}}}{N} < 0$ in (12)). Hence, the effect on abatement in the dirty country is ambiguous.

With linear damage function in the dirty country, marginal environmental costs of the dirty county do not change as abatement increases in the clean country. Hence, there is only a positive effect on abatement in the dirty country through technology spillovers, that is, abatement and thus technology level are increased in the dirty country. To sum up:

Proposition 3: With linear technology spillovers and no R&D expenditures in the dirty country, a shift in the environmental damage function of the clean country increases abatement and R&D expenditures in the clean country. If the damage function in the dirty country is linear, abatement in the dirty country increases. Otherwise, the effect on abatement in the dirty country is ambiguous.

7. Technology complementarity

In the previous sections we studied unilateral emissions reductions when technology spillovers between countries are linear. As mentioned in the Introduction, however, a more generalized approach may be preferable. In the present section we shall assume that the technology level of the home country *y* is given by the function $\Phi(x, X)$. The partial derivatives of this function with respect to *x* and *X* are denoted by Φ_1 and Φ_2, respectively. We assume that $\Phi_i > 0, i = 1, 2,$ and $\Phi_1 > \Phi_2$ for $x = X$ as technology diffusion is not perfect. (For the foreign country the technology level is given by $Y = \Phi(X, x)$) We assume that Φ is homogenous of degree 1. Moreover, for each country the marginal benefits of R&D expenditures undertaken in the other country depend positively on the magnitude of its own R&D expenditures, that is, $\Phi_{12} > 0$. We will refer to the latter assumption as technology complementarity.

Note that as Φ is homogenous of degree 1, Φ_1 is homogenous of degree 0, that is, $\Phi_{11}x + \Phi_{12}X = 0$. From our assumption of technology complementarity it now follows that $\Phi_{ii} < 0, i = 1, 2$, that is, both own R&D expenditures and spillovers from the other country have "decreasing returns". Finally, in the case of identical countries $(x = X)$, we have $\Phi_{11} + \Phi_{12} = 0$. Below we examine the different cases studied in Sections 4-6 under the assumption of technology complementarity.

7.1 Identical countries

With technology complementarity, the initial equilibrium is given by *(*with $f = 0$ initially*)*

$$\Omega_a(a, \Phi(x, X)) = e'(2 - a - A) + f \tag{13}$$

$$-\Omega_y(a, \Phi(x, X))\Phi_1(x, X) = 1 \tag{14}$$

$$\Omega_A(A, \Phi(X, x)) = E'(2 - a - A) \tag{15}$$

$$-\Omega_Y(A, \Phi(X, x))\Phi_1(X, x) = 1 \tag{16}$$

Consider first the case of linear environmental cost functions. From Section 4 we know that for the special case of linear spillovers, the foreign country's desired technology level (and abatement level) is unaffected by the preference shift in the home country. However, as R&D expenditures increase in the home country as a response to the preference shift, we see from *(16)* that this is no longer true in the present case. Due to technology complementarity, the foreign country will want a higher technology level as *x* increases. (It is, however, not obvious whether or not this implies larger R&D expenditures in the foreign country.) Moreover, a higher technology level raises (cet. par) the abatement level in the foreign country. If marginal environmental costs are increasing (not constant as above), higher abatement in the home country tends to crowd out abatement in the foreign country. Combined with the previous result we thus expect the effect on abatement in the foreign country to be ambiguous.

In order to check the above intuition, we have differentiated *(13) - (16)* with respect to *f*. The details are given in the Appendix, and the results are as follows:

Proposition 4: With technology complementarity and identical countries, a shift in the environmental damage function in the home country increases abatement and R&D expenditures in that country. The effect on abatement and R&D expenditures are ambiguous in the foreign country. However, if the damage functions are linear, abatement in the foreign country is increased.

From Proposition 1 and 4 (identical countries) we see that a shift in the environmental damage function in the home country has similar effects in the home country in the two cases (linear technology spillovers vs. technology complementarity). In the foreign country the effects differ: Under strictly convex damage functions, abatement and R&D expenditures are reduced under linear spillovers but have ambiguous effect under technology complementarity. Similarly, with linear damage functions abatement in the foreign country is unchanged under linear spillovers, whereas abatement in the foreign country increases under technology complementarity. These differences reflect that under technology complementarity it is more profitable to invest in R&D, which tends to increase abatement as costs of abatement are reduced when the technology level is increased.

7.2 Different countries

In Section 5 (home country is dirty and undertakes no R&D) we had $y = \gamma X$ and $Y = X$. The only change from Section 5 to the present section is that these two equations are replaced by $y = \Phi(0, X)$ and $Y = \Phi(X, 0)$, respectively. The derivatives of *y* and *Y* with respect to *X* are thus changed from γ and 1 in Section 5 to Φ_2 and Φ_1 (which are both positive) in the present section. Going through the derivations in Section 5, it is straightforward to see that the three inequalities derived are unaffected (but the sizes of these derivatives will of course depend on the spillover function). Similarly, the only change from Section 6 (home country is clean) to the present section is that $y = x$ and $Y = \gamma x$ are replaced by $y = \Phi(x, 0)$ and $Y = \Phi(0, x)$, respectively. Going through the derivations in Section 6, it is straightforward to see that the three inequalities derived are unaffected. We thus have the following proposition:

Proposition 5: The results in Proposition 2 and 3 are valid also under technology complementarity.

8. Welfare effects

In this section we study welfare effects of increased environmental concern in the home country. First, the welfare effects in the foreign country are easily derived. For any given policy in the foreign country, this country is better off the higher is abatement and the higher are R&D expenditures in the home country. Since the foreign country maximizes its own welfare given the choices made by the home country, welfare in the foreign country moves in the same direction as abatement and R&D expenditures in the home country, provided these two home country variables move in the same direction. Going through propositions 1-5 we see that when the home country becomes more concerned about the environment, abatement is increased in this country. R&D expenditures in the home country also increase, or are unchanged for the case in which the home country is dirty (no R&D expenditures). These changes in the home country are unambiguously to the advantage of the foreign country. We therefore have the following proposition:

Proposition 6: When the concern for the environment increases in the home country, welfare increases in the foreign country.

Next, consider the home country. Since we are considering a change in preferences, it is not obvious how to measure welfare effects in the home country. In order to measure welfare effects in a meaningful way, we shall interpret the preference change as follows. There are two groups of citizens of roughly equal size in the home country. The members of the two groups are identical except for their preferences for the environment. One group, called group I, has preferences corresponding to our initial environmental cost function $e(\sigma)$, while the other group, called group II, has preferences corresponding to the environmental cost function $e(\sigma)+f\sigma$. We have studied the consequences of changing the home country's preferences from $e(\sigma)$ to $e(\sigma)+f\sigma$. We shall now interpret this change in preference as a (small) increase in the size of group II and a corresponding reduction in the size of group I, thus swinging the majority (and median) preference from $e(\sigma)$ to $e(\sigma)+f\sigma$. With this interpretation of the home country's change in preferences, we can study the welfare change of group I members and group II members[6].

Consider first group I of the home country. Clearly, if no changes occurred in the foreign country, the welfare of group I would go down as a consequence of the policies of the home country being determined by the preferences of group II instead of as initially by its own preferences. However, changes also occur in the foreign country. If these changes are to the disadvantage of the home country, then this reinforces this negative welfare change for group I in the home country. Going through propositions 1-5, we see that that there are two cases where the home country is unambiguously negatively affected (or unaffected) by the policy change in the foreign country. This occurs if the home country is dirty, and also if countries are identical and technology spillovers are linear.

From proposition 3 we know that if the home country is clean, whereas the foreign country is dirty and has a linear environmental damage function, increased environmental concern in the home country generates changes in the foreign country that are beneficial for the home country (increased abatement). If the difference in preferences between the two groups in the home country is sufficiently small (i.e. if f in $e(\sigma)+f\sigma$ is sufficiently small), the welfare effect for group I due to changes in the foreign country must dominate the welfare effects for group I of the domestic preference change. The reason is that the latter effect is of zero order[7], while the effect of the change in the foreign country is a first order effect.

We now turn to group II. If no changes occurred in the foreign country, the welfare of group II would increase because the policy of the home country is now determined by this group's preferences, instead of as initially by the preferences of group I. For the same reason as given above, the welfare effect for group II due to changes in the foreign country must dominate the welfare effects for group II of the domestic preference change if the difference in preferences between the two groups

[6] With our interpretation we cannot in a meaningful way measure the welfare change of the small number of persons who move from group I to group II.

[7] A small policy change has a negligible effect on welfare when policy is initially optimized.

in the home country is sufficiently small. Reasoning as we did for group I, we can therefore find the welfare effects for group II for the different cases: If the home country is dirty and has a linear environmental damage function, or if the foreign country is dirty and has a linear environmental damage function, the welfare of group II in the home country increases as a consequence of increased environmental concern in the home country. Moreover, if the difference in preferences between the two groups in the home country is sufficiently small, and if either the home country is dirty and has a strictly convex environmental damage function, or countries initially are identical and technology spillovers are linear, the welfare of group II in the home country declines as a consequence of increased environmental concern in the home country.

Our results may be summarized as follows:

Proposition 7: When the concern for the environment increases in the home country, the welfare effects for both groups in the home country are ambiguous. The effects depend on (a) whether or not the two countries initially are identical, (b) whether or not environmental damage cost functions are linear, and (c) whether or not technology spillovers are linear. If the difference in preferences between the two groups in the home country is sufficiently small, the welfare of the two groups move in the same direction. Table 1 gives details.

Table 1: Welfare effects in the home country.

	Damage functions	Group I	Group II
Home country dirty ($x = 0$)	Linear	-	+
	Strictly convex	-	? (- if *f* small)
Foreign country dirty ($X = 0$)	Linear	? (+ if *f* small)	+
	Strictly convex	?	?
Identical countries, linear technology spillovers	Linear	-	? (- if *f* small)
	Strictly convex	-	? (- if *f* small)
Identical countries, technology complementarity	Linear	?	?
	Strictly convex	?	?

9. Concluding remarks

A number of studies suggest that the effect of a unilateral action taken by a group of countries in order to reduce its emissions is likely to be undermined by increases in emissions from other countries (carbon leakage). While analyses of carbon leakage typically have regarded the technology in each country as given, abatement technologies are in reality endogenous, and thus technology development may be affected by environmental policies. The main lesson from our paper is that the *isolated* effect of technology diffusion is decreased emissions. We have thus demonstrated that with endogenous technologies and technology diffusion between countries, it is no longer obvious that reduced emissions in one country will increase emissions in other countries. In fact, in our two-country model there are cases where the opposite is true, so that increased environmental concern in one country might lead to lower emissions in both countries.

More specifically, we have showed that if countries differ, and the unilateral action is undertaken by countries with the highest valuation of environmental damage, welfare in these countries, as well as abatement in the other countries, will increase if there are no R&D expenditures in the countries with the lowest valuation of environmental damage and the environmental damage function of these countries is linear. Yet, under other assumptions a unilateral action will be undermined by decreased abatement in other countries.

Throughout the paper we assumed no international environmental agreement. An alternative approach would be to study unilateral environmental actions in the presence of an international agreement. Suppose first that some (or all) countries participate in an international agreement with emissions quotas. Each country receives a predetermined number of quotas. If quotas are tradable, countries are free to trade in quotas. For each country emissions cannot exceed the country's amount of quotas (after trade). If some countries undertake a unilateral action, that is, in these countries emissions are lower than their number of quotas, there will of course be no effect on emissions from other countries as for these countries emissions follow from their total amount of quotas.

An alternative to the quota agreement is a tax agreement in which each participating country imposes a common emission tax on all sources of emissions, e.g., on all users of fossil fuels. In each country emissions follow from the condition that marginal costs of abatement should equal the imposed tax. Because marginal abatement costs are decreasing in the technology level (see Section 2), abatement will be increasing in the technology level. Hence, increased R&D in one country will, through technology diffusion, increase the technology level in other countries, and thus increase abatement in other countries. However, as in the present paper increased abatement in one country will tend to decrease environmental damage in other countries (if damage functions are strictly convex), and thus, *cet. par.*, will decrease abatement in other countries. We therefore expect that a unilateral action in one country may increase abatement and R&D in that country, whereas the impact on abatement in other countries may be ambiguous, depending on e.g. the environmental damage function and the technology function.

Throughout the paper we have assumed that a unilateral action has no effect on the preferences of other agents. However, a person may exhibit social preferences, that is, the person does not only care about his own material resources but also cares about the material resources allocated to relevant reference agents, see Fehr and Falk (2002). One kind of social preference is reciprocity, that is, agents respond in a friendly (hostile) manner to actions that reveal a friendly (hostile) intention. Hence, reciprocity may be a driving force for voluntary cooperation, see e.g. Fischbacher et al. (2001) who shows that many people may increase their contribution to a public good if others also increase their contributions. A topic for further research is therefore whether a unilateral action by one country - increased abatement - lead to increased abatement also in other countries due to reciprocity.

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Appendix

Proof of Proposition 1:
Differentiating (3) - (6) with respect to f ($f=0$ initially), and substituting for da and dA, yields the system

$$\begin{aligned} Bdx + DdX &= df \\ Ddx + BdX &= 0 \end{aligned} \tag{17}$$

where $B = (\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay}) - e'' \frac{\Omega_{yy}}{\Omega_{ya}}(1+\gamma) > 0$ and $D = (\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay})\gamma - e'' \frac{\Omega_{yy}}{\Omega_{ya}}(1+\gamma) > 0$. Note that $B > D$ since $\gamma < 1$, but $D \geq \gamma B$ ($D = \gamma B$ when $e'' = 0$).

Solving (17) yields

$$\frac{dx}{df} = \frac{B}{L} > 0 \tag{18}$$

$$\frac{dX}{df} = \frac{-D}{L} < 0 \tag{19}$$

where $L = B^2 - D^2 > 0$. Note that $\frac{dy}{df} = \frac{d(x+\gamma X)}{df} = \frac{B-\gamma D}{L} > 0$, $\frac{dY}{df} = \frac{d(X+\gamma x)}{df} = \frac{\gamma B - D}{L} < 0$. Moreover, using (4) and (6) we find

$$\frac{da}{df} = \frac{\frac{\Omega_{yy}}{-\Omega_{ya}}(B-\gamma D)}{L} > 0 \tag{20}$$

$$\frac{dA}{df} = \frac{\frac{\Omega_{YY}}{-\Omega_{YA}}(\gamma B - D)}{L} \leq 0 \tag{21}$$

Proof of Proposition 4:
Differentiating (13) - (16) w.r.t. f, and substituting for da and dA, yields the system

$$\begin{aligned} Gdx + HdX &= df \\ Hdx + GdX &= 0 \end{aligned} \qquad (22)$$

where $G = e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{-\Omega_{ya}} + \Phi_1(\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay}) - \frac{\Omega_{aa}\Omega_y}{\Omega_{ya}}\frac{\Phi_{11}}{\Phi_1} > 0$ and $H = e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{-\Omega_{ya}} + \Phi_2(\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay}) - \frac{\Omega_{aa}\Omega_y}{\Omega_{ya}}\frac{\Phi_{12}}{\Phi_1}$. Note that the two first terms in G and H are positive. The third term in G is positive, whereas the third term in H is negative. Hence, the sign of H is ambiguous, but $G > H$ and due to Φ being homogenous of degree 1 we also have $|G| > |H|$.[8]

Solving (22) yields

$$\frac{dx}{df} = \frac{G}{K} > 0 \qquad (23)$$

$$\frac{dX}{df} = \frac{-H}{K} \qquad (24)$$

where $K = G^2 - H^2 > 0$. Moreover, using (4) and (6) we find

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[8] If $H > 0$ then $|G| > |H|$ since $G > H$. Assume $H < 0$. If $|H| \geq |G|$ then $-e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{-\Omega_{ya}} - \Phi_2(\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay}) + \frac{\Omega_{aa}\Omega_y}{\Omega_{ya}}\frac{\Phi_{12}}{\Phi_1} \geq e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{-\Omega_{ya}} + \Phi_1(\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay}) - \frac{\Omega_{aa}\Omega_y}{\Omega_{ya}}\frac{\Phi_{11}}{\Phi_1}$, which implies that $\frac{\Omega_{aa}\Omega_y}{\Omega_{ya}}\frac{(\Phi_{11} + \Phi_{12})}{\Phi_1} \geq 2e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{-\Omega_{ya}} + (\Phi_1 + \Phi_2)(\frac{\Omega_{aa}\Omega_{yy}}{-\Omega_{ya}} + \Omega_{ay})$. In the latter inequality the right hand side is positive, whereas the left hand side is zero since Φ is homogenous of degree 1 and the two countries are identical. Hence, the latter inequality is not fulfilled, that is, $|G| > |H|$.

$$\frac{da}{df} = \frac{[2\Omega_y(\frac{\Omega_{AA}\Omega_{YY}}{-\Omega_{YA}} + \Omega_{AY}) + \Omega_y\Omega_{yy}\ \frac{\Omega_{AA}}{-\Omega_{YA}}]\Phi_{11}(1+\frac{\Phi_2}{\Phi_1})}{K} +$$

$$\frac{\Omega_{yy}(\frac{\Omega_{AA}\Omega_{YY}}{-\Omega_{YA}} + \Omega_{AY})(\Phi_1^2 - \Phi_2^2)}{K} +$$

$$\frac{e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{\Omega_{ya}^2}[\Omega_{yy}(\Phi_1 - \Phi_2) + 2\Omega_y\ \frac{\Phi_{11}}{\Phi_1}]}{K} +$$

$$\frac{e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{\Omega_{ya}^2}[\Omega_{yy}(\Phi_1 - \Phi_2) + 2\Omega_y\ \frac{\Phi_{11}}{\Phi_1}]}{K} > 0 \qquad (25)$$

$$\frac{dA}{df} = \frac{\Omega_Y\ \Phi_{11}(1+\frac{\Phi_2}{\Phi_1}) + e''(\Phi_1 + \Phi_2)\frac{\Omega_{yy}}{\Omega_{ya}^2}[\Omega_{YY}(-\Phi_1 + \Phi_2) + 2\Omega_Y\ \frac{\Phi_{12}}{\Phi_1}]}{K} \qquad (26)$$

In *(26)* the first term is positive, whereas the second term is negative, that is, the effect on abatement in the foreign country is ambiguous. Note that with linear damage functions ($e'' = 0$) the nominator in *(26)* is positive, and hence abatement in the foreign country increases.