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The Noncooperative Provision of International Environmental Goods when Countries Differ in Size

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The Noncooperative Provision of International Environmental Goods when Countries Differ in Size

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Abstract:

National reductions of CO_2 emissions as a way to manage unilaterally the use of global environmental resources can be interpreted as the noncooperative provision of an international public good. This paper analyses two basic sources of inefficiency if countries abate their emissions noncooperatively. One is caused by the possibility to take a free ride on abatement activities of other countries, the second results from comparative cost advantages of emission abatements not being exploited. In a simple two-country, two-goods model it is analysed how asymmetries in population size influence the relative importance of these welfare losses by deriving for both an index of efficiency. The efficiency-properties of the Nash equilibrium are compared to the Stackelberg equilibrium.

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1 Introduction

After the end of the cold war we observe a fragmentation of the international political geography and even the emergence of quite a lot of new countries. One might wonder how these structural changes towards disintegration on the one hand and the building of regional economic blocks on the other hand influence the decentralized management of common natural resources. Global environmental problems have become a growing field of interest, both in academic research and in the political arena. From an economic point of view these environmental problems are interpreted as international externalities. In the case of greenhouse gas emissions or the depletion of the ozone layer, externalities work on a global level, regardless where they have their origin. Thus, national policies to stabilize the climate or to ensure UV protection through the ozone layer can be regarded as the decentralized provision of an international public good.

Interpreting unilateral national measures to abate harmful emissions in this way brings up the question what might be the analogies to the private provision of public goods on a national level. One fundamental aspect to it is the possibility that there may exist, both in the national as well as in the international context, cooperative and noncooperative scenarios for the supply of public goods. Cooperative solutions in an international context, however, suffer from the nonexistence of a higher authority that can force the cooperating agents to fulfill their contractual obligations. Therefore it is useful to follow either of two different approaches in the analysis of international environmental policy: The first is to concentrate on international cooperative solutions that are self-enforcing in the sense that there is no ex-post incentive to defect from an agreement. The other approach is to analyse the incentives of countries to manage global environmental resources noncooperatively.

When looking at the noncooperative case it is obvious that the standard hypothesis about the inefficiency of an uncoordinated, decentralized supply of public goods also applies for international environmental goods. Moreover, it is a well-known result in international environmental economics that there exist different reasons for these welfare losses. One is the incentive of each country to take a free ride on the efforts of other countries, the other is the fact that comparative cost advantages in the supply of an international environmental good may not be exploited.

An important question in the context of international environmental goods is

how heterogeneities between the actors influence the decentralized provision of such goods. Especially with regard to the inefficiencies mentioned above, one might wonder how certain asymmetries affect these, and in which quantitative dimensions. We can illustrate this idea with the modified SAMUELSON CONDITION for an efficient supply with an *international* public good. It requires the sum of the marginal rates of substitution (MRS) to be equal to the marginal rate of transformation (MRT) of *each* country. This means that we have as many equations to hold for an efficient allocation as there are countries involved. From a second-best perspective the question is which of these equations (in general none of them holding in the noncooperative equilibrium) should be brought to an equalisation most urgently, since it generates the largest welfare gains. In the present analysis we focus on the relative importance of welfare gains from equalizing the different MRTs, i.e. from the point of view of cost-effectiveness. The motivation for this perspective is that we want to be able to make general judgements on the profitability of instruments in international environmental policy to reach cost-effectiveness, as i.e. the concept of 'joint implementation'.

This paper concentrates on only one kind of asymmetry: countries differing in population size. In reality countries also differ in economic performance, endowments with primary resources, abatement technologies, information available to their governments or the political process of decision-making. But as can be shown, different kinds of heterogeneity (as e.g. national income and population size) often have a similar influence on the noncooperative allocation. We therefore look at only one kind of asymmetry here when analysing the impact of different extents of asymmetry on equilibrium allocation, inefficiencies, and their different sources. Although general, the judgements have to be made on an empirically plausible basis. For the problem of global warming there exist empirical estimations of the costs and benefits of abatement policies that allow to specify our general model. In section 3 we therefore look at noncooperative CO_2 emissions reductions.

The present analysis is connected with basically three branches of literature. The first and fundamental one is literature on the private provision of public goods (see e.g. [7] Bergstrom et al. (1986), [10] Cornes/Sandler (1986) or [22] Warr (1983)). One interesting question is for example if the striking neutrality-result of [22] Warr (1983) concerning the provision of a single public good in a Nash equilibrium also holds for other kinds of heterogeneity. In his model aggregate provision is unaffected by a

redistribution of income. In the model presented here, national population is redistributed, not income. The branch of literature that also focuses on cost-effectiveness and international transfers for the provision of international environmental goods is the theoretical and empirical work on the concept of joint implementation[1]. Joint implementation (JI) involves an agreement in which countries with high costs of pollution abatement invest in abatement efforts in a country with lower costs. It is not necessary that this happens in the context of an international environmental agreement where the investing country receives a credit for the abatement resulting from JI, although the discussion focuses on this. A country may trade with another simply to lower its own noncooperative abatement costs. A third branch of related literature are contributions in international environmental economics that analyse different kinds of asymmetries for noncooperative as well as cooperative solutions[2].

The paper is organised as follows: In section 2 we describe the basic two-countries, two-goods model that captures essential features of the noncooperative provision of international environmental goods. The efficiency conditions for national optimal behavior are oposed to those of a globally efficient allocation. In section 3 we suggest a plausible specification of this general model for CO_2 abatements and describe the properties of its noncooperative Nash and Stackelberg equilibria. For the case of Nash behavior, an index of inefficiency for each of the two sources of welfare losses is derived. In addition, we compare the quantitative importance of cost-effectiveness in the Nash equilibrium with that in the Stackelberg equilibrium. A discussion of the results and of possible extensions of the model of decentralized CO_2 abatements concludes the paper.

[1]For an overview see e.g. [19] Pearce (1994). For an empirically oriented work on JI under the framework convention on climate change see e.g. [14] Jackson (1995).

[2][12] Hoel (1991) analyses the effects of unilateral environmental policy on international negotions about reduced emissions. The welfare losses of uniform emission reductions in an international environmental convention with heterogenous countries are analysed in [13] Hoel (1992). The effects of asymmetries for the outcome of international environmental cooperations are discussed by [4] Barrett (1993), [6] Bauer (1992), [11] Folmer et al. (1993) or [21] Stähler (1994).

2 The Basic Model

Consider a world of two countries A and B with a world population N living in these two countries[3]: $N = n_A + n_B$. National populations are exogenously given, i.e. there is no migration between countries. In both countries, individuals derive utility from the consumption of a private good x and a pure international public good Q. The strictly concave utility function of individual i living in country k is

$$U_k^i = U_k^i(x_k^i, Q) \qquad \text{with} \qquad i = 1, ..., n_k \qquad \text{and} \qquad k = A, B\,. \tag{1}$$

Utility functions are twice differentiable and increasing in their arguments. For the purpose of national and international welfare comparisons we further assume that utility is measurable on an absolute scale and that it is interpersonally comparable[4]. The public good is pure in the sense that it makes no difference where it is provided, implying that national contributions are perfect substitutes. The total amount Q of the international environmental good is a function of national contributions q_A and q_B (i.e. this general formulation also includes crowding out of national contributions):

$$Q = f(q_A; q_B) \tag{2}$$

National income Y_k of country k is exogenously given and can be spent either on private consumption X or for the contribution q to the international public good Q. Normalizing the price of the private good to unity, national budget constraints are given by

$$\begin{aligned} &Y_k = X_k + T_k(q_k) \qquad \text{with} \qquad X_k = \sum x_k^i \qquad i = 1, ..., n_k \\ &\partial T_k/\partial q_k > 0\,, \quad \partial^2 T_k/\partial q_k^2 \geq 0\,, \qquad k = A, B \end{aligned} \tag{3}$$

$T_k(q_k)$ can be interpreted as the opportunity costs of providing q_k units of the international environmental good. The costs of providing one unit of it may vary,

[3]With minor modifications we use the standard two-country model of [20] Samuelson (1954) and [10] Cornes/Sandler (1986), chapter 5. We consider only two countries for the sake of simplicity and to be able to give a graphical illustration. Alternatively to the interpretation of the two actors as single countries, one of them could be regarded as the 'rest of the world'. Extensions are discussed in section 4.

[4]However, in this general model individuals may be different with respect to their preferences or their exogenous income.

whereas the price of the private good is held constant. $T'(q)$ represents the marginal rate of transformation ($dX/dq = -T'(q)$). The second derivative of $T(q)$ determines the curvature of the transformation line, i.e. the available technology to provide units of q.

Social welfare is characterized by an individualistic social welfare function W of the BERGSON-SAMUELSON type that is increasing in all arguments, twice differentiable and concave. National welfare depends directly on the utilities of the individuals belonging to that country and indirectly on their consumption bundles:

$$W_k = W_k(U_k^1, ..., U_k^{n_k}) = W_k(U_k^1(x_k^1, Q), ..., U_k^{n_k}(x_k^{n_k}, Q)) \qquad k = A, B \tag{4}$$

Correspondingly, global welfare is a function of the utilities of all individuals in both countries:

$$W = W(W_A, W_B) = \tilde{W}(U_A^1, ..., U_A^{n_A}, U_B^1, ..., U_B^{n_B}) \tag{5}$$

2.1 National Welfare Maximisation

The government of each country is assumed to maximize national welfare subject to its exogenous national income by choosing the national optimal contribution q_k to the international environmental good. We assume NASH behaviour of each government, i.e. the contribution level of the other country $\overline{q}$ is taken as given. The optimisation problem for each country k is:

$$\begin{aligned} &\max \quad W_k(U_k^1(x_k^1, Q), ..., U_k^{n_k}(x_k^{n_k}, Q)) \qquad \text{s.t.} \qquad Y_k = X_k + T_k(q_k) \\ &\text{with} \quad Q = f(q_A, q_B) \quad \text{and} \quad X_k = \sum x_k^i\,, \qquad i = 1, ..., n_k \qquad k = A, B\,. \end{aligned} \tag{6}$$

Differentiating the Lagrangian of the maximisation problem with respect to the control variables x_k^i and q_k and rearranging yields the necessary condition that implicitly determines the *national* optimal provision level q_k for each country k:

$$\sum_{i=1}^{n_k} \frac{\partial U_k^i / \partial Q}{\partial U_k^i / \partial x_k^i} = T_k'(q_k) \qquad k = A, B \tag{7}$$

This is the familiar SAMUELSON CONDITION for an efficient supply of a pure public good. It requires that the sum of individual marginal rates of substitution equals the marginal rate of transformation between the public and the private good ($\sum MRS = MRT$). However, the public good is an international one here. Hence, the efficiency condition (7) that ensures national optimal provision levels does not characterize internationally efficient allocations.

2.2 Global Welfare Maximisation

Globally optimal provision levels of the international public good Q can be derived through maximisation of global welfare $\tilde{W}$ by selecting globally optimal contributions q_A *and* q_B and choosing optimal quantities of x_k^i simultanously, subject to the global budget constraint:

$$\begin{aligned} \max \quad & \tilde{W}(U_A^1(x_A^1, Q), ..., U_A^{n_A}(x_A^{n_A}, Q), U_B^1(x_B^1, Q), ..., U_B^{n_B}(x_B^{n_B}, Q)) \\ \text{s.t.} \quad & Y = X + T_A(q_A) + T_B(q_B) \end{aligned} \tag{8}$$

The first order conditions for a globally efficient outcome together give

$$\sum_{k=A}^{B} \sum_{i=1}^{n_k} \frac{\partial U_k^i / \partial Q}{\partial U_k^i / \partial x_k^i} = T_k'(q_k) \qquad k = A, B\,. \tag{9}$$

Equation (9) is the SAMUELSON CONDITION for *globally* efficient quantitites of a pure international public good. It requires that the sum over all individual MRS in the world equals the marginal costs of providing q in both countries ($\sum MRS_{QX} = T_A'(q_A) = T_B'(q_B)$). Comparing (9) with the conditions for optimal national behaviour (7) we can state the following[5]:

As long as there exists more than one country there will be underprovision with the international public good because single countries do not choose abatement levels that take into account the positive effects on welfare in the rest of the world. Instead they consider only their national fraction of the global sum of individual MRS. Moreover, (9) requires an equalization of marginal costs across countries. Thus, even if every country took into account the positive international spillovers of its own environmental policy completely, uncoordinated national action would still generate welfare losses as long as marginal costs are not equalized. Therefore the comparison of (7) and (9) shows that there exist two sources of inefficiency. The first one is given through the possibility of *free-riding* on the contributions of other countries, the second one results from *comparative advantages* in the provision of the international public good that may not be exploited. Which of these effects is in fact dominating when countries differ in population size depends mainly on the characteristics of the international environmental problem considered. In order to analyse the relative importance of these two sources of inefficiency the general model has to be specified further. This is done in section 3.

[5]See [1] Arnold (1984), p. 118.

3 Costs and Benefits of Noncooperative Reductions of CO_2 Emissions

In the following we apply the model of the previous section to the problem of noncooperative CO_2 abatements of two countries that differ in size. A governments' decision on how much national CO_2 emissions should be abated ensues from balancing national benefits against costs of unilateral environmental policy. National benefits B of reducted CO_2 emissions depend on aggregated abatement efforts in the whole world, whereas national costs C depend only on the individual contribution of a country to global abatements. Net abatement benefits Π of country k are

$$\Pi_k = B_k(Q) - C_k(q_k) \,, \qquad k = A, B \tag{10}$$

and national abatements q_k add up to

$$Q = q_A + q_B \,. \tag{11}$$

The next step in order to explore the properties of a noncooperative equilibrium is to specify the costs and benefits of CO_2 abatements by a plausible functional form. To incorporate the population size adequately into the net benefit function it is useful to investigate how (10) is related to the general welfare analysis of section 2 and which additional assumptions have to be made. At first we assume that all individuals in the world are identical with respect to their preferences and their exogenous income. This is done in order to separate the influence of country size on noncooperative abatement levels from other aspects of asymmetry. Then the population size n_k of each country enters exogenous national income (3) in a trivial way:

$$Y_k = \sum_{i=1}^{n_k} y_k^i = n_k\,\overline{y} = n_k\,x_k + T_k(q_k) \,, \quad y_k^i = \overline{y}\;\forall\, i \,, \quad k = A, B \tag{12}$$
$$\Leftrightarrow\; x = \overline{y} - T(q_k)/n_k$$

Moreover, we assume now an additive separable utility function of the form

$$U(x, Q) = \beta(Q) + \gamma(x) \,, \tag{13}$$
$$\beta' > 0 \,, \quad \beta'' < 0 \,, \quad \gamma' > 0 \,, \quad \gamma'' < 0 \,.$$

This formulation leads from individual utility over to individual net benefits π from abatements. A discrete change in the abatement level is to be valued by calculating

utility with and without the abatement project. Its difference indicates the change in utility, i.e. individual net benefits from abatements[6]:

$$\pi(q) = U(x, Q) - U(q = 0) = \beta(Q) + \gamma(x) - \gamma(x_{max} = \overline{y}) \tag{14}$$

Assuming an *Utilitarian* welfare function, national net benefits Π_k from abatements are

$$\Pi_k(q_k) = \sum_{i=1}^{n_k} \pi(q_k) = n_k\, \pi = \underbrace{n_k\, \beta(Q)}_{B_k(Q)} - \underbrace{n_k\, [\gamma(\overline{y}) - \gamma(x_k)]}_{C_k(q_k)}\,, \quad k = A, B\,. \tag{15}$$

The first term represents gross national benefits from total abatements and can be specified as

$$B_k(Q) = n_k\, b\, (aQ - 1/2\, Q^2) \qquad \text{with} \quad a > Q\,, \quad b > 0 \qquad k = A, B \tag{16}$$

where b is an exogenous parameters that determines the slope of the marginal benefit function, and a is the abatement level where marginal benefits would become zero[7]. The second term expresses the social costs of national abatement quantities. The latter are zero for a country that does not abate any emissions ($C(q = 0) = 0$). Instead of using for the specification of $\gamma(x)$ a function that corresponds to (16), national abatement costs alternatively can be approximated[8] by

$$C_k(q_k) = \frac{c}{2}\,\frac{q_k^2}{n_k} \qquad \text{with} \quad c > 0 \qquad k = A, B \tag{17}$$

where c is an exogenous parameters that determines the slope of the marginal cost function. It comprises simultaneously the valuation of foregone units of the private consumption good and the type of the available abatement technology. A better abatement technology ceteris paribus implies a lower value of c, whereas a higher valuation of the private good X c.p. implies a higher value of c. Abatement costs also depend on the size of a country's population. Abatement costs are c.p. higher for lower n_k because the marginal utility of the private consumption good X depends on

[6]See e.g. [15] Johansson (1993), p. 21.

[7]We assume initial emissions being so high that global abatements Q never reach the point of satiation a. See [5] Barrett (1994), p. 4.

[8]We can see this from $C(q) = n\gamma(\overline{y}) - n\gamma(\overline{y} - T(q)/n)$ and $C'(q) = -n\gamma'\,(-T'(q)/n) = \gamma'\, T'(q)$. If $\gamma(x) = b_x(a_x\, x - 1/2\, x^2)$ as in (16), then marginal utility γ' is increasing with q and decreasing with n because of the individual budget constraint (12). The marginal rate of transformation $T'(q)$ is increasing with q and depends on the technology, i.e. $T''(q)$ as in (3).

how many units of it each individual has to give up for one unit of national abatement q. This in turn depends on population size. The more populated a country is, the more shoulders there are that can share the burden of i.e. one ton of CO_2 emission reduction. Having specified the cost and benefit functions of CO_2 abatements, net benefit function (10) can be rewritten as[9]

$$\Pi_k = n_k\, b\,(aQ - \frac{1}{2}\,Q^2) - \frac{c}{2}\,\frac{q_k^2}{n_k}\,. \tag{18}$$

Parameters a, b and c are taken to be the same for both countries[10].

Empirical estimations of costs and benefits of greenhouse gas emissions reductions confirm the above functional specification. Choosing a certain benefit function is difficult for several reasons: First of all, despite extensive empirical work in this field[11] there is still substantial lack of knowledge about the consequences of global warming for the earth's biosystem and especially its different regional and long-term impacts. Moreover, the individual judgements that people in different countries put on these consequences are private information. Thus, the adoption of a monotonic, well-behaved benefit function is somewhat arbitrary. If we take into account long-term effects and assess a significant risk aversion against potential catastrophic scenarios[12], it seems reasonable to suppose that marginal damages will increase with the level of greenhouse gas emissions, implying positive but decreasing marginal benefits of reducing carbon dioxide emissions. One possibility to specify such a benefit function is to choose one that exhibits *linear decreasing marginal benefits* as in (16). It has been argued for the case of carbon dioxide, however, that it might be appropriate to assess constant marginal abatement benefits. At least for relatively moderate emission changes warming is not linear but logarithmic in CO_2 concentrations so that marginal damages that rise in temperatures may well be constant in CO_2 emissions and concentrations[13]. This assumption would imply that countries do not react to changes in the other countries' abatement activities, i.e. there would be

[9]This is a modified version of the functional form used by [3] Barrett/OECD (1992), p. 17-22.

[10]As mentioned above this is done to isolate the effect of asymmetry in population size on the noncooperative equilibrium. Choosing different parameter values for each country would allow to incorporate also other heterogeneities.

[11]For an overview see [8] Cline (1992), chapter 4, and [18] OECD (1991), chapter 1.

[12]See [9] Cline (1992), chapter 6.

[13] See [6] Bauer (1992), p. 4. [16] Nordhaus (1991), p. 148 also assesses constant marginal benefits as a rough approximation for the US.

no 'carbon leakage' resulting from strategic behavior[14]. Anyhow, assuming *constant* marginal benefits does not change the qualitative results concerning the relationship between asymmetry in size and the two sources of inefficiency to be reported below.

The cost function of national CO_2 emission reductions is specified by most of the literature by assessing increasing marginal costs. Although existing empirical estimations differ in their quantitative dimensions, the general shape of the estimated cost schedule is barely controversial[15]. In line with this we assume *linear increasing marginal costs* of abatements, as implied by the *quadratic* cost function (17). This form reflects the fact that it becomes the more costly for a country to reduce additional CO_2 emissions (in terms of foregone consumption of the private good X) the higher are its absolute abatement quantities.

3.1 Nash Behavior

In this section we discuss the properties of the noncooperative equilibrium when national governments exhibit NASH behaviour. In this case there is an independent maximization of net benefit function (18) for each country by choosing *national* optimal abatement levels given the abatement quantity of the other country. For national abatement quantities to be optimal, marginal benefits $B'(Q)$ have to be equal to marginal costs $C'(q)$:

$$\frac{\partial \Pi_k}{\partial q_k} = n_k\, b\,(a - Q) - c/n_k\, q_k \stackrel{!}{=} 0 \quad \Leftrightarrow \quad n_k\, b\,(a - Q) = c/n_k\, q_k \tag{19}$$

Solving (19) for q_k gives the optimal reactions of country k for given abatement levels $\overline{q}$ in the other country:

$$q_A(\overline{q}_B) = \frac{a - \overline{q}_B}{1 + \frac{c}{n_A^2\, b}} \tag{20a}$$

$$q_B(\overline{q}_A) = \frac{a - \overline{q}_A}{1 + \frac{c}{n_B^2\, b}} \tag{20b}$$

[14] This is due to the fact that individual marginal benefits and costs have to be equal in the national optimum. If marginal benefits are decreasing and marginal costs increasing with abatement quantities, an increase of abatement in the rest of the world, for example, will lower marginal benefits in the home country and induce a decrease in national abatement. When marginal benefits are constant, there is no such interdependency.

[15] [17] Nordhaus (1991), p. 929.

The intersection of these two reaction curves determines the COURNOT-NASH equilibrium CN. This equilibrium is unique because the reaction curves are linear and it is stable, since the slopes of the curves are less than 1 in absolute value. The equilibrium values q_k^{CN} of national abatements are

$$q_A^{CN} = \frac{a\, n_A^2}{n_A^2 + n_B^2 + c/b} \tag{21a}$$

$$q_B^{CN} = \frac{a\, n_B^2}{n_A^2 + n_B^2 + c/b} \tag{21b}$$

and aggregate abatement in the equilibrium is

$$Q^{CN} = \frac{a(n_A^2 + n_B^2)}{n_A^2 + n_B^2 + c/b} = \frac{a(\alpha^2 N^2 + (1-\alpha)^2 N^2)}{\alpha^2 N^2 + (1-\alpha)^2 N^2 + c/b} \tag{22}$$

where $\alpha \equiv n_A/N\ , \qquad 1/2 \leq \alpha < 1\ .$

The parameter α defines the size of country A relative to world population N and indicates the extent of asymmetry in population size. Country A is taken to be the big country ($\alpha \geq 1/2$).

National abatement levels that are *globally* optimal are derived by maximising the sum of net benefits $\Pi = \pi_A + \pi_B$ with respect to q_A and q_B:

$$\frac{\partial \Pi}{\partial q_A} = N\, b\, a - N\, b\, q_A - N\, b\, q_B - c/n_A\, q_A \stackrel{!}{=} 0 \tag{23a}$$

$$\frac{\partial \Pi}{\partial q_B} = N\, b\, a - N\, b\, q_A - N\, b\, q_B - c/n_B\, q_B \stackrel{!}{=} 0 \tag{23b}$$

which yields

$$q_k^* = \frac{a\, n_k}{N + \frac{c}{bN}}\ , \qquad k = A, B\ . \tag{24}$$

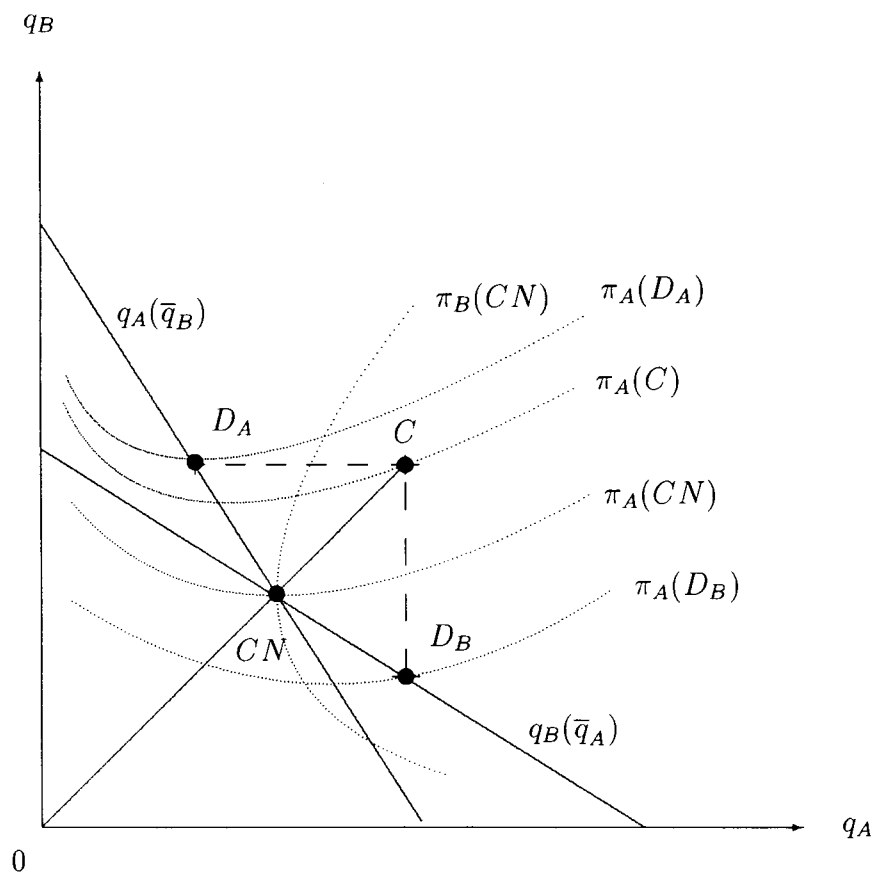
Efficient aggregate CO_2 abatement is

$$Q^* = \frac{a}{1 + \frac{c}{bN^2}} \tag{25}$$

The globally efficient allocation could be reached through full cooperation of the countries. However, due to the prisoner's dilemma type of the decision problem in this simplyfied model, a cooperative solution cannot be reached. The underlying incentive structure is shown in Fig.1. It illustrates the above model of noncooperative

CO_2 abatements for the case of symmetric countries ($n_A = n_B$) and is basically a graphical representation of the pay-off matrix for country A. The two linear reaction curves correspond to equations (20). Their intersection CN represents the COURNOT-NASH equilibrium. The abatement combinations D_A, D_B and C are other allocations that illustrate the strategic character of the abatement decision by indicating possible pay-offs for country A.

Figure 1



C (Cooperation) represents the globally efficient abatement combination (q_A^*, q_B^*). Allocations D_A and D_B indicate the net benefit for country A, when starting from C, either of the two countries decides to take a free ride on the cooperative abatement level of the other country and defects. As we see from iso-net benefit curves $\pi_A(\cdot)$ drawn for country A, the ranking of net-benefits for country A in Fig. 1

$$\pi_A(D_A) > \pi_A(C) > \pi_A(CN) > \pi_A(D_B)$$

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corresponds to the payoff-structure of the 2x2 normal form prisoner's dilemma game[16]

$$(D,C) \succ (C,C) \succ (D,D) \succ (C,D)$$

where defection (D) is the dominant strategy for both players.

Comparing the globally efficient with the noncooperative allocation of abatements illustrates the two sources of inefficiency mentioned above. From a comparison of (25) with (22) we can calculate that total noncooperative abatements reach only a suboptimal level ($Q^{CN} < Q^*$ for $\alpha < 1$), reproducing the standard result of decentralized underprovision with a pure public good. Moreover, not only aggregate abatement is suboptimal, but also its distribution on the countries is inefficient: (24) implies that the globally efficient distribution of national abatements is $q_A^*/q_B^* = n_A/n_B = \alpha/(1-\alpha)$. However, from (21) follows that national abatements in the Nash equilibrium are distributed as $q_A^{CN}/q_B^{CN} = n_A^2/n_B^2 = \alpha^2/(1-\alpha)^2$.

How do inefficiencies through decentral noncooperative abatements change when there is more or less asymmetry in size? The extent of undersupply of abatement activities resulting from such an independent adjustment equilibrium can be measured when we compare aggregated abatement Q^{CN} in the noncooperative equilibrium with globally efficient aggregate abatement Q^*. In Fig.1 the ratio $\overline{0CN}/\overline{0C}$ reflects this extent of undersupply[17]. We call it Φ and use equations (22) and (25) for an analytical expression:

$$\begin{aligned} \Phi \equiv \frac{Q^{CN}}{Q^*} &= \frac{n_A^2 + n_B^2 + c/b\left(\frac{n_A^2+n_B^2}{N^2}\right)}{n_A^2 + n_B^2 + c/b} \qquad (26) \\ &= \frac{\alpha^2 N^2 + (1-\alpha)^2 N^2 + c/b\,(\alpha^2 + (1-\alpha)^2)}{\alpha^2 N^2 + (1-\alpha)^2 N^2 + c/b} < 1 \end{aligned}$$

As the ratio (26) increases there is less underprovision through 'easy riding'. The extent of underprovision with abatement policies depends on the parameters b and c, world population N and the asymmetry in population size α. As b or N increase[18], there is less underprovision and as c increases, underprovision becomes more important. As long as the benefit parameter b and/or world population N exhibit

[16]The first term in brackets indicates the behaviour of country A, the second that of country B.

[17]This is the 'index of easy riding' proposed by [10] Cornes/Sandler (1986), p. 80-82.

[18]N has an influence on Φ since in this model exogenous income Y increases with N by assumption. Thus, the more populated the world is the cheaper it gets to abate 1 unit of emissions.

considerably greater values than the cost parameter c, the inefficiency from too low abatement quantities tends to be small.

Index Φ shows how the distribution of the world's population over its (two) countries affects easy riding. The more asymmetric in size the countries are, the less inefficiencies are generated by 'easy riding'. This is because the population size of a country enters its net benefit function (19) and thereby influences aggregate noncooperative abatement. Consider for a moment the hypothetical scenario where world population is allocated in just one single country ($n_A = N \Leftrightarrow \alpha = 1$). In this extreme case the decision problem of the national government is identical to the planning problem of a world's central planner. Then by definition, there do not exist any transnational spill-overs of environmental policy and thus, there is no underprovision. Analytically, we can observe the influence of asymmetry in population size on inefficiencies through undersupply by derivating Φ with respect to α:

$$\frac{d\Phi}{d\alpha} = \frac{2\, c/b\, N^2 \left(1 + \frac{c}{bN^2}\right)(2\alpha - 1)}{(\alpha^2 N^2 + (1-\alpha)^2 N^2 + c/b)^2} > 0 \quad \text{for} \quad \alpha > 1/2 \tag{27}$$

With growing asymmetry there are less inefficiencies through 'easy riding' of national governments on abatement efforts of other countries.

Underprovision, however, is not the only source of inefficiency. Even if $Q^{CN} = Q^*$, there may be welfare losses from a cost-inefficient distribution of abatements over the countries. The latter is the case if marginal social costs are not equalized across countries. These welfare losses could be measured directly by comparing world welfare under globally efficient abatements with welfare under national contributions that sum up to Q^*, but that are as inefficiently distributed as in the Nash equilibrium. Alternatively, we can compute the hypothetical quantity of cost-effective abatements Q^{CE} that could have been realized at equal total costs as in the Nash equilibrium. By calculating for a given asymmetry total costs C^{CN} of abating CO_2 emissions in the COURNOT-NASH equilibrium and setting this equal to hypothetical total costs C^{CE} where national abatements q^{CE} are cost-effective,

$$C_A(q_A^{CN}) + C_B(q_B^{CN}) = C^{CN} \stackrel{!}{=} C^{CE} = C_A(q_A^{CE}) + C_B(q_B^{CE}) \tag{28}$$

we can determine[19] aggregate cost-effective abatements Q^{CE}:

$$Q^{CE} = \frac{aN}{n_A^2 + n_B^2 + c/b} \sqrt{\frac{n_A^3 + n_B^3}{N}} = \frac{aN^2\sqrt{3\alpha^2 - 3\alpha + 1}}{\alpha^2 N^2 + (1-\alpha)^2 N^2 + c/b} \tag{29}$$

[19]This is done by substituting (21) into cost functions $C_k(q_k^{CN})$, $q_A^*/q_B^* = n_A/n_B$ into $C_k(q_k^{CE})$, and solving (28) for q_k^{CE}.

Correspondingly to the 'index of easy riding' (26), we define an 'index of cost-effectiveness' Ψ by setting aggregate noncooperative abatements Q^{CN} in relation to cost-effective abatements Q^{CE}:

$$\Psi \equiv \frac{Q^{CN}}{Q^{CE}} = \frac{2\alpha^2 - 2\alpha + 1}{\sqrt{3\alpha^2 - 3\alpha + 1}} \tag{30}$$

From (30) we see that cost-inefficiencies in this model only depend on the relative size of country A, i.e. the extent of asymmetry. This comes from the fact that we have excluded any other kind of heterogeneity (e.g. different national abatement technologies), here. For $1/2 < \alpha < 1$, $\Psi < 1$ and for $\alpha = 1/2$, $\Psi = 1$. In the latter case there is no cost-ineffectiveness, since both countries abate identical quantities at same marginal costs. Although Q^{CN} includes also inefficiencies from easy-riding, the same is true for Q^{CE}, so that this effect cancels out when calculating Ψ for different scenarios of asymmetry (i.e. different values of α). Thus, index Ψ can be directly compared with index Φ that measures the inefficiencies through underprovision.

How does cost-effectiveness through decentral noncooperative abatements change when there is more or less asymmetry in size? Deriving Ψ with respect to α gives

$$\frac{d\Psi}{d\alpha} = \frac{6\alpha^3 - 9\alpha^2 + 4\alpha - 1/2}{(3\alpha^2 - 3\alpha + 1)^{3/2}} \,. \tag{31}$$

For different values of asymmetry α, (31) may be positive or negative. In the case of two countries of equal size ($\alpha = 1/2$) there is full cost-effectiveness. Starting from this symmetric case, cost-inefficiencies are increasing with asymmetry until they reach their maximum, indicated by the minimum value of Ψ. Beyond this extent of asymmetry cost-ineffectiveness becomes smaller again[20]. There is again full cost-effectiveness in the case of only one country ($\alpha = 1$). The reason for this non-monotonic relationship is as follows: when countries are very different in size, marginal costs of abatements will be very high for the small country, since those are the higher the smaller is a country's population. At the same time marginal costs are also very high for the big country, since it chooses big abatement quantities. If this is the case, marginal costs are not as much different as in the case of only moderate asymmetry.

Since we observe two sources of inefficiency when countries abate their CO_2 emissions noncooperatively, one might wonder which of them is quantitatively more

[20]For $\tilde{\alpha} \approx 0.8$, $d\Psi/d\alpha = 0$ and cost-effectiveness has its minimum value $\Psi_{min}(\tilde{\alpha})$.

relevant for a given extent of asymmentry. As we have stated already there is cost-effectiveness if the population size is the same in both countries. However, for large differences in population size cost-ineffectiveness is becoming substantial and may exceed even welfare losses resulting from underprovision with abatement efforts. If this was the case potential cooperative solutions, i.e. international environmental agreements about CO_2 abatements should aim at *redistributing* national abatement quantitites as a matter of priority and not only try to *raise* national abatements.

If we compare for example the maximal welfare loss through mis-distribution of national abatements (Ψ_{min}) with the corresponding welfare loss resulting from easy riding $\Phi(\tilde{\alpha})$ we can calculate that the former is greater, if

$$-\frac{(2\tilde{\alpha}^2 - 2\tilde{\alpha} + 1)(1 - \Psi_{min})}{2\tilde{\alpha}^2 - 2\tilde{\alpha} + 1 - \Psi_{min}} > \frac{c}{bN^2} \,. \tag{32}$$

If this inequality holds, maximal cost-ineffectiveness is greater than the corresponding welfare loss from too low abatement quantities. The latter is the case when c is small relative to b and N. This is because parameters b and c influence the slopes of the (marginal) abatement cost and benefit functions and thereby have an effect on the balancing of costs and benefits for each individual country when determining its noncooperative abatements. The larger b in relation to c, the higher are ceteris paribus noncooperative abatement quantities and the lower is the extent of underprovision. Cost-inefficiencies however only depend on the asymmetry in population size α. Thus, the welfare loss from undersupply c.p. gets less severe in relation to cost-ineffectiveness for smaller values of c/b.

From the above considerations, we can conclude two conditions for a substantial cost-ineffectiveness to exist that may exeed even the welfare loss from free riding behavior:

- countries are different in population size
- national costs of intensified unilateral CO_2 abatements are growing with a greater rate than their benefits.

In our two-country model the asymmetry in country size does not have to be extreme for (32) to hold. If these asymmetries play an important role in the real-world situation of non-cooperative greenhouse gas abatements as well, there is a strong case for the concept of 'joint implementation' as a mechanism to allocate abatement

activities to those countries in which they have the smallest social costs. At the same time it is an argument against negotiating a uniform percentage reduction of CO_2 emissions.

3.2 Stackelberg Behavior

If the asymmetry in country size is substantial, one might argue that this affects also the nature of the strategic interaction between different national governments. In such a case countries might differ not only with respect to some exogenous characteristics, but due to their strongly uneven position there may also exist a systematic difference with respect to their behavior. A possible way to take into account this aspect within the present context is to assume that one of the two countries behaves as a *Stackelberg* leader. In our model it is not unplausible to presume that the 'big' country A plays this role. The country that is much bigger than its counterpart may have the power to act first in the game of noncooperative environmental policy because of a threat-potential that it has vis-a-vis the small country. The small country may be vulnerable to actions of the big country in other fields of international policy.

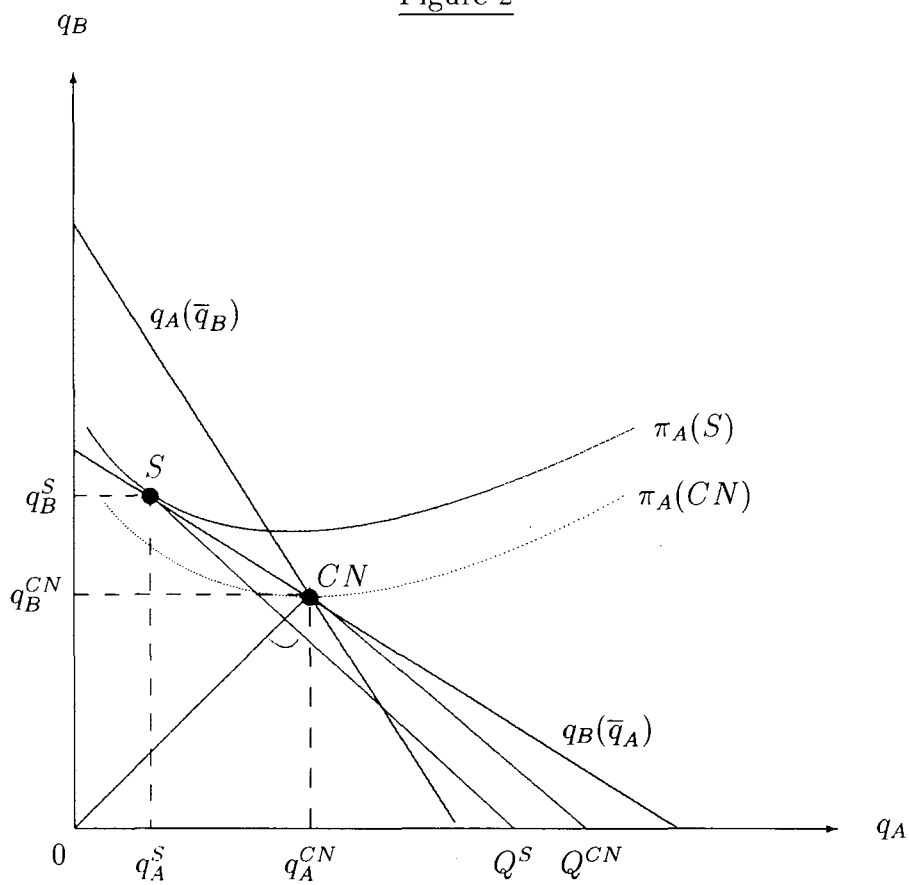
If Stackelberg behavior is more appropriate to model the strategic interaction between to (or more) asymmetric countries than Nash behavior, one might wonder about the properties of the noncooperative equilibrium with regard to the two sources of welfare losses analysed above. Since only the type of behavior, but not the basic decision-problem changes, we can use net-benefit function (18) in order to derive the Stackelberg equilibrium. Whereas the 'small' country B still takes the abatement level of the other country as given and decides about its own abatements on the basis of reaction function (20b), country A as the Stackelberg leader has a different rationale. Being aware of the decision-problem for country B, country A chooses itself an abatement quantity that induces an abatement decision of country A which maximizes its own national welfare. In other words, country A maximizes its welfare not subject to a given abatement level $\overline{q}$, but subject to the Nash behavior (the reaction function) of country B.

The resulting Stackelberg equilibrium S is shown in Fig.2 for the case of two countries of equal size[21]. It illustrates the gain for country A relative to

[21]Although Stackelberg behavior was introduced above for the asymmetric case, for the

the Nash equilibrium CN as well as the consequences for underprovision and cost-effectiveness.

Figure 2



Country A as the Stackelberg leader can improve its welfare position to $\pi_A(S)$ in comparison to its welfare $\pi_A(CN)$ in the Nash equilibrium. By choosing abatements of q_A^S that are lower than its abatements under Nash behavior, it causes country B to abate more than in the symmetric Nash equilibrium. Thus, country A exploits its position as a leader to improve its national welfare on the expense of national welfare in country B. From a global perspective, however, the Stackelberg equilibrium is even more inefficient than the Nash equilibrium. Not only are total abatements lower[22] ($Q^S < Q^{CN}$), i.e. the extent of underprovision is greater, but also there is no cost-effectiveness. This is because in the symmetric case countries should abate identical

comparability with Fig.1 it is shown here the symmetric case.

[22]This can be seen in Fig.1 from the lines with a slope of -1 that are drawn from the 2 equilibrias to the horizontal axis.

quantities ($q_A^*/q_B^* = n_A/n_B$) which is not the case here. The relevant case with Stackelberg behavior, however, is when countries are (much) different. Also then, the welfare loss from 'easy riding' is greater than with Nash behavior (for all values of α). On the other side welfare losses from a cost-ineffective misdistribution of abatements are smaller compared to the Nash equilibrium. From the latter we know that the big country will abate more than would be cost-effective ($q_A^{CN}/q_B^{CN} = n_A^2/n_B^2$). In the Stackelberg equilibrium this cost-ineffectiveness is reduced to a certain extent, since the big country induces the smaller one to abate more.

If the reduction of cost-ineffectiveness can be so large that it overcompensates the higher extent of underprovision, i.e. if the Stackelberg equilibrium for a given asymmetry can be less inefficient than the corresponding Nash equilibrium, has to remain open here. What can be said is that cost-ineffectiveness plays a less important role under Stackelberg behavior than with Nash behavior. This means that if big countries really behave as Stackelberg leaders in noncooperative CO_2 abatements, then the most important problem to solve is underprovision, not misdistribution of abatements. On the other side it is questionable if Stackelberg behavior is not a too strong assumption on the strategic interdependence in the case of national CO_2 abatements, i.e. if the decisions of national governments really depend strongly on the abatement decisions in the rest of the world.

4 Discussion

The paper shows that there exist two sources of inefficiency from the noncooperative provision of an international environmental good if countries differ in size. From the Samuelson condition for international public goods we see that inefficiencies arise from "beggar thy neighbour" behaviour of national governments as well as from not exploiting comparative cost advantages in the supply of such environmental goods. In the case of global warming linear decreasing marginal benefits and increasing marginal costs of unilateral CO_2 abatements are plausible to mirror the decision problem of a rational welfare-maximising national government. With this specification there exists a unique and stable noncooperative equilibrium of national CO_2 abatements, viz. a prisoner's dilemma. The welfare losses that go along with a Nash equilibrium depend on the asymmetry in population size. Whereas underprovision becomes less important the more asymmetric in size the countries

are, cost-ineffectiveness may grow or shrink with growing asymmetry. For certain parameter values cost-ineffectiveness is quantitatively more important than the welfare loss from 'easy riding'. If in reality the latter is the case cannot be answered in this framework. When the asymmetry is substantial, cost-ineffectiveness is important. But in such a scenario noncooperative abatements may be according to a Stackelberg equilibrium. In the Stackelberg equilibrium, however, cost-ineffectiveness is not as important as in the Nash equilibrium. In order to assess if e.g. the concept of 'joint implementation' as an instrument to reach cost-effectiveness is of great empirical importance, the type of strategic behavior has to be known. Moreover, costs and benefits of CO_2 abatements have to be empirically estimated and other aspects have to be taken into account that have been ignored here.

A heterogeneity which has not been considered are differences in (per capita) national income. It can be easily seen, however, that this aspect is implicitly incorporated in our analysis. If we presume that national benefits of CO_2 abatements are cet. par. higher for richer countries (i.e. there is more to lose from global warming) and that this can be expressed by a higher benefit parameter b_k[23], then the results generally also hold for asymmetry in national income, since b and n_k always show up together as a product in the equations of the model.

An alternative plausible way to specify national abatement costs would be to incorporate explicitly the level of emissions before abatements are undertaken, thereby indicating the upper bound for potential cost-effective redistributions of abatement quantities. Clearly marginal costs of CO_2 abatements are the higher the lower the status quo of emissions E_k is. If we assume that the marginal cost of abatement is the same for all countries for the same level of *percentage* abatement, the corresponding cost function is[24] $C_k(q_k) = cq_k^2/2E_k$. Assuming that $E_k = n_k \cdot \overline{e}$, with $\overline{e}$ being the identical per capita emission of every individual in the world, we see that this modification does not change the qualitative result of the model used here.

Countries may also differ with respect to abatement technologies they have available. They may have different alternatives at their disposal to substitute 'dirty' against 'clean' energy production, for example. In our model this kind of asymmetry could be mirrored by different parameter values c_k for each country, i.e. different slopes of the (marginal) abatement cost function. The effects of nationally differing

[23]A similar specification is used by [3] Barrett/OECD (1992, p. 22).

[24]See e.g. [3] Barrett/OECD (1992, p. 19).

abatement costs on the relative importance of cost-ineffectiveness when countries differ in size are not unambiguous. If the 'big' country is the one with a less costly abatement technology, the two asymmetries work in the same direction and the above results are strengthened. The opposite is true if the 'small' country has e.g. better substitution possibilities in the energy sector. Which of these scenarios may be more realistic for the most important greenhouse gas emitting countries is an empirical question[25].

Even more important than the extensions discussed so far is the consideration of more than just two countries. The results of this model are very sensitive to the number of competing countries. It is obvious that also with numerous countries there will exist the two sources of inefficiency described above. Their relative quantitative importance, however, may change considerably. Intuitively one expects the inefficiencies from underprovision to become more severe as the number of countries involved increases. This is because the positive international spill-overs from noncooperative environmental policy will be greater in relation to national net benefits. This in turn implies that cost-ineffectiveness gets less important in relation to undersupply and the results of the two-country model are at least weakened in a n-country framework. This drawback even holds if we only take into consideration the limited number of countries that is responsible for e.g. 80% of global greenhouse gas emissions. It is thus necessary to assess the relevance of this extension by a model that incorporates an empirically plausible number of countries as well as the other kinds of heterogeneity discussed above.

There are a number of other simplifying assumptions: the analysis is presented in a static, partial equilibrium framework where prices are not affected, income and emissions are exogenously determined, there is no trade in private goods, and national governments are treated as unit benevolent actors. The focus of the model, however, is the strategic interaction of countries when determining in a decentral way their international environmental policies. For this basic problem the classic COURNOT model can serve as a useful basis.

The preceding analysis tried to give at least partly an answer to the question raised initially how heterogeneities between countries influence their international environmental policies and how these have to be judged with regard to global wel-

[25]See e.g. [2] Barbier et al. (1991) or [14] Jackson (1995).

fare. We have not considered other asymmetries than population size here. Neither we have treated the question of how specific differences influence the outcome of cooperative solutions. In real politics, though, we observe numerous international environmental agreements that have been implemented more or less successfully. Knowing the potential welfare gains from cooperation as discussed here, the attractiveness of cooperative arrangements for an effective management of common environmental resources is obvious. Therefore the analysis of noncooperative scenarios in international environmental problems is only a starting point for the question of how asymmetries between countries can be exploited to promote international cooperation over environmental goods.

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