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Abstract

From the perspective of standard public good theory the total amount of greenhouse gas mitigation (or public good supply in general) will be lower in a leader-follower game than in a simultaneous Nash game so that strategic leadership is disadvantageous for climate policy. We show that this need no longer be true when the leading country has the option to employ a technology by which it can reduce its abatement costs and thus improve the productivity of its contribution technology. Our general result is illustrated by an example with Cobb-Douglas preferences and, finally, an empirical application to global climate policy is briefly discussed.

JEL-Codes: C720, H410, O310, Q540, Q550.

Keywords: public goods, leadership, choice of technology, climate policy.

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1. Introduction

The potential and likely effects of leadership play a prominent role in the scientific and public debate on global public goods, for which climate protection is the most prominent example. On the one hand, climate policy in some countries like Germany is driven by the hope that leadership of a country or a group of countries will improve public good provision. On the other hand, standard public good theory (see ,e.g., Sandler, 1992, pp. 57 – 58, and Varian, 1994) has shown that in the leader-follower (Stackelberg) game with sequential moves public good supply becomes smaller than in the case with simultaneous moves so that "the tendency toward underprovision is even more marked at the equilibrium of the sequential process than at the Nash-Cournot equilibrium" (Cornes and Sandler, 1996, p. 331). But also in a cooperative scenario, in which a bargaining solution is attained, leadership may be detrimental to public good supply (see Hoel, 1991, and Buchholz and Konrad, 1994). But there have also been several attempts to vindicate the position of leadership optimists (see Edenhofer et al., 2015, and Schwerhoff, 2016, for overviews), e.g. by taking into account that leadership may resolve uncertainties on the costs and benefits of public goods (see Hermalin, 1998, and Brandt, 2004), and facilitate communication (see Barbieri, 2012) or by integrating features of behavioral economics (e.g. other-regarding preferences and expectations of reciprocity) into models of voluntary public good provision (see Buchholz and Sandler, 2016). In this paper we add another argument to support the belief that leadership can have a positive effect both on the level of public good supply and on the utilities of the two countries involved so that a Pareto improvement may result.

The mechanism, which underlies these positive effects of leadership, completely works within the standard framework of public good theory (see Bergstrom, Blume and Varian, 1986, and Cornes and Sandler, 1996). In particular, it does without assuming specific preferences or asymmetric information but sticks − in a scenario with certainty and complete information − to the conventional weak assumption that "governments are … the narrow payoff-maximizers postulated in models as those of Hoel (1991) and Varian (1994)" (Schwerhoff, 2016, p. 200). At the same time, the analysis takes an empirically relevant element of leadership behavior in climate policy into account, which consists in the development of new climate friendly technologies to make greenhouse gas mitigation less expensive. Against this background, the main point of our analysis is that by acting as the leader in the Stackelberg game a country has a higher incentive to utilize a cost-saving "green" technology than in the Nash game. The positive effect on public good supply that is caused by the improved technology then may be so strong that it overcompensates the negative effect that would occur in the usual leader-follower scenario.

The structure of the paper will be as follows: In Section 2 we describe an otherwise standard public good model with two countries L and F in which one of the countries, i.e. country L, has the possibility of applying a new technology, which improves its productivity in public good provision without causing any cost for country L. Building on Buchholz and Konrad (1994) and Ihori (1996) Section 3 first of all provides a condition that country L does not want to take this opportunity in the Nash game but adheres to a less productive technology. If country L instead is the leader in a Stackelberg game of public good provision it always has an incentive to apply such a productivity-enhancing technology, which is also shown in Section 3. In Section 4 we then present a general condition, which ensures that public good supply in the Stackelberg equilibrium with the new improved technology in country L exceeds public good supply in the original Nash equilibrium with the old less productive technology. In that case leadership in public good provision not only is beneficial for public good supply but also yields a Pareto improvement. In Section 5 it is confirmed through a Cobb-Douglas example that this general condition is not void. In Section 6 we conclude by especially giving some brief hints at empirical applications of our theoretical results.

2. The Framework

We assume that there are two countries L and F, which have the same utility function $u(x_i, G)$, where x_i is private consumption of country $i = L, F$, respectively, and G is public good supply. This utility function has the standard properties, i.e. it is twice continuously differentiable and strictly monotone increasing in both variables and quasi-concave. The first partial derivatives of $u(x_i, G)$ w.r.t. x_i and G are denoted by u_1 and u_2, respectively. Moreover, it is assumed that both the private and the public good are non-inferior. This implies that the (income) expansion paths $e(G, \rho)$, which connect all points in the x_i-G-diagram where the marginal rate of substitution *mrs* between the private and the public good is equal to ρ, are well defined and strictly monotone increasing in G.

The public good is produced by a summation technology, i.e. $G = g_L + g_F$, where g_L and g_F are country L's and country F's public good contributions. The productivity parameters of both countries, i.e. their marginal rates of transformation *mrt* between private consumption and the public good, are assumed to be constant and equal to $a_0 = 1$ in the initial state. But while country F's productivity parameter will stay at $a_0 = 1$ throughout the whole analysis country L may − at a stage before the public good provision game starts − choose a technology with a higher productivity parameter $a > 1$. The costs of public good provision then fall to $\frac{1}{a}$ for country L, which in the context of greenhouse gas mitigation means the transition to an improved technology for greenhouse gas abatement. Unlike, e.g., Stranlund (1996) there is no technology spillover from country L to country F.

If the initial endowment ("income") of country L is denoted by w_L and that of country F by w_F an allocation (x_1, x_2, G) is feasible (and no resources are wasted) if and only if $az_L + z_F = G$, where $z_i = w_i - x_i$ denotes the part of income country $i = L, F$ spends on public good provision. This feasibility constraint is obviously equivalent to $ax_L + x_F + G = aw_L + w_F$, which is the foundation for our characterization of the interior Nash equilibria NE, where both countries make strictly positive contributions to the public good. To that end we observe in the spirit of the Aggregative Game Approach (see Cornes and Hartley, 2007) that in such an interior NE the *mrs* of both countries must coincide with their respective *mrt,* which implies that country L's position lies on the expansion path $e(G,a)$ and that of country F is on the expansion path $e(G,1)$. Combining this with the feasibility constraint gives the following condition, which characterizes public good supply $G^N(a)$ in an interior NE for some given contribution productivity parameter a:

(1) $$ae(G^N(a),a) + e(G^N(a),1) + G^N(a) = aw_L + w_F .$$

Private consumption of country L in an interior NE then is $x_L^N(a) = e(G^N(a),a) < w_L$ and that of country F is $x_F^N(a) = e(G^N(a),1) < w_F$. Country L's public good expenditures then are $z_L^N(a) = w_L - x_L^N(a)$ which yields the public good contribution $g_L^N(a) = az_L^N(a)$. Analogously, for country F we have $g_F^N(a) = z_F^N(a) = w_F - x_F^N(a)$. Existence and uniqueness of the NE follow from normality of the public good and, given equal preferences of both countries, interiority of the NE is ensured when incomes of the both countries do not diverge too much (see, e.g., Cornes and Hartley, 2007). To define upper bounds for public good supply in an NE let, similar as in Andreoni (1988), $\bar{G}_L(a)$ be defined by the condition $e(\bar{G}_L(a),a) = w_L$ and $\bar{G}_F(1)$ by $e(\bar{G}_F(1),1) = w_F$. As expansion paths are increasing in G in an interior NE we clearly have $G^N(a) < \bar{G}_L(a)$ and $G^N(a) < \bar{G}_F(1)$.

In the same situation an interior Stackelberg equilibrium SE results from maximizing utility of the leading country L, i.e. $u(w_L - z_L, az_L + z_{RF}(az_L)) \to \max$, where $z_{RF}(g_L) = z_{RF}(az_L)$ is country F's reaction function. The f.o.c. for this optimization problem, which characterizes the optimal level $z_L^S(a)$ of country L's public expenditures for the public good in an interior SE, then can be written by equating country L's *mrs* with its *mrt* in the Stackelberg case, i.e. as

(2) $$mrs(w_L - z_L^S(a), G^S(a)) = \frac{u_1(w_L - z_L^S(a), G^S(a))}{u_2(w_L - z_L^S(a), G^S(a))} = a(1 + z'_{RF}(az_L^S(a))),$$

where $G^S(a) = az_L^S(a) + z_{RF}(az_L^S(a))$ is public good supply in the SE and $z'_{RF}(g_L) = \frac{\partial z_{RF}}{\partial g_L}$ is the slope of country F's reaction path at $g_L = az_L$.

Depending on the size of the productivity parameter a (and on the income distribution too as shown by Buchholz, Lommerud and Konrad, 1997) the SE may also become a corner solution, in which only one country actively contributes to the public good. For low levels of a the SE is the standalone allocation of country F, which results from maximizing $u(w_F - z_F, z_F)$ and has public good supply G_F^A. Country L then attains the position (w_L, G_F^A), which it only wants to leave if its $mrt = a(1 + z'_{RF}(0))$ at $z_L = 0$ exceeds $mrs(w_L, G_F^A)$. For high levels of a the SE instead is the standalone equilibrium of country L, which results from maximizing $u(w_L - z_L, az_L)$, and in which public good supply is denoted by $G_L^A(a)$. This follows because country F will stop contributing to the public good as soon as the public good contribution of country L attains $\bar{G}_F(1)$, because country F's mrs then starts to exceed its $mrt = 1$. This, however, implies that $\bar{G}_F(1)$ is maximum public supply that can result in a SE, in which country F is a contributor. Consequently, $u(w_L, \bar{G}_F(1))$ is an upper bound for the utility level country L can have in an interior SE. But if a is chosen high enough the budget line $G = -ax_L + aw_L$ will cut the indifference curve corresponding to $u(w_L, \bar{G}_F(1))$, which ensures that the SE is the standalone allocation of country L and $G_L^A(a) > \bar{G}_F(1)$. Since $\bar{G}_F(1) > G_F^A$ we have $u(w_L - \frac{G_L^A(a)}{a}, G_L^A(a)) > u(w_L, \bar{G}_F(1)) = u(w_L, G_F^A)$. Thus country L's standalone solution, which is brought about in this way, is also better for country L than being in F's standalone solution.

3. Incentives for Technological Improvements in the Nash and the Stackelberg Game

In the *Nash case* we are interested whether starting from the initial NE, where both countries have the productivity parameter $a_0 = 1$, country L will decrease or increase its NE-utility through a marginal increase of its contribution productivity. Differentiating $u(w_L - z_L^N(a), G^N(a))$ w.r.t. to a and observing $u_1(x_L^N(1), G^N(1)) = u_2(x_L^N(1), G^N(1))$ utility of country L falls if and only if

(3)
$$\frac{\partial z_L^N}{\partial a} > \frac{\partial G^N}{\partial a}$$

holds at $a_0 = 1$. Let $\hat{e}_1$ and $\hat{e}_2$ denote the partial derivatives of the expansion path $e(G, \rho)$ w.r.t. G and ρ at $(x^N(1), G^N(1))$, respectively, where $x^N(1) = x_L^N(1) = x_F^N(1) = e(G^N(1), 1)$. But differentiating $z_L^N(a) = w_L - x_L^N(a) = w_L - e(G^N(a), a))$ w.r.t. a at $a_0 = 1$ gives $\frac{\partial z_L^N}{\partial a} = -(\hat{e}_1 \frac{\partial G^N}{\partial a} + \hat{e}_2)$, which implies that condition (3) turns into

(4)
$$\frac{\partial G^N}{\partial a} < \frac{-\hat{e}_2}{1 + \hat{e}_1},$$

Differentiating condition (1) w.r.t. a also at $a = 1$ yields

(5)
$$\frac{\partial G^N}{\partial a} = \frac{z_L^N(1) - \hat{e}_2}{1 + 2\hat{e}_1} > 0.$$

We then have the following result on incentives for technological improvement in the Nash model, which extends some of the results in Buchholz and Konrad (1994), Ihori (1996) and Hattori (2005).

Proposition 1: If

(6) $$w_L < x^N(1) - \frac{\hat{e}_1 \hat{e}_2}{1+\hat{e}_1}$$

there exists some critical level $\overline{a} > 1$ with $u_L^N(\overline{a}) = u_L^N(1)$ so that country L does not benefit from choosing a productivity parameter $a \in [1, \overline{a}]$ and moving to the corresponding new NE. If country L's income w_L decreases while total income $w_L + w_F$ remains constant, the threshold $\overline{a}$ becomes higher.

Proof: Observing $z_L^N(1) = w_L - x^N(1)$ the first part of the assertion follows by combining (4) and (5) and applying the intermediate value theorem since $u(x^N(a), G^N(a))$ is a continuous function of a, whose value exceeds $u_L^N(1)$ if a is large enough. The second part holds since for any $a > 1$, redistribution of income from country L to country F makes the right hand side of condition (1) smaller. Monotonicity of the expansion paths $e(G,a)$ and $e(G,1)$ then implies that $G^N(a)$ and $x_L^N(a) = e(G^N(a), a)$ and thus $u_L^N(a) = u(x_L^N(a), G^N(a))$ decrease, while $u_L^N(1)$ does not change. QED

If condition (6) is not fulfilled we set $\overline{a} = 1$, which indicates that country L would increase its utility in the Nash game by choosing a productivity parameter $a > 1$.

Proposition 1 in particular shows that a negative incentive for technological progress becomes more likely if income of country L is relatively small. This is intuitively plausible since in this case country L's expenditure for the public good in the original NE is relatively small so that it cannot benefit much from falling costs of its contribution. As normality implies $\hat{e}_1 > 0$ and $\hat{e}_2 < 0$ and thus $x^N(1) - \frac{\hat{e}_1 \hat{e}_2}{1+\hat{e}_1} > x^N(1)$, it is – irrespective of the underlying preferences in both countries – always possible to meet condition (6) through a redistribution of income from country L to country F that brings country L's income close enough to $x^N(1)$. Note that such a transfer will not change public good supply and private consumption in the NE as long as $w_L > x^N(1)$ and $w_F > x^N(1)$ holds. This, on the one hand, reflects Warr neutrality (see, e.g., Cornes and Sandler, 1996, pp. 164-165) result but on the other hand is also a direct consequence of the characterization of the NE as provided by condition (1).

In order to explore the incentives for technological improvement, which the leading country L has in the *Stackelberg case*, we look at the entire possibility curve along which country L moves, when it varies its expenditure for the public good anticipating the reaction of the follower country F. Remember from the end of Section 2 that country F will stop contributing to the public good as soon of country L's public good supply $G_L^A(a)$ in its standalone solution has attained $\overline{G}_F(1)$. As a function of its public good expenditure z_L the possibility curve of country L therefore is given by

(7) $$G_P(z_L, a) = az_L + z_{RF}(az_L)$$

if $z_L < \overline{z}_L(a) := \frac{\overline{G}_F(1)}{a}$. Then a positive public good contribution $z_{RF}(az_L)$ of country F results. If, however, $z_L \geq \overline{z}_L(a)$ we have $G_P(z_L, a) = az_L$, i.e. country F makes no public good contribution and country L is in its standalone position. In Figure 1 the two segments of $G_P(z_L, a_i)$ meet at the point $P(a)$.

If now a is increased (from a to $\tilde{a}$) it is obvious that the standalone segment is shifting outwards and the point $P(a)$ is shifting to the right. For the interior segment this is shown by taking the derivative of $G_P(z_L, a)$ w.r.t. a, which gives

(8) $$\frac{\partial G_P}{\partial a}(z_L, a) = z_L(1 + z'_{RF}(az_L)) > 0\,.$$

The inequality sign in (8) holds since $z'_{RF}(g_L) > -1$, which follows from normality of the public good and which means that an increase of public good supply by country L will not be completely crowded out by country F. At the same time, the point $P(\tilde{a})$ lies to the right of $P(a)$ since (also from normality) standalone public good supply $G_L^A(a)$ is increasing in a. Taken together an increase of a shifts country L's entire possibility curve outwards (as visualized in Figure 1), which implies that the incentives for technological improvement are unequivocally positive for country L. This generalizes a special result, which Hattori and Yamada (2016) have obtained for the Cobb-Douglas case.

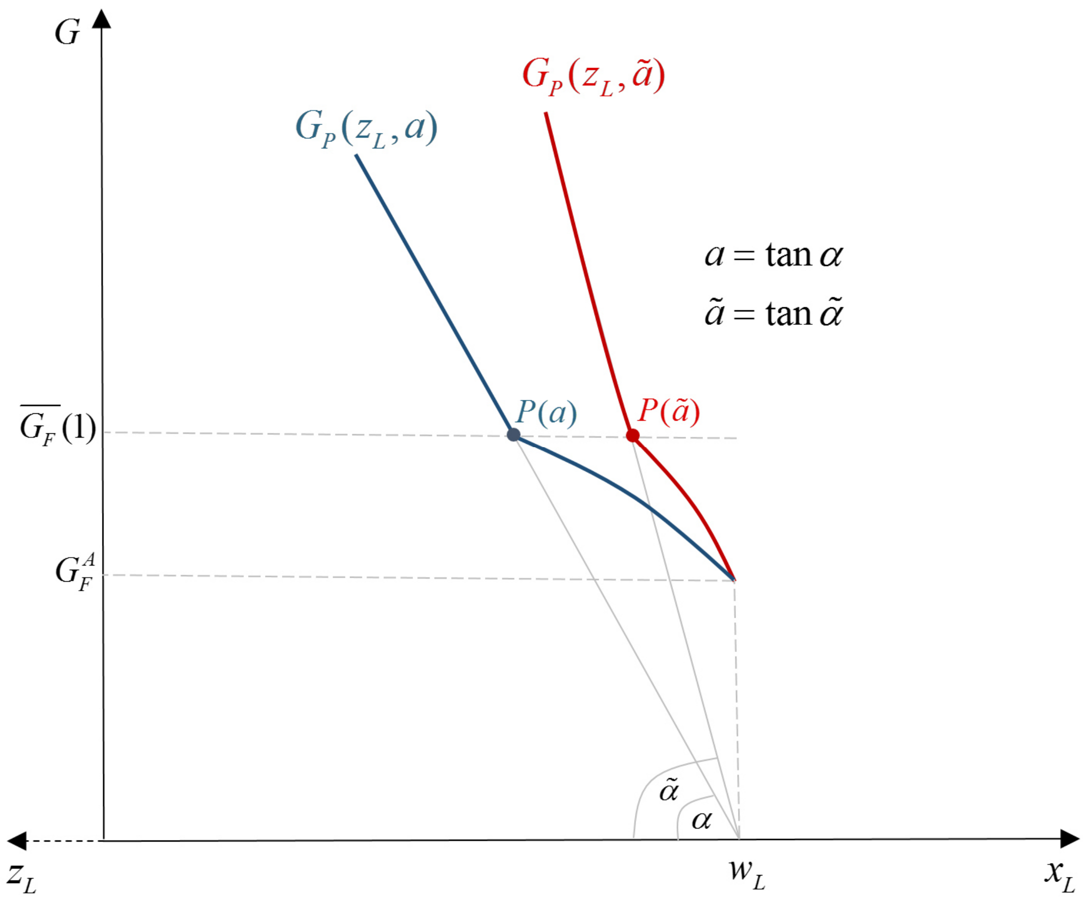

Figure 1

Proposition 2: If Country L is the leader in the Stackelberg game it will never lose when it chooses a higher productivity parameter and the technological improvement is costless. It will definitely benefit when it actively contributes to the public good after the technological change.

Proof: Country L does not benefit from the outward shift of its possibility curve only if it remains a non-contributor after the increase of the productivity parameter. But also in this case it will not be hurt by the technological change because the SE still is the standalone allocation of country F . QED

Based on the significant difference for technological improvement, which thus exists between the Nash and the Stackelberg game, we now describe how in a scenario, in which country L can choose its contribution technology, public good supply may become higher in the SE than in the NE.

4. Increasing Public Good Supply through Leadership: A General Condition

As a preparatory step, we first of all infer the effect that a technological improvement has on the level of public good supply in the SE. It is assumed that for an initially given productivity parameter a an interior SE results, where the leading country L spends $z_L^S(a)$ for the public good so that its public good contribution is $g_L^S(a) = az_L^S(a)$. Now the productivity parameter again rises to some $\tilde{a} > a$ and, for a moment, we suppose that country L adapts by reducing its expenditure for the public good to $\tilde{z}_L = \frac{g_L^S(a)}{\tilde{a}}$. Since this keeps L's public good contribution constant at $g_L^S(a)$ the reaction of country F and hence total public good supply $G^S(a)$ do not change. In Figure 2 this means that the position of country L moves to the right on the parallel to the x_L-axis (z_L-axis) passing through the point $S_L(a) = (x_L^S(a), G^S(a))$.

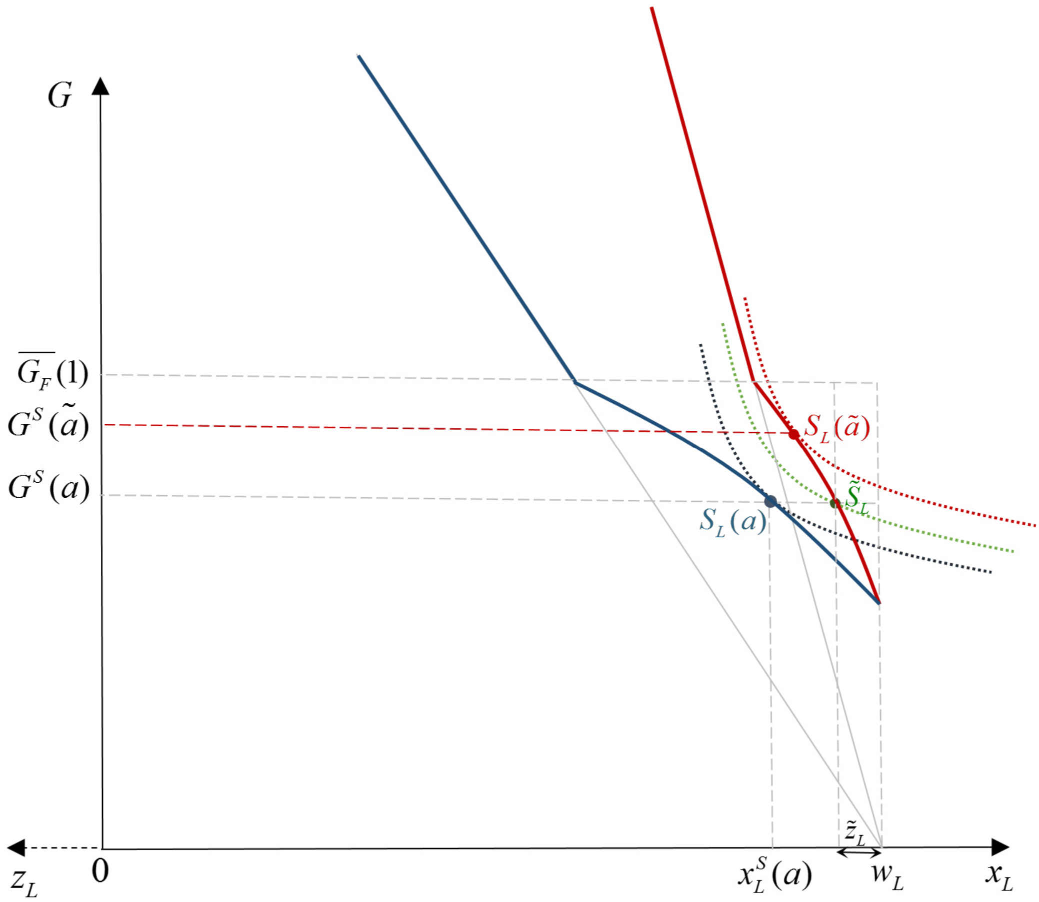

Figure 2

On the one hand, it follows from normality that in country L's new position $\tilde{S}_L$ the mrs between the private and the public good is lower than in $S_L(a)$, i.e. that the indifference becomes flatter. On the other hand (7) yields that

$$(9) \qquad \frac{\partial G_p}{\partial z_L}(\tilde{z}_L, \tilde{a}) = \tilde{a}(1 + z'_{RF}(g_L^S(a))) > \; a(1 + z'_{RF}(g_L^S(a))) = \frac{\partial G_p}{\partial z_L}(z_L^S(a), a),$$

so that in $\tilde{S}_L$ country L's possibility curve for $\tilde{a}$ is steeper than the possibility curve in $S_L(a)$. Taken together a lens opens up above $\tilde{S}_L$ between the indifference curve and the possibility line passing through this point, which implies that country L wants to choose a higher public good supply after its productivity parameter has risen. We thus have the following result.

Proposition 3: In the interior SE an increase of the leading country L's public good productivity a leads to a higher public supply.

As a second step we now show that the original NE for the same productivity parameter $a_0 = 1$ in both countries can partially be mimicked as an SE for an appropriately chosen productivity parameter $\hat{a}$ of country L. Analogous as in the demonstration of Proposition 3 above we adjust country L's public good expenditure so that for any $a > 1$ its effective contribution to the public good now stays at $g_L^N(1)$. Country L's public good expenditures thus are reduced to $\widehat{z}_L(a) = \frac{g_L^N(1)}{a}$ and its private consumption increases to $\widehat{x}_L(a) = w_L - \widehat{z}_L(a)$. As before country L's position $(\widehat{x}_L(a), G^N(1)) = (w_L - \frac{g_N^L(1)}{a}, G^N(1))$ moves to the right on a parallel to the x_L-axis when a is increased. The productivity parameter $\hat{a}$, for which $G^N(1)$ becomes the level of public good supply in the SE, then is determined by the following condition:

$$(10) \qquad mrs(\widehat{x}_L(\hat{a}), G^N(1)) = \hat{a}(1 + z'_{RF}(\hat{a}\widehat{z}(\hat{a}))) = \hat{a}(1 + z'_{RF}(g_L^N(1))).$$

Given $\hat{a}$ according to (10) the f.o.c. condition (2), which characterizes country L's optimal behavior in an interior SE, is clearly satisfied when country L chooses $\widehat{z}(a)$ as its expenditure for the public good.

It remains to show that a productivity parameter $\hat{a}$ for which condition (10) holds actually exists: If $a=1$ we have

(11) $$mrs(\hat{x}_L(1), G^N(1)) = mrs(x^N(1), G^N(1)) = 1 > 1 + z'_{RF}(g_L^N(1))$$

as $z'_{RF}(g_L^N(1)) < 0$. Since, moreover, $z'_{RF}(g_L^N(1)) > -1$ the linear function $a(1+z'_{RF}(g_L^N(1))$ is increasing in a with $\lim_{a\to\infty} a(1+z'_{RF}(g_L^N(1))) = \infty$. But normality implies that $mrs(\hat{x}_L(a), G^N(1))$ is a decreasing function of a, for which $\lim_{a\to\infty} mrs(\hat{x}_L(a), G^N(1)) = \lim_{a\to\infty} mrs(w_L - \frac{g_L^N(1)}{a}, G^N(1))$ $= mrs(w_L, G^N(1)) < \infty$ holds. As the implied functions are continuous the intermediate value theorem ensures the existence of a unique productivity parameter $\hat{a}$, for which the equality of the both sides in (10) actually obtains. We thus have the following result:

Proposition 4: Assume that the original NE, where both countries have the productivity $a_0 = 1$, is interior. Then there exists a threshold $\hat{a}$ so that in the SE for all productivity parameters $a > \hat{a}$ of country L public good supply and utility of both countries are higher than in this NE.

Proof: If $a > 1$ leads to an interior SE the increase of public good directly follows from the definition of $\hat{a}$ and Proposition 3. If, however, the SE is a standalone allocation of country L we have $G_L^A(a) > \bar{G}_F(1)$. But as the initial NE has assumed to be interior $\bar{G}_F(1) > G^N(1)$ holds so that the assertion thus also holds in this case. Concerning the increase of utilities first note that given $\hat{a}$ utility of country L's is higher than in the original NE as it attains the same public good supply $G^N(1)$ with a lower expenditure for the public good. Utility of country F, however, is the same if $a = \hat{a}$. If then $a > \hat{a}$ country L will improve further in the SE because it could have $G^N(1)$ even with a lower expenditure for the public good than in the SE for $\hat{a}$. Country F also becomes better off: As long as an interior SE results Proposition 3 implies that public good supply is higher than $G^N(1) = G^S(\hat{a})$ and country F is moving outwards on the expansion path $e(G,1)$, which clearly increases its utility. When instead for some $a > \hat{a}$ the SE becomes country L's standalone allocation with public good supply $G_L^A(a)$ from interiority of the original NE we have $x_F^N(1) = x^N(1) < w_F$. Moreover, $G_L^A(a) > \bar{G}_F(1) > G^N(1)$ so that $u(w_F, G_L^A(a)) > u(x_F^N(1), G^N(1))$, i.e. country F's utility in such an SE also exceeds that in the original NE. QED

Comparing Proposition 1 and Proposition 4 shows that a conflict arises between having negative incentives for technological improvement in the Nash game and having higher public good supply in the SE with higher contribution productivity of country L than in the original NE. While the first requirement is fulfilled by low values of the productivity parameter a, the second requirement demands a high level of a. It is possible to fulfil both requirements simultaneously, when the regions for a that follow from Propositions 1 and 4, respectively, overlap so that leadership becomes favorable for public good supply and utility of both countries in this case.

Our results on the potential advantages of leadership in case of an endogenous production technology for the public good are summarized in the following Proposition, which provides our central criterion on the potential advantages of leadership in public good provision when the leader's contribution technology is endogenous.

Proposition 5: Assume that the original NE with $a_0 = 1$ in both countries is interior and that $\overline{a} > \hat{a}$. Then in the Nash game country L has no incentive to adopt a new contribution technology with a productivity $a \in (\hat{a}, \overline{a})$, while as the leader in the Stackelberg game it has. In the SE, which results for such a productivity parameter $a \in (\hat{a}, \overline{a})$ of country L, public good supply and both countries' utilities are larger than in the original NE, where the productivity parameter $a_0 = 1$ is the same in both countries.

It is, however, not obvious that the assumption underlying Proposition 5 can actually be satisfied. Therefore we have to provide an example, in which $\overline{a} > \hat{a}$ actually holds. This is done in the next section through an example with Cobb-Douglas preferences.

If, however, the assumption in Proposition 5 is not fulfilled, i.e. if $\overline{a} \leq \hat{a}$, we have to distinguish two cases. If $\overline{a} = a_0 = 1$ country L has an incentive to apply a technology with $a > 1$ also in the Nash case, and with the improved technology public good supply clearly becomes larger in the NE than in the SE. The same holds true if $\hat{a} \geq \overline{a} > 1$ and $a > \overline{a}$. In this case an improved technology with $a \in (1, \overline{a})$ will be chosen by country L in the Stackelberg case but not in the Nash case. In the corresponding SE public good supply then is still lower than in the NE.

5. A Cobb-Douglas Example

Let both countries have the same symmetric Cobb-Douglas utility function $u(x_i, G) = x_i G$ for $i = L, F$. The marginal rates of substitution are given by $mrs(x_i, G) = \frac{G}{x_i}$ and the expansion paths then by $e(G, \rho) = \frac{G}{\rho}$. For the partial derivatives we thus have $e_1(G, \rho) = \frac{1}{\rho}$ and $e_2(G, \rho) = -\frac{G}{\rho^2}$.

Applying condition (1), which characterizes interior equilibria of the Nash game, to this special case gives

(12) $$G^N(a) = x_F^N(a) = \frac{aw_L + w_F}{3} \quad \text{and} \quad x_L^N(a) = \frac{aw_L + w_F}{3a}.$$

The interiority conditions $x_L^N(a) < w_L$ and $x_F^N(a) < w_F$ for the NE then become

(13) $$\frac{1}{2}q < a < 2q,$$

where $q := \frac{w_F}{w_L}$ is the ratio of both countries' income levels. If the initial NE is to be interior condition (13) has to hold especially for $a_0 = 1$, which boils down to

(14) $$\frac{1}{2} < q < 2$$

Since $\hat{e}_1 = 1$ and $\hat{e}_2 = -G^N(1) = -\frac{w_L + w_F}{3}$ it follows from Proposition 1 that country L has no incentive to apply an improved technology and to leave the original NE, i.e. that $\bar{a} > 1$, if

(15) $$w_L < x^N(1) + \frac{G^N(1)}{2} = \frac{3}{2}G^N(1) = \frac{w_L + w_F}{2} \quad \Leftrightarrow \quad q > 1.$$

Thus country L has no incentive to adopt an improved technology when it is poorer than country F. Given $q > 1$ the threshold level $\bar{a}$, below which technological improvement is not profitable for country L, then is calculated from

(16) $$u_L^N(\overline{a}) = \frac{(\overline{a}w_L + w_F)^2}{9a} < \frac{(w_L + w_F)^2}{9} = u_L^N(1),$$

which gives

(17) $$\overline{a} = q^2.$$

Concerning the Stackelberg game we first note that maximizing country F's utility $(w_F - z_F)(g_L + z_F)$ for a given g_L yields country F's reaction function

(18) $$z_{RF}(g_L) = \frac{1}{2}(w_F - g_L),$$

which has the constant slope $z'_{RF} = -\frac{1}{2}$. To determine an interior SE the leader therefore has to maximize $(w_L - z_L)\cdot(z_L + z_{RF}(z_L)) = \frac{1}{2}(w_L - z_L)\cdot(w_F + z_L)$ when originally the productivity parameter is $a_0 = 1$. This optimization problem has a strictly positive solution in z_L only if $w_F < w_L$, i.e. if $q < 1$. If instead $q > 1$, which according to (15) is needed for the desired example, a corner SE with country F as the sole contributor to the public good necessarily arises.

Higher productivity parameters a, however, can bring about interior SE. In particular, interiority results if a is chosen at that level, which in the corresponding SE makes public good identical to that in the original NE, i.e. if $a = \hat{a}$ according to Proposition 4. We now determine this threshold level $\hat{a}$ for our special case: Since $\widehat{x}_L(a) = w_L - \frac{g_N^L(1)}{a} = w_L - \frac{2w_L - w_F}{3a}$ for any $a \geq 1$ condition (10), by which $\hat{a}$ is defined, becomes

(19) $$mrs(\widehat{x}_L(\hat{a}), G^N(1)) = \frac{\frac{w_L + w_F}{3}}{\left(w_L - \frac{2w_L - w_F}{3\hat{a}}\right)} = \hat{a}\left(1 - \frac{1}{2}\right) = \hat{a}(1 - z'_{RF}).$$

Solving (19) for $\hat{a}$ then yields

(20) $$\hat{a} = \frac{1}{3}(4 + q).$$

Combining (17) and (20) then gives that $\overline{a} > \hat{a}$ as the focal condition as stated in Proposition 5 if $3q^2 - q - 4 > 0$. Determining the zeros of this quadratic function yields

(21) $$\bar{a} > \hat{a} \quad \Leftrightarrow \quad q > \frac{4}{3}.$$

In summary, it follows from condition (13), (14), (17), (20) and (21) that any combination (q, a) can provide the desired example if

(22) $$q \in \left(\frac{4}{3}, 2\right) \quad \text{and} \quad a \in \left(\frac{1}{3}(4+q), q^2\right).$$

In this context note that the upper bound condition (16) is stronger than (13) if $q < 2$. The (q, a)-combinations, which satisfy the condition (21), are visualized in Figure 3.

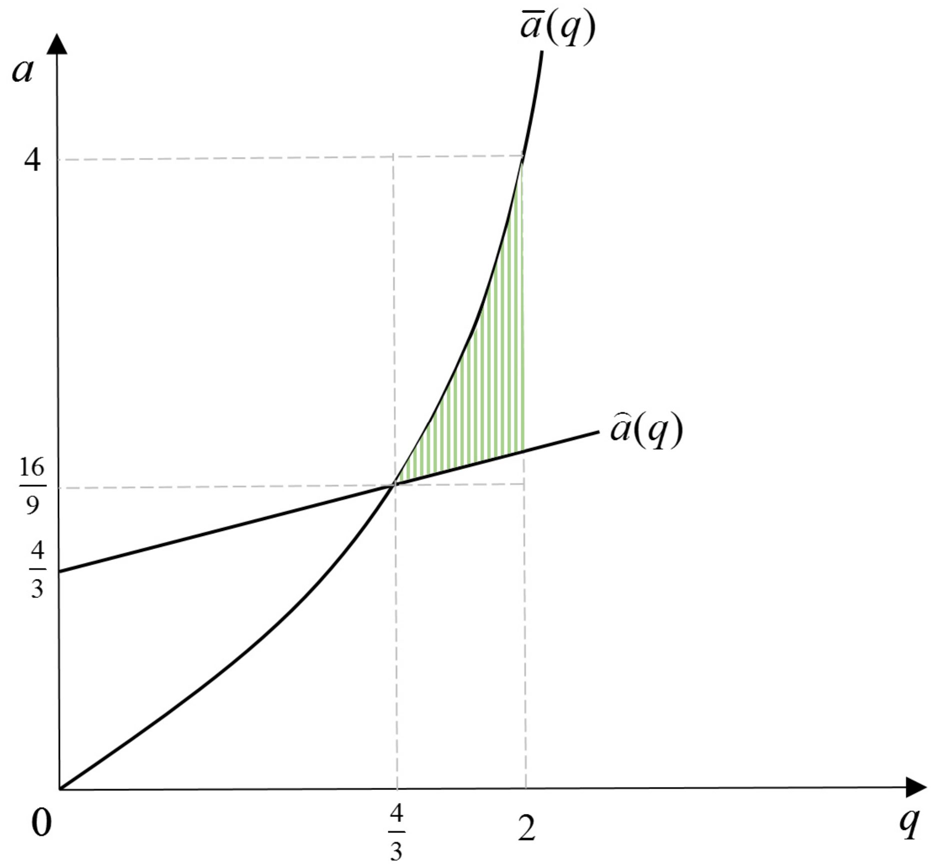

Figure 3

Based on these general considerations a specific numerical example, e.g., is provided by letting $w_L = 2$ and $w_F = 3$, i.e. $q = \frac{3}{2}$, and $a = 2$. In the Nash model from (1) we then have an interior initial NE with $G^N(1) = x^N(1) = \frac{5}{3} = 1{,}67 < 2 = \min\{w_L, w_F\}$ so that

$u_L^N(1) = u_F^N(1) = \left(\frac{5}{3}\right)^2 = \frac{25}{9} = 2,78$. The NE for $a = 2$, which is interior, too, is given by $G^N(2) = \frac{2 \cdot 2 + 3}{3} = \frac{7}{3} = x_F^N(2) < 3 = w_F$ and $x_L^N(2) = \frac{G^N(2)}{2} = \frac{7}{6} < 2 = w_L$. Utility of country L is $u_L^N(2) = \frac{7}{6} \cdot \frac{7}{3} = \frac{49}{18} = 2,72 < 2,78 = u_L^N(1)$. This confirms that country L does not want to adopt the improved public good production technology in the Nash case.

In the Stackelberg case country L determines its optimal public good expenditure $z_L^S(2)$ by maximizing utility $(w_L - z_L)(az_L + z_{RF}(az_L)) = \frac{(2 - z_L)(3 + 2z_L)}{2}$. From the f.o.c. we get $z_L^S(2) = \frac{1}{4}$ as the optimal solution, i.e. country L contributes $g_L^S(2) = 2 \cdot \frac{1}{4} = \frac{1}{2}$ to the public good. Country F then reacts by choosing $z_{RF}(g_L^S(2)) = z_F^S(2) = \frac{1}{2}\left(3 - \frac{1}{2}\right) = \frac{5}{4}$. As the expenditure levels of both countries, which result in this way, are positive and below their income levels an interior solution is obtained, in which total public good supply is $G^S(2) = \frac{1}{2} + \frac{5}{4} = \frac{7}{4} = 1,75 > 1,67 = G^N(1)$ so that public good supply indeed becomes higher than in the Nash game. Private good consumption of country L and country F in this SE are $x_L^S(2) = w_L - z_L^S(2) = 2 - \frac{1}{4} = \frac{7}{4}$ and $x_F^S(2) = w_F - z_F^S(2) = 3 - \frac{5}{4} = \frac{7}{4}$. Their equality, however, is a peculiarity of the special example. Henceforth, the utilities of both countries are equal too, i.e. $u_L^S(2) = u_F^S(2) = \left(\frac{7}{4}\right)^2 = \frac{49}{16} = 3,06 > 2,78 = u_L^N(1) = u_F^N(1)$, which confirms that a Pareto improvement over the initial NE is attained.

Looking at $u_L^S(2)$, moreover, directly shows that country L will actually prefer the interior solution calculated just now over the two standalone solutions, which also are potential candidates for a SE: Country L's utility in its own standalone allocation is $\frac{w_L}{2} \cdot \frac{2w_L}{2} = 1 \cdot 2 = 2$ as in this case country L spends half of its income w_L on public good supply and its public good productivity is $a = 2$. In country F's standalone allocation country L spends nothing on the public good so that its private consumption is w_L while country F spends half of its income w_F. Country L's utility thus is $w_L \cdot \frac{w_F}{2} = 2 \cdot \frac{3}{2} = 3$.

6. Conclusion

In public good theory, it appears to be a common belief that leadership will aggravate the underprovision problem, which is a typical feature when a public good is supplied non-cooperatively and which is of great empirical importance in particular with regard to global climate policy. Without leaving the standard framework of public good theory, this assertion, however, needs no longer to be true if the leading country can choose the technology, by which it generates its public good contribution. Rather, leadership may remove the obstacle, which could prevent the application of a cost-saving abatement technology in the Nash game, and by application of this improved contribution technology, public good supply may become larger. It has been the central message of this paper that such a possibility exists. The example that confirms this result, moreover, has shown that this effect becomes more likely if the poorer country acts as a leader since the incentives to adopt the improved technology in the Nash case then are particularly weak.

For some rather tentative empirical application look at China as an important player in global climate policy. In the process following the Paris agreement (and after political changes that happened most dramatically in the US but also in the EU), high hopes for a substantial progress in combating climate change are resting on this country, which by now seems to have adopted a leadership position in global climate policy. Statements by high-ranking Chinese representatives at the Davos meeting of the World Economic Forum in January 2017 are clearly indicative of such a change of attitude (see, e.g., Tabuchi, 2017). In this context, a central role is attributed to the development and application of cost-saving abatement technologies like renewables, e.g. by asserting that China's "leadership had identified low-carbon technologies as the technologies of the future …" (Hilton, 2016). For a further interpretation note that in 2015 China's total net national product has been 11 trillion Dollars, while that of the US was 60 percent more amounting to about 18 trillion Dollars. The fact that, somewhat paradoxically, leadership by the "poorer" country is favorable for technological improvement in this case complies with our theoretical results as we have shown that in the Nash case having a low income reduces a country's innovation incentives (see Proposition 1), while such a disincentive effect never occurs when this country acts as a Stackelberg leader (see Proposition 2). Against this background, we not only have shed some light on the relationship between leadership in public good provision and technological progress in general but also may have outlined some rationale for recent trends in global climate policy.

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