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On International Compensations for Environmental Stocks[1]

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Abstract. This paper sheds some light on the possible implications of compensations which are paid for the maintenance of an environmental stock. It shows that serious complications can arise if the resource-owner may influence the compensation price strategically. If the incentive to raise the compensation price dominates the preservation incentive, the steady-state stock falls short from that which is voluntarily held. Whether compensation policies can neglect this feature depends crucially on the institutional setting which determines the compensation price.

Key words: international compensations, strategic behaviour, international environmental problems, environmental stocks

1. Introduction

This paper sheds some light on the possible implications of compensations which are paid for the maintenance of an environmental stock. International compensations for environmental purposes are still in their infancy and the resources devoted to encourage the protection of globally beneficial environmental resources merely support environment-friendly projects. This project support is criticized as an insufficient and inefficient instrument to avoid environmentally harmful repercussions of resource extractions. In addition to the well-known arguments for the need of North-South compensations, compensations for mere preservation seem to gain increasing political support because they can seemingly guarantee preservation in a very cost-effective manner.[2]

Many global environmental services are produced by environmental stocks and preservation measures can often only address stocks like oceans, forests, etc. The most outstanding environmental stock are the tropical forests because the environmental services they produce are threefold. First, tropical forests are a carbon sink and deforestation adds significantly to the accumulation of carbon dioxide in the atmosphere, thereby potentially changing the global climate. Second, tropical forests play an important role in regional climate patterns. Third, tropical forests serve as an *in-situ* resource for genetic materials which are likely to benefit research and development in the pharmaceutical industry (Stähler, 1994). Taken together, the services tropical forests produce are obviously significant.

Table I. Stocks of closed forests in 1000 hectares.

Bolivia	44,010	Venezuela	31,870
Brazil	357,480	Zaire	105,750
Columbia	46,400	India	36,540
Mexico	46,250	Indonesia	113,395
Peru	69,680	Total	851,875
		World	1,436,492

Source: Mohr (1993), p. 21.

Environmental stocks are not equally distributed over the world. Table I shows that a few countries host a large portion of the world's forests.

The few number of resource-owning countries pronounces the relevance of strategic interactions among resource owners. This paper will demonstrate that the success of monetary compensations is by no means clear when compensations are paid for the maintenance of environmental stocks and the donors are not able to pursue a constant compensation price policy. It demonstrates that strategic interactions may result in a long-run stock which falls short of that which resource owners maintain in the long run without any compensation policy. Because preserving environmental stocks is basically a matter of long-run policies, the paper addresses stability aspects explicitly to ensure that the steady states are reachable. The models which it employs are fairly simple and employ optimal control theory. Accordingly, the paper is organized as follows. Section 2 demonstrates the basic model of compensating for environmental stocks. Section 3 discusses the optimal policies of a resource-owning country with a constant compensation price paid per maintained unit of stock. Section 4 addresses compensation policies when the compensation price is not fixed but is influenced by the resource owner. Section 5 concludes the paper.

Compensations for the maintenance of an environmental stock are an interesting international policy instrument because they may be able to overcome sovereignty problems. In an international setting, the agents who receive compensations are sovereign countries, and sovereignty imposes two constraints on international environmental policies. On the one hand, no country can be forced into a multinational treaty (Barrett, 1992). Thereby, countries are able to free-ride. On the other hand, if international environmental regulations are agreed upon, no authority is able to enforce the national environmental policies agreed upon (Stähler, 1996). Consequently, no country is able to commit itself credibly not to breach an international environmental agreement. Compensations for the maintenance of an environmental stock may cure this problem because they are paid unilaterally and depend directly on the degree of environmental services, thereby making an explicit contract superfluous.[3] From this perspective, all the donor needs is an account number, a sufficient monitoring technique and a consistent pricing rule. The need for a monitoring technique does not raise serious problems because modern satellite techniques are very successful in monitoring even very small-scale outdoor regions, e.g. the verification of the size of tropical forests and the evaluation of corresponding stock-dependent payments seems to be a comparatively easy task. Therefore, this paper assumes that the donors have complete information about the size of the stock in question. It is these stock-dependent services and two sets of pricing rules which this paper focuses upon.

2. The Basic Model of Compensating for Environmental Stocks

A resource-owner is assumed who derives utility from a global environmental stock only via extractions, i.e. the environmental stock services accrue solely to the donor. This assumption will facilitate developing the dynamic model without touching the qualitative results. Let B denote the net benefits from extractions E,

$$B(t) = B[E(t)],\ B_E > 0,\ B_{EE} < 0,\ B_{EEE} = 0,\ \lim_{E \to 0} B_E < \infty.^4 \tag{1}$$

The resource owner faces positive, marginally decreasing net benefits from extractions. Extractions are neither necessary nor essential resource inputs into production. The environmental resource is exhaustible and renewable which is mirrored by the regeneration function which depends on the stock:

$$\begin{aligned} R(t) = R[S(t)] \quad & 0 < S < S^{\circ}: R(S) > 0,\ R_{SS} < 0 \\ & S\left\{ \begin{matrix} =0 \\ \rangle S^{\circ} \end{matrix} \right\}: R(S) = 0 \\ & 0 < S \leq S^{MY}: R_S \geq 0,\ \lim_{S \to 0^+} R_S(S) = \infty \\ & S^{MY} < S \leq S^{\circ}: R_S < 0,\ \lim_{S \to S^{\circ -}} R_S(S) \geq -\infty \end{aligned}$$

MY denotes the stock level which gives the maximum yield. Equation (2) defines a fairly convenient regeneration function.[5] Assuming infinite marginal regeneration for a stock approaching zero ensures that extinction does not occur because any discount rate cannot exceed positive marginal regeneration. Due to the assumption of no directly stock-dependent benefits, the dynamic problem resembles the one of optimal fishery (see Clark, 1976; Dasgupta and Heal, 1979). Assume that the planning horizon is infinite and that the resource-owner discounts the future benefits by the time-invariant discount rate r. Without compensations, the maximization problem of a resource-owning country is given by

$$\max \int_0^{\infty} e^{-rt} B(t) \mathrm{d}t \quad \text{s.t.} \quad \dot{S} = R(t) - E(t), \tag{3}$$

and the respective initial stock. The corresponding current-value Hamiltonian H_c is given by

$$H_c = B(t) + \lambda(t)\{R(t) - E(t)\}. \tag{4}$$

Rewriting the optimality condition and substituting for the costate variable λ gives

$$B_{EE}\dot{E} = B_E[r - R_S]. \tag{5}$$

Equation (6) describes the steady state which is reached when the discount rate and the marginal regeneration equalize:[6]

$$\begin{aligned} \dot{E} &= \frac{B_E[r - R_S]}{B_{EE}} \stackrel{!}{=} 0 \\ \Leftrightarrow r &= R_S \\ \dot{E} &= R(t) - E(t) \stackrel{!}{=} 0. \end{aligned} \tag{6}$$

As this model variant repeats the results of the standard fishery model, the stability proof is omitted. Note that the $\dot{E} = 0$-isocline of (6) is a vertical line in the corresponding phase diagram.

Now assume that a donor is willing to pay $Q[S(t)]$, $Q_S \geq 0$, for the preservation of the stock. This donor may represent the international community which consumes the global environmental services supplied by the stock. $Q[S(t)]$ gives his willingness-to-pay for a certain stock level.[7] The steady stream of payments $Q[S(t)]$ changes the benefits of the receiver which now depend also on the stock. Hence, he optimizes according to

$$\max \int_0^\infty e^{-rt}\{B(t) + Q[S(t)]\}\mathrm{d}t \quad \text{s.t.} \quad \dot{S} = R(S) - E(t). \tag{7}$$

The corresponding Hamiltonian is given by

$$H_c = B(t) + Q[S(t)] + \mu(t)\{R(t) - E(t)\}. \tag{8}$$

Applying the Maximum Principle demands the Arrow Sufficiency Condition to be fulfilled:

$$\frac{\partial^2 H_c}{\partial S^2} = Q_{SS} + B_E R_{SS} \stackrel{!}{\leq} 0. \tag{9}$$

This paper will assume that (9) always holds. Equation (9), however, is not in all cases a weak assumption. Q_{SS} can be expected to be very high for necessary and essential resources because the willingness-to-pay may be expected to increase tremendously when the stock reaches the critical level. Whether compensation policies aim at tackling a problem of an essential or necessary environmental resource stock depends crucially on the availability of a backstop technology (Nordhaus, 1973). If substitution of the stock services is possible for finite costs, condition (9) can be assumed for the whole relevant range without significant loss of generality. After rewriting the optimality conditions and substituting for the costate variable μ, extraction policies are determined by

$$B_{EE}\dot{E} = B_E[r - R_S] - Q_S. \tag{10}$$

Comparing (10) with (5) reveals that the resource owner's extraction policy is varied by the donor's preservation policy. The term Q_S gives the marginal change of transfers received if the environmental stock is marginally varied. The next two sections will specify different compensation functions. Section 3 will discuss the implications of a constant compensation price whereas Section 4 assumes a compensation function which wants the compensation price to increase if the environmental stock is decreased.

3. A Constant Compensation Price Model of Compensating for Environmental Stocks

This section assumes that the donor is able to pursue a constant compensation price policy. His policy specifies a constant compensation price q which is paid per unit of stock. For this set of compensation policies, Q_S is simply given by the constant compensation price q and demands for the change of extractions

$$B_{EE}\dot{E} = B_E[r - R_S] - q. \tag{11}$$

Equation (12) describes the steady state:

$$\begin{aligned} \dot{E} &= \frac{B_E[r - R_S] - q}{B_{EE}} \overset{!}{=} 0 = \varepsilon^*(E, S) \\ &\Leftrightarrow r - \frac{q}{B_E} = R_S \\ \dot{S} &= R(t) - E(t) \overset{!}{=} 0 = \sigma^*(E, S). \end{aligned} \tag{12}$$

Partial differentiation reveals the positive inclination of the ε^*-curve:

$$\left.\begin{aligned} \varepsilon_E^* &= r - R_s = \frac{q}{B_E} > 0 \\ \varepsilon_S^* &= -\frac{B_E R_{SS}}{B_{EE}} < 0 \end{aligned}\right\} \Rightarrow \left.\frac{dE}{dS}\right|_{\dot{E}=0} = \frac{B_E R_{SS}}{B_{EE}[r - R_S]} > 0,$$

$$\left.\frac{d^2E}{dS^2}\right|_{\dot{E}=0} = \frac{B_E R_{SSS}[r - R_S] + B_{EE} R_{SS}}{B_{EE}[r - R_S]^2}.$$

When E approaches zero, (11) guarantees a zero change in extractions by an R_S which falls short from r as long as $B_E(E = 0) < \infty$. Hence, the isocline $\dot{E} = 0$ starts on the R.H.S. of the one which (6) specifies and increases in

E as S increases. Due to the ambiguous sign of R_{SSS} (see note 5), nothing is known about the concrete curvature on purely theoretical grounds. The local stability analysis of the corresponding Jacobi matrix reveals a positive trace of J:

$$tr(J) = r, \; |J| = [r - R_S]R_S - \frac{B_E R_{SS}}{B_{EE}} .$$

The sign of the determinant is negative because a positive determinant which would induce global instability demanded a positive R_S at the equilibrium. Hence, instability would be given if

$$R_S > \frac{B_E R_{SS}}{B_{EE}[r - R_S]} = \left.\frac{dE}{dS}\right|_{\dot{E}=0} .$$

This instability condition conflicts with the path properties which have been derived because a concave regeneration function cannot intersect an always increasing function at a point of larger inclination when the other function starts on the R.H.S. of the regeneration function.[8] Figure 1 shows the phase diagram for a policy which aims at a long-run preservation of a stock that produces a negative marginal regeneration. The broken line gives the isocline $\dot{E} = 0$ when no compensations are paid.

This result could be rather helpful for global environmental policies because the preservation of any stock belonging to the range of positive regeneration can be obtained in the long run by introducing an appropriately fixed compensation price. Every compensation policy which can rely on a constant compensation price achieves a long-run stock which exceeds that which is

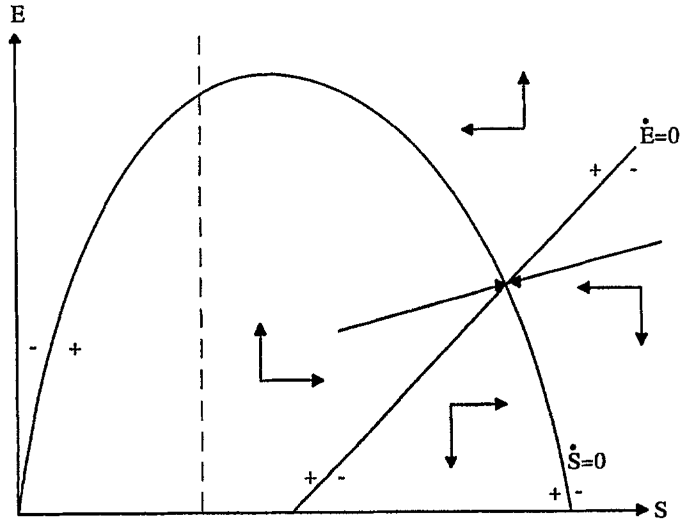

Figure 1. The intertemporal adjustment in the case of a fixed compensation price.

voluntarily held. Thus, this model lends support to the hypothesis that monetary compensations are able to preserve environmental stocks.

4. A Price Adjustment Model of Compensating for Environmental Stocks

Section 3 assumed that the donor is able to fix the compensation price at a certain level. However, freezing the compensation price at a certain level is no weak assumption with respect to commitment. As the marginal benefits can be expected to increase with a decreasing stock, the willingness-to-pay can be expected to rise with a decreasing stock. This effect would not be taken into account if resource owners are large in number and therefore take the compensation price as given. Such an assumption is obviously inappropriate for many resource stocks (see Table I). Observing that the resource-owning countries are often only few in number justifies an approach which takes monopolistic imperfections into account.

Consider a resource-owning country which knows that stock decisions vary the compensations according to

$$q(t)S(t) = [a - bS(t)]S(t), \; S^{\max} = \frac{a}{b}\,. \tag{13}$$

Equation (13) assumes that the donors' willingness-to-pay rises with a declining stock because their marginal utility is decreasing with the available stock. Equation (13) gives the perceived demand function for a single resource-owning country and not the total demand function. Alternatively, one could model oligopolistic interactions more explicitly by considering n identical countries. In that case, the compensation price would be given by

$$q(t) = \alpha - \beta\sum_{n} S^{i}(t).$$

But the reinterpretation of several regeneration functions is not straightforward and one has to take possible collusion among resource owners into account, too. Hence, this section concentrates on the same resource owner as in the previous sections, and the compensation function should be regarded as a perceived demand function of this resource owner. This perceived demand function may mirror Cournot oligopoly or collusion.

Equation (13) sets the stage for the other set of compensation policies which may be based on an international institution like a supernational environmental agency which, e.g., compensates the resource-owners on the basis of marginal utilities. It could be imagined as possessing tax-raising power to cover its expenses. This approach may mirror reality more appropriately than Section 3's model because it can approximate the institutional setting of an environmental fund whose members reconsider the success and the 'appropriate' compensation price periodically according to (13).[9] The parameter a represents the per-unit costs of the backstop technology or some other substitution option which defines the reservation price for compensations. The parameter b determines the degree of compensation price responses on the resource owner's stock policy. The higher b, the higher is the effect of the stock size on the compensation price.

The new maximization problem is given by

$$\max \int_0^\infty e^{-rt}\{B(t) + [a - bS(t)]S(t)\}\mathrm{d}t \quad \text{s.t.} \quad \dot{S} = R(S) - E(t) \tag{14}$$

and the respective initial stock. The new Hamiltonian is given by

$$H_c = B(t) + [a - bS(t)]S(t) + \gamma(t)\{R(S) - E(t)\}. \tag{15}$$

Rewriting the optimality condition and substituting for the costate variable γ gives

$$B_{EE}\dot{E} = B_E[r - R_S] - [a - 2bS]. \tag{16}$$

The steady state conditions are

$$\begin{aligned} \dot{E} &= \frac{B_E[r - R_S] - [a - 2bS]}{B_{EE}} \overset{!}{=} \varepsilon = 0 \\ \dot{S} &= R(t) - E(t) \overset{!}{=} 0. \end{aligned} \tag{17}$$

Equalizing $B_E[r - R_S]$ and $a - 2bS$ is much more complex compared to the case of fixed prices because the stock does not only enter the regeneration function but determines marginal compensations as well. Therefore, the resource owner's policy does not only vary the marginal regeneration but influences the compensation price as well.

In order to discuss the potential impact of variable compensation prices, it is helpful to consider the shape of the $\dot{E} = 0$-isocline. Evaluating the first and second derivative of the corresponding ε-function gives the shape of this curve:

$$\begin{aligned} \left.\frac{\mathrm{d}E}{\mathrm{d}S}\right|_{\dot{E}=0} &= \frac{B_E R_{SS} - 2b}{B_{EE}[r - R_S]} \\ \left.\frac{\mathrm{d}^2E}{\mathrm{d}S^2}\right|_{\dot{E}=0} &= \frac{B_E R_{SSS}[r - R_S] + R_{SS}[B_E R_{SS} - 2b]}{B_{EE}[r - R_S]^2} \end{aligned} \tag{18}$$

If $r - R_S$ is positive for the whole relevant range, monopolistic imperfections imply a mere decrease in services as one expects from static models, too. But the positive sign of $r - R_S$ is not guaranteed. In order to demonstrate this effect, consider the stock level which equalizes $\dot{E} = 0$ for $E = 0$, i.e. the stock level which solves the upper line of (17) for $E = 0$. This stock level is denoted by $\hat{S}$ and is implicitly defined by

$$[r - R_S(\hat{S})]B_E(0) = a - 2b\hat{S}. \tag{19}$$

To balance both terms, $\hat{S}$ is not restricted on positive signs of $r - R_S$. The sign of the L.H.S. of (19) is determined by the marginal biological regeneration and the discount rate which both define the net interest. The R.H.S. displays the conventional marginal yield which arises in a competitively imperfect environment. If

$$R_S(\hat{S}) > r \Leftrightarrow a - 2b\hat{S} < 0, \tag{20}$$

holds, equalizing both terms leads to negative signs. This case is depicted in Figure 2, which demonstrates the case of a stock level $\hat{S}$ which lies on the L.H.S. of the voluntarily held stock because the marginal regeneration exceeds the discount rate due to (20). According to the upper line of (18), all stocks which equalize $\dot{E} = 0$ for other than zero extraction levels decrease with extractions. Hence, (20) is a necessary and sufficient condition for a negatively sloped $\dot{E} = 0$-curve and implies

$$\begin{aligned} &B_E[r - R_S(S^*)] = a - bS^* < 0 \\ &\text{with } S^* < \hat{S}. \end{aligned} \tag{21}$$

S^* denotes the steady-state stock which solves (17) for condition (21) and falls short of $\hat{S}$ (see Figure 2). The economic intuition behind (21) which implies steady-state stocks which fall short from that which is voluntarily held is straightforward. The R.H.S. of (21) reflects the marginal, compensation-based yield of the resource owner and the L.H.S. can be considered as the marginal, extraction-based benefits which are due to the net interest weighted by the marginal benefits of extractions. From the point of view of pure extraction

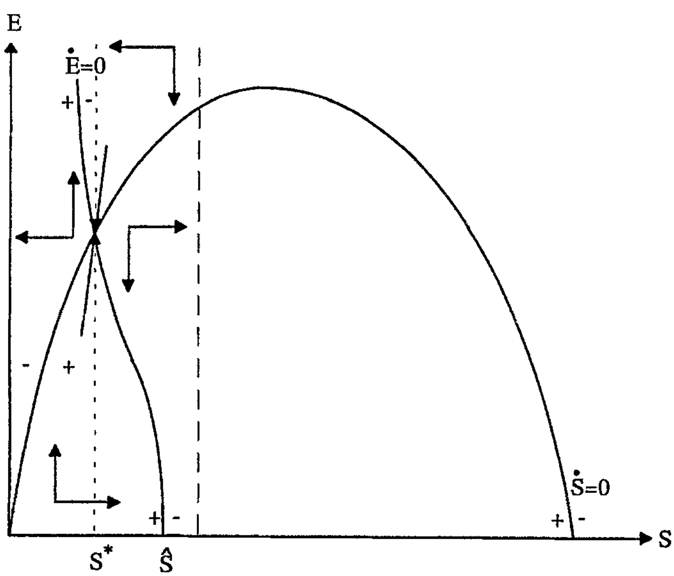

Figure 2. The intertemporal adjustment in the case of a variable compensation price and dominant imperfections.

policies, the resource owner wants to hold a stock which exceeds $\hat{S}$. From the point of view of pure price policy, the resource owner wants to hold a stock which falls short of $\hat{S}$. Taken together, (21) implies dominant imperfections in that the second, compensation-driven effect overcompensates the first, extraction-driven effect. Accordingly, market imperfections can set *incentives to hold a lower stock than a resource owner would like to hold voluntarily without any compensation policy*. If (21) applies, the resource owner must outweigh the marginal, extraction-based benefits and the marginal, compensation-based yields in the *negative* domain.

The phase diagram of dominant imperfections is also given in Figure 2. $\hat{S}$ which (19) defines lies leftwards from the no-compensation isocline. The no-compensation isocline of extractions is defined by the identity of r and R_S. All points leftwards indicate $r - R_S < 0$. According to (18) and the assumptions of (2), the ε-function may exhibit an inflection point and must exhibit a negative slope which approaches $-\infty$ when the stock approaches zero. Local stability is proven by

$$tr(J) = r, \quad |J| = [r - R_S]R_S - \frac{B_E R_{SS} - 2b}{B_{EE}} < 0$$

for $r - R_S < 0$.

Writing (19) as an implicit function,

$$\rho(a, b, r, \hat{S}) = [r - R_S(\hat{S})]B_E(0) - a + 2b\hat{S} = 0, \tag{22}$$

allows for investigating the effects of parameter changes on $\hat{S}$:

$$\left.\begin{aligned} \rho_a &= -1 \\ \rho_b &= 2\hat{S} > 0 \\ \rho_{\hat{S}} &= -R_{SS}(\hat{S})B_E(0) + 2b > 0 \\ \rho_r &= B_E(0) > 0 \end{aligned}\right\} \Rightarrow \begin{aligned} &\frac{\partial \hat{S}}{\partial a} > 0 \\ &\frac{\partial \hat{S}}{\partial b} < 0 \\ &\frac{\partial \hat{S}}{\partial r} < 0 \end{aligned} \tag{23}$$

Equation (23) evaluates the impact of parameter variations on $\hat{S}$. If a parameter change decreases $\hat{S}$, the chances for dominant imperfections are increased: a decreased $\hat{S}$ increases the chances that this stock level, and all other ones for positive E's which are candidates for the steady-state stock, fall short of the voluntarily held stock level. Three effects can be observed:

First, the higher the reservation price, i.e. the higher the costs of substituting the environmental resource completely, the lower are the chances of dominant imperfections. An increase of a decreases the price elasticity for a given b and a decreased price elasticity restricts the scope for compensation-driven policies. Second, it is not surprising that a low b increases the chances of a successful compensation policy because fixed prices are a special case of this model for $b = 0$. A high b pronounces the compensation-driven component of the resource owner's policy. This feature may not be obvious when compensation policies are introduced. Starting with a relatively high stock level, the donors may rely on a low compensation price level and will trap into rising prices only very slowly. Third, it seems surprising that a low discount rate increases the chances of a stock which meets condition (21). But (21) is only fulfilled if exploiting monopolistic imperfections leads to a stock which falls short from the voluntarily held one. Therefore, a lower discount rate increases the voluntarily held steady-state stock and thereby increases the chances of a failing compensation policy.

This section has shown that oligopolistic imperfections may lead to a lower degree of environmental services than in the case of no compensations because the oligopolist's incentive to influence the compensation price strategically may dominate the preservation incentive. Neglecting the issue of imperfections and relying on a sufficient workability of compensation policies could therefore result in severe complications if the price sensitivity is very high and the resource owners are more patient than expected. Hence, a credible commitment to a fixed compensation price policy turns out as a crucial prerequisite to compensate successfully for the maintenance of a stock which produces environmental services.

5. Conclusions

This paper has questioned the advantages of compensating for global environmental services on a steady basis when compensations try to maintain an environmental stock. It has shown that compensation policies may fail dramatically if the resource-owning countries are few in number and the price sensitivity of the donor is very high. In that case, extraction-driven stock preservation policies are dominated by those which are compensation-driven and which aim at rising compensation prices. This feature may be non-observable today but can turn out as a severe complication in managing resource stocks in the long run. Whether compensation policies can neglect this feature depends crucially on the institutional setting which determines the compensation price. Hence, the design of international organizations is not merely a subordinate matter but influences the long-run success of monetary compensation policies. Any institutional deficiency of organizing compensations may endanger the success of international environmental policies. But whether the donors can pursue a fixed compensation price policy depends not only on the institutional setting but also on the donors' intertemporal performance. If the donors are represented by the countries' governments, the agents reconsidering compensation policies change in the course of time. This change renders any credible commitment more difficult.[10]

When the institutional design of compensation policies calls for sophisticated mechanisms, project support may not be too bad an alternative when preservation policy is felt to be an urgent task. Project support ensures direct control of the donor on the use of part of the environmental resource, e.g., project support financed by the World Bank or the Global Environmental Facilities which imply the management of the resource use by the donor. Compensations leave the property rights untouched but project support changes the factual ownership structure. If monetary compensations are likely to be dominated by compensation-driven policies of resource owners, project support can compensate for its higher administrative costs by directly saving an essential part of the resource for the donor. Thus, project support may at least be a good starting-point for international environmental policies.

Notes

1. This paper originated from a research project about the stability of international environmental agreements. I gratefully acknowledge financial support by the Volkswagen Foundation. A predecessor of this paper was presented at the Annual Meeting of the Ausschuß für Umwelt- und Ressourcenökonomie of the Verein für Socialpolitik in Ladenburg. I am indebted to the participants for many helpful comments which improved this paper significantly. Thanks are also due to Gernot Klepper, Peter Michaelis and two anonymous referees whose comments and suggestions were very helpful. The usual disclaimer applies.
2. For a thorough discussion of financial instruments, see Nunnenkamp (1992) and the quoted literature there. For a general discussion of the role of compensations for international environmental problems, see Mäler (1990).
3. Compensations are not the only instrument available to achieve cooperation. Mohr and Thomas (1993) discuss the stabilizing effect of cross-default clauses between environmental and credit contracts, Stähler (1996) discusses the stabilizing role of in-kind transfers to compensate non-complaint agents, and Folmer et al. (1993) discuss the role of interconnected games.
4. $B_{EEE} = 0$ is only met by a quadratic benefit function and shows up as a convenient assumption for the stability of the solution in this section's model. See note 8. Partial differentiations are denoted by a respective subscript whereas differentiations with respect to time are denoted by a dot. Throughout the paper, the time index is suppressed whenever suitable.
5. Note that a conventional logistic function cannot catch the corresponding properties of the regeneration function because it assumes a finite limit for the zero stock. To present an example, the circle function (defined for a positive $R(S)$ only)

$$R(S) = \sqrt{[S^{MY}]^2 - [S - S^{MY}]^2}\,, \quad R_S = \frac{S - S^{MY}}{R(S)}\,,$$

$$R_{SS} = \frac{1}{R(S)} - \frac{[S - S^{MY}]^2}{[R(S)]^3} < 0,$$

produces infinite limits for $S = 0$ and $S = S^{\circ}$. Note also that the second derivative of this function is indeed negative, whereas the third derivative can be shown to depend on the stock.
6. The infinitely positive limit of the zero stock ensures an interior solution. If instead $\lim_{S \to 0^+} R_S(S) = i < \infty$ holds, the resource could be completely extinct if $r > i$.
7. Whether these utilities are Lindahl-based or imperfect marginal willingness-to-pay measures is not considered here.

8. Now it is evident that $B_{EEE} = 0$ is a very convenient assumption for the stability of this problem because it guarantees an always positive $\varepsilon_E^* = r - R_S$. If $B_{EEE} > 0$, ε_E^* must be supplemented by

$$-\frac{B_{EEE}\{B_E[r - R_S] - q\}}{B_{EE}^2}$$

This term causes ambiguity with respect to the sign of ε_E^* except in a sufficiently narrow neighborhood around ε^* where the term vanishes due to the optimality condition. Hence, a non-zero B_{EEE} does not endanger local but global stability because stable branches may not exist when the resource owner is far away from the steady state.

9. The paper assumes that this re-evaluation is undertaken steadily. The alternative assumption of discrete evaluation jumps merely complicates the analysis. Unless the resource-owning countries can manipulate the jump by other means in addition to their extraction policies, the problem remains the same in qualitative terms. For the role of jumps in optimal control theory, see Seierstad and Sydsaeter (1987).
10. See for the decisive role of a player's attributes Güth (1990). According to the Coase Conjecture, the coalition of donors can be expected to be unable to commit itself on a fixed compensation price.

References

Barrett, S. (1992), *Self-Enforcing International Agreements*, Mimeo, London Business School.

Clark, C. W. (1976), *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, Wiley, London.

Dasgupta, P. S., G. M. Heal (1979), *Economic Theory and Exhaustible Resources*, Cambridge: Cambridge University Press.

Folmer, H., P. V. Mouche, S. Ragland (1993), 'Interconnected Games and International Environmental Problems', *Environmental and Resource Economics* **3** (4), 313–335.

Güth, W. (1990), *Game Theory's Basic Question: Who is a Player?* Mimeo.

Mäler, K.-G. (1990), 'International Environmental Problems', *Oxford Review of Economic Policy* **6** (1), 80–108.

Mohr, E. (1993), *Sustainable Development and International Distribution: Theory and Application to Rainforests as Carbon Sinks*, Kiel Working Paper No. 602, The Kiel Institute of World Economics.

Mohr, E., J. Thomas (1993), *Pooling Sovereignty Risks: The Case of Environmental Treaties and International Debt*, Kiel Working Paper No. 568, The Kiel Institute of World Economics.

Nordhaus, W. D. (1973), 'The Allocation of Energy Resources', *Brookings Papers on Economic Activity* **3**, 529–570.

Nunnenkamp, P. (1992), *International Financing of Environmental Protection. North-South Conflicts on Concepts and Financial Instruments and Possible Solutions*, Kiel Working Paper No. 512, The Kiel Institute of World Economics.

Seierstad, A., K. Sydsaeter (1978), *Optimal Control Theory with Economic Applications*, Amsterdam: North-Holland.

Stähler, F. (1994), 'Biological Diversity: The International Management of Genetic Resources and its Impact on Biotechnology', *Ecological Economics* **11**, 227–236.

Stähler, F. (1996), 'Some Reflections on the Multilateral Environmental Agreements', in A. Xepapadeas, ed., *Designing Economic Policy for Management of Natural Resources and the Environment*, Aldershot: Edward Elgar (forthcoming).