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Trade Sanctions and Effects on Long-Run Stocks of Marine Mammals

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Abstract *Trade sanctions are used to influence the long-run management of an ecological system in another country, trying to secure a large predator stock by using sanctions on the exports of the products from the predator or the prey. This corresponds to U.S. sanctions on Norwegian fish exports aiming to prevent or reduce harvesting of Minke whales. Threats of sanctions influence long-run equilibrium, but do not secure increased stocks and decreased harvesting. The outcome depends on the bioeconomic interaction between the species, and the managerial system in the Target country. It is neither obvious that the sanctions are credible, nor that the Sender will succeed. The interaction between the species is crucial for evaluating the effects of the sanctions.*

Key words Economic sanctions, marine mammals, multispecies marine management.

Introduction

The management of ecological systems will often be of international interest, even when they are managed domestically. This is the basis for international negotiations and multilateral agreements. There are a large number of such problems in resource management, including externalities in the extraction or harvesting, and the existence of public goods. The atmosphere, the existence of species, and biodiversity are all international public goods; and there is a need for second-best policies to handle the noncooperative situation if international agreements are not reached.

Policy interventions to protect one species influence the whole ecological system of interacting species. In the short-run it is reasonable to exclude such effects, but they must be considered in the long-run management. The International Convention on Trade in Endangered Species (CITES) is a multilateral agreement which uses trade bans as a main measure to protect species. The U.S. Marine Mammal Protection Act goes even further, by including the possibility of U.S. unilateral use of trade sanctions on imports of all sea products to influence other countries to adopt U.S. policy of protection of marine mammals (Porter and Brown 1996). Here trade sanctions on the prey are used to influence the management of the predators within the same ecological systems.

This policy option has been brought into the discussion on the management of the Northeast Atlantic Minke whale.[1] Norway has insisted on starting sustainable harvesting of this resource, and wants to remove the Minke whale from the CITES trade ban. The U.S. considered using trade sanctions on Norwegian sea products—

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[1] Amundsen, Bjørndal, and Conrad give an overview of the Northeast Atlantic Minke whale harvesting.

including fish from the Barents Sea—as a pressure to stop Norwegian whaling. In this case, there are no exports of whale products, but there are exports of products from the other species within the same marine ecosystem. In the short-run, trade sanctions will only decrease the profits in the fisheries. However, in the long-run, sanctions will change the profitability and the equilibrium stocks for all species. We shall focus on this interaction, and how international trade interventions influence the long-run stocks of marine mammals—like the seal species and different whale species.

The discussion is limited to two species because the main purpose is to analyze the principles of interaction. We concentrate on a predator-prey relationship, while Schulz (1997a) also analyzes a system of competing species. It is usually possible to introduce international pressure directly on the management of the actual species. This is the case for seals where the products are mainly for export. However, in some cases, such as the Norwegian Minke whale, the products are sold domestically and trade policy only works through other exports like fish products. Flaaten (1988, 1989) has studied harvesting of predator-prey ecosystems. The present analysis builds on his work. However, in the comparative statics of the equilibrium solution he ignores some of the interspecies effects. Hence, our analysis reaches different, and sometimes opposite conclusions to his studies. In the model, the ecological system is harvested by national fishermen who are using the natural resource as a source for extraction of an economic rent. The national multispecies management is under pressure from another nation, which has objections to the management. Sanctions are then used to enforce the policy abroad.

The organization of the paper is as follows. We first give a short background on economic sanctions, we then build a traditional model for long-run development of a marine predator-prey ecological system. The bioeconomic system is connected with a national economic management system, and the products are tradables internationally. Starting from this, we analyze how economic sanctions influence the long-run stocks in the ecological system. A policy discussion closes the paper. Some of the technical analysis is placed in the appendix.

Background on Sanctions

Some nations are willing to use resources to protect nature abroad, and trade sanctions are among the measures used for this. In some cases trade policy is used to regulate international flows of commodities or pollution. We concentrate on situations where trade sanctions are measures to influence the stocks abroad, while the trade flows as such are of minor interest. Hufbauer, Schott, and Kimberly (1990) give a short general bibliography of economic sanctions, Schulz (1996) discusses the one-species case, and Schulz (1997b) discusses the rationality of sanctions.

Trade sanctions are measures for both expressive and instrumental goals (Galtung 1967). We concentrate on the latter, by analyzing restrictions on imports as a measure to influence marine management in the Target country. The experiences from economic sanctions lead to the conclusion that trade sanctions are not prohibitive, but that they add costs for the Target, like a special tax on exports from the Target. We assume that sanctions work like a negative demand shift in the Sender country, and we assume throughout the analysis that this results in a lower producer price for the sanctioned products from the Target country.

We do not specify the strength of the demand for protection. A possible way is to assume that a low level will lead to consumer boycotts, a higher level to governmental sanctions on imports of sea products, and a still higher level will lead to a general ban on trade. The effects of the sanctions depend heavily on the market conditions. In a market with free competition and homogeneous products, a bilateral sanction will have no effect. In markets with imperfect competition, the effects of sanctions depend on the specified situation in production, demand, and competition (Lundborg 1987; Moe 1993; and Schulz 1997b).

The Sender country wants to 'protect' the marine mammal, while this species is part of the marine ecosystem in the Target country. We model this as a demand for increased stock of the marine mammal.[2] The Target country is supposed to have a joint management regime of the marine mammal and the fish stock. Products from both species are tradables, and we assume net exports from the Target country of both (with no sanctions).

The short-run effects of sanctions are obvious. A lower producer price makes harvesting less profitable, and this decreases the harvesting rate (Barbier *et al.* 1990). We concentrate on the effects on the stock size and on the ecological system which occur only in the long-run. As for marine mammals, the long-run equilibrium is reached after decades. However, sanctions, or threats of sanctions, will influence the expected long-run producer price. We also investigate how a lower rate of discount, or an increased nonconsumptive stock value of the marine mammal, will influence the long-run stock.

The Model

We use a standard bioeconomic model (Clark 1976), adding a specification of the predator-prey relationship following Flaaten (1989). The predator-prey interaction has also been studied in Ströbele and Wacker (1995). Flaaten and Stollery (1996) refer to the diet of the Minke whale as consisting mainly of herring, krill, capelin, and cod.

$X_i(t)$	is the normalized biomass stock of species i, $0 \le X_i \le 1$, letting all stocks vary from 0 to 1 (the carrying capacity of the normalized stock). We set X_1 for the fish (prey) stock, and X_2 for the marine mammal (predator) stock.
r_i	is the intrinsic growth rate of species i
$y_i(t)$	is the harvest rate for species i
ν	is the normalized predation coefficient

We analyze only the biomass of the species, and for convenience we drop the function symbols for t. Partial derivatives are denoted by a subscript, $\partial u/\partial \nu = u_\nu$, and $\partial u/\partial X_i = u_i$.

Following Flaaten (1989), we specify a two-species biological interaction as

$$dX_1/dt = F(X_1, X_2) = r_1X_1(1 - X_1) - \varphi X_1X_2 = r_1X_1(1 - X_1 - \nu X_2) \qquad (1)$$

$$dX_2/dt = G(X_1, X_2) = r_2X_2(1 - X_2/X_1). \qquad (2)$$

The predation coefficient φ specifies the reduction in the growth rate of the prey per unit of the predator. The carrying capacity of the predator is a function of the prey stock, normalized to equal 1, and the carrying capacity of the prey with no predation pressure is also 1. To simplify we introduce $\nu = \varphi/r_1$ as the normalized predation coefficient.

We assume throughout the analysis, independent fisheries of each species, and the unit profit, $b_i = b_i(X_i, p_i)$, is assumed to be an increasing function of the price and the stock of the species. The profit from harvesting species i, π_i, is

[2] The demand for protection may include both an existence value, a nonconsumptive value of the stock, and a demand for stopping the harvesting.

$$\pi_i = b_i(p_i, X_i)\, y_i, \quad b_{ip} > 0,\ b_{ix} \geq 0, \quad b_{ipx} = 0,\ i = 1, 2. \tag{3}$$

We specify a Schaefer production function in each fishery, with the harvest rate proportional with both the stock and the harvesting effort

$$y_i = r_i H_i X_i, \quad i = 1, 2. \tag{4}$$

The term $(r_i H_i)$ is the constant effort per unit time, with H_i scaled so that $H_i = 1$ corresponds to a constant catchability coefficient equal to r_i. For a constant product price p_i and constant cost a_i per unit effort, we find by using the equations (3) and (4)

$$b_i(X_i, p_i) = p_i - a_i/X_i, \quad i = 1, 2. \tag{5}$$

Using the equations (1), (2), and (4) we have the growth rates with harvesting

$$dX_1/dt = F(X_1, X_2) - y_1 = r_1X_1(1 - X_1 - \nu X_2) - y_1 = r_1X_1(1 - H_1 - X_1 - \nu X_2) \tag{6}$$
$$\text{if } dX_1/dt = 0 \Rightarrow F(X_1, X_2) = y_1 = r_1H_1X_1$$

$$dX_2/dt = G(X_1, X_2) - y_2 = r_2X_2(1 - X_2/X_1) - y_2 = r_2X_2(1 - H_2 - X_2/X_1) \tag{7}$$
$$\text{if } dX_2/dt = 0 \Rightarrow G(X_1, X_2) = y_2 = r_2H_2X_2$$

where $F(.)$ and $G(.)$ indicate the biological growth of the species, giving the isoclines for $dX_i/dt = 0$ as:

$$X_2 = (1/\nu)(1 - H_1 - X_1) \tag{8}$$

$$X_2 = (1 - H_2)X_1. \tag{9}$$

We assume that a positive equilibrium exists,[3] and it is found at the intersection of the isoclines, giving

$$X_1^H = (1 - H_1)/[1 + \nu(1 - H_2)] \tag{10}$$

$$X_2^H = (1 - H_1)(1 - H_2)/[1 + \nu(1 - H_2)]. \tag{11}$$

Equations (10) and (11) imply that there will only exist a positive equilibrium for both stocks for $H_1 < 1$. The solution is illustrated in figure 1. Quantities $X_1^\#$, $X_1^\#$ are the long-run equilibrium stocks without harvesting, and X_1^H, X_2^H are the long-run equilibrium stocks with the harvesting efforts H_1 and H_2. The triangle ABC in figure 1 gives the sustainable yield area for the two-species. Any combination of stocks outside the triangle will give a decrease in one or both stocks until they are within the triangle. The predator will only survive if also $H_2 < 1$. Both stocks will increase with decreasing H_1. If H_2 decreases (decreasing fishing pressure on the predator) the stock of the predator will increase and the equilibrium stock of the prey will decrease.

The open access management has an incentive to increase the harvesting effort until $\pi_i = 0$. The open access equilibrium stocks are independent of the ecological

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[3] It is quite possible that the stocks will have cyclical variations. If so, the interpretation of X_i^H is the point which the stocks are fluctuating around. Our purpose is to discuss how sanctions work, and the dynamic behavior of the model. The conditions for stable equilibria are not discussed. We assume that the equilibria are stable, and the conditions for this are discussed by Flaaten (1989).

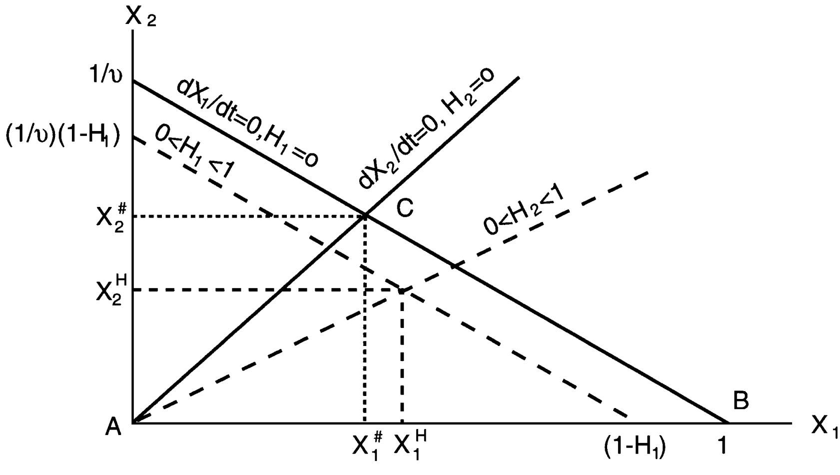

Figure 1. Phase Diagram for the Predator-Prey Model (Flaaten 1989)

interaction between the species, due to the assumption of independent fisheries. In the Schaefer case the open access equilibrium stocks must satisfy

$$X_i^\infty = a_i/p_i, \quad H_1^\infty = 1 - a_1/p_1 - \nu a_2/p_2, \quad H_2^\infty = 1 - a_2 p_1/(a_1 p_2), \quad i = 1, 2. \tag{12}$$

Optimal Management

In the optimal management regime, the objective of the social manager is to maximize the present value of the joint rent from the two resources, denoting δ for the social rate of discount. We add a nonconsumptive value of the predator stock, RX_2, $R \geq 0$, and we assume that the Sender country sets $R > 0$, while the Target country only values the harvest, $R = 0$. The total profit from the harvesting is $\pi = \pi_1 + \pi_2$. The maximization problem is now

$$\max PV = \int_0^\infty [\pi + RX_2]e^{-\delta t}\,dt = \int_0^\infty [b_1(X_1, p_1)y_1 + b_2(X_2, p_2)y_2 + RX_2]e^{-\delta t}dt \tag{13}$$

with the catch or efforts as controls. The effects of a shift in the marginal nonconsumptive value of the stock are demonstrated as $\partial X_i/\partial R$. The restrictions for the maximization problem are the equations (6) and (7).

The solution to equation (13), substituting for the specified growth functions in equations (6) and (7), and the profit functions (5), gives the equations (14) – (17) as necessary conditions for long-run equilibrium stock levels X_1^* and X_2^*, denoting $\pi^i = \partial\pi/\partial X_i$ (see appendix).

$$\pi^1 = \delta b_1(X_1^*, p_1) \Leftrightarrow b_1(X_1^*, p_1)F_1 + b_2(X_2^*, p_2)G_1 + b_{1x}(X_1^*, p_1)F(.) = \delta b_1(X_1^*, p_1) \tag{14}$$

$$\Rightarrow p_1 r_1(1 - 2X_1^* - \nu X_2^*) + (p_2 - a_2/X_2^*)r_2 X_2^{*2}/X_1^{*2} + a_1 r_1 = (p_1 - a_1/X_1^*)\delta$$

$$\pi^2 = \delta b_2(X_2^*, p_2) \Leftrightarrow b_2(X_2^*, p_2)G_2 + b_1(X_1^*, p_1)F_2 + b_{2x}(X_2^*, p_2)G(.) + R = \delta b_2(X_2^*, p_2) \quad (15)$$
$$\Rightarrow p_2 r_2(1 - 2X_2^*/X_1^*) - (p_1 - a_1/X_1^*)\nu r_1 X_1^* + a_2 r_2/X_1^* + R = (p_2 - a_2/X_2^*)\delta$$

$$F(X_1^*, X_2^*) = y_1 \Leftrightarrow r_1 X_1^*(1 - X_1^* - \nu X_2^*) = y_1 \text{ or } H_1 = 1 - X_1^* - \nu X_2^* \quad (16)$$

$$G(X_1^*, X_2^*) = y_2 \Leftrightarrow r_2 X_2^*(1 - X_2^*/X_1^*) = y_2 \text{ or } H_2 = 1 - X_2^*/X_1^*. \quad (17)$$

The equations (14) and (15) demonstrate that there is a joint management of both species simultaneously. In optimum, the prey stock will always be larger than the open access level, but the predator stock might be lower than the open access level, (see Flaaten 1989; and Clark 1976). We see from equation (15) that setting $R > 0$ is similar to managing the predator stock with a lower rate of discount than for the prey. If so, the predator stock must be larger than the optimal one with $R = 0$. Both stocks are evaluated to the return from other investment options, δ.

If the two stocks are managed independently and optimally, the prey stock will be lower than the joint optimal one (ignoring the positive effect of the prey stock to the growth of the predator) (Ströbele and Wacker 1995). However, the predator stock may be larger or smaller depending on the effects of transformation of the nature assets from prey to predator under multispecies management.

Four factors affect the relative distribution of the nature asset on the predator and the prey stocks: the predation costs from the predator stock, the rent from harvesting the stocks, the unit harvesting cost functions, and the nonconsumptive value of the stocks. The predation effect gives an economic incentive for depleting the stock. If $R = 0$, $b_2 \leq 0$, $b_{2X} = 0$, it is economically rationale to make the predator extinct. A positive nonconsumptive value of the predator is enough to protect the stock as long as this effect on the margin outweighs the predation costs. The effect of the resource rent may be seen partially by setting $b_2 > 0$, $b_{2X} = 0$, $R = 0$. If so, we see from equation (15) that $(\delta - G_2) = (b_1/b_2)F_2 = -\nu r_1 X_1 b_1/b_2 < 0$, pushing the predator stock to a lower size than the single species management due to the predation costs. However, a positive b_{2X} makes in optimum $(\delta - G_2) = (b_1/b_2)F_2 + (b_{2X}/b_2)G(.) + R/b_2$, and it is possible with a positive optimal predator stock with positive, but even unprofitable, harvesting. The increased unit harvesting costs for a small predator stock protects the stock against extinction in the Schaefer case.

Copes (1970) and Clark (1976) conclude that the long-run supply curve in a search fishery may be backward bending. A negative shift in demand may increase the equilibrium quantity, but the equilibrium price will decrease. This is true both in an open access fishery, and in an optimally managed one.

The open access solution and the optimal solution without sanctions are two benchmarks for the analysis of sanctions. Now we use a comparative static technique to compare the changes in the long-run equilibrium solutions under the threat of sanctions.

How Sanctions Work in the Long-Run

Let sanctions make an exogenous marginal negative shift in the price of one product.[4] We concentrate on the Schaefer case, and we study the effects on the long-run

[4] It is not obvious that this is the case. If, for instance, the manager of the resources faces a downward sloping demand curve for products from the sanctioned species, and sanctions produce a negative shift in the demand for these products, this will also influence the supply curve for both species. The final outcomes for the long-run prices are not obvious.

equilibrium stock levels, while the long-run harvesting and profit are both functions of the stock. We assume positive equilibrium stocks and harvesting rates throughout the paper, and concentrate on independent fisheries of the two-species—this is the case for fisheries and harvesting of marine mammals.

Under an open access regime we find the long-run effect of a price shift in equation (18) from the partial differentiation of equation (12), and we see that the long-run stock of the sanctioned species will increase, while the effort decreases, and the harvest rate y_i may increase. The sanction has no effect on the economic rent, since it is totally dissipated anyway. As for the other species, the stock size is unchanged.

$$\partial X_i^\infty/\partial p_i = -a_i/p_i^2 < 0,\ \partial H_1/\partial p_1 = a_1/p_1^2 > 0, \qquad (18)$$
$$\partial H_2/\partial p_2 = a_2 p_1/(a_1\, p_2^2\,) > 0;\ \ \partial X_i^\infty/\partial p_j = 0,$$
$$\partial H_1/\partial p_2 = \nu a_2/p_2^2\ > 0,\ \partial H_2/\partial p_1 = -\,a_2\,/(a_1 p_2\,) < 0, \quad i \neq j.$$

These results are illustrated in the phase diagram in figure 2. The point A represents the long-run equilibrium stock mix with no sanctions, while *E* denotes the stocks with sanctions on the predator, and *C* denotes the stocks with sanctions on the prey. The harvesting effort of each species is illustrated with the lines H_1^∞ and H_2^∞ in the figure. Sanctions on the predator decrease the harvesting effort in both fisheries, while sanctions on the prey decrease the effort in the prey fishery, but the effort in the predator fishery increases. The effects on the harvest rates are ambiguous. The economic interpretation of these results is straightforward. Sanctions on the predator make this fishery less profitable, and the stock increases to obtain the zero profit situation. The increased predator stock makes the predation pressure on the prey larger—resulting in a lower profitability and a lower effort in the prey fishery as well. The increased prey stock following from sanctions on the prey increases the growth and the profitability in the predator fishery. Hence the open access effort increases. The situation with no harvesting of the predator is denoted B in figure 2. Compared with the presanction situation, this gives decreased effort in the fishery of the prey. Sanctions on the prey may lead to even lower effort in the prey fishery.

CITES uses trade bans on single species for protection in a multispecies situation. Our analysis demonstrates that this increases the sanctioned stock under open access and independent harvesting.

In the optimal management case, it is a well known textbook result for the one-species case when there is a stable positive equilibrium stock, this stock increases when the producer price decreases, but the catch may either increase or decrease (Clark 1976). Hence, sanctions increase the stock, but do not necessarily decrease the catch. For an optimal management regime, the sanctions decrease the resource rent of the Target country. In a predator-prey system, sanctions on the prey should intuitively increase the supply of food for the predator and add to that stock as well; while sanctions on the predator should intuitively decrease the prey stock due to increased predation pressure. However, these conclusions are not generally valid for the two species case. The effects of sanctions depend on both the biological and the economic interaction and of the management system, and we must consider this a joint management of two interacting nature assets. Flaaten (1988, 1989) argues that $\partial X_i^*/\partial p_i < 0$, while $\partial X_i^*/\partial p_j > 0$ for $i \neq j$, $b_2(X_2) << 0$. However, Flaaten (1991) concludes that these results are incorrect, but the effects are not reassessed. We find these effects by differentiation of the system of equations (14) and (15), as demonstrated in the appendix.

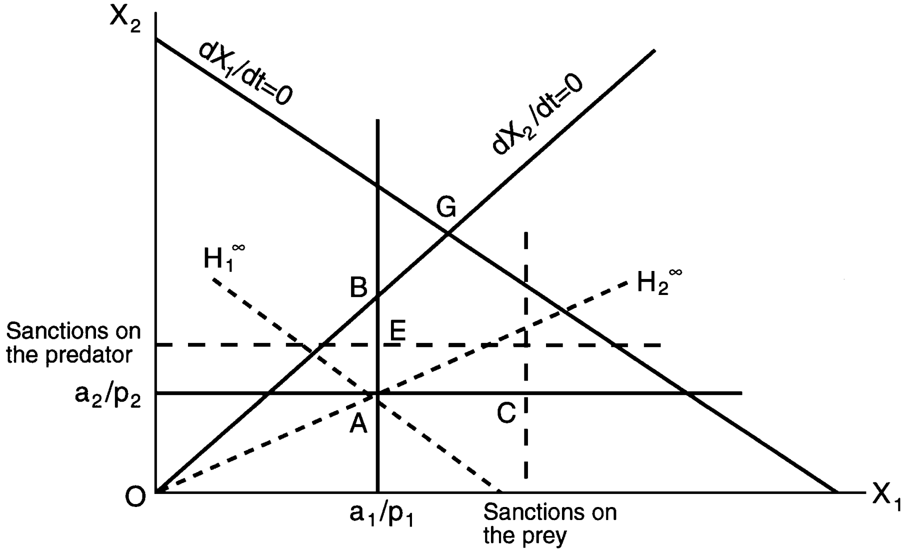

Figure 2. Long-Run Equilibrium for a Predator-Prey Model with Open Access Fisheries and Sanctions

$$\partial X_2^*/\partial p_2 = \{1/|D|\}\{\pi^{21}G_1 + (\pi^{11} - \delta b_{1x})(\delta - G_2)\} \tag{19}$$
$$= \{1/|D|\}\{(r_2 X_2^{*2}/X_1^{*2})[(r_2 X_2^*/X_1^{*2})(2p_2 - a_2/X_2^*) - p_1 r_1 \nu]$$
$$-[\delta - r_2(1 - 2X_2^*/X_1^*)][2p_1 r_1 + (p_2 - a_2/X_2^*)\, r_2 X_2^{*2}/X_1^{*3} + \delta a_1/X_1^{*2}]\}$$

$$\partial X_1^*/\partial p_2 = \{1/|D|\}\{-(r_2 X_2^{*2}/X_1^{*2})(\pi^{22} - \delta b_{2X}) - \pi^{12}[\delta - r_2(1 - 2X_2^*/X_1^*)]\} \tag{20}$$

$$\partial X_2^*/\partial p_1 = \{1/|D|\}\{-\pi^{21}(\delta - F_1) - (\pi^{11} - \delta b_{1x})F_2\} = \{1/|D|\} \tag{21}$$
$$\cdot\{-[\delta - r_1(1 - 2X_1^* - \nu X_2^*)]p_1 r_1[\beta(2X_2^* - X_2^\infty)/(X_1^*)^2 - \nu] + (\pi^{11} - \delta b_{1x})\,\nu r_1 X_1^*\}$$

$$\partial X_1^*/\partial p_1 = \{1/|D|\}\{[\delta - r_1(1 - 2X_1^* - \nu X_2^*)](\pi^{22} - \delta b_{2X}) \tag{22}$$
$$- \nu\, r_1^2 X_1^* p_1\, [\beta(2X_2^* - X_2^\infty)/(X_1^*)^2 - \nu]\}$$

where $\beta = p_2 r_2/p_1 r_1$, and we denote $\pi^i = \partial\pi/\partial X_i$, $\pi^{ji} = \pi^{ij} = \partial^2\pi/\partial X_i \partial X_j$, $b_i = (p_i - a_i/X_i)$, $i, j = 1, 2$, and we have substituted for $\partial\pi^i/\partial p_1 = F_i$, $\partial\pi^i/\partial p_2 = G_i$. In equilibrium $\pi^{ii} < 0$, $|D| > 0$, due to the conditions for maximum (Flaaten 1988). The sign of the equations (19) – (22) are all ambiguous, and the specification of the functions does not make the interpretation of the effects any easier. The reason for the ambiguous effects of price shifts is that the sanctions influence both the value of each stock and the economic effect of the predation. Since the stocks are managed jointly, the optimal mix of the natural assets may change in different directions when the value of one asset is changed. For our discussion we must concentrate on whether a lower price increases the long-run stock of the marine mammal. If so, the sanctions work. If the lower price triggers a lower optimal stock, sanctions work opposite of their intention.

First, we found above that if $R = 0$, $b_{2X} = 0$, a nonpositive unit profit from harvesting the predator, $b_2 \leq 0$, makes it profitable to make the predator extinct. For schooling stocks b_{2X} is close to or equal to zero. Hence, sanctions on a schooling predator stock may be a threat to the species in such cases, unless R is large for the manager.

The effect on the predator stock from sanctions on its products, $\partial X_2^*/\partial p_2$, is demonstrated in equation (19). We have $G_1 = r_2 X_2^{*2}/X_1^{*2} > 0$, $G_2 = r_2(1 - 2X_2^*/X_1^*)$, and $(\pi^{11} - \delta b_{1x}) < 0$ due to the second order conditions for maximum, $|D| > 0$. The term $\pi^{21} = -p_1 \nu r_1 + (r_2 X_2^*/X_1^{*2})(2p_2 - a_2/X_2^*)$. The sign of π^{21} is ambiguous, and so is the sign of equation (19), quite contrary to economic intuition. However, $\partial X_2^*/\partial p_2 < 0$ if $\pi^{21} < -(\pi^{11} - \delta b_{1x})(\delta - G_2)/G_1 = \Omega$. Since $G_1 > 0$, $(\delta - G_2)$ decides the sign of Ω. An interpretation of $(\delta - G_2)$ is as follows. We know from equation (15) that in optimum $(\delta - G_2)b_2 = b_{1X}F_2 + b_{2X}G(.) + R$, $b_{iX} > 0$, $F_2 = -\nu r_1 X_1^* < 0$, $R \geq 0$. The term $b_{1X}F_2$ is the marginal economic costs of predation, while $b_{2X}G(.)$ is the effect of unit harvesting costs decreasing with the stock size, and R is the marginal nonconsumptive value of the stock. For positive profit in the predator harvesting, $b_2 > 0$, we see that $(\delta - G_2) < 0$ as long as the predation effect dominates, or else $(\delta - G_2) \geq 0$. If $(\delta - G_2) < 0$ in optimum, X_2^* is smaller than the optimal stock in a single species management with no stock-dependent costs, and we say that the predator is an economic nuisance in the sense that the predation costs dominate the solution.[5] We denote $(\delta - G_2) \geq 0$ as the normal situation.

The economic interpretation of $\pi^{21} < 0$ is that the marginal effect on the profit from an increase in one of the stocks decreases with the size of the other stock. If so, we say that the stocks are marginal economic substitutes. If the predator is not a nuisance, and the stocks are marginal economic substitutes, we always have $\partial X_2^*/\partial p_2 < 0$. If $\pi^{21} > 0$ we say that the stocks are marginal economic complements. If so, and when the predator is an economic nuisance, then $\partial X_2^*/\partial p_2 > 0$. Otherwise the two effects still make the sign of the effect of a price shift ambiguous. This demonstrates that the use of trade sanctions to influence the management of predators may be counterproductive. We conclude that if the sanctions make the predator less profitable, it is in some cases optimal to keep more of the natural asset as prey biomass, and decrease the predator stock.

The equation (21) demonstrates the effect on the predator stock from sanctions on products from the prey, $\partial X_2^*/\partial p_1$. The sign of equation (21) is also ambiguous, but the last term is always negative. The first term is always negative if π^{21} and $(\delta - F_1)$ have the same sign. If so, $\partial X_2^*/\partial p_1 < 0$ and sanctions on the prey always increase the predator stock. For small prey stocks $(\delta - F_1) < 0$, and sanctions always work if the species are marginal economic substitutes. For large optimal prey stocks, sanctions always work if the stocks are marginal economic complements. We see from equation (14) that always $(\delta - F_1) > 0$ if $b_2 > 0$, $b_{1X} \geq 0$. Formally, $\partial X_2^*/\partial p_1 < 0$ if $-\pi^{21}(\delta - F_1) < -(\pi^{11} - \delta b_{1x})\nu r_1 X_1^*$. We observe from the equations (19) and (21) that $F_i \neq 0$ and $G_i \neq 0$ are the basic effects leading to the ambiguous results of sanctions. Hence, our conclusions build on the basic biological interaction of the species.

The phase diagram in figure 3 illustrates effects on the predator stock from sanctions on the prey (see discussion in the appendix). The optimal stock combination must yield a positive joint profit and $X_1 \geq X_1^\infty$ (Flaaten 1989). Hence, the stock combination must be inside the area of the straight lines EGCB plus the dotted line EB. The sanctions only decrease the predator stock for optimal equilibria close to

[5] Economic nuisance may also be defined otherwise—for example if $b_2(X_2^*, p_2) < 0$. Flaaten (1989) uses $b_2(X_2^*, p_2) << 0$.

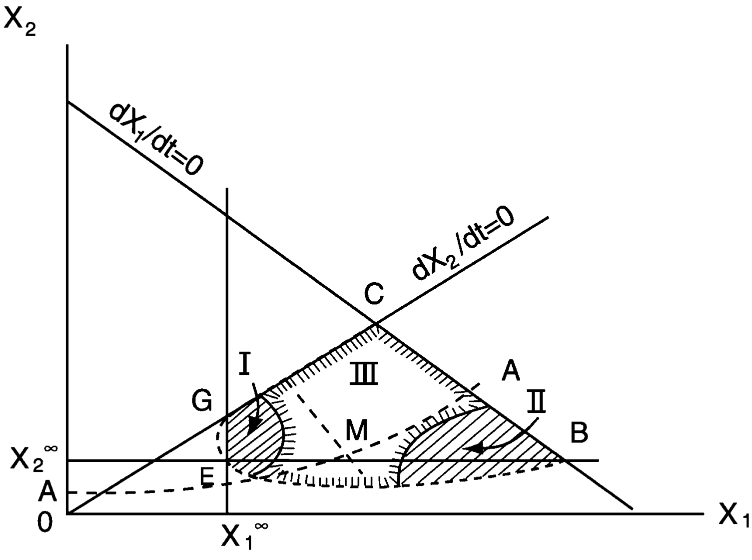

Figure 3. Stock Combinations Where Sanctions on Prey Decrease the Predator Stock

The shaded areas I and II illustrate stock combinations where $\partial X_2/\partial p_1 > 0$. The shade bordered area III illustrates stock combinations where $\partial X_2/\partial p_1 < 0$. Together they include the possible sustainable stock combinations with positive joint rent.

the open access solution, or with a combination of a large optimal prey stock and a small predator stock in the optimal equilibrium. The first situation may occur if both stocks are valuable, and the predation pressure makes it optimal to deplete the predator stock close to, or beyond, the open access solution. The second situation may occur for a combination of a small value of the prey and a large predation effect. It is possible to have a situation where sanctions on the prey decrease the predator stock even when $b_2(X_2^*, p_2) > 0$.

Other Regimes: Constant Prey Stock or Constant Effort in the Prey Fisheries

The optimal management regime assumes a rational manager who maximizes the present value of the rent. In the real world there usually exist constraints to this maximization problem. We shall investigate two other regimes: Management with constant prey stock and management with constant efforts in the prey fisheries. For convenience, we set $R = 0$.

In the Barents Sea there is a negotiated joint fisheries management of Russia and Norway. The fishing quotas are set each year for the main fish stocks. This may be done to obtain some long-run level of biomass. A constant part of the stock is then left for harvesting to each country. If so, we may model this as a management policy with a constant fish stock. The marine mammals are assumed left for optimal management within each country.

The case with constant fish stock illustrates a situation like the above, where the national government through some other reasons decides a benchmark for long-run fish stock. The case with constant effort in the fishery illustrates a situation with strong pressure on the government from the fishermen, or a situation where the government uses the fishery in regional employment policy, while the marine mammals are left for maximizing the rent.[6] For both cases, we want to find the effects of sanctions on exports from one of the stocks. The management with constant stock or constant harvesting efforts are also discussed by Flaaten and Stollery (1996).

The constant fish stock situation is modeled by setting $X_1 = X_1^0$, $R = 0$, in the general model. If so, and assuming positive profit from the X_1 fisheries and positive harvesting of both species, we find as necessary optimal conditions, $X_1 = X_1^0$ (also see appendix 1):

$$p_2 r_2 + a_2 r_2 / X_1^0 - 2 p_2 r_2 X_2^* / X_1^0 = \delta(p_2 - a_2 / X_2^*) + \nu r_1 (p_1 X_1^0 - a_1). \tag{23}$$

The predator stock is managed like a single species management, but with a larger discount rate. The last term on the right hand side of equation (23) is the economic value of the predation, and this adds to a single species optimum condition in the same way as a larger rate of discount, decreasing the long-run predator stock. We find the effects of sanctions from differentiation of equation (23), which yields

$$\partial X_2^* / \partial p_1 = -\nu r_1 X_1^0 / (\delta a_2 / X_2^{*2} + 2 p_2 r_2 / X_1^0) < 0 \tag{24}$$

$$\partial X_2^* / \partial p_2 = -[\delta - r_2 (1 - 2 X_2^* / X_1^0)] / (\delta a_2 / X_2^{*2} + 2 p_2 r_2 / X_1^0). \tag{25}$$

Sanctions on the prey increases the predator stock. The prey is made less valuable, and this reduces the economic value of the predation, and makes it preferable to harvest from a larger predator stock. We conclude that sanctions on the prey make it optimal for the manager to increase the predator stock. The stock effect from sanctions on the predator is ambiguous. In the nuisance case, $[\delta - r_2(1 - 2X_2^*/X_1^0)] < 0$, sanctions decrease the marine mammal stock, while they increase the stock in the normal case. In the nuisance case, a positive market value for marine mammal products works to support the stocks of mammals from a one-sided policy for maximum rent in the fisheries. This situation may occur for small mammal stocks, and now sanctions will trigger a smaller stock of the marine mammal.

Figure 4 illustrates the phase diagram for the situation with sanctions and a constant fish stock, X_1^0. The point A illustrates the two-species management solution in equation (23), B is the situation with no harvesting of the predator, C is the situation with sanctions on the prey, and D is the single species management of the predator stock. Sanctions on the fish products move the optimal solution from A towards D as the value of the prey decreases; and sanctions on the predator products may move D towards B.

However, our analysis concludes that if the sanctions trigger a situation where the marine mammal is a nuisance, the effects change completely. If so, it is optimal to decrease the stock when the price for its products decreases, to protect the valuable prey fisheries. In this situation sanctions on the marine mammal shift the optimal X_2^* down and below A in figure 4. This demonstrates the limitations of sanctions. The International Whaling Commission (IWC) management procedure of 1992 is a single species management of each whale stock (Young 1992).[7] This

[6] The employment policy may also include the employment in onshore processing. If so, even the catches, and not only the efforts, are arguments in the objective function of the Target.

[7] The International Whaling Commission compromised on a management scheme aiming to give a long-run stock of Minke whales of 72% of the unexploited one. This is higher than the estimated maximum sustainable yield stock, which is 60% of the unexploited one.

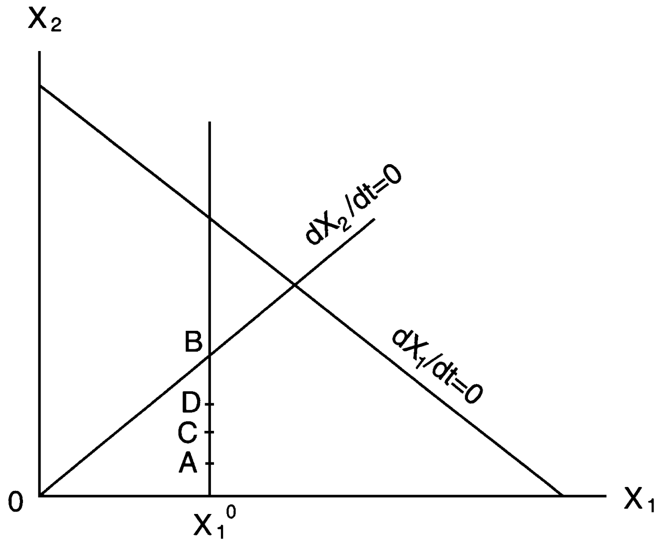

Figure 4. Sanctions with a Constant Fish Stock, $X_1 = X_1^0$

means that the predation effect is excluded, and no sanctions on fish products can increase the whale stock beyond this point. Hence, D is the maximum whale stock as long as the Target country continues whaling and the predator products are sold domestically. Both H_1 and H_2 decrease when X_2 increases in figure 4.

The case with constant effort in the fishery is modeled by setting $H_1 = H_1^0$ in the general model. Substituting for this in equation (13) yields as a necessary condition in optimum (see appendix 1):

$$b_{2X}(X_2^*, p_2)G(X_1^*, X_2^*) + b_2(X_2^*, p_2)[r_2(1 - 2X_2^*/X_1^*) - \nu r_2 X_2^{*2}/X_1^{*2}] = \delta b_2(X_2^*, p_2) + \nu H_1^0 r_1 p_1. \quad (26)$$

Here, the term $[r_2(1 - 2X_2^*/X_1^*) - \nu r_2 X_2^{*2}/X_1^{*2}] = (d/dX_2^*)[G(\theta(X_2^*), X_2^*)]$ is the restricted marginal change in the growth of the marine mammal. We see from equation (26) that the management of the marine mammal shall be like a one-species management, but with “a larger rate of discount,” reflecting the cost of the predation pressure, $\nu H_1^0 r_1 p_1$. Differentiation of equation (26) yields (see appendix 1):

$$\partial X_2^*/\partial p_1 < 0, \text{ and } \partial X_2^*/\partial p_2 < 0 \text{ if } \{\delta - (d/dX_2^*)[G(\theta(X_2^*), X_2^*)]\} > 0. \quad (27)$$

In this situation, sanctions on the fish products work, while sanctions on the marine mammal only work in the situation where $\{\delta - (d/dX_2^*)G[\theta(X_2^*), X_2^*]\} > 0$, *i.e.*, when the predator is not a nuisance. If the predator is a nuisance, sanctions will decrease the stock. In this case, the revenue from selling the marine mammal products makes it optimal not to deplete the stock according only to the needs of the fisheries.

Figure 5 illustrates this situation, letting X_1 be at the line $H_1 = H_1^0$. The point A is still the two-species optimal solution, while B is the situation with unexploited predator stock, and C the situation with sanctions on the prey. The point D is the

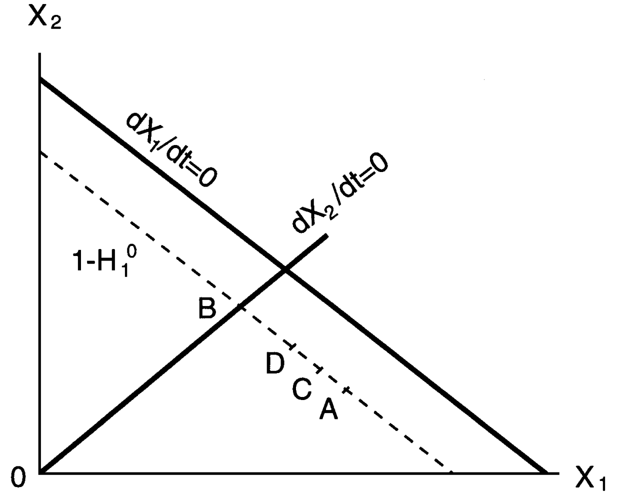

Figure 5. Sanctions with Constant Harvesting Effort on the Prey, $H_1 = H_1^0$

single species optimal management of the predator stock.

Still, this management procedure for the predator considers a predation loss, which is not included in the single species management. We conclude as for the constant prey stock situation that sanctions on the prey work like a decreased δ—making the optimal predator stock larger as long as there is positive profit in the harvesting. Sanctions on the predator products also increase the stock in the normal case. However, in the nuisance case, sanctions on the predator products will move the optimum from the point A towards a smaller long-run stock in the figure.

Besides the trade policy two other policy options are easily evaluated. We find for the two other parameters, R and δ (see appendix 1):

$$\partial X_2^*/\partial\delta = [1/|D|][(\pi^{11} - \delta b_{1x})b_2 - b_1\pi^{21}]. \qquad (28)$$

$$\partial X_2^*/\partial R = [1/|D|][-(\pi^{11} - \delta b_{1x})] > 0 \qquad (29)$$

Equation (28) demonstrates that the well known negative stock effect from increased rate of discount in the single species case is not obvious in the two-species case. In a single species management, a decreased rate of discount yields a larger long-run optimal stock. A policy intervention which reduces the rate of return from capital will increase the long-run stock. Flaaten (1988) demonstrates that this is the case for a prey stock as well, but it is not so for the predator stock. The argument is that when $\delta \to \infty \Rightarrow X_i^* \to X_i^\infty$. The optimal predator stock may be lower than the open access one. If so, increased δ will increase the stock, quite opposite to the single species effect. Anyway, policy interventions affecting the rate of discount for the manager will work, and it is probably easy to observe if $X_i^* \leq X_i^\infty$. The effect of an increased nonconsumptive stock value was found in equation (29) generally to increase the stock, $\partial X_2^*/\partial R > 0$.

The optimal single management case, and the optimal management with $H_1 = H_1^0$ or $X_1 = X_1^0$ yield the well known results that $\partial X_2^*/\partial\delta > 0$, $\partial X_2^*/\partial R > 0$. For an open access situation, the discount rate or a public goods effect have no influence on the long-run solution. Table 1 sums up the results of our discussion.

Table 1
The Effects of Sanctions on the Size of the Long-Run Stocks

	Open Access		Optimal Management	
Effect on: → Effect of: ↓	Predator Stock	Prey Stock	Predator Stock	Prey Stock
Sanctions on Predator Products				
Single species management	+	0	+	?
Multispecies management	+	0	?	?
and $H_1 = H_1^0$	+	–	+ in normal case – in nuisance case	– in normal case + in nuisance case
and $X_1 = X_1^0$	+	0	+ in normal case – in nuisance case	0
Sanctions on Prey Products				
Single species management	0	+	+	+
Multispecies management	0	+	?	?
and $H_1 = H_1^0$	0	0	+	–
and $X_1 = X_1^0$	0	0	+	0
Increased rate of discount, δ	0	0	+ if $X_2^* < X_2^\infty$ – if $X_2^* > X_2^\infty$	–
Increased nonconsumptive value of the predator, R	0	0	+	–

Policy Implications and Concluding Remarks

We have studied the effects of sanctions in predator-prey marine ecosystems and four different management regimes: open access, optimal management, and two restricted optimal management situations. In the trade conflict both parts have more than one option, and we need to discuss their choice of policy. The Sender country has three options: no action, a trade sanction, or a policy which influences the discount rate or the nonconsumptive values of the resources. The Target country can comply to the pressure and leave the predator unexploited, or resist the pressure and sell its products with the sanctioned prices.

The short-run rationality will often dominate the Sender country (Hufbauer, Schott, and Kimberly 1990). If so, only the effects on harvesting are valued, and trade sanctions on the marine mammal products are always working, while sanctions on the fish are only an economic punishment of the Target. Sanctions on the products from the fish will only influence the marine mammal stock if there is a link from the decreased profitability of this harvesting to the profit for the marine mammal harvesting. This occurs through the long-run bioeconomic effects.

The long-run instrumental objective of the Sender country is to increase the marine mammal stock. However, other objectives may be added. An expressive goal

[8] U.S. restricted the import of tuna from Mexico to protect the dolphins—a bycatch in the tuna fisheries. This policy also included restrictions on other countries which imported tuna from Mexico—an attempt to influence the world market for tuna (Brack 1996).

may be to decrease the trade flow in sea products with the Target country. For some goods this may be part of a policy to harm the Target as well.[8] If less bilateral trade in sea products with the Target country is a specific goal for the Sender, trade sanctions always work. The harvest rate and the harvesting effort may also be part of the objective function of the Sender. For small stocks the long-run sustainable harvest rate increases with the stock. This may influence the political pressure for conservation of stocks, or it may introduce a policy for leaving the marine mammals unexploited. We concentrate on the demand for increased stock of the marine mammal, and we define the credible threat of sanctions as a situation where this threat will increase the marine mammal stock regardless of whether the Target complies or resists the pressure. This means either that the Sender is sure both options will increase the marine mammal stock, or that the Sender has enough information to know that the optimal choice of the Target will increase that stock.

The open access situation leaves no rent for the Target country anyway. If the Sender launches a threat of sanctions, this will never decrease the marine mammal stock. If the Target complies to the pressure and leaves the marine mammal unexploited, we have $X_2 = X_1$ in equilibrium and X_2 increases compared with the presanction situation. If sanctions on X_1 are added, this will further increase the marine mammal stock. If the Target country resists the sanction threat, only sanctions on X_2 will work, sanctions on the fish products leave the marine mammal stock constant.

Under optimal management, compliance with the sanction threat is to set $y_2 = 0$, $X_2 = X_1$ as constraints, and to maximize the present value of the rent from the fisheries. We find the optimal condition for the fish stock by substituting this in equations (1) and (2), which yields $F(X_1) = r_1X_1[1 - (1 + \nu)X_1]$, and we have a one-species management of the fish stock. Using this in equation (13) gives as a necessary condition in optimum, for $R = 0$

$$b_1(X_1^*, p_1)F_1(X_1^*) + b_{1x}(X_1^*, p_1)F(X_1^*) = \delta b_1(X_1^*, p_1). \tag{30}$$

Comparing this with the equations (14) and (15) respectively does not leave an unambiguous effect on the marine mammal stock when it is left unexploited. If, for instance, the prey has low value, but still leaves a positive harvesting profit—while the predator is valuable, the optimal solution with harvesting from both species may use the prey mainly as food for the predator stock. With the predator left unexploited, harvesting the prey may still yield some profit, and the depleted prey stock may reduce the food base and the long-run stock of the predator. However, it seems reasonable that an unexploited marine mammal stock usually will be larger than the optimally managed one within the two-species model. In a single species optimal management regime of the marine mammal stock, or a management with constant effort or constant stock of the fish, it is obvious that the marine mammal stock increases when it is left unexploited. Hence, the threat of sanctions is credible if sanctions work—both resistance and compliance yields a larger marine mammal stock. However, our analysis does not support that sanctions always work.

Our analysis concludes that sanctions on the predator do not work in two cases. First, in the general optimal management of the joint sea resources, the effects of sanctions were undecided. Sanctions decrease the stock of the predator if they are marginal economic complements, and the predator is a nuisance. Even if the stocks are marginal economic substitutes, sanctions may not work if the predator is a nuisance. And even if the predator is not a nuisance, sanctions may not work if the stocks are marginal economic complements. These results add new knowledge to earlier studies. They oppose the conclusions of Flaaten (1989), and they add to generally ambiguous effects from Flaaten (1991). Second, if the fish stock is managed with a constant harvesting effort or a constant stock, sanctions do not work if the predator is a nuisance. These two special cases add new results, and the analysis unveils the importance of the marine mammals as a potential economic nuisance in the resource management.

Sanctions on the prey have quite unpredictable effects on the predator stock. For small prey stocks, sanctions always work if the species are marginal economic substitutes. For large optimal prey stocks, sanctions always work if the stocks are marginal economic complements. For a lot of situations the effect of sanctions is ambiguous. These conclusions also oppose Flaaten (1989).

In sum, the effects of sanctions depend on the biological and economic interaction of the species, giving no general conclusions. The reason for this is that sanctions on products from one-species change the relative value of the species as nature assets, and the social manager may prefer to transform some of the biomass to the most valuable species.

It is obvious that the introduction of a threat of sanctions decreases the expected total rent from the fisheries. But it is not obvious that the best reaction for the Target is to stop harvesting the mammal. Resistance gives a lower producer price for one or both fisheries, while compliance means no rent from the marine mammal, and an increased predation pressure. This affects the present value of the joint nature rent for the Target country. The Target will choose the management which yields the largest present value of the rent, and we cannot decide the difference between the two situations unless we know the specific parameters in the model. The Sender country is only sure to succeed if both responses yield increased stock of the marine mammal.

This conclusion is important because then the Sender must take the possibility of resistance from the Target into consideration before launching a threat of sanctions. The IWC management system from 1992 (Young), seems to support the notion that this is the best solution the U.S. can reach within a two-species management scheme with sanctions. The IWC regime also makes it possible for all nations to participate in the management of the stocks, and it makes the threat of trade sanctions credible.[9]

Sanctions on the marine mammal products are well known—like the ban of trade in such products (seal meat and fur, whale oil and meat), or the CITES trade ban on products from different endangered species. Our analysis demonstrates that these policy measures have a weak theoretical base. For terrestrial species it is even worse, since a lower profitability in harvesting may trigger conversion of the habitat (Schulz 1997c). The same ambiguous results appear from sanctions on the fish stock. This demonstrates that the U.S. policy of sanctions on fish products against countries that violate U.S. marine mammal legislation may even decrease the stocks of marine mammals in the long run. While the single species management models yield that sanctions work, the more 'holistic' approach in a two-species analysis may change the direction of the sanction effects in the long run.

An easy way for the Target country to make the known effects of sanctions ambiguous is to insist on a multispecies management, and not informing the international opinion on the biological or economic parameters of the model. It must anyway be important for the Target country to declare that the predation effect of the marine mammals is considered in the management, because this makes the country less vulnerable to sanction threats. More surprisingly, it seems that sanctions on the predator are more likely not to work if the predator is a nuisance. The reason is that the sanctions harm the market for products from the predator, and leave the stock only as a nuisance. This means that the Target country is less vulnerable to sanctions when the predator is a

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[9] The maximal sustainable stock of the marine mammals requires that the prey is left unexploited in the predator-prey model.

nuisance. If a predator is not economically valuable, it is often under threat of depletion caused by its negative influence on other economic activity in the ecosystem.

In an optimal management system a reduced rate of interest works to protect a single stock, but this policy only works for stocks with profitable harvesting in predator-prey interaction. We include a nonconsumptive value of the marine mammal stock in the objective function. A policy which increases this value for the manager will always increase the stock. This result demonstrates that a nonconsumptive value of the marine mammal stock for the international society which is ignored by the Target country will give a stock that is too small. However, it is possible for the Sender country to intervene in the management two ways. The market approach is that a positive international nonconsumptive value of the stock gives a willingness to pay for the stock internationally. The Sender country may alternatively buy the property rights to the marine mammal resource, and leave it unexploited.[10] For the Target country this is a favorable deal as long as there is a joint management of both resources. If not, the owners of the right to exploit the marine mammal will gain, and leave the costs to the owners of the fish stock. Some marine mammal stocks may have an unexploited tourist value,[11] making it profitable to increase the stock for eco-tourism (Whelan 1991; Shah 1995). The Sender country may introduce a market for this value, or subsidize existing activity in eco-tourism.

Throughout the analysis we have used a model which does not permit extinction, and we assumed that harvesting from the ecosystem would be profitable with both species present. In the real world, however, there is a danger of extinction. Amundsen, Bjørndal, and Conrad (1995) show this for a specified production function in an open access model. Hence, the risk of extinction must be taken into account outside of our model.

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[10] This policy is adapted by some environmental organizations—buying rainforests and habitats for wildlife. It is also the base for the policy of "Debt for Nature."

[11] Some whale species, like the humpback whale and the sperm whale are easy to use for whale watching. Others, like the Minke whale, are difficult to observe.

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Appendix

The management problem for overall optimality is given by maximization of equation (13) with the constraints (6) and (7). The current value Hamiltonian to this problem is $H = \pi + RX_2 + \lambda_1[F(X_1, X_2) - y_1] + \lambda_2[G(X_1, X_2) - y_2]$ with y_1 and y_2 as control variables. Flaaten (1988), building on Clark (1976) finds the equations (14), (15), and $dX_i/dt = 0$ as necessary conditions for long-run equilibrium sustainable stocks.

$$\pi^1 = \delta b_1(X_1^*, p_1) \Leftrightarrow b_1(X_1^*, p_1)F_1 + b_2(X_2^*, p_2)G_1 + b_{1x}(X_1^*, p_1)F(.) = \delta b_1(X_1^*, p_1) \qquad (14)$$

$$\begin{aligned}\pi^2 = \delta b_2(X_2^*, p_2) \Leftrightarrow\ & b_2(X_2^*, p_2)G_2 + b_1(X_1^*, p_1)F_2 \\ & + b_{2x}(X_2^*, p_2)G(.) + R = \delta b_2(X_2^*, p_2)\end{aligned} \qquad (15)$$

where $\pi^i = \partial\pi/\partial X_i$. Concentrating on positive stocks we find the comparative statics of the equilibrium conditions by total differentiation of equations (14) and (15). This yields the results in (A1)

$$|D|\begin{vmatrix} dX_1^* \\ dX_2^* \end{vmatrix} = \begin{vmatrix} (\pi^{11} - \delta b_{1X}) & \pi^{12} \\ \pi^{21} & (\pi^{22} - \delta b_{2X}) \end{vmatrix}\begin{vmatrix} dX_1^* \\ dX_2^* \end{vmatrix} \qquad (A1)$$

$$= \begin{vmatrix} (\delta b_{1p} - \partial\pi^1/\partial p_1) & -\partial\pi^1/\partial p_2 & b_1 & 0 \\ -\partial\pi^2/\partial p_1 & (\delta b_{2p} - \partial\pi^2/\partial p_2) & b_2 & -1 \end{vmatrix}\begin{vmatrix} dp_1 \\ dp_2 \\ d\delta \\ dR \end{vmatrix}$$

and $\pi^{ij} = \partial^2\pi/\partial X_i \partial X_j$, $b_i = (p_i - a_i/X_i)$, $i, j = 1, 2$. In optimum $\pi^{ii} < 0$, $|D| > 0$, due to the maximum conditions (Flaaten 1988). We find $\partial\pi^i/\partial p_1 = F_i$, $\partial\pi^i/\partial p_2 = G_i$, $b_{2p} = 1$, and $(\pi^{11} - \delta b_{1x}) < 0$. We substitute for the predator-prey interaction from the equations (1) and (2), $F_1 = r_1(1 - 2X_1 - \nu X_2)$, $F_2 = -\nu r_1 X_1$, $G_1 = r_2 X_2^2/X_1^2$, $G_2 = r_2(1 - 2X_2/X_1)$. We also have $\pi^{21} = -\nu r_1(b_1 + b_{1x}X_1) + (r_2 X_2/X_1^2) + (2b_2 + b_{2x} X_2^2) = (2p_2 - a_2/X_2) r_2 X_2/X_1^2 - p_1 r_1 \nu$. This substitution yields the equations (19) – (22).

The conditions for $\partial X_2^*/\partial p_2 > 0$ are discussed in the main text. Here we discuss the effects of sanctions on the prey, see also Schulz (1994). The signs of $\partial X_2^*/\partial p_1$ and $\partial X_1^*/\partial p_1$ in the equations (21) and (22) are both ambiguous. But for some optimal stock combinations we can decide the signs of the price effects. In optimum, the joint rent must be nonnegative and the prey fishery must be profitable [while the predator fishery may be unprofitable (Flaaten 1989)]. In a phase diagram these restrictions together with the assumption of both stocks at positive long-run sustainable levels make up a set of possible stock combinations as the area inside the dotted line EB and the lines BC, CG, and GE in figure 3. Along the dotted line GEB the joint profit is zero. Since $|D| > 0$, the sign of the numerator decides the effect of a price shift. As for $\partial X_2^*/\partial p_1$ in equation (21) the first term of the numerator is $[-(\delta - F_1)] p_1 r_1[\beta(2X_2^* - X_2^\infty)/(X_1^*)^2 - \nu]$. The first part of this term is positive for small values of X_1^*, but it becomes negative when X_1^* increases. The second part of this term is positive for values of X_2^* above a parabola indicated as AA in figure 3. Since these two parts are multiplicative, only for stock combinations NW or SE of the point M we get a positive value. The second term of the numerator is always negative, since $\nu r_1 X_1 > 0$, and in optimum $(\pi^{11} - \delta b_{1X}) < 0$. Summing up, this makes only two possible areas for a positive value of equation (21). First, for some optimal values close to the open access long-run equilibria stocks of both species we may get $\partial X_2^*/\partial p_1 > 0$. Second, for optimal stock combinations implying a large X_1^*, and X_2^* close to or below X_2^∞, we may get $\partial X_2^*/\partial p_1 > 0$. These areas are shaded in figure 3, while $\partial X_2^*/\partial p_1 < 0$ is the shade bordered area.

The effects on the prey stock of an own-price increase in equation (22) may be studied in a similar way. The first part of the first term in the numerator is negative for small values of X_1, but becomes positive when X_1 increases. The second part of the first term, $(\pi^{22} - \delta b_{2X}) < 0$, due to the second order conditions for optimum. As for the second term, the first part $(-\nu r_1^2 X_1^* p_1)$ is always negative, while the sign of the second part was discussed above. Figure A1 illustrates, for two different sets of parameters, optimal stock combinations where the effect of an own-price increase may increase the prey stock. The shaded areas illustrate such stock combinations (Schulz 1994), while the area EBCG still defines the sustainable long-run stock combinations.

A restricted maximization problem is to set $X_1 = X_1^0$. Now $y_1 = F(X_1^0, X_2) = \varphi(X_2) = r_1 X_1^0 (1 - X_1^0 - \nu X_2)$, $\varphi' = -\nu r_1 X_1^0$, which must be satisfied in equilibrium. We substitute for this in equation (13), setting $R = 0$ for convenience

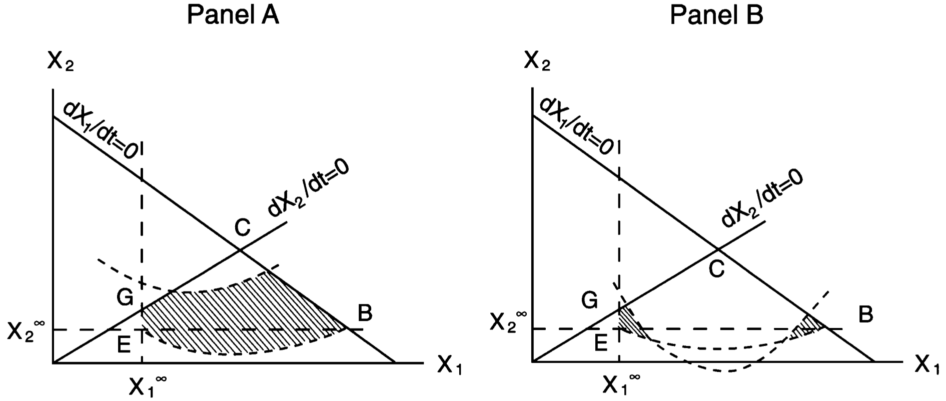

Figure A1. Effects on the Prey Stock of an Own-Price Increase

Note: Areas with $\partial X_1^*/\partial p_1 > 0$ are shaded.

$$\max PV = \int_0^\infty [b_1(X_1^0, p_1)\ \varphi(X_2) + b_2(X_2, p_2)y_2]e^{-\delta t}dt \tag{A2}$$

$$dX_2/dt = G(X_1^0, X_2) - y_2. \tag{A3}$$

The Hamiltonian to this problem is $H = [b_1(X_1^0, p_1)\ \varphi(X_2) + b_2(X_2)y_2] + \lambda[G(X_1^0, X_2) - y_2]$ with y_2 as control variable. We find necessary conditions for maximum when an interior solution is supposed to be present, by setting $d\lambda/dt = \delta\lambda - \partial H/\partial X_2$, $\partial H/\partial y_2 = 0$, $G(X_1^0, X_2) = y_2$. This yields

$$b_{2X}(X_2^*, p_2)\ G(X_1^0, X_2^*) + b_2(X_2^*, p_2)\ G_2(X_1^0, X_2^*) = \delta b_2(X_2^*, p_2) + b_1(X_1^0, p_1)\nu r_1 X_1^0 \tag{A4}$$

which with substitution for the predator prey interaction and the Schaefer production functions yields equation (23) in the main text.

The other restricted problem is to set $H_1 = H_1^0$. If so, $y_1 = H_1^0 r_1 X_1 = F(X_1, X_2) = r_1 X_1(1 - X_1 - \nu X_2)$, and we also know that the isocline for $dX_1/dt = 0$ will define an implicit function $X_1 = \theta(X_2) = 1 - H_1^0 - \nu X_2$, $\theta' = -\nu$, which must be fulfilled in equilibrium. Now, the optimization problem is

$$\max PV = \int_0^\infty \{b_1[\theta(X_2), p_1]\ F[\theta(X_2), X_2] + b_2(X_2, p_2)y_2\}e^{-\delta t}dt \tag{A5}$$

$$dX_2/dt = G[\theta(X_2), X_2] - y_2. \tag{A6}$$

The current value Hamiltonian to this problem is $H = \{b_1[\theta(X_2), p_1]\ F[\theta(X_2), X_2] + b_2(X_2, p_2)y_2\} + \lambda\{G[\theta(X_2), X_2] - y_2\}$ with y_2 as the control variable. We find necessary conditions for maximum when an interior solution is supposed to be present, by setting $d\lambda/dt = \delta\lambda - \partial H/\partial X_2$, $\partial H/\partial y_2 = 0$, $G[\theta(X_2), X_2] = y_2$. This yields

$$X_1^* = \theta(X_2) = 1 - H_1^0 - \nu X_2^* \tag{A7}$$

$$b_{2X}(X_2^*, p_2)G(X_1^*, X_2^*) + b_2(X_2^*, p_2)[r_2(1 - 2X_2^*/X_1^*) - \nu r_2 X_2^{*2}/X_1^{*2}] = \delta b_2(X_2^*, p_2) + H_1^0 r_1 \nu[b_1(X_1^*, p_1) + b_{1X}(X_1^*, p_1)\ X_1^*] \tag{22}$$

or $$(p_2 - 2a_2/X_2^*)r_2(1 - X_2^*/X_1^*) - (p_2 - a_2/X_2^*)\nu r_2 X_2^{*2}/X_1^{*2} = \delta(p_2 - a_2/X_2^*) + H_1^0 r_1 \nu p_1$$

where $r_2(1 - 2X_2^*/X_1^*) - \nu r_2 X_2^{*2}/X_1^{*2} = (d/dX_2^*)\{G[\theta(X_2), X_2]\} = \Psi$ is the restricted marginal change in the growth of the predator. Differentiation of this system yields

$$[(2\Psi - \delta)b_{2X} + b_{2XX}G(.) + b_2(X_2^*, p_2)(d\Psi/dX_2^*)]dX_2^* = (\delta - \Psi)dp_2 + \nu H_1^0 r_1 dp_1. \tag{A8}$$

In optimum it can be demonstrated that $b_{2XX}G(.) + 2b_{2X}\Psi + b_2(X_2^*, p_2)(d\Psi/dX_2) < 0$ due to the second order conditions for optimum, Schulz (1994). This secures that the term in brackets on the left-hand-side is negative. Hence, we see from equation (A8)

$$\partial X_2^*/\partial p_1 < 0, \text{ and } \partial X_2^*/\partial p_2 < 0 \text{ if } (\delta - \Psi) > 0. \tag{27}$$