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A Model of Bycatch Involving a Passive Use Stock

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Abstract *We develop a simple extension of the theory of multispecies fisheries management to analyze a problem where one fish or animal stock has no commercial market but instead is valued passively. We interpret a typical bycatch problem as a standard multispecies fisheries management problem, and we develop a multispecies model incorporating both monetary damages associated with bycatch and variable biological relationships. We examine the behavior of the model with a numerical example focusing on the case of the bycatch of spotted and other dolphins in the eastern tropical Pacific (ETP) yellowfin tuna fishery.*

Key words Biological association, bycatch, eastern tropical Pacific, incidental take, multispecies fishery, passive use value, spotted dolphin, yellowfin tuna.

Introduction

In this paper we present an extension of the theory of multispecies fisheries management to analyze a problem where one fish or animal stock has no commercial market but instead is valued passively.[1] This formulation has relevance to a fisheries "bycatch" problem: the conservation of biological stocks that are taken "incidental to" the commercial harvest of another stock.

This paper serves two functions. First, we construct a bioeconomic model to analyze a situation in which the commercial exploitation of one renewable resource has an external effect on individuals who value another renewable resource. Although the approach is straightforward, it has not yet been considered in the literature. The model helps to clarify the social tradeoffs involved in the implementation of a policy to reduce or eliminate bycatch of noncommercial stocks. Second, the paper serves as a prospectus for further research on the problems associated with biological or technological linkages among resources, where only one resource has a ready market.

We start with a discussion of the importance of understanding the institutional setting when analyzing fisheries bycatch problems. Following that, we suggest a

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[1] We model "passive use value" as the value associated with avoiding the bycatch of noncommercial marine fish or animals when another biological species is harvested commercially. This kind of passive use value is best described as a kind of "inherent value." Mitchell and Carson (1986, p. 65) define inherent values as those that "stem from the respondent's satisfaction that an amenity itself—a wilderness area for example—is preserved regardless of whether it will be used by anyone."

straightforward relationship between the bycatch of a noncommercial stock and monetary damages. A multispecies model is then developed followed by a numerical analytical example that focuses on the case of the bycatch of spotted and other dolphins in the eastern tropical Pacific (ETP) yellowfin tuna fishery. Results and suggestions for further research are considered in the conclusion.

Defining Bycatch

Bycatch is the capture of nontargeted cohorts or stocks in a directed fishery (Alverson *et al.* 1994). Bycatch can have economic significance because it may result in opportunity costs. Opportunity costs arise because real resources must be used to discard and replace bycatch or because some proportion of bycatch is often lost either to the ecosystem or to others who value the bycatch (Boyce 1996; Anderson 1994; Arnason 1994).[2] Note that the occurrence of a bycatch problem, and potentially its economic effects, may depend upon the relevant institutional setting (cf. Bromley 1986). This fact has not yet been fully recognized in the burgeoning literature on bycatch.

Take, for example, a fishery in which two commercial stocks exist. Fishers direct their efforts on the two stocks using one kind of nonselective gear, so that when they target one stock, they also catch individuals from the other. If the institutional setting is such that the two stocks are regarded as separate fisheries, and fishers who target each of the stocks have rights to do so, then externalities exist when bycatch occurs in each fishery. This type of bycatch problem has been analyzed by Androkovitch and Stollery (1994) for the cod and haddock fisheries off the coast of Nova Scotia.

However, if the two stocks are considered to be part of one fishery, with no preferential allocation of rights to distinct stocks within the fishery, then, by institutional arrangement, inefficient levels of bycatch cannot occur. Overharvesting can occur, if the fishery is open access.[3] In such a fishery, in theory, a level of effort can be selected to optimize economic yield, given, as constraints, the biological relationships between stocks and the technological selectivity of the gear. In determining an optimal level of effort in such a fishery, the biological and technological relationships must, of course, be fully specified. Even if discarding of individuals from the lesser-valued stock occurs, there is no economic bycatch problem as long as the effects of both discard costs and mortalities are accounted for and effort is controlled at the optimal level (cf. Arnason 1994).

Invoking the proper assumptions, we might expect the outcome, in terms of yields and effort levels, to be invariant of the institutional arrangement. However, some of the most interesting features of bycatch problems may turn out to be the economic or distributional effects of transactions or management costs associated with alternative institutional arrangements.

Here, for purposes of presentation, we will ignore transactions and management costs to interpret a bycatch problem within the context of a standard multispecies modeling framework.[4] We focus on a case in which one stock is harvested commercially. Another stock is caught, but it is discarded because it has no market. Legal rights to the target stock are distributed to fishers, and protection of the nontarget

[2] Note that the size and sign of any opportunity costs may depend upon the relevant biological relationships among stocks in a marine ecosystem.

[3] In such a fishery, overharvesting might be considered a type of “own” bycatch.

[4] This approach is analogous to the case of “rival exploiters” studied by Bishop and Samples (1980), although here we examine multiple stocks.

stock implies the distribution of legal rights to those who value the existence of the latter.[5] Thus, due to institutional arrangements, the situation is analogous to the case of two fisheries in which fishers have rights to each separate stock.

Because the nontarget stock is valued passively, damages are incurred when individual nontarget fish or animals are harmed. A managing agency must reconcile the rights of the fishers with those of individuals who value the existence of the nontarget stocks. The agency is, therefore, responsible for selecting an optimal level of effort to result in efficient levels of combined target stock harvest and nontarget stock bycatch.

Damage Function

Consider the case of the bycatch of fish or animals that are not used or consumed directly but whose existence is valued by some segments of society. Assume first that these segments are opposed "in principle" to the bycatch of fish or animals from a nontarget stock in a commercial fishery so that they experience a damage associated with any level of bycatch (this damage can be represented as a step up to some positive damage level at one "unit" of bycatch expressed in terms of a suitable measure such as numbers of animals or biomass). Assume next that increasing levels of bycatch imply that higher damages are incurred.[6] Finally, assume that if a nontarget stock approaches eradication, a threshold effect is encountered where the damages increase sharply.

A simple damage function associates a constant marginal damage with each unit of bycatch. The damage function might look like the one represented in figure 1, which plots damages as a function of bycatch in each time period. A more complicated damage function might associate varying levels of marginal damage with varying levels of the stock, but we focus on the simple function in this paper.

Measuring the damage in any specific case obviously involves serious empirical issues when no market for the passive use of a nontarget fish or animal exists. We recognize that some individuals or groups may feel that it is inappropriate or even repugnant to attach a "value" to certain marine animals, such as cetaceans. For example, D'Amato and Chopra (1991) argue on both philosophical and legal grounds that the evolution of international law is such that cetaceans (particularly whales) are entitled to a consideration as moral entities—in other words whales have a "right to life." Consistent with these arguments, others may believe that marine animals have very large or "infinite" values.

As a practical matter, these arguments are difficult to substantiate when the individuals or groups that make them face the true opportunity costs involved in tradeoffs among the different things that they value. Some social scientists are sanguine about the potential of survey approaches to clarify these tradeoffs and, thereby, to help reveal passive use values (Hanemann 1994; Mitchell and Carson 1989).

In reality, however, social institutions may be organized such that certain individuals or groups do not face the true opportunity costs of these tradeoffs, thereby allowing them to ascribe infinite values to some things. Further, survey techniques, as currently practiced, have come under sharp criticism (Binger *et al.* 1995; Diamond and Hausman 1994; Phillips and Zeckhauser 1989). Additional difficulties may arise when willingness to accept compensation for the damage incurred may be

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[5] In the case of passive-value stocks, the existence of protection rights is not a necessary condition for an externality to occur.

[6] The presence of "scope" effects as suggested by this assumption have been found in many other nonmarket environmental resource problems (Hanemann 1994).

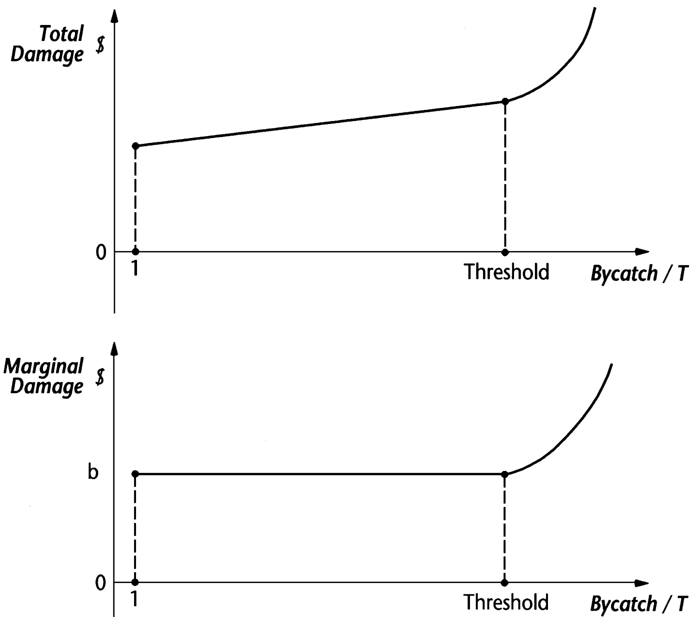

Figure 1. A Damage Function

the appropriate welfare measure, as in a case in which individuals have legal rights to the protection of a resource (cf. Bromley 1995).

It may be difficult to measure the loss of passive use value occurring through the bycatch of noncommercial stocks. However, if a society agrees on a policy to reduce bycatch in a fishery, then there is, at least, a crude indication that protection of the nontarget species has value.[7] Even if that value can be determined only roughly, it is useful and appropriate to begin to clarify the tradeoffs thereby implied. For our purposes, we will assume that individuals or groups have rights to the protection of the nontarget stock, to which they ascribe an economic value, but they do not or cannot place infinite values on these rights.

Bioeconomic Model and Interpretation

There are many models that could be chosen as descriptions of the growth and equilibrium behavior of biological stocks (Clark 1990; May 1981). In order to develop a general theoretical understanding of the behavior of an ecological system (two stocks), we choose first a simple model. This theory can be modified later inductively as empirical evidence is gathered and understanding is enhanced.

We employ a conventional surplus production model, where all state and control variables are functions of time. Let the commercial stock be denoted x and the bycatch stock be denoted y. Subscript the parameters in the following system ac-

[7] Within the context of the model described in the next section, it is possible to impute a damage associated with the bycatch of noncommercial stocks. In an economic sense, this should be considered to be a lower bound on the passive use value of dolphin stocks. Mitchell and Carson (1989, p. 75) point out the difficulties of using a damage function to estimate passive use values.

cording to the stock that each represents. Define $\alpha = \rho/K$ and $\beta = (\gamma\rho)/K$, where ρ is a stock's intrinsic growth rate and K is a stock's carrying capacity, with no initial restrictions on the sign of γ. Write the system:

$$\dot{x} = \rho_x x - \alpha_x x^2 + \beta_x xy = F(x, y) \tag{1}$$
$$\dot{y} = \rho_y y - \alpha_y y^2 + \beta_y yx = G(x, y)$$

This system has been widely used to handle a range of possible multistock interactions (*e.g.*, Hannesson 1983). We account for the interaction between stocks by evaluating the sign of γ. If $sgn\{\gamma_i\}$ is negative for $i = (x, y)$, then the two stocks are described as competing over some biological dimension such as a common food source or space. If $\gamma_i = 0$ for $i = (x, y)$, then the two stocks are described as being independent. If $sgn\{\gamma_i\}$ is positive for $i = (x, y)$, then the two stocks are described as mutualistic (benefiting each other). If $\gamma_i > 0 > \gamma_j$ then the relationship between stocks i and j is described as parasitic (or predatory). Finally, if $\gamma_i > 0 = \gamma_j$, then the relationship between i and j is described as commensalistic.

We make the following simplifying assumptions. The surplus production models are symmetric (*i.e.*, they do not exhibit depensation, and they are not skewed). Assume that all inputs other than the stock can be combined into a single variable called effort, E.

Using a restrictive form of the technology, we examine the technical interactions with the following catch equations. Catch per unit of effort is modeled simply as a linear function of the stock. Assume that the bycatch stock is caught according to the same functional form but with a different catchability, q_y. Because of gear nonselectivity, the effort (E) involved in bycatch is identical to the effort involved in the harvest of the target stock. In principle, q_y could adjust to reflect technological developments designed to reduce bycatch. Thus, harvests of the target stock (h_x) and the bycatch (h_y) can be defined as:

$$h_x = q_x xE \tag{2}$$
$$h_y = q_y yE$$

Now subtract the harvest of the target stock and the bycatch of the noncommercial stock from the relevant state equations in the system:

$$\dot{x} = F(x, y) - h_x \tag{3}$$
$$\dot{y} = G(x, y) - h_y$$

We formulate the problem as that of a fisheries management agency seeking to maximize the net economic benefit from the fishery. Assume that an optimal level of effort can be achieved costlessly through the application of an instrument or combination of instruments such as taxes or (tradeable) quotas. Within the context of a single-season model, Boyce (1996) discusses cases of bycatch by one fleet of another's target stock and bycatch by one fleet of nonmarket stocks. He finds that a system of tradeable quotas is capable of maximizing social welfare.

The economic benefit associated with the harvest of fish from the target stock (x) can be defined as:

$$B(h_x) = \int_0^{h_x} p(\eta)d\eta \tag{4}$$

Thus, for a linear demand function, $p = p_0 - k_x h_x$ with p_0 as the choke price and k_x as the slope, we have:

$$B(E, x) = p_0 q_x x E - \tfrac{1}{2} k_x (q_x x E)^2 \tag{5}$$

The damage associated with bycatch h_y may be calculated as

$$D(h_y) = \int_0^{h_y} b(\zeta) d\zeta \tag{6}$$

Similarly, for a linear damage function,[8] $b = b_0 + k_y h_y$ with b_0 as the intercept (*e.g.*, value of first unit of y) and k_y as the slope, we have:

$$D(E, y) = b_0 q_y y E + \tfrac{1}{2} k_y (q_y y E)^2 \tag{7}$$

The cost of fishing operation, cE, is linear in effort.

The objective of the agency is to choose a level of fishing effort (E) at each instant in time to maximize the net present value of the multistock fishery (total benefits less the sum of total damages and total costs) over an infinite horizon, subject to the flow of the target and bycatch stocks, bounds on feasible effort levels, and parameter values that describe the relevant biological scenario. Assume that the values of all parameters (p, b, c, q, δ, ρ, α, and β) are exogenous.

A managing agency chooses E to solve

$$\max_{\{E\}} \int_0^{\infty} [B(E, x) - D(E, y) - cE] e^{-\delta t} dt \tag{8}$$

with B and D defined as in equations (5) and (7), respectively.
Subject to equation (3) and additional constraints

$$\begin{gathered} 0 \le x,\ 0 \le y,\ 0 \le E \le E_{\max} \\ \alpha_i,\ \rho_i > 0;\ 0 \le q_i \le 1;\ \text{for } i = (x, y) \end{gathered} \tag{9}$$

The current value Hamiltonian is:

$$\begin{aligned} \tilde{H} = {} & B(E, x) - D(E, y) - cE + \lambda_x [F(x, y) - q_x x E] \\ & + \lambda_y [G(x, y) - q_y y E] + \mu_1 x + \mu_2 y + \mu_3 (E_{\max} - E) + \mu_4 E \end{aligned} \tag{10}$$

As in Clark (1990, p. 318), assume that an interior solution exists ($\mu_j = 0,\ \forall j$). The first order conditions include:

$$\frac{\partial B}{\partial E} - \frac{\partial D}{\partial E} - \lambda_x q_x x - \lambda_y q_y y = c \tag{11}$$

$$-\dot{\lambda}_x + \delta \lambda_x = \frac{\partial B}{\partial x} + \lambda_x \left(\frac{\partial F}{\partial x} - q_x E \right) + \lambda_y \frac{\partial G}{\partial x} \tag{12}$$

[8] For simplicity, we assume that the demand function and the loss function are independent.

$$-\dot{\lambda}_y + \delta\lambda_y = -\frac{\partial D}{\partial y} + \lambda_x \frac{\partial F}{\partial y} + \lambda_y\left(\frac{\partial G}{\partial y} - q_y E\right) \tag{13}$$

Equation (11) requires that, at the optimum, the marginal net benefit of an increment in effort (LHS) must equal *c*, the marginal cost of an increment in effort. At any instant, the marginal net benefit is defined as the difference of the sum of the benefit available from harvesting *x* and the user cost (or user "benefit") from the bycatch of *y* and the sum of the damages from the bycatch of *y* and the user cost from harvesting *x*.

We now have four equations [(3), and (11) through (13)] that, in principle, can be solved to yield optimal values of five unknown variables (E, x, y, λ_x, λ_y). Due to the complexity of the differential equations, a purely analytical solution to this problem may be difficult to derive.[9]

Assume that the multistock system reaches a steady-state equilibrium and that the system responds instantaneously with an equilibrium steady state (Clark 1990, p. 197). Conrad and Adu-Asamoah (1986) employ an "iterative method" to solve a steady-state multispecies system for optimal values of the control, state, and costate variables. This method involves solving equations (3), (12), and (13) at the steady-state for the relevant costate and state variables as functions of the other variables and then solving these equations simultaneously to derive $x(E)$ and $y(E)$ and $\lambda_x(x, y, E)$ and $\lambda_y(y, x, E)$. Next, the linear stock equilibrium functions are transformed into sustained harvest functions (Anderson 1986). Finally, an equilibrium level of the target and bycatch stocks can be determined.

In order to solve for the steady-state, we employ the following approach. Setting each equation in (3) equal to zero, we have:

$$y = \frac{\rho_y + \dfrac{\beta_y \rho_x}{\alpha_x} - \left(\dfrac{\beta_y q_x}{\alpha_x} + q_y\right)E}{\alpha_y - \dfrac{\beta_x \beta_y}{\alpha_x}} \tag{14}$$

$$x = \frac{\rho_x + \beta_x y - q_x E}{\alpha_x} \tag{15}$$

From equation (1), we obtain:

$$\frac{\partial F}{\partial x} = \rho_x - 2\alpha_x x + \beta_x y \tag{16}$$

$$\frac{\partial F}{\partial y} = \beta_x x \tag{17}$$

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[9] Using a combined approach of analytical and numerical techniques, Mesterton-Gibbons (1987) has solved this problem for an optimal equilibrium and optimal approach path when γ_i is constrained to equal zero for both stocks (independency). In practice, numerical approaches can be employed to seek a solution (Conrad and Clark 1987).

$$\frac{\partial G}{\partial x} = \beta_y y \tag{18}$$

$$\frac{\partial G}{\partial y} = \rho_y - 2\alpha_y y + \beta_y x \tag{19}$$

Also, from equations (5) and (7), we have:

$$\frac{\partial B}{\partial E} = p_0 q_x x - k_x q_x^2 x^2 E \tag{20}$$

$$\frac{\partial B}{\partial x} = p_0 q_x E - k_x q_x^2 x E^2 \tag{21}$$

$$\frac{\partial D}{\partial E} = b_0 q_y y + k_y q_y^2 y^2 E \tag{22}$$

$$\frac{\partial D}{\partial y} = b_0 q_y E + k_y q_y^2 y E^2 \tag{23}$$

Using equations (12) and (13), λ_y and λ_x can be calculated as:

$$\lambda_y = \frac{\frac{\partial D}{\partial y}\left(\frac{\partial F}{\partial x} - q_x E - \delta\right) + \frac{\partial B}{\partial x}\frac{\partial F}{\partial y}}{\left(\frac{\partial G}{\partial y} - q_y E - \delta\right)\left(\frac{\partial F}{\partial x} - q_x E - \delta\right) - \frac{\partial G}{\partial x}\frac{\partial F}{\partial y}} \tag{24}$$

$$\lambda_x = \frac{\frac{\partial B}{\partial x} + \lambda_y \frac{\partial G}{\partial x}}{q_x E + \delta - \frac{\partial F}{\partial x}} \tag{25}$$

Finally, we rewrite equation (11) as:

$$Q(E) = \frac{\partial B}{\partial E} - \frac{\partial D}{\partial E} - c - \lambda_x q_x x - \lambda_y q_y y = 0 \tag{26}$$

The solution at steady-state (E, x, y, λ_x, λ_y, B, and D) can be determined using the systems of equations (14) through (26). Specifically, find an E such that $Q(E) = 0$. In this study, we employ the bisection technique (Conrad and Clark 1987) to solve equation (26).

Because of the possibility of multiple and suboptimal equilibria, these conditions are necessary, but not sufficient, for an economically efficient outcome. These possibilities exist because the sustained "benefit minus damage" for both stocks (B′ in figure 2) is the sum at each level of effort of the sustained benefit function for the target stock and the sustained damage function for the bycatch stock.

Using a static analysis, figure 2 depicts graphically four out of many possible shapes that the sustained "benefit minus damage" function might take. Figure 2a shows two possibilities depending upon the total cost function that is used. If total cost is represented by TC_1, then E_1 is an efficient outcome. This effort level exceeds the level at which stock y can continue to exist, and *y* is eradicated.

If, instead, total cost is represented by TC_2, then there are two outcomes where the slopes of the sustained "benefit minus damage" and total cost curves are equal. The first is inefficient because total costs exceed sustained "benefit minus damage." The second coincides with the discontinuity where, again, stock *y* is eradicated. Figure 2b depicts a situation where the total damages from harvesting stock *y* are so

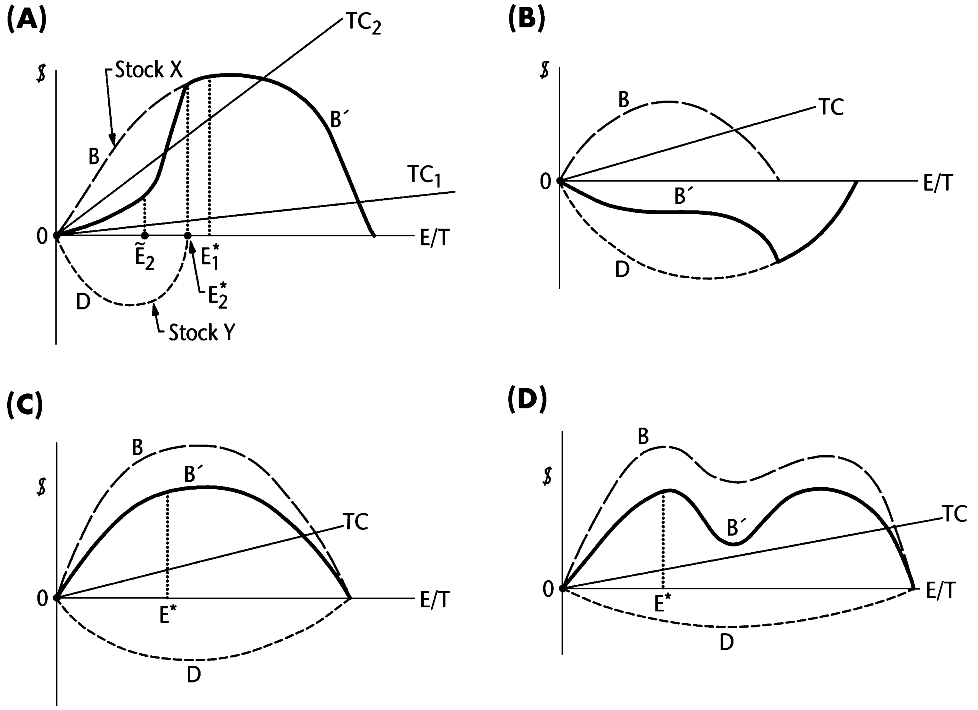


Figure 2. Static Model Scenarios

Some static model scenarios examining sustained benefit (*B*), sustained damage (*D*), resultant sustained "benefit minus damage" (*B*′), and total costs (*TC*) as functions of effort per unit of time (*E*/*T*). Static efficient levels of effort are labeled as *E**. Panel A considers a case in which the carrying capacity for the passive value stock is much smaller than that for the commercial stock and damages are relatively small. When TC_2 is the total cost curve, two outcomes exist in which marginal "benefit minus damage" equals marginal cost. One is inefficient ($\tilde{E}_2$) and one is at the discontinuity (E_2^*). When TC_1 is the relevant cost, one efficient outcome exists (E_1^*). Panel B considers the case in which the carrying capacity for the commercial stock is much smaller than that for the passive value stock and damages are large. No efficient outcome exists. Panel C considers the case in which carrying capacities for the two stocks are the same and damages are not as large in absolute value as benefits. One efficient outcome exists. Panel D considers the case in which the double-humped shape of the sustained benefits curve results from inelastic demand for the commercial stock. One efficient outcome exists where the difference between sustained "benefits minus damages" and total costs is maximized.

Table 1. Parameters for Tuna-Dolphin Models

Variable	Value		Unit
ρ_x	1.911 [a]		time^{-1}
ρ_y	4.5×10^{-2} [b]		time^{-1}
α_x	2.967×10^{-3} [a]		$(ST \times 10^3 \times time)^{-1}$
α_y	6.818×10^{-5} [c]		$(ST \times 10^3 \times time)^{-1}$
β_x	0	Independent	
	2.5×10^{-3}	Commensalistic	$(ST \times 10^3 \times time)^{-1}$
	-1×10^{-5}	Competitive	
β_y	0	Independent	
	0	Commensalistic	$(ST \times 10^3 \times time)^{-1}$
	-5×10^{-5}	Competitive	
q_x	3.9×10^{-5} [a]		10^{-3}
q_y	1×10^{-6}		10^{-3}
δ	0.1		-
p_0	860 [d]	when $k_x = 0$	\$ST^{-1}
	42,860	when k_x varies	
k_x	0		$\$(ST \times 10^3)^{-2} \times 10^3$
b_0	10^4		\$ST^{-1}
k_y	0		$\$(ST \times 10^3)^{-2} \times 10^3$
c	4.362 [e]		10^3\$/SD

Sources: [a] IATTC (1990), [b] Allen (1985), [c] IWC (1983), [d] NMFS (1992), [e] Conrad and Adu-Asamoah (1986).
Notes: ST = short ton, SD = standard fishing day.

great that it is economically inefficient to allow any positive level of effort. Figure 2c depicts the situation where the combination of carrying capacity and stock interactions is such that the two stocks have approximately the same eradication point, and one efficient outcome exists. Figure 2d depicts the situation where the slope of the demand for stock *x* is increased, resulting in the two-humped shape of the sustained "benefit minus damage" function (Anderson 1986). In the case shown here, the point at which the difference between sustained "benefit minus damage" and total costs is the greatest is the efficient outcome.

An Example

We turn now to the ETP yellowfin tuna fishery for an example. In this fishery, large, mature yellowfin tuna are the target stock, and several stocks of dolphin are bycatch. Values for model parameters have been selected from a combination of published and unpublished sources and credible guesses (table 1).

The institutional setting within which the ETP yellowfin tuna fishery is managed is complex. The fishery is an international, high seas fishery. Historically, vessels with many different nationalities have participated in the fishery. Quotas on tuna are recommended by the Inter-American Tropical Tuna Commission (IATTC), but there is no strict enforcement. The United States has acted to reduce the level of dolphin bycatch through restrictions on its own vessels, embargoes on tuna from other nations, and international negotiations. Over the years, these efforts have been increasingly successful in reducing dolphin takes. Several rounds of international negotiations have resulted in an agreement, known as the "Declaration of Panama, " to reduce the incidental take of dolphin species in the fishery.[10] In this section, we assume that the bycatch problem can be described as a multispecies fisheries management problem. Rich descriptions of the evolution of the institutional arrangements can be found in Buck (1997), Joseph (1995, 1994), NRC (1992), and Cicin-Sain *et al.* (1986).

One interesting feature of the tuna-dolphin system is that both the sign and the size of γ_i for $i = (x, y)$ are unknown. One hypothesis is that the two stocks are independent (Clark 1990, p. 316), and therefore $\gamma_x = \gamma_y = 0$. The interaction under this hypothesis is not one that limits the size of either stock. A second hypothesis is that the two stocks are competitors for a common food source (Allen 1985). If the food source is limited, then the interaction parameter will be negative for both stocks. A third hypothesis is that the tuna follow the dolphin because of the dolphin's ability to echo-locate food sources with sound (Allen 1985). Under this hypothesis, the tuna receive some benefit from the presence of dolphin in a commensalistic relationship. As a result, the interaction term for tuna might be positive.

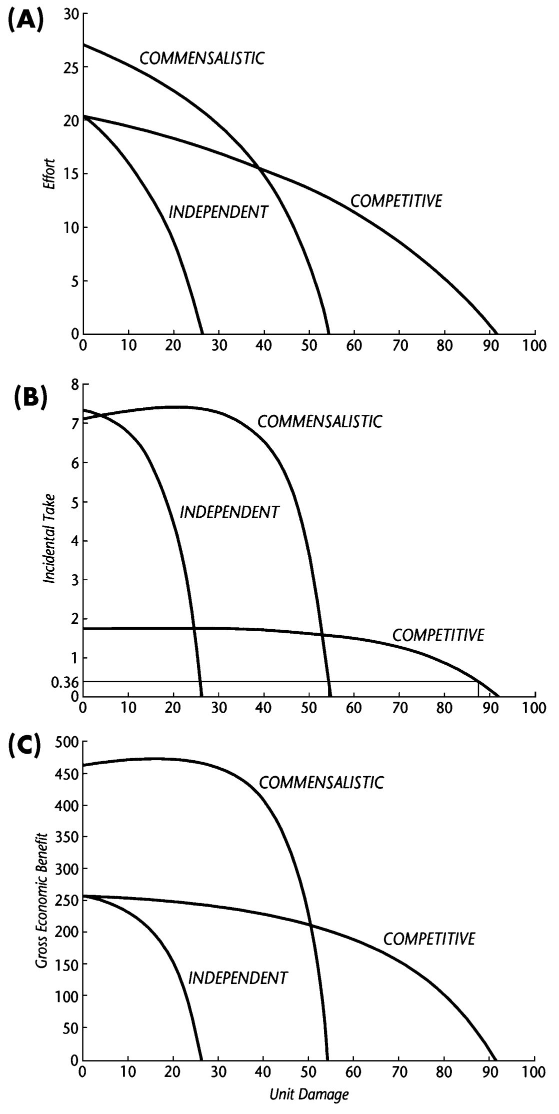
Table 1 lists parameter values for the three biological scenarios: independent, commensalistic, and competitive. In all three models, joint harvest of tuna and take of dolphin occurs. The biological interaction parameters are credible guesses made to demonstrate the behavior of the model. Parameters for the growth, carrying capacity, and catchability of the tuna stock were approximated from IATTC data (IATTC 1990). Dolphin growth and carrying capacity is uncertain, but estimates from Allen (1985) and averages from data gathered by the International Whaling Commission (IWC 1983) were used. When converted into biomass units, the dolphin stock is roughly the same size as the tuna stock. The model is sensitive to the choice of the catchability parameter for dolphin. We employ a credible guess for dolphin catchability, and, because technological innovations to reduce bycatch will affect this parameter (as well as the cost of effort), more careful identification of the value of this parameter should be an important focus of further research. We employ an average of cost estimates reported by Conrad and Adu-Asamoah (1986), converted to 1990 dollars.

There is no market for dolphin existence (ETP dolphins are not "used" for this purpose—even in the sense of "whale-watching"), but we have assumed that the existence of ETP dolphin stocks conveys benefits to some individuals and groups. In theory, it may be feasible to measure the passive use benefits of dolphins through survey techniques. Hageman (1985) has used contingent valuation to estimate the willingness to contribute to a fund to prevent populations of bottlenose dolphins and other marine mammals from falling to levels that would both endanger the populations and decrease the respondents' chances of seeing them. Loomis and Larson (1994) have used contingent valuation to demonstrate positive but diminishing marginal valuation of non-marginal increases in grey whale populations. However, neither study attempts to evaluate the economic effects of incidental dolphin takes.

In figure 3, we have plotted optimal levels of effort E^* (panel A), incidental take of dolphin h_y^* (panel B), and gross economic benefits B^* (panel C) against unit damage (B) for each of the three hypothesized biological relationships. For clarity, we have set $k_x = k_y = 0$ for the simulations depicted in figure 3 (and also in figures 4 and 5). Under all three scenarios, optimal effort declines smoothly and monotonically as unit damage increases from zero to the point at which the fishery must shut down. Under the independent and competitive relationships, as unit damage increases from zero to the point at which the fishery must shut down, both incidental take of dolphin and gross benefits decrease smoothly and monotonically. At low lev-

[10] Declaration of Panama, October 4, 1995, http://www.greenpeace.org/~usa/campaigns/biodiversity/panama.html.

els of unit damage, however, incidental take and gross benefits increase for increasing levels of damage under the commensalistic scenario. The reason for this result is that, for the values of the parameters examined, lower levels of effort imply higher levels of dolphin stocks (y) and tuna stocks (x), which in turn allow higher levels of tuna harvest and incidental take [see equation (2)]. The damage associated with the higher levels of incidental take is more than compensated for by higher benefits from tuna harvests.



Units: Effort (thousands of standard days); incidental take (thousands of short tons); gross economic benefits ($millions); and unit damage ($thousands)

Figure 3. Variation of Optimal Levels of Effort (Panel A), Incidental Take (Panel B), and Gross Economic Benefit (Panel C) with Increasing Unit Damage

The horizontal line in panel B of figure 3 represents the limit on take of dolphins under the provisions of the Declaration of Panama, which limit total incidental take of dolphins from the ETP yellowfin tuna fishery at 5,000 in any year. Even under the independent scenario, the damage per short ton of dolphin is fairly large. The biological interaction scenarios suggest that unit damage could be much larger, but we recognize that the interaction parameters are unknown. These results imply that an understanding of the biological association is quite important for management purposes.

In figure 4, panels A and B, we take a closer look at the commensalistic model. Panel A represents, for varying levels of unit damage, the optimal levels of two of the components of the objective function, gross economic benefits B and gross damages D, and a measure of net benefits, excluding user costs, of $B - D - cE$. Panel B displays the corresponding optimal values of the user costs λ_x and λ_y. Panel A shows

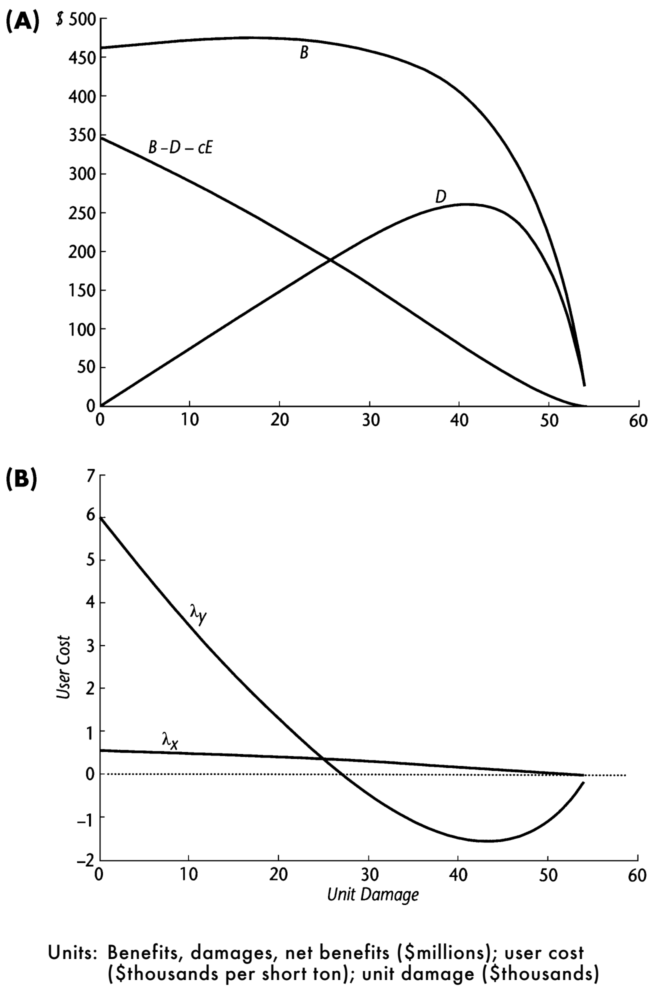
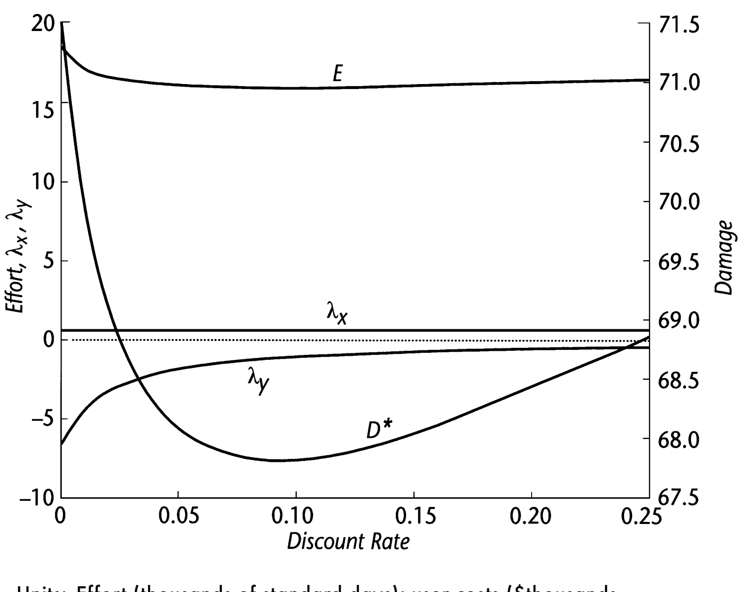


Figure 4. Commensalistic Scenario: Variation of Optimal Levels of Gross Benefits, Damages, and Net Economic Benefits (Panel A) and User Costs (Panel B) with Increasing Unit Damage

net benefits declining over the entire range. As seen in panel B, the user cost for tuna is declining over the entire range, but the user cost for dolphin starts out positive, becomes negative, reaches a minimum, and reverses direction.

Referring to the shape of the gross damage curve, *D**, in panel A, as unit damage increases, the optimal level of gross damage increases at a decreasing rate, reaches a maximum, and declines. The main reason for this decline is the reduction in the level of effort at high levels of unit damage. At low levels of unit damage, it is costly to take dolphin because of the positive biological relationship under commensalism. As effort declines fairly rapidly with increasing unit damage, however, the increase in gross damages slows. As a result, the future penalty for taking a dolphin in the current period declines and, at very high levels of unit damage, there is a user "benefit" (the opposite of user cost). What happens is that the influence of the biological relationship diminishes for low levels of effort and concomitant high levels of both stocks. At high levels of unit damage, λ_y is negative just as it is under the independent and competitive specifications. Intuitively, a lower stock of dolphin in future periods implies lower levels of damage; thus there is a user "benefit" to taking dolphin in the current period.

Figure 5 examines the change in optimal levels of effort, *E**, user costs for tuna harvest, λ_x^*, user "benefits" for dolphin take, λ_y^*, and damage due to incidental take, *D** (on the right hand scale) for the independent biological relationship as the discount rate is varied. In a typical single-species model, we expect optimal effort levels to increase monotonically as the discount rate is increased from zero to ∞ (open access). In our model, however, we find that effort decreases at low levels of the discount rate. Hannesson (1983) describes a similar situation in which, depending upon the levels of the parameters, the size of the stocks of either one or both species in a two species model can increase as the discount rate is increased. There may be no elegant explanation for what is occurring here. The discount rate δ enters into the



Units: Effort (thousands of standard days); user costs ($thousands per short ton); damage ($millions)

Figure 5. Independent Scenario: Variation of Optimal Levels of Effort, User Costs, and Damages with Increasing Levels of the Discount Rate

expressions for both λ_x and λ_y, and we have depicted the optimal levels of these variables as the discount rate varies. For example, increasing the discount rate lowers the user "benefit" of the incidental take of dolphin over the range depicted in figure 5. Also, damages, D^*, drop sharply over the policy-relevant range from 0 to 0.1; in combination, these two effects imply that lower levels of effort are optimal over the policy-relevant range. As a result, as the future is valued more heavily by lowering the discount rate, particularly over the policy-relevant range from 0 to 0.1, optimal levels of effort may be higher. Once again, this result depends upon the parameter values that are employed.

A final simulation involves the change in the optimal level of effort as the slope of the demand function is increased. In our example, the change in slope has little effect on the optimal level of effort until it reaches a critical point at which optimal effort drops significantly with increases in the slope of demand. The critical point appears to be more pronounced under the commensalistic relationship than under the independent and competitive models. The critical point corresponds to the situation depicted in figure 2, panel D, in which the net sustained benefit function develops a double humped shape. At this point there may be three equilibria. In this case, the maximum net economic benefit is associated with the lowest level of effort, hence the sharp drop in effort. Our simulation suggests that the results of the analysis are not particularly sensitive to small changes in the elasticity of demand for a good for which we expect demand to be elastic, such as tuna.

Discussion

Conflicts among the different kinds of uses for renewable fishery resources are perhaps most striking in the case where two stocks interact biologically and technologically, and one stock is commercially exploited while the other has no market but is valued passively. In this paper, we propose a method for constructing a multispecies model that incorporates the external effect of the bycatch of fish or animals from a noncommercial stock in a commercial fishery.

There may be several reasons why this method has not been employed in the past to analyze the management of bycatch. First, the biological relationships may be uncertain. Traditionally, the stocks have been assumed to be biologically independent. Allen (1985) has suggested that there may be commensalistic or competitive interactions. In this paper, we have shown that the choice of an optimal level of effort is sensitive to the biological interaction that exists. Further research efforts should be directed at identifying the nature of the biological relationship and understanding the extent to which the relationship may change due to environmental factors.

Second, surplus production models have not been constructed to model the status of dolphin stocks in the ETP. The IATTC has focused its efforts on monitoring stock sizes and incidental take of dolphin but, until recently, has not published empirical estimates of parameters for dolphin such as intrinsic growth rate, carrying capacity, biological interaction, and catchability. A serious limitation to the use of a surplus production model for dolphin is that the data on dolphin bycatch have been considered inadequate. Dolphin bycatch data have been collected by government observers on tuna boats, and observer coverage has become more complete in recent years. Regardless of the approach taken to manage the fishery, if the reduction of dolphin bycatch is to remain a goal, monitoring must play an important part in both data collection and ensuring conformance with the management objective. With improved data, we might expect that a surplus production model could be constructed and applied more easily.

Third, application of the method proposed in this paper is hampered by the diffi-

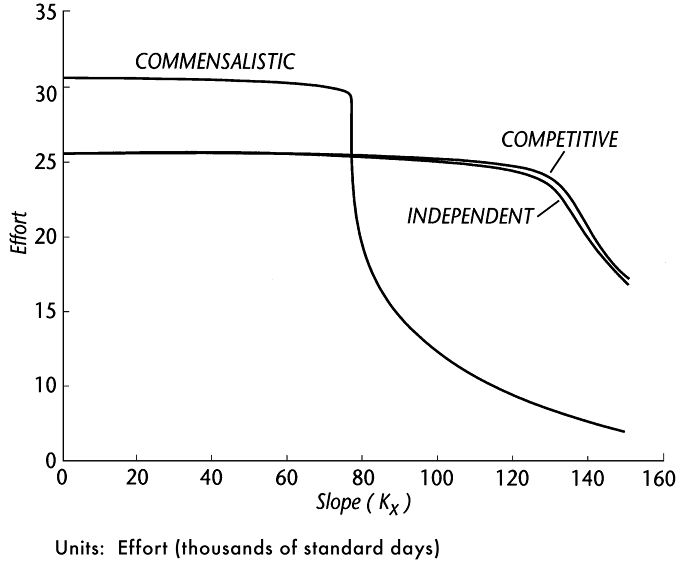


Figure 6. Variation in the Optimal Level of Effort for Each Biological Scenario with Increases in the Slope of the Demand Function

culties associated with assigning a marginal damage to the incidental take of dolphin. In theory, it is possible to measure the benefits associated with avoiding the incidental take of dolphin, but the proper application of direct valuation methods can be quite costly. If all nations participating in the fishery agree to set a limit on dolphin bycatch, then the reduced levels of effort in the tuna fishery implied by such a policy can give us a rough indication of how much these nations value avoiding the incidental take of dolphin.

In this paper, we have proposed a damage function for the incidental take of dolphin. The shape of the function appears plausible over a broad range of dolphin takes. If dolphin bycatch rises to a level that threatens the viability of a stock, then a threshold effect might occur. The threshold effect has not been incorporated specifically into the model presented in this paper. Because some dolphin species (spinner dolphin, striped dolphin) have very small ETP stocks, explicit modeling of the threshold effect might be an important component of a more complete analysis.

Even if the marginal damage for dolphin bycatch is very small (or zero), it may be important to model the fishery as a multispecies fishery. The reason is that if the stocks are not independent, then the biological interaction between tuna and dolphin has an effect on the tuna stock. The direction of the effect (positive or negative) will depend upon the relative sizes of the stocks and the nature and degree of biological and technological interactions.

The kind of analysis presented in this paper can help clarify the analysis of resource tradeoffs. It should be recognized that the analysis represents only one kind of input into the policymaking process. There may be deep philosophical or emerging legal reasons for terminating the incidental take of dolphins. There may be pragmatic political reasons as well. We argue that careful bioeconomic modeling should be at least a part of the decision process.

In constructing the model, we have ignored potential distributional effects. There are certain to be winners and losers from any policy that requires a change in the status quo. For example, a 1992 U.S. policy to ban Venezuelan tuna is believed to have resulted in increased unemployment and criminal activity in Cumana, Venezuela's largest fishing port. It may be useful to adopt a policy instrument that has the potential for achieving a politically determined target of reductions in dolphin mortality in a cost-effective manner, and that can be implemented in such a way as to ameliorate distributional problems. Tradeable quotas for dolphin take might be such an instrument.[11]

References

Allen, R.L. 1985. Dolphins and the Purse-seine Fishery for Yellowfin Tuna. In *Marine Mammals and Fisheries*, J.R. Beddington, R.J.H. Beverton, and D.M. Lavigne, eds. Boston MA: George Allen & Unwin, pp. 236–52.

Alverson, D.L., M.H. Freeberg, S.A. Murawski, and J.G. Pope. 1994. A Global Assessment of Fisheries Bycatch and Discards. FAO Fisheries Technical paper 339. Rome: Food and Agriculture Organization, United Nations.

Anderson, L.G. 1994. An Economic Analysis of Highgrading in ITQ Fisheries. *Marine Resource Economics* 9(3):209–26.

___. 1986. *The Economics of Fisheries Management.* Baltimore MD: The Johns Hopkins University Press.

Androkovitch, R.A., and K.R. Stollery. 1994. A Stochastic Dynamic Programming Model of Bycatch Control in Fisheries. *Marine Resource Economics* 9(1):19–30.

Arnason, R. 1994. On Catch Discarding in Fisheries. *Marine Resource Economics* 9(3):189–207.

Binger, B.R., R. Copple, and E. Hoffman. Contingent Valuation Methodology in the Natural Resource Damage Regulatory Process: Choice Theory and the Embedding Phenomenon. *Natural Resources Journal* 35(3):443–60.

Bishop, R.C., and K.C. Samples. 1980. Sport and Commercial Fishing Conflicts: A Theoretical Analysis. *Journal of Environmental Economics and Management* 7(3):220–33.

Boyce, J.R. 1996. An Economic Analysis of the Fisheries Bycatch Problem. *Journal of Environmental Economics and Management* 31(3):314–36.

Bromley, D.W. 1995. Property Rights and Natural Resource Damage Assessments. *Ecological Economics* 14(2):129–35.

___. 1986. Markets and Externalities. In *Natural Resource Economics*, D.W. Bromley, ed. Boston MA: Kluwer-Nijhoff, pp. 37–88.

Buck, E.H. 1997. 96011: Dolphin Protection and Tuna Seining. Washington: Environment and Natural Resources Policy Division, U.S. Congressional Research Service.

Cicin-Sain, B., M.K. Orbach, S.J. Sellers, and E. Manzanilla. 1986. Conflictual Interdependence: United States-Mexican Relations on Fishery Resources. *Natural Resources Journal* 26(Fall):769–92.

Clark, C.W. 1990. *Mathematical Bioeconomics.* 2nd ed. New York: John Wiley & Sons, pp. 310–42.

Conrad, J.M., and R. Adu-Asamoah. 1986. Single and Multispecies Systems: The Case of Tuna in the Eastern Tropical Atlantic. *Journal of Environmental Economics and Management* 13(1):50–68.

Conrad, J.M., and C.W. Clark. 1987. *Natural Resource Economics: Notes and Problems.* New York: Cambridge University Press.

[11] Boyce (1996) develops a single-season model of bycatch in contrast to the dynamic approach developed here. He finds that separate quota markets must exist for both the target and bycatch stocks. Moreover, in cases in which the bycatch stock has existence value, the tradeable quota must be supplemented with a charge in order to account for nonmarket damages. Note that tradeable quotas cannot be implemented for a policy that calls for zero dolphin bycatch.

D'Amato, A., and S.K. Chopra. 1991. Whales: Their Emerging Right to Life. *American Journal of International Law* 85(1):21–62.

Diamond, P.A., and J.A. Hausman. 1994. Contingent Valuation: Is Some Number Better Than No Number? *Journal of Economic Perspectives* 8(4):45–64.

Hageman, R. 1985. *Valuing Marine Mammal Populations: Benefit Valuations in a Multi-species Ecosystem.* Administrative Report LJ-85-22. La Jolla CA: Southwest Fisheries Center, National Marine Fisheries Service.

Hanemann, W.M. 1994. Contingent Valuation and Economics. *Journal of Economic Perspectives* 8(4):1–44.

Hannesson, R. 1983. Optimal Harvesting of Ecologically Interdependent Fish Species. *Journal of Environmental Economics and Management* 10(4):329–45.

Inter-American Tropical Tuna Commission (IATTC). 1990. Annual Report. La Jolla CA: Scripps Institution of Oceanography.

International Whaling Commission (IWC). 1983. Report of the Subcommittee on Small Cetaceans. Reports of the International Whaling Commission 33:152–66.

Joseph, J. 1995. Testimony on the International Dolphin Conservation Act [P.L. 102-523]. Washington: U.S. House Committee on Resources, Subcommittee on Fisheries, Wildlife, and Oceans.

___. 1994. The Tuna-Dolphin Controversy in the Eastern Pacific Ocean: Biological, Economic, and Political Impacts. *Ocean Development and International Law* 25(1):1–30.

Loomis, J.B., and D.M. Larson. 1994. Total Economic Value of Increasing Gray Whale Populations: Results from a Contingent Valuation Survey of Visitors and Households. *Marine Resource Economics* 9(3):275–86.

May, R.M. 1981. Models for Two Interacting Populations. In *Theoretical Ecology,* R.M. May, ed. Sunderland MA: Sinauer Associates, Inc., pp. 78–104.

Mesterton-Gibbons, M. 1987. On the Optimal Policy for Combined Harvesting of Independent Species. *Natural Resource Modeling* 2(1):109–34.

Mitchell, R.C., and R.T. Carson. 1989. *Using Surveys to Value Public Goods: The Contingent Valuation Method.* Washington: Resources for the Future.

National Marine Fisheries Service (NMFS). 1992. Canned Tuna Industry Update. Long Beach, CA: National Oceanic and Atmospheric Administration, U.S. Department of Commerce. 17 April 1992.

National Research Council (NRC). 1992. *Reducing Dolphin Mortality from Tuna Fishing.* Washington: National Academy Press.

Phillips, C.V., and R.J. Zeckhauser. 1989. Contingent Valuation of Damage to Natural Resources: How Accurate? How Appropriate? *Toxics Law Reporter* 4(October):520–29.