Bycatch in Marine Fisheries

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Introduction

Since the initial article on the bioeconomics of incidental catch and discarding of marine fish species (Ward, 1994), 18 articles have referenced it in furtherance of the fisheries economics study of bycatch or incidental catch. This is by no means a definitive list, since in the same issue of *Marine Resource Economics*, Arnason (1994) and Anderson (1994) both addressed discarding and high-grading in individual transferable quota (ITQ) fisheries. Discarded bycatch has been a problem of note in the fisheries management literature as reviewed by Ward (1994) since the early 1980's (FAO and IDRC, 1982). Hall et al. (2000) characterized bycatch, estimated at 8% of global catch (7.3 million t) during 1992–2001 (Kelleher, 2006), as one of the most significant problems affecting fisheries management. This level of bycatch was alleged to affect biodiversity, waste life (creating, for some, a moral issue), hinder profitability, increase management costs, lead to sociocultural problems and conflicts, and increase juvenile fish mortality.

Solutions proposed for the bycatch management problem that have been deemed successful (Hall et al., 2000) are primarily command and control methods, for example:

- Spatial and temporal closures (closed areas and seasons);
- Harvest performance criteria (backing down tuna purse seines to aid dolphin, *Tursiops* spp., release);
- Gear modifications (bycatch reduction devices (BRD); turtle excluder devices (TED), gear bans, acoustical pingers, discard bans, hook size, mesh sizes, etc.) that reduce catchability for nontarget species; and
- Bycatch limits per vessel.

These command and control measures have been termed "Darwinian selection of fishers," which actually translates to the idea that less efficient fishermen are forced from the fishery as increasingly complex regulations are imposed to reduce bycatch levels (Hall et al., 2000).

Although no clear management objective for these command and control regulations is stated, one can infer from Hall et al. (2000) that economic efficiency is a second-best consideration, if it is considered at all. Only fishermen who can produce catches at the lowest ecological cost, that is, with the least waste and habitat impact, will survive to inherit the fishery. The eradication of bycatch in and of itself, for no other reason and at whatever cost to fisheries, is the inferred management objective. If a neoclassical interpretation of economics is used, then this management goal is recast in terms of the trade-off in alloca-

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ABSTRACT—A review of the significant contributions in the peer-reviewed literature indicates that the discarding of marine fish known as bycatch remains one of the most significant problem facing fisheries managers. Bycatch has negative affects on marine biodiversity, is ripe with ethical and moral issues surrounding the waste of life from increased juvenile fish mortality, hinders commercial profitability and recreational satisfaction, increases management costs, and results in socio-cultural problems and conflicts. While appearing to have a simple conservation engineering solution, reducing or eliminating bycatch in marine fishing operations given the presently existing regulated open access management environment is demonstrated to actually be so complex that its effects can appear to be counter-intuitive. An ecosystem simulation model that explicitly incorporates the human and biological dimensions is used to evaluate proposed bycatch reduction regulations for two fishing fleets exploiting three out of seven species of fish, each with ten cohorts, in two resource areas. One of the fishing fleets is divided into two components representing commercial fishermen and recreational anglers. The seven fish species represent predator, prey, and competitor behaviors and one stock is treated as an endangered species. The results displayed in a series of figures demonstrate the potential unintended effects of simplistic management approaches and the need for a holistic and comprehensive approach to bycatch management. That is, an ecosystem model that explicitly incorporates socio-cultural and biophysical attributes into a common framework allows the magnitude and direction of behavioral responses to be predicted based on changes in governance or biophysical constraints to determine if management goals and objectives have been obtained through the use of quantitative metrics.

tion of species between discards in one fishery and harvest in another fishery.

Discarded bycatch continues to be a concern in the marine fisheries literature, with additional theoretical, empirical, and policy analyses being published each year. One weakness of these separate analyses is the lack of comparability of their results. A common framework is needed to compare and contrast these different studies using the same analytical approach based on a common set of underlying assumptions. Comparability of results will provide additional information to fishery managers who are faced with this problem in actual fisheries.

The initial analysis by Ward (1994) and Ward and Macinko (1996) is presented and then modified into a multi-cohort, multi-species, multi-stock, multi-fleet, multi-vessel capable framework. We then adapt this model to incorporate additional analytical results from selected authors including, but not limited to, Arnason (1994), Boyce (1996), and Abbott and Wilen (2009). Although still a qualitative approach, the increasing complexity of the framework should provide information not presently inferable from the independent assessments. This approach should allow the short-sightedness of the present parochial biological approach to bycatch and discard management to be replaced by an enlightened, multidisciplinary, scientific approach in the future.

Review

The foundation for any scientific assessment is a strong theoretical model from which a working hypothesis can be developed for statistical testing. This section will review bycatch, discarding, and high-grading from a theoretical perspective. Empirical applications will then be reviewed to determine whether evidence exists in support of the theoretical conclusions.

Theoretical Analyses

Since its original recognition (Gunter, 1936; Lindner, 1936), bycatch has been analyzed in the biological literature in terms of its impact on fish population abundance (Nichols et al.[1]). The first study of economic effects (Blomo and Nichols, 1974) found a negligible price effect if total trawl bycatch (368,000,000 lb) were converted to fish meal or oil reduction instead of being discarded.

The first bioeconomic specification (Clark, 1985) suggested that discarding in commercial fishing operations occurs because retention of the discarded species is prohibited by regulation, the discarded species has a nonmarket value, the discarded species has no commercial value, or a valuable species is discarded to make room for a more valuable species in the hold of a fishing craft (high-grading).

Clark (1985) also developed a linear programming model to calculate the optimal trip length for a fishing firm that harvests progressively more valuable species in a multi-species fishery that is unconstrained by stock abundance. Ward (1994) extended this linear programming model into a long-run, static, Gordon-Schaeffer model with stock size constraints that included downstream effects on bycatch species-dependent commercial and recreational fisheries. Thus, the undesirable output in one directed fishery becomes the desirable output of a second directed fishery—a rather paradoxical result in and of itself.

The initial analysis by Ward (1994) focused on the effect of a BRD on stock conservation using a simple two-species Gordon-Schaeffer model of the form:

$$\begin{aligned} \delta x/\delta t &= F(x) - q_x E_x X \\ \delta y/\delta t &= G(y) - q_{yx} E_x Y \end{aligned} \tag{1}$$

where $F(x)$ is the growth function of directed fishery species X,

$G(y)$ is the growth function of the bycatch species Y,

$q_x E_x X = h_x$ is the harvest level of species X in the directed fishery,

$q_{yx} E_x Y = h_{yx}$ is the bycatch of species Y in the directed fishery for species X,

q_x is the catchability coefficient of the gear for species X in the directed fishery for species X,

q_{yx} is the catchability coefficient of the gear for species Y in the directed fishery for species X,

x is the biomass of species X,

y is the biomass of the bycatch species Y, and

E_x is the level of total fishing effort for both species in the fishery for species X.

This simple bioeconomic model of a stylized fishery that generates and discards a bycatch species that is utilized by another independent directed fishery consisting of commercial and recreational components is based on the assumptions that underlie the perfectly competitive market model with two exceptions. First, a key input in the production process is limited, acting as a constraint which is represented by:

$$\begin{gathered} F(X) > 0, F''(X) < 0, \\ \text{and } F'(X) = K_x = 0 \text{ for } 0 \leq X \leq K_x \\ G(Y) > 0, G''(Y) < 0, \\ \text{and } G'(Y) = K_y = 0 \text{ for } 0 \leq Y \leq K_y \end{gathered}$$

where K_x and K_y are the carrying capacities of the environment for species X and Y.

Second, the clearly defined, enforceable property rights that ensure free mobility of inputs and outputs are lacking for the in situ marine fishery resource. Under this open-access scenario, bionomic equilibrium is found where:

$$\pi = P_x h_x + P_y h_{yx} - C_x E_x = 0 \tag{2}$$

where π is profits,

P_x is the ex-vessel price for species X,

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[1] Nichols, S., A. Shah, and G. Pellegrin, Jr. 1987. Estimates of annual shrimp fleet bycatch for thirteen finfish species in the offshore waters of the Gulf of Mexico. Draft Rep., Miss. Lab., Southeast Fish. Sci. Cent., Natl. Mar. Fish. Serv, NOAA, Pascagoula, Miss., 28 p.

P_y is the ex-vessel price for species Y, and

C_x is the unit cost of fishing effort in the directed fishery for species X.

Based on this simple model specification harvest (h_x) and bycatch (h_{yx}) are calculated at their long-run equilibrium levels:

$$h_x = (r_x C_x)/(P_x q_x)\left[1 - C_x/(P_x q_x K_x)\right] \quad (3)$$

$$h_{yx} = \begin{bmatrix} (q_{yx} K_y r_x)/q_x - \\ (q_{yx} K_{yx} r_x C_x)/(P_x q_x^2 K_x) \end{bmatrix} \begin{bmatrix} 1 - (q_{yx}\ r_x)/(r_{yx} q_x) + \\ (q_{yx} r_x C_x)/(r_{yx} P_x q_x^2 K_x) \end{bmatrix} \quad (4)$$

where r_x is the logistic growth rate,

K_x, K_y are the carrying capacity of the environment for species X and Y, and

$P_y = 0$ because the bycatch is discarded.

Harvest levels for the commercial (h_{yc}) and recreational (h_{yr}) fisheries directed at the bycatch species (Y) are similarly derived:

$$h_{yc} = (C_{yc} r_y)/(P_y q_{yc}) \begin{bmatrix} 1 - (q_{yx}\ r_y)/(r_y\ q_x) \\ \left[1 - (C_x)/(P_y\ q_x K_x)\right] - \\ (C_{yc})/\ (P_y\ q_{yc} K_y) \end{bmatrix} \quad (5)$$

and based on the assumption that utility (U) is equal to zero in the long run, then

$$h_{yr} = (C_{yr} r_y)/(V_y\ q_{yr}) \begin{bmatrix} 1 - (q_{yx} r_x)/(r_y\ q_x) \\ \left[1 - (C_x)/(P_x\ q_x K_x)\right] - \\ (C_{yr})/(V_y\ q_{yr} K_y) \end{bmatrix}, \quad (6)$$

where V_y is the marginal value of a recreationally caught fish, with a stable long run equilibrium at

$$Y_c = C_{yc}/P_y\, q_{yc} = C_{yr}/V_y\, q_{yr} = Y_{r.} \quad (7)$$

Based on this stylized fishery model, the comparative static analysis of costless conservation engineering management measures results in no long-run increase in the bycatch species (Y) abundance level. Fishing effort levels are shown to expand to offset any improvement in stock size, and only a small increase in harvest levels result in the bycatch species (Y) fisheries.

Arnason (1994) focuses instead on the possibility that different management regimes can create different incentive levels for discarding bycatch that can affect the magnitude of the discarding and could lead to a remedy for the problem different from that of the conservation engineering strategy analyzed in Ward (1994). The evaluation of a dynamic sole-owner model of the form:

$$\text{Max}_{e,d} \int \pi(e,d,x,p)\exp(-rt)\,dt, \quad (8)$$

$$\text{s.t. } \delta x/\delta t = G(x) - \sum x(i) \quad (9)$$

where π is the profit function,

e is fishing effort,

d is the discard level,

x is biomass,

p is price,

$G(x)$ is the growth function of species x, and

$x(i)$ is the harvest level of species x by grade levels (i),

this results in the discarding rule:

$$d(i) > 0 \text{ if } p(i) + CD_d(0,i) < CL_1(e,x,i) - 0,i \quad (10)$$

where $CD(d(i),i)$ is the cost associated with the discarding of fish of grade i,

$CD_d(0,i)$ is the marginal discarding cost,

$CL(1(i),i)$ is the retained catch cost of fish of grade i, and

$CL_1(e,x,i)$ is the marginal cost of retaining catch.

Therefore, $p(i) + CD_d(0,i)$ is the marginal cost of discarding and $CL_1(e,x,i) - 0,i$ is the marginal benefit of discarding. Equation 10 indicates that discarding occurs [$d(i)>0$] if the marginal costs of discarding catch are less than the marginal benefit of discarding fish of grade (i). With one minor modification, because the discarding activity of a single fishing craft as formulated by Arnason (1994) does not generate a stock externality effect, the discarding rule for an open-access fishery is the same as Equation 10:

$$\begin{gathered} d(I,j) > 0 \text{ if } p(i) + \\ CD_d(0,I,j) < \\ CL_l\big(y(e(j),x,I,j) - 0,I,_j\,\big) \quad \text{for all } j \end{gathered} \quad (11)$$

where j refers to the fishing firm.

Of particular interest is the analysis of the discarding issue under ITQ management systems with continuous and discontinuous ITQ programs. Under the continuous ITQ system, the fishing firm has a permanent stock of ITQ's not differentiated by grade (i), but based on aggregate catch volumes where discards are not counted against ITQ holdings. Equation 8 for firm (j) becomes:

$$\begin{gathered} MaxV = \\ \int\left[\pi\big(e(j),d(j),x,p\big) - s\right]\exp(-rt)\,dt \\ \text{s.t. } \delta q/\delta t = Z \\ \delta x/\delta t = G(x) - Q - \Sigma_j \Sigma_i d(i,j) \quad (12) \\ q \geq \Sigma_j\left[y(e,x,i) - d(i)\right] \Xi \\ \Sigma_i l(I,j)e(j),\ d(j) \geq 0, \end{gathered}$$

where Z is the level of quota holdings traded, and

Q is the total allowable catch (TAC) that is equal to the total quota issued.

This results in the discard rule:

$$\begin{gathered} d(I,j) > 0 \text{ if } p(i) + CD_d(0,i,j) < \\ CL_l y\big(e(j),x,I,j - 0,i,j\big) - \\ \sigma(j) - \delta(j) \quad \text{for all } i \end{gathered} \quad (13)$$

where σ(j) represents the shadow price of ITQ's for firm j or the instantaneous gain from renting the quota foregone by using the ITQ share for landings; i.e.,

$$\sigma(j) = rs - \delta s/\delta t > 0$$

where r is the discount rate,

s is the market price of quota share, and

$\delta s/\delta t$ is the capital gain or loss of holding quota.

$\delta(j)$ is the firm's shadow price for biomass; $\delta(j) = \delta V/\delta x > 0$.

ITQ's lead to an excessive incentive to discard if shares are tied to landings and not to catch.

The ITQ discarding function is:

$$\Gamma\ (i) = CL_l(y(i) - 0,i) + \Omega(j) - p(i) - CD_d(0,i). \qquad (14)$$

The optimal discarding function is:

$$\Gamma\ (i) = CL_l(y(i) - 0,i) - \mathrm{p}(i) - CD_d(0,i). \qquad (15)$$

If $\Omega(j)\ \Xi\ \sigma(j) - \delta(j) > 0$, then an incentive to discard above the social optimum defined in Equation 10 and 11 exists. If $\delta(j) \rightarrow 0$ as $j \rightarrow \infty$, then $\Omega(j) \rightarrow \sigma(j)$; i.e.,

$$lim_{j\rightarrow\infty}\ \Omega(j) \rightarrow \sigma(j),$$

when $\Omega(j)\ \Xi\ \sigma(j) - \delta(j) = 0$, this indicates an indifference to discarding, but when

$\Omega(j)\ \Xi\ \sigma(j) - \delta(j) < 0$, no incentive to discard is implied.

In an analysis similar to Clark (1985), Anderson (1994) created a fishing-vessel, hold-capacity criteria for high-grading. Instead of a multi-species fishery with harvests progressively focusing on more valuable species, demand for fishing craft hold capacity is determined when high and low valued species grades exist. The Lagrangian formulated by Anderson (1994) for constrained trip profit is:

$$\mathrm{L} = \pi_t + \lambda_1\ (B+D - yE) + \lambda_2\ (\alpha_L ye - D), \qquad (16)$$

where π_t is profit,

λ_1 is the shadow price for landing minus discards plus hold capacity,

λ_2 is the discard shadow price,

B is the hold capacity of a vessel,

D is the discard of one unit of low valued fish,

y is the annual catch per unit of effort,

E is fishing effort, and

α_L is the percentage of yield consisting of low valued individuals.

The demand for vessel hold capacity can be expressed in terms of its marginal shadow price:

$$\lambda_1 = P_H - 1/\ \alpha_H\ [C'/y + \alpha_L C_D], \qquad (17)$$

where P_H is the price of the high value component of the species,

α_H is the percentage of the yield that is high valued,

$C' = CE(E)$ is the marginal trip cost, and

CD is the variable cost of discarding one unit of fish.

When λ_2 equals zero, for the case that the discard constraint does not hold, the demand for hold capacity becomes:

$$\lambda_1 = P_L + C_{D.} \qquad (18)$$

The shadow price λ_1 represents the price for ITQ (P_{ITQ}). If P_{ITQ} is greater than $P_L + C_D$ when λ_2 is equal to zero, then high-grading will occur just as in the case when hold capacity constrains landings; i.e., $P_{ITQ} > P_L + C_D$ creates an incentive to high-grade, and when $P_{ITQ} \leq P_L + C_{D,}$ no incentive to high-grade is created.

These three studies indicate that, first, discarding of bycatch can have serious effects on fisheries dependent on the bycatch species when a stock externality exists. Second, when the stock externality is not binding on an individual vessel, the open-access and socially optimal or sole-owner fishery face the same high-grading criteria in a differentiated fishery, which could be represented by different sizes or cohorts for a single species. Finally for the sole-owner fishery, high-grading can occur under conditions where the hold capacity of a vessel constrains landings just as ITQ's constrain landings.

To explicitly incorporate ITQ's into an open-access fishery, Boyce (1996) assumed that of two species, one is harvested solely in fishery 1 and the other species is harvested as bycatch in fishery 1 while being the target species in fishery 2. Boyce (1996) extended the analysis in Ward (1994) by establishing a total allowable catch (TAC) for species one (S_1) and species two (S_2). Boyce investigated the effect of allowing bycatch in fishery 1 to be sold, not sold, or have an existence value [δ = 1,0,-1, respectively] where the sale price P_2 and existence value are identical; and for the case of an active commercial fishery 2 (γ =1) and no active commercial fishery 2 (γ =0). The optimization problem for the social planner for two fisheries is:

$$\begin{aligned} V = T_1 n_1 \left[\pi_1(h_1) + \delta P_2 b(h_1)\right] - \\ K_1 n_1 + T_2 n_2 \gamma \pi_2 (h_2) - K_2 n_2 \end{aligned} \qquad (19)$$

where K_1 is the cost of an additional fishing craft in fishery i,

$b(h_1)$ is the per day removal of the bycatch species by fishery 1 for a harvest level (h_1) of the target species,

n_i is the number of firms,

T_i is the length of the fishing season in fishery I, and

P_i is the price for species i.

The key finding from Boyce (1996) is his proposition 8 that fishery 1 would have lower aggregate bycatch if rationalized due to a reduction in the number of vessels, even though bycatch per vessel may increase or decrease. This is a somewhat different result than in Arnason (1994) or Anderson (1994) for the individual vessel because the open-access stock externality was corrected by adopting ITQ's.

That ITQ's could reduce the aggregate level of bycatch was also found by Hoagland and Jin (1997), which determined that market-based incentives have several advantages over traditional command-and-control approaches such as BRD's. These advantages include cost-effective allocations of environmental controls, incentives for firms to seek technological solutions, flexibility, returns to the public for the use of its natural resources, and the potential for lower administrative costs relative to regulated open-access fisheries. Even if unsuccessful in reducing discarded bycatch sufficiently on its own, improvements in economic efficiency due to ITQ adoption should be more than sufficient to cover the costs of regulated BRD gear adoption in ITQ fisheries.

The comparative statics analysis of Boyce (1996) assumes that bycatch is a function of the harvest rate of the target species, which fails to allow for changes in bycatch species abundance or gear selectivity. Ward and Macinko (1996), after recognizing the complex ecosystem implications of bycatch discards, introduced a dynamic framework to the bioeconomics of this management problem as an extension to Ward (1994).

In addition to introducing optimal control techniques, the dynamic bioeconomic model relaxes the assumption that the commercial sector exploits the bycatch species before the recreational sector, establishes a stock recruitment relationship, introduces a cost for the gear modification, and reduces the efficiency of the fishing gear that generates the bycatch due to the adoption of the BRD. This approach also allows the estimation of net benefits over time between the long-run equilibriums in the fishery, which can be used as an indicator of management success.

As in the static model, the population dynamics are expressed as:

$$\begin{gathered} \delta x/\delta t = F(x) - q_x E_x X \\ \delta y/\delta t = G(y) - q_{yx} E_x Y - \\ q_{yc} E_{yc} Y - q_{yr} E_{yr} Y \end{gathered} \qquad (20)$$

where $q_{yx}E_xY$ is the bycatch level of species Y in the species X fishery,
$q_{yc}E_{yc}Y$ is the commercial harvest level of species Y in the species Y fishery, and
$q_{yr}E_{yr}Y$ is the recreational harvest of species Y in the species Y fishery.

Changes in fishing effort with respect to time are represented by:

$$\begin{aligned} \delta E_x/\delta t &= K(P_x q_x X - C_x)E_x \\ \delta E_{yc}/\delta t &= K(P_{yc} q_{yc} Y - C_{yc})E_{yc} \\ \delta E_{yr}/\delta t &= K(V_y q_{yr} Y - C_{yr})E_{yr} \end{aligned} \qquad (21)$$

where P_i is the exogenously determined ex-vessel price for species (X) and (Y), $i = x, yc$,
K is now a constant of proportionality between current profits and the change in the effort level (E_i),
C_i is the constant unit effort cost $i = x, yc, yr$, and
V_y is the marginal value of recreationally caught fish.

The more realistic assumptions underlying this simple, stylized-fishery, bioeconomic model reveal the complexity of the bycatch problem for fishery managers. First, any short-run improvement in species Y abundance caused by the adoption of a BRD in the fishery for species X will be eliminated in the long run because fishing effort levels can expand in the open-access fisheries for species Y. Second, the greater the inefficiency in the fishing gear for species X caused by the adoption of the BRD, the less bycatch will be reduced as a result of the increase in fishing effort by fishermen in the species X fishery. Third, increased harvesting costs resulting from the BRD regulations cause both effort and bycatch levels to decline, implying that landing taxes or ITQ's that would allow resource rents to be captured rather than squandered as in the BRD scenario would decrease bycatch levels as found by Boyce (1996). The implication for conservation engineering is that an expensive BRD that does not reduce gear efficiency for the directed fishery that generates the bycatch will not increase the abundance of the bycatch species if regulated open-access commercial and recreational fisheries exist that are directed at the bycatch species.

A slightly different tack on gear selectivity is provided by Escapa and Prellezo (2003), who focus on assessing the effect of harvest levels on growth rates of a fish stock. Modifying the optimal control problem so that growth becomes:

$$G(x,\theta) = (r + \theta)x(1 - x/k), \qquad (22)$$

where $G(x,\theta)$ is the growth function of species x,

θ is $\theta(\gamma_1, \gamma_2, \alpha) = 1 - \alpha\gamma_1 - (1 - \alpha)\gamma_2$ is the selectivity level of the fishing gear,

$\gamma_1 = 1$ for a very selective gear that does not affect the growth rate of the resource, and

$\gamma_2 > 1$ for nonselective gear that does affect the growth rate of the resource, the modified Golden Rule (Clark, 1990) becomes:

$$\delta = G_x(x^*,\theta) - \left[\begin{matrix} c'(x^*)G(x^*,\theta)\,/ \\ \left(P - c(x^*)\right) \end{matrix} \right], \qquad (23)$$

where δ is the discount rate,

$c(x)$ is the harvest cost, and

$c'(x)$ is the marginal harvest cost.

This implies that arbitrary harvest shares between user groups are no longer optimal if the harvesting gear affects the resource growth rate.

If harvest costs differ between user groups exploiting the fish stock, then Equation 23 becomes:

$$\begin{gathered} \delta = G_x(x^*,\theta) - \\ \left[\begin{matrix} \begin{pmatrix} \alpha c_1'(x^*) + \\ (1-\alpha)c_2'(x^*) \end{pmatrix} \\ G(x^*,\theta)\,/ \\ (P - \begin{bmatrix} \alpha c_1(x^*) + \\ (1-\alpha)c_2(x^*) \end{bmatrix} \end{matrix} \right] \end{gathered} \qquad (24)$$

The social planner's role now requires the joint determination of the optimal stock and the fishing quota. Maximizing the present value of both user groups exploiting the fish stock further modifies the Golden Rule to:

$$\delta = G_x(x^*,\theta) - \begin{bmatrix} (h_i / h)c_i'(x^*) + \\ (h_j / h)c_i'(x^*) \end{bmatrix} \quad (25)$$
$$G(x^*,\theta)\big(1 - G_{hi}(x^*,\theta)\big) / \big(P - c_i(x^*)\big)$$

This revised "Golden Rule," represented by Equation 25, can be used to set both optimal stock and harvest rates for both user groups where the least selective gear also has the lowest harvest cost relative to the other user group. Otherwise, one or the other user group will not be able to participate in the fishery if optimal stock size is to be achieved when growth rates are affected by the harvest technology. This result is particularly problematic for setting sector shares in fisheries because suboptimal efficiency levels might result.

Regulating bycatch using common pool output quotas is assessed in a predictive renewable resource model (Abbott and Wilen, 2009) that complimented Ward (1994) by finding that short-run utility from technological improvements may be limited even when a target fishery for the bycatch species does not exist. Without an increase in resource rents from conservation engineering gear modifications, the rational fisherman has no incentive to "invest in or assist in the development of such technologies" (Abbott and Wilen, 2009).

An additional contribution by Abbott and Wilen (2009) is the explicit derivation of one of the remedies recommended by Arnason (1994). A Pigouvian tax (τ) can be derived where the marginal benefits of increased harvest equal the marginal cost ($c + \tau$) at the optimal season length (T) utilizing a Nash equilibrium game theory strategy where both the target species and bycatch species common-pool quotas could be binding:

$$\tau^* = \big[P(1 - 1/n)/b(\alpha - 1/n)\big] \quad (26)$$
$$[Tn/Q_x]\ \alpha - 1 - C,$$

where P is the price of the target species,
C is a unit cost due to potential losses in processing, yield, and product caused by the diversion of resources to the sorting and discarding of bycatch,
Q_x is the target species quota,
n is the number of participants (overcapacity),
α and b are positive constants that relate bycatch levels to target species harvest levels (h_B and h_x, respectively).

Equation 26 indicates that this bycatch tax increases with the target species price (P) and the number of participants (n). The bycatch tax declines with increases in the sorting and discarding costs (C). Inefficient gears that are characterized as having high catchability coefficients (b) for bycatch species result in lower unit taxes. Since taxes and ITQ unit prices are theoretically equivalent (Clark, 1980), the Pigouvian tax could represent the bycatch ITQ market price.

Empirical Studies

The preceding theoretical model results, supported as they are by the strict logic of mathematics, need to be confirmed by empirical testing as in any scientific field of research. Unfortunately, empirical studies of bycatch, discards, and high-grading are few and far between in the literature. Hoagland and Jin (1997) extended Ward and Macinko (1996) to include competitive ($\gamma_i < 0, i = x,y$), independent ($\gamma_i = 0, i = x,y$), mutualistic ($\gamma_i > 0, i = x,y$), predatory ($\gamma_i > 0, \gamma_j < 0, i \neq j$), and commensalistic ($\gamma_i > 0, \gamma_j = 0, i \neq j$) biological relationships between species.

Rather than a commercial and recreational fishery for the bycatch species, Hoagland and Jin (1997) developed a dynamic model for a nonconsumptive, passive use bycatch species as might be expected for a protected or endangered species; their example species was the harbor porpoise, *Phocoena phocoena,* or dolphin. This required the development of a damage function that changed the maximization problem to:

$$Max_E = \int \big[B(E,x) - D(E,y) - CE\big] e^{-rt} dt, \quad (27)$$

where $B(E,x)$ is the social benefit function,
$D(E,y)$ is the damage function,
CE is the total cost of effort (E),
X is the biomass of the target species, and
Y is the biomass of the bycatch species.

Rather than solving for the time-paths between equilibrium values as in Ward and Macinko (1996), Hoagland and Jin (1997), and Hoagland et al.[2] solve for the steady-state or long-run equilibrium values. Nonetheless, one interesting implication can be derived from this empirical model based on parameters taken from the literature for eastern tropical Pacific yellowfin tuna, *Thunnus albacares*. That is, the biological relationships affect the optimal level of fishing effort when a damage function exists as a management tool.

A similar analysis was conducted by Griffin et al. (1993) to determine the change in net benefits for the Gulf of Mexico shrimp (*Panaeus setiferous, Panaeus axtecus, Panaeus duorarum*) fishery due to the adoption of TED's through Amendment 9 to the Gulf of Mexico Shrimp Fishery Management Plan. This assessment resulted in the estimation of negative rents that would cause this regulated open-access fishery's fleet to decline in size.

Ward et al.[3] reestimated the net present value lost due to the regulatory TED requirement at \$86.2 million to the shrimp fishery, which was accompanied by a 1.8% decline in fishing fleet size. Similarly for finfish BRD's, the cost to the Gulf of Mexico shrimp fishery in

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[2] Hoagland, P., D. Jin, P. Lee, C. Croft, L. Davidson, and S. Wallis. 1996. Market-based incentives to reduce fisheries bycatch. NOAA Contr. 50-DGNF-5-00172, Natl. Mar. Fish. Serv, NOAA, Silver Spring, Md., Feb., 120 p.

[3] Ward, J. M., J. Kirkley, and W. Keithly. 2009. A meta-analysis of the cumulative effects of regulation on the Gulf of Mexico shrimp fishery. Draft Rep., Natl. Mar. Fish. Serv, NOAA, Silver Spring, Md., Jan., 35 p.

lost present value of net benefits was estimated at \$27.4 million. As part of the Environmental Impact Assessment of Amendment 9, the economic value changes in terms of adjustments to total revenue were positive for the commercial red snapper, *Lutjanus campechanus*, fishery but had no impact on the recreational reef fish fishery[4] as predicted by Ward (1994).

Although not directly related to the estimation of the effect of reducing or eliminating the discarding of bycatch species in a directed fishery, Schuhmann and Easley (2000) use the theoretical approach of Ward (1994) and Ward and Macinko (1996) to estimate the benefits transfer between the commercial and recreational red drum, *Sciaenops ocellatus*, fishery. This assessment is based on derived demand analysis (Thurman and Easley, 1992) for the commercial fishery and a recreational random utility model. Although a change in red drum bycatch levels in the Gulf of Mexico shrimp fishery is not the focus of the benefits transfer between the directed commercial and recreational red drum fisheries, the analysis does create an empirical framework that could be used to estimate this type of fishery change.

Lastly, an empirical study by Garza-Gil and Varela-Lafuente (2007) analyzed the intra-species bycatch impacts on the European southern hake, *Merluccius merluccius*, stock. Gear selectivity for trawl and longline fisheries was investigated to determine whether hake stocks were being efficiently exploited. Results from a dynamic model based on values estimated from a hake database found that if trawling selectivity improved from 0.6 to 0.2 such that juvenile fish were excluded from the catch, then the biomass level and its shadow price would increase from \$2,917 to \$4,208 (44%). Even though total fishing effort declines by 10%, trawl effort increases by 147% with a decline of 36% in the longline fishery. However, harvest for both fisheries increases by 45% and 7%, respectively.

Review Summary

In short, Ward (1994) analyzed the discarding of an incidentally caught species in the classical open-access fishery to determine the efficacy of the conservation engineering approach to fisheries management, which, even though cost less to harvesters, was unsuccessful in conserving bycatch species stocks. Alternative remedies offered by Arnason (1994) and Anderson (1994) for the ITQ high-grading and discard management problem include taxes, subsidies, and landings restrictions as well as better enforcement.

Arnason (1994) focused on discarding within different grades of the same species as a cause of high-grading in ITQ fisheries, while high-grading in ITQ fisheries according to Anderson (1994) was due to limited hold capacity for the individual fishing craft. That is, according to Anderson's analysis, ITQ's, which act as a substitute for a hold capacity constraint, can increase high-grading more than would exist in an optimal fishery. Although still a comparative statics analysis, Boyce (1996) suggested that a fishery could have lower aggregate bycatch if rationalized due to a reduction in the number of vessels, even though bycatch per vessel may increase or decrease because the open-access stock externality was corrected by adopting ITQ's.

Using a dynamic approach, the implication of Ward and Macinko (1996) for conservation engineering is that an expensive BRD that does not reduce gear efficiency for the directed fishery that generates the bycatch, will not increase the abundance of the bycatch species if regulated open-access commercial and recreational fisheries that are directed at the bycatch species exist. In a general dynamic analysis, Escapa and Prellezo (2003) revise the "Golden Rule" derived by Clark (1990) when fish stock growth rates are affected by the harvest technology. Both optimal stock and harvest rates for both user groups must be set where the least selective gear also has the lowest harvest cost relative to the other user group. If not, one user group will not be able to participate in the fishery if optimal stock size is to be achieved. This result is particularly problematic for setting sector shares in fisheries because suboptimal efficiency levels might result.

The Abbott and Wilen (2009) analysis of common-pool quotas, season length, taxes, and ITQ prices to achieve a Nash (1950) equilibrium under game theoretic conditions confirms concerns about the conservation engineering approach and suggests that the behavioral and institutional solutions have not been adequately addressed. Bycatch is a complex result of gear, spatial ecology, and regulatory interactions, but it is primarily behavioral. Research should be based on incentive-based approaches such as individual transferable bycatch quotas (ITBQ's), fishing cooperatives, and voluntary group sanctions.

Although not complete, this review of the bioeconomics of fisheries bycatch does provide a synthesis of the major results over the last 15 years of research. The next step is to assess these results in an integrated framework to compare and contrast their efficacy in measuring, managing, and eliminating the discarding of bycatch in fisheries dependent upon living marine resources.

Simulation Model

Because bycatch is a complex problem, by necessity, a model to address bycatch is also complicated. Figure 1 represents what is essentially a multi-species, stock, cohort, resource area, fleet, and vessel class ecosystem model. Rather than pursuing a simplistic surplus production or Gordon-Schaeffer-Copes model of limited practical application, a multi-cohort Beverton-Holt model (Beverton and Holt, 1957) is used to represent the population dynamics of a single or group of fish species. Although alternatives are available within the model, the von Bertalanffy growth function is employed to determine the biomass level for each cohort of each species in this bycatch scenario (Quinn and Deriso, 1999). The level of biomass then influences natural mortality (*M*) in Figure 1 through a predator-prey model (Larkin, 1979), which is also

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[4] MRAG Americas, Inc. 1997. Peer review of the science and management of red snapper (*Lutjanus campechanus*) in the Gulf of Mexico" Tech. meeting, New Orleans, La., Aug.

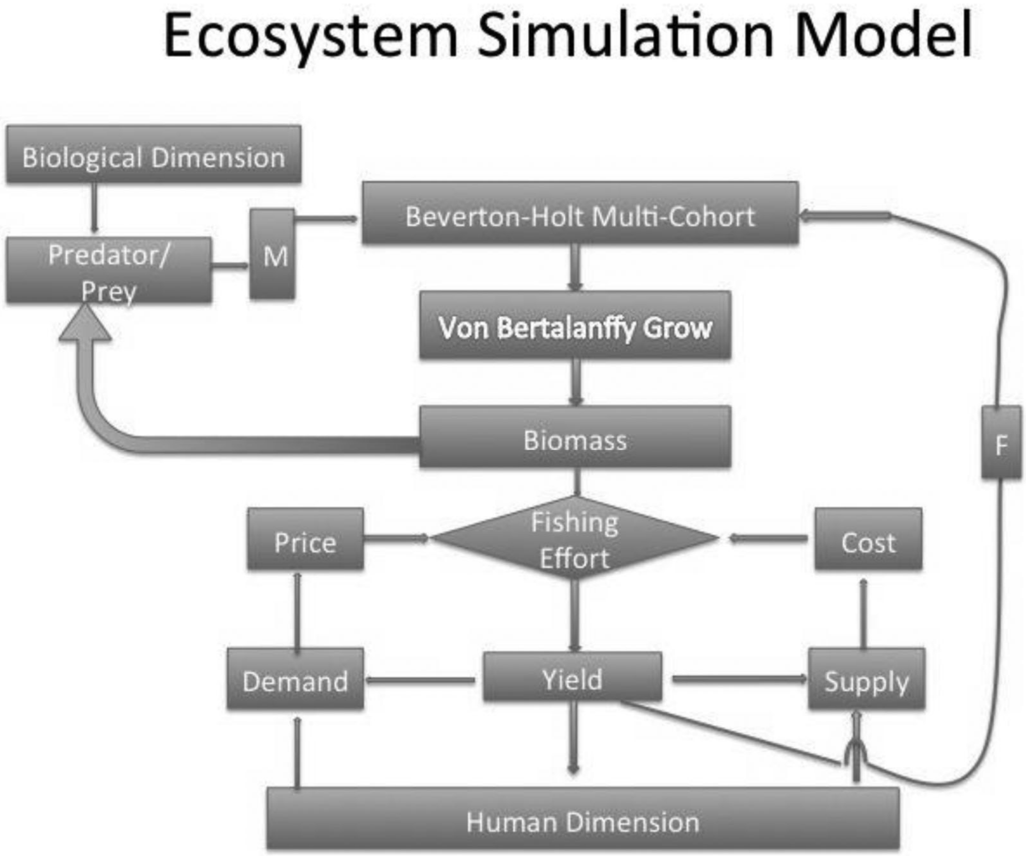

Figure 1.—Ecosystem simulation model.

affected by the biological dimension of the ecosystem (e.g., water temperature, salinity, acidity).

Applying fishing effort to biomass generates yield, which is mapped into fishing mortality (F) in Figure 1. Yield also directly and indirectly affects, via the human dimension, unit input costs through the supply function and output price through the demand function. The combined effect of price, cost, and biomass determine changes in the level of fishing effort that feeds back into the Beverton-Holt multi-cohort model through fishing mortality, in conjunction with natural mortality, to determine the change in number of fish in the next time period.

The relationship between these different components and fishing effort is the key innovation that allows the effects of different bycatch strategies to be compared. Extending Clark (1990), a general theoretical relationship can be derived. Beginning with:

$$J(H) = \int e^{-\delta t} R(h)\,dt$$

$$\text{s.t.} \qquad o$$

$$B = F(B) - h(t)$$

The long run equilibrium fishing effort level is represented as:

$$e_i = \frac{\begin{array}{c} \left[F'(B)-\delta\right] \\ \begin{bmatrix} (qB\big(P(qe_iB)-c\big)+ \\ PB(qe_iB) \end{bmatrix} \\ +P'(qe_iB) \end{array}}{F(B)P'(qe_iB)} \tag{28}$$

where B is the change in biomass with respect to time,

$F'(B)$ is the growth rate of the stock biomass (B),

$F(B)$ is the growth function,

$c(B)$ is harvest cost,

P is the price of fish,

δ is the discount rate,

$R(h)$ is a nonlinear net revenue function $= P(h)h - c(h)$,

$P(h)$ is an inverse demand function,

h is harvest $= qe_ix$,

e_i is individual firm or angler fishing effort level (McConnell and Sutinen, 1979), and

q is the catchability coefficient.

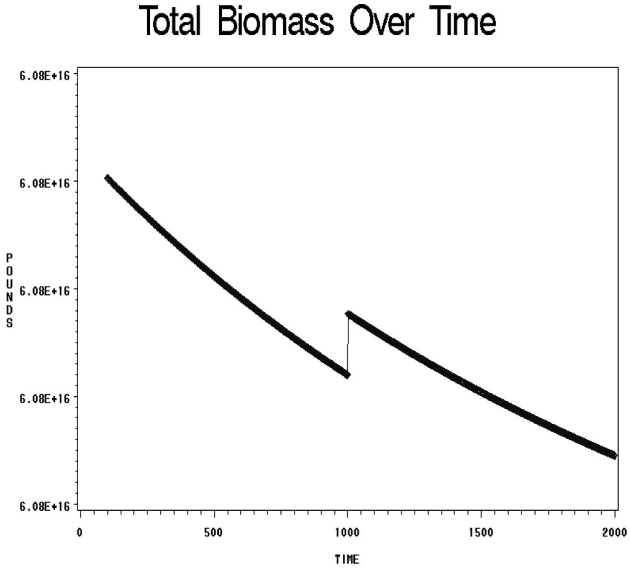

Figure 2.—Conservation engineering regulatory effect on bycatch species biomass.

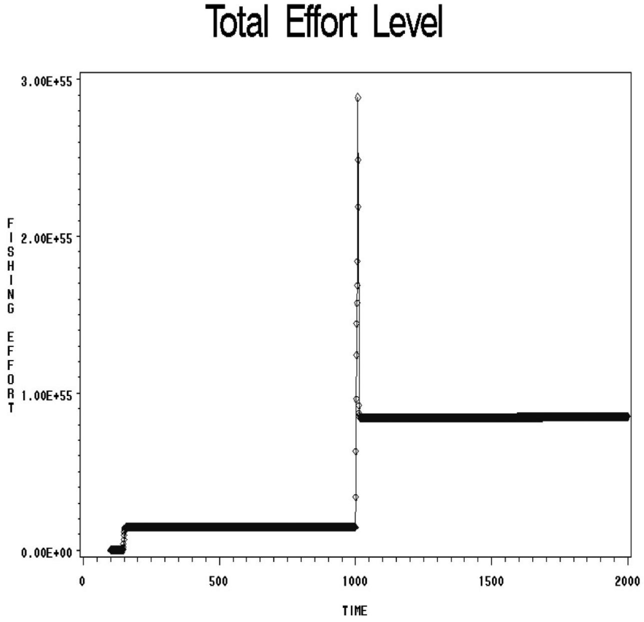

Figure 3.—Change in species 2 fishing effort levels due to the adoption of a BRD in the fishery for species 1.

$P'(qe_iB)$ is marginal revenue with respect to a change in fishing effort, and

$P^B(qe_iB)$ is marginal revenue with respect to a change in stock size.

That is, regardless of the functional form chosen to represent a growth function or an inverse demand function, Equation 28 describes its relationship to fishing effort (*e*). Although magnitudes might change, Equation 28 demonstrates that the direction of change remains the same across a broad array of functional forms chosen to represent a commercial or recreational fishery.

The change in fishing effort level is calculated at the most disaggregated level in the simulation model to ensure that the conversion to fishing mortality (*F*) is not biased due to nonhomogeneity (Clark, 1985). This specification also allows the comparison of different management regimes; specifically for the sole owner ($\delta = 0$), rights based ($\delta > 0$), and open-access ($\delta = \infty$) scenarios.

This model is adapted to the study of bycatch by assuming that two fishing fleets exploit three out of seven species of fish, with ten cohorts each. Each species is assumed to exist in two resource areas (fishing grounds). The first fishing fleet has a directed harvest from species 1 and a partially or wholly discarded bycatch from species 2. The second fishing fleet consists of two vessel classes that directly harvest species 2 as a commercial and recreational set of fisheries. The third species is a protected resource that was initially harvested by both fishing fleets, but now is solely treated as a predator of species 2 through 7; species 4–7 act as prey of or competitors to the three fish species (species 1 to 3) being harvested.

Regulatory Effects

The bycatch reduction regulation of choice (BRD) developed out of the conservation engineering concept of fisheries management. Using a single-species approach, the fishing gear is modified to eliminate the harvest of incidentally caught fish species. These gear modifications, which have direct costs in and of themselves, can also increase or reduce the technical efficiency of the fishing gear for the directed species and indirectly increase or reduce the costs of harvesting fish, respectively.

As demonstrated in Ward (1994) and Ward and Macinko (1996), the adoption of a gear modification to reduce bycatch in the directed species 1 fishery results in an initial increase in the biomass of the bycatch species 2, but does not prevent species 2 continued decline in biomass over time (Fig. 2). The continued decline in species 2 biomass is the combined effect of an increase in fishing effort levels for the commercial and recreational fishing fleet directed at species 2 (Fig. 3) and the growth in the predator species 3 that is recovering as a result of a reduction in its bycatch in the fishery for species 1 (Fig. 4).

Although the present value of net benefits peaked higher with BRD gear modifications than without, neither resulted in significant increases in commercial fisherman or recreational angler quality of life (i.e., both are very close to zero due to resource rent dissipation in the open-access resource management scheme for species 1 and 2).

A second proposed bycatch reduction regulation is the adoption of a TAC for the bycatch of species 2 in the directed fishery for species 1. Although biomass level results are similar to Figure 1, the regulation causes the fishery for spe-

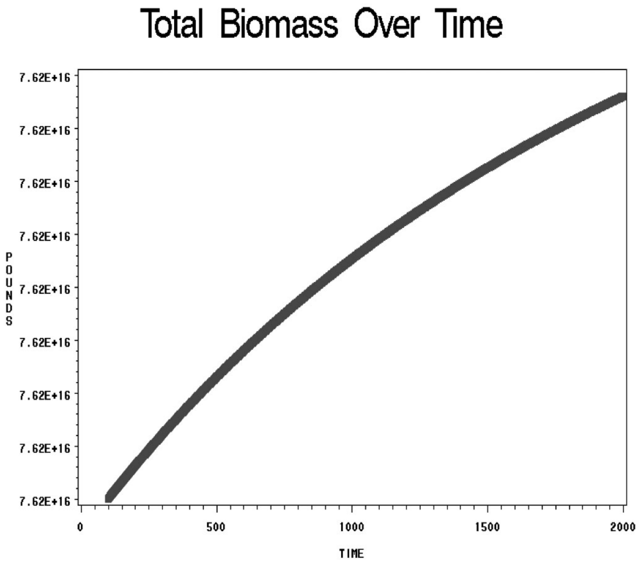

Figure 4.—Change in biomass of species 3 over time after adoption of BRD in the fishery for species 1.

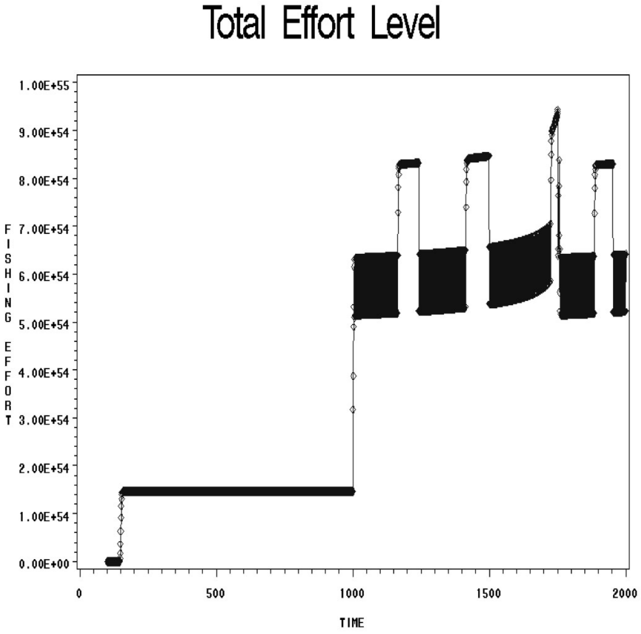

Figure 5.—Fishery 1 bycatch TAC effect on fishing effort levels for species 2 fisheries.

cies 1 to be shut down when the bycach TAC is reached, causing harvest levels of species 1 to decline appreciably. This introduces an oscillation into the fishing effort level for the fisheries for species 2 (Fig. 5). Although the present value of net benefits improved with the adoption of the bycatch TAC, it was not appreciably different from zero. In fact, command and control regulations in the directed species 1 fishery neither improve species 2 stock size nor improve net benefits in either fishery.

Surprisingly, the sole owner regulation of the directed fishery does not necessarily improve performance in the fishery for the bycatch species 2 if the fishery remains managed as an open-access resource. Figure 6 indicates that the switch to sole owner management causes a gradual decline in fishing effort levels and a commensurate reduction in the rate of decline in yield, in this example. However, even though net benefits improve (Fig. 7) for the directed fishery, bycatch continues to increase (Fig. 8). Only with the adoption of sole owner management in both directed commercial fisheries for species 1 and 2 does a decline in bycatch levels in the directed fishery for species 1 result (Fig. 9).

Unfortunately, maintaining the recreational fishery as open-access results in the expansion of total fishing effort for species 2 even as fishing effort levels decline for its commercial fishery component (Fig. 10). The rent-dissipating effects of the open-access recreational fishery prevent improvements in net benefits for both the commercial and recreational fisheries even though the directed commercial fishery for species 1 has marked increases in net benefits over time due to sole owner management.

Finally, combining sole ownership management in the commercial fisheries directed at species 1 and 2 with BRD's should result in substantial reductions in the bycatch of species 2 in the directed fishery for species 1. The resulting short-term increase in species 2 biomass does cause some unexpected results. Figure 11 indicates that the adoption of BRD's in the fishery for species 1 results in an increased oscillation in the total fishing effort for the fisheries directed at species 2, relative to Figure 10, as the recreational open-access fishery expands its effort levels, augmenting uncertainty and risk levels in this fishery.

Summary

Presentations on the ecosystems approach to fisheries management often tout the importance of the economic component. Although the biophysical components are fully presented and discussed in these presentations, rarely if ever is the role of economics or other social sciences explained in an ecosystem context. This attempt, although simplistic, indicates the need to explicitly consider fishery economic relationships.

Bycatch, the discarding of incidentally caught fish in fishing operations, is the perfect analogue for the ecosystems approach to fisheries management. A seemingly simplistic fisheries management problem in appearance, bycatch has biophysical and socio-cultural attributes that result in counter-intuitive and even paradoxical outcomes that create a complex, intricate management environment. The changes in governance assessed in a simulation model using this multi-disciplinary scientific approach to modeling the ecosystem

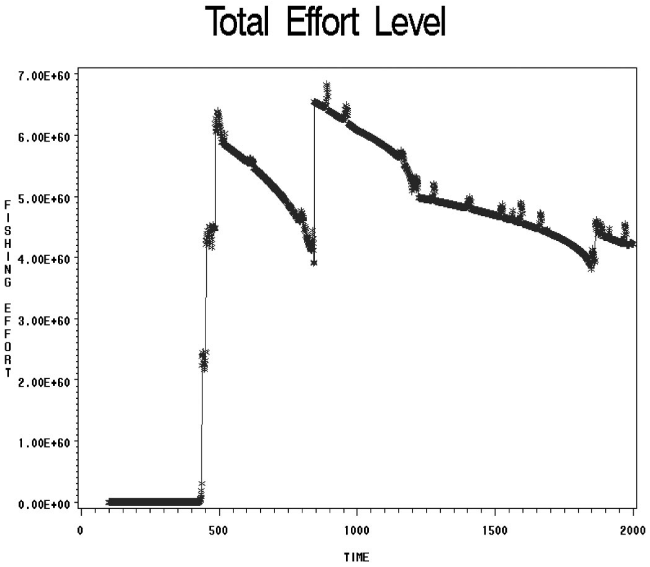

Figure 6.—Transition from open access to sole ownership in the directed species fishery.

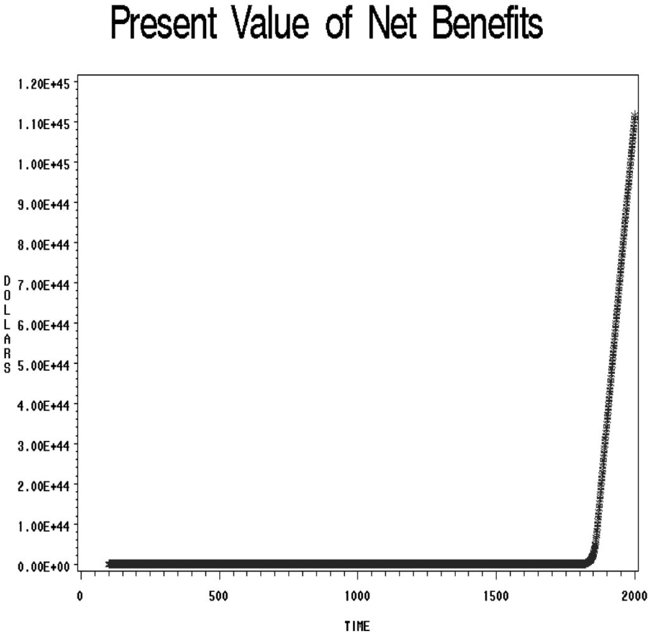

Figure 7.—Transition from open access to sole ownership for commercial fishery 1.

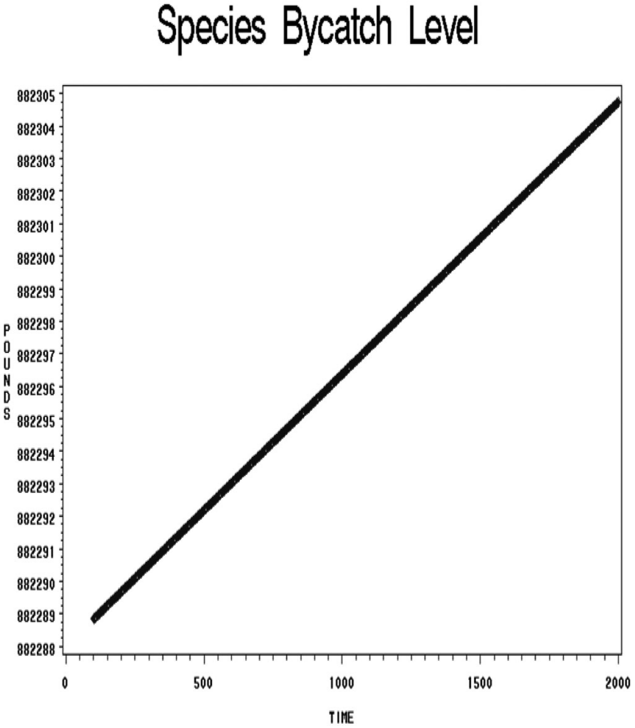

Figure 8.—Transition from open access to sole ownership in fishery 1 for species 2 bycatch level.

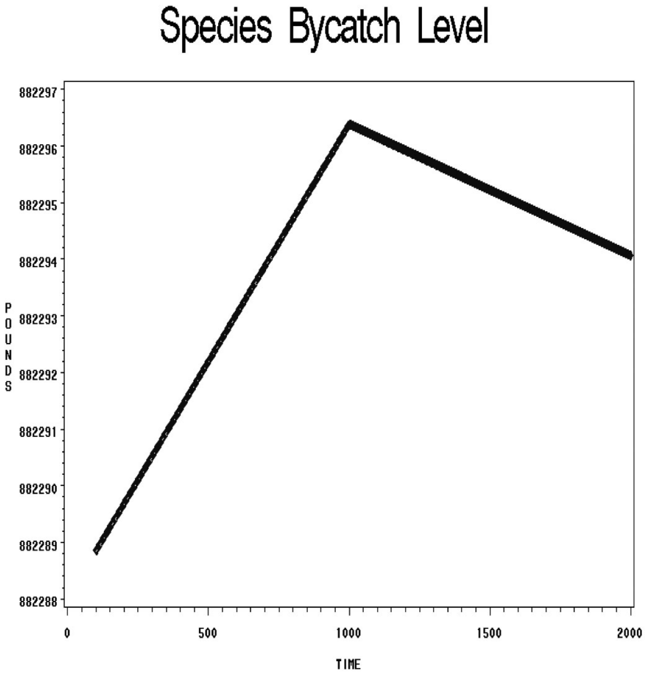

Figure 9.—Transition from open access to sole ownership for all commercial fisheries.

resulted in unexpected oscillations that would increase uncertainty and risk in the fisheries affected.

Although the results predicted by the theoretical analyses generally hold, another example of unexpected and counterintuitive responses occurs with the adoption of predator-prey and competitor ecological relationships

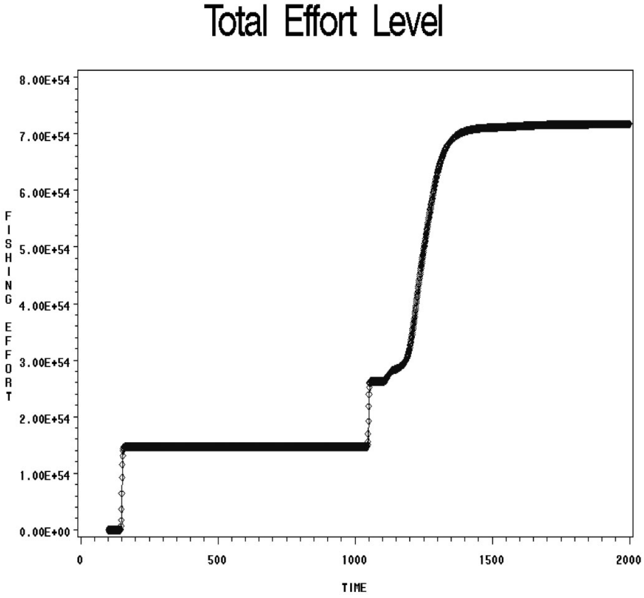

Figure 10.—Open access to sole ownership transition for the directed commercial fishery for species 2.

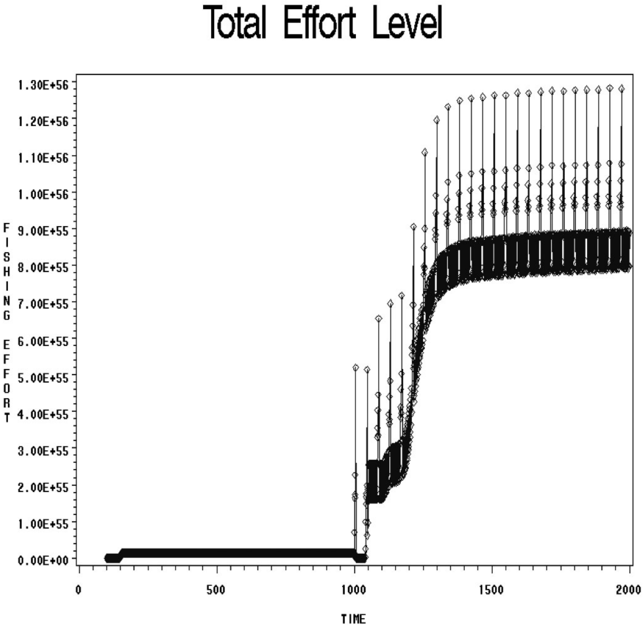

Figure 11.—Sole ownership with conservation engineering.

in the biological component of the ecosystem model. The overwhelming effect of the growing biomass of the competitor–predator species (Species 3–7) prevented the recovery of the bycatch species (Species 2) in our simulation model under any management scenario. In addition, the application of sole owner governance (ITQ, sector shares, catch shares, cooperatives, etc.) to commercial fisheries without considering the recreational component still resulted in the dissipation of resource rents. Even though simulation models can generate different results depending on the values used to parameterize the theoretical economic and biological relationships, management approaches to dealing with bycatch and discarding can have radically different effects on the fisheries involved.

If nothing else comes from this assessment of bycatch reduction management techniques applied to an ecosystem that explicitly incorporates the human dimension, it should now at least be clear that the traditional practice of simply assuming that net benefits exist for any proposed biophysical management regulation is problematic. This approach incorporates socio-cultural and biophysical attributes into a common framework from which 1) the magnitude and direction of behavioral responses can be predicted based on changes in governance or biophysical constraints, 2) the attainment of management goals and objectives can be assessed, and 3) metrics can be derived.

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