Nutrient Enrichment and Marine Ecosystem Disturbance:
A Deterministic and Stochastic Analysis

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Abstract. Pollution of the marine areas that support much of the world's commercial fisheries is regarded as a pressing global environmental problem. One often-cited issue is nutrient enrichment, but this may be a mixed blessing: it contributes to primary productivity and increases the sustainable fish catch, while simultaneously causing occasional and damaging ecosystem events. Thus, enrichment's aggregate impact on the economic value of fisheries may be ambiguous. This research develops a method for analyzing such problems, using the example of the Black Sea anchovy fishery. Employing a bioeconomic model that incorporates nutrients directly into fish population dynamics, the problem is formulated in deterministic and stochastic terms and the results compared. The deterministic model assumes that nutrients only contribute positively to fish production for a given ecological state, and ignores stochastic events leading to shifts between states. Accordingly, marginal abatement of nutrients leads to annual welfare losses of US$ 45,000 to 713,00 per μM (1989/90 prices), depending upon the ecosystem state. The stochastic formulation recognizes that planners may have some knowledge of potentially damaging shifts in ecological states, and wish to take this into account. When these shifts are related stochastically to the level of enrichment, nutrient abatement is shown to have an indeterminate welfare effect. However, an experimental empirical analysis indicates that a marginal change in nutrients can generate positive and sizeable aggregate benefits for the Black Sea anchovy fishery under certain conditions. The general applicability of such an approach for analyzing a range of marine environmental problems is noted.

Keywords: marine fisheries, marine environment, nutrient enrichment, anchovy, Black Sea

1.   INTRODUCTION

Increasing concern has been expressed about the deterioration of coastal environments and particularly the fisheries these ecosystems support. In many of the affected coastal regions, declining natural resource stocks have been a response to disruptions in marine ecosystems, as well as the more familiar problem of overharvesting. Policymakers are already hard-pressed to implement the necessary policies to address the problem because of transboundary issues and socio-economic constraints. In the absence of information about the benefits of marine habitat improvements to help in targeting corrective policies effectively, their task is made even more difficult. This paper addresses one aspect of marine ecosystem management, namely the influence of nutrient enrichment on small pelagic fisheries and the valuation of the benefits of nutrient abatement investments.

The theoretical and empirical economic implications of altering habitats for commercial fisheries (or similar renewable resources) have been examined by various researchers (Barbier and Strand 1998, Swallow 1994, Tahvonen 1991, Swallow 1990, McConnell and Strand 1989, Kahn and Kemp 1985 and Lynne *et al.* 1981). Most of these studies concentrate on the valuation of coastal

inputs to fisheries production or the destructive influence of pollution on resource stocks, as well as the evaluation of optimal policies for resource allocation.

In addition to these works are a number of studies of marine coastal areas and semi-enclosed seas, that address the more complex interactions of fisheries and nutrient enrichment or eutrophication (Boddeke and Hagel 1991, Caddy 1990 and Silvander and Drake 1989). Of particular interest is the recognition in these latter works that nutrient enrichment can be a 'mixed blessing', enhancing fisheries by augmenting primary productivity but also having more adverse consequences, such as fostering oxygen-suppressing algal blooms or invasions by exotic species. However, most of these studies address the physical dimensions of the problem and few attempt to value the complex consequences of changing nutrient levels in economic terms (an exception is Turner *et al.* 1997).

This paper attempts to capture the more sophisticated relationship between small pelagic fisheries and nutrient enrichment portayed in these latter papers within a bioeconomic modelling framework, and to value the welfare effects of changes in nutrient levels under these conditions. A key element in the analysis is the distinction between the problem's deterministic and stochastic elements. The former

tends to characterize the direct influence of nutrients on small pelagic recruitment, as nutrient limitations are gradually relaxed under increasing nutrient loads. For a number of small pelagics, this influence has been positive within moderate ranges for nutrient levels (see references above, especially Boddeke and Hagel 1991). More likely to have a negative impact are the occasional ecosystem disturbances cited above (e.g. algal blooms, invasions) that are generally stochastic in nature.

Assuming the two influences can occur together results in offsetting impacts on fisheries with no clear aggregate positive or negative effect, which contrasts with standard pollution problems. In the sections below, a bioeconomic model is developed that integrates both these effects. To resolve some of the uncertainty regarding the aggregate impact, an empirical model is applied to a representative small pelagic fishery, the Turkish anchovy fishery in the Black Sea.

The next section presents a relatively simple deterministic spawner-recruit model incorporating only the direct and beneficial influence of nutrients on fish recruitment. It captures only the role of nutrients as a habitat input to fish recruitment, as typified in earlier papers concerned with the valuation of habitat change (see above). After solving for the steady state values in the deterministic model, and valuing nutrient inputs using comparative statics techniques, an approach for integrating the more complex and offsetting stochastic effect of nutrients is introduced. Subsequently, the deterministic model is reformulated in stochastic terms and the value of changes in nutrient levels is derived under these more complex ecosystem conditions. The analysis confirms that a 'mixed blessings' type model yields ambiguous welfare results from marginal changes in nutrient levels. To demonstrate the approach empirically, results for the Turkish Black Sea anchovy are presented and compared for both the simple deterministic model and experimentally for the more complex stochastic case.

2. A DETERMINISTIC BIOECONOMIC MODEL WITH NUTRIENT ENRICHMENT AND NO ECOSYSTEM DISTURBANCE

The modelling approach begins with a dynamic, deterministic bioeconomic model of the fishery in discrete time (see Clark 1990). I also assume a representative ecological regime, so that environmental conditions are constant. The relationship between exploitable adult biomass X, harvest h and spawning biomass S can be expressed as:

$$S_t = X_t - h_t \tag{1}$$

where t denotes the time period in years. With (1) in mind, the exploitable adult biomass in the next period is indicated by the following transition equation:

$$X_{t+1} = \sigma S_t + R(S_t, P_t) \tag{2}$$

where σ is the natural survival rate with $0 < \sigma < 1$, and $R(S,P)$ is the recruitment function. Recruitment is not only a function of spawning biomass, but of nutrients P as well. Next period biomass is determined by the carryover of adults escaping the harvest and by the addition of new recruits. Note that R_S is first > 0 then < 0, and I assume that $R_P > 0$, as discussed earlier. Both assumptions are consistent with recruitment in small pelagics under modest nutrient enrichment (e.g. a Ricker recruitment curve), but other assumptions could be employed too..

If fish demand is perfectly elastic, the economic component of the model comprises the producers' surplus or economic profits π generated by the harvest:

$$\pi_t = p h_t - C(X_t, h_t) \tag{3}$$

where p is the real ex-vessel, fish price determined by a perfectly elastic demand curve. Rearranging (1), the resulting expression $h = X - S$ can be substituted into (3), eliminating the variable h. This substitution yields the following statement for profits:

$$\pi_t = p(X_t - S_t) - C(X_t, X_t - S_t)$$
$$= p(X_t - S_t) - C(X_t, S_t) \tag{4}$$

Assuming the general cost function $C(X,S)$ is separable in X and S, the resulting profit function can be rewritten in the following way:

$$\pi_t = \theta_1(X_t) - \theta_2(S_t)$$
$$\theta_i' > 0, \quad \theta_i'' > 0 \quad i = 1, 2 \tag{5}$$

If nutrients are treated as a fixed parameter, ie. $P = \bar{P}$, the planner's problem under the assumption of optimal management can be expressed as:

$$\max \sum_{t=0}^{\infty} \rho^t \pi(X_t, S_t) = \sum_{t=0}^{\infty} \rho^t [\theta_1(X_t) - \theta_2(S_t)]$$

$$s.t. \quad X_{t+1} = \sigma S_t + R(S_t, \bar{P}) \tag{6}$$

$$with \ 0 \le S_t \le X_t, \ and \ S_0, X_0 \ given$$

In (6), ρ is the discount term, defined as $1/(1+\delta)^t$, with δ denoting the appropriate social discount rate. Clark (1990) shows that by manipulation, this type of problem can be simplified to the maximization of a value function $V(S)$ in the single variable S. As a result, the optimization problem can be rewritten as:

$$\max \sum_{t=0}^{\infty} \rho^t V(S_t)$$

$$s.t. \ 0 \le S_{t+1} \le [\sigma S_t + R(S_t, \bar{P})] \tag{7}$$

$$with \ P = \bar{P} \ and \ S_0 \ given$$

where the value function $V(S)$ is defined as:

$$V(S_t) = \rho \theta_1 [\sigma S_t + R(S_t, \bar{P})] - \theta_2(S_t) \tag{8}$$

The optimal solution to (7) can be characterized as a constant optimal escapement rule and is found by taking the first derivative of (8) and setting this equal to zero.[1]

So far I have assumed that the nutrient influence is constant under a fixed ecological regime, but our interest lies in the valuation of potential welfare effects arising from a change in nutrient levels. Relaxing this assumption, we can examine the comparative static effects of marginal changes in the fixed level of nutrient enrichment $\bar{P}$. Although an expression for the change in producers' surplus from such a change can be elicited via several methods, I select the most direct approach. This technique involves differentiation of the maximized value function $V(S^*)$, defined at the optimum level of input usage for a given set of environmental conditions (eg. nutrients).

In taking the value function approach, I exploit the

following relationship between the change in optimal profits due to a marginal change in nutrients and the maximized value function $V(S^*)$:

$$\frac{\partial \pi [S^*(\bar{P})]}{\partial \bar{P}} = \frac{\partial V[S^*(\bar{P})]}{\partial \bar{P}} \tag{9}$$

Proof of the validity of (9) is provided in Knowler (1999). Since the lefthand side of (9) constitutes the desired welfare measure, its relationship with the maximized value function can be used to value the welfare effects of a marginal change in nutrients. Furthermore, the optimal choice of inputs depends on the exogenous level of nutrients, so that the maximized value function can be expressed as the following function of nutrients alone:

$$V[S^*(\bar{P})] = \rho \theta_1 \{\sigma S^*(\bar{P}) + R[S^*(\bar{P}), \bar{P}]\}$$
$$\tag{10}$$
$$- \theta_2 [S^*(\bar{P})]$$

In taking the partial derivative of the maximized value function with respect to nutrients $\bar{P}$, the envelope theorem can be applied. This exercise yields the following statement for the impact of a marginal change in nutrients on the maximized value function:

$$\frac{\partial V[S^*(\bar{P})]}{\partial \bar{P}} = \rho \theta_1' R_P \quad > 0 \tag{11}$$

Expression (11) indicates that the welfare effect stemming from a marginal adjustment in nutrients is determined by marginal profits θ_1' on the last unit of stock harvested (measured at X^*) times the additional harvestable units arising from increased nutrients (R_P), holding escapement constant at S^*. Since the effect of a change in nutrients is not expressed until the next period, once new recruits have joined the exploitable adult stock, the welfare value must be discounted back one period using the discount factor ρ. The welfare effect in (11) is positive, since $R_P > 0$ and I have already assumed $\theta_1' > 0$. For marginal changes in nutrients taking place under fixed ecosystem conditions (i.e. with no stochastic ecosystem disturbances permitted), the 'within regime' welfare effects described here would constitute the full economic impact.

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[1] If $V(S)$ is quasi-concave, then the solution is a 'bang bang' or Most Rapid Approach Path to the steady state (Clark 1990).

3. CHARACTERIZING A STOCHASTIC MARINE ECOSYSTEM DISTURBANCE PROCESS UNDER NUTRIENT ENRICHMENT

As argued earlier, nutrient enriched marine ecosystems may experience disturbances or 'surprises' that are unpredictable and harmful to fish stocks (e.g. algal blooms or invasions). In the terminology of Tsur and Zemel (1997), this type of stochastic element can be characterized as exogenous, reversible and recurrent. Moreover, random variations in the disturbed state of the marine ecosystem frequently may serve as the trigger mechanism for these events. One means of modelling this process is to allow for the triggering of individual events when some time-varying threshold disturbance level is exceeded. Moreover, the current level of nutrient concentrations P_t can be used as a proxy for the level of disturbance associated with eutrophication at a given point in time. If disturbance events lead to consistently reduced recruitment, then the stock-recruitment relationship during the intervals between events can be approximated by its 'normal' disturbance-free form. In such a case, a stochastic model would describe a sequence of alternating but well-defined ecosystem regimes, with the jumps between regimes triggered by environmental conditions when these exceed a random threshold level.[2]

Capturing the full effects of nutrient enrichment on pelagic recruitment in this more complex world requires incorporation of both the negative stochastic element described above and the beneficial aspects captured in the deterministic model of the previous section, based on $R_P > 0$. To simplify the stochastic analysis, I assume the following:

■   Recurring ecosystem disturbances modify the marine ecosystem similarly during each event and this can be modelled as a temporary structural change in the recruitment function.

■   An event's duration is determined by the persistence of disturbance conditions above the time-varying random threshold or trigger.

■   Fishery managers know the relevant probability distributions and magnitudes of the two possible states of the world and are risk neutral, but they do not know whether an event will occur until after deciding upon the escapement level for that period.

■   The optimal levels of effort and harvest for a given level of nutrients are determined on the basis of expected welfare values from the fish harvest alone (i.e. no ecosystem services).

With these assumptions in mind, a stochastic transition equation equivalent to (2) can be written now as:

$$X_{t+1} = \sigma S_t + R^i(S_t, P_t), \quad where \; i = 1 \, or \, 2 \quad (12)$$

where $R^i(S,P)$ refers to recruitment under state of the world i and is a function of spawning biomass S and the nutrient concentration P. Two states of the world are recognized: either it is between disturbance events and the recruitment function $R^1(S,P)$ prevails, or there is an event and $R^2(S,P)$ is the relevant stock-recruitment relationship. Note that $R^1(S,P) > R^2(S,P)$ over the entire domains of X and P for any given values for these two variables. As the system shifts between event and non-event conditions, the recruitment relationship governing the anchovy stock 'jumps' from one variant to the other, but retains the direct and positive impact of enrichment on recruitment via the variable P ($R_P > 0$).

The stochastic variable in the analysis is the unknown threshold nutrient concentration at time t which may trigger a disturbance event, leading to a jump between the two states. This random variable, denoted as P^*, is assumed to be distributed over the interval $[0,\infty]$ with a probability density function $f(P^*)$, and is also assumed to be identically and independently distributed over time.

The next step links the random threshold P^* with the current level of nutrients P_t and draws on Cropper (1976). The following expression describes the probability mass function governing the recruitment function, which randomly fluctuates between two possible states:

$$\Pr\{R^i(S_t,P_t) = R^1(S_t,P_t)\} = \Pr\{P^* > P_t\}$$
$$= \int_P^\infty f(P^*)\,\mathrm{d}P^* = \Lambda(P_t)$$

$$\Pr\{R^i(S_t,P_t) = R^2(S_t,P_t)\} = \Pr\{P^* < P_t\}$$
$$= \int_0^{P_t} f(P^*)\,\mathrm{d}P^* = \varphi(P_t) \quad (13)$$

$$with \quad \int_0^\infty f(P^*)\,\mathrm{d}P^* = 1$$

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[2] Cropper (1976) uses a similar approach to analyse the economics of catastrophic events, such as a collapse resulting from a nuclear accident where the relevant threshold is related to concentrations of radionuclides above a random level.

The first line in (13) shows the probability of an outbreak *not* occurring, which assumes the threshold $P*$ lies within the interval P_t to ∞; that is, it lies above the current phosphate concentration P_t. Formally, this probability is expressed as the cumulative distribution function of the random variable $P*$ with density $f(P*)$ over the interval 0 to P_t, as shown on the extreme right. In contrast, the second line indicates the probability of an outbreak occurring and assumes the threshold is lower, lying within the interval 0 to P_t and, therefore, encountered in time t. The cumulative distribution function in this case covers the interval 0 to P_t, as indicated by the term shown at the end of the second line in (13). Denoting the first probability or cumulative density function in (13) as $\Lambda(P_t)$ and the second as $\varphi(P_t)$, we can note that $\Lambda(P) = 1 - \varphi(P)$, $\varphi' = f(P*) > 0$ and $\Lambda' = -f(P*) < 0$.

In statistical terms, the stochastic process described above implies that the parameters of the recruitment function are random variables (as is recruitment itself), which are determined jointly by the current level of nutrients P_t and the random variable $P*$. Additionally, the recruitment function includes the explanatory variable P to account for the direct deterministic influence of nutrients on population dynamics. As a result, the current level of phosphates influences population dynamics in two ways, one is direct and deterministic while the other is indirect and stochastic.

4. VALUING NUTRIENT CHANGES IN THE STOCHASTIC MODEL WITH MARINE ECOSYSTEM DISTURBANCES

Assuming certain conditions for a constant optimal escapement rule are met (see below), setting up and solving the stochastic problem can follow the approach described in the previous section with only minor modification. Drawing on (7), the problem can be restated as:

$$\max \sum_{t=0}^{\infty} \rho^t \varepsilon\{V(S_t)\}$$

$$s.t. \ 0 \leq S_{t+1} \leq \sigma S_t + R^i(S_t, \bar{P}), \ i = 1 \ or \ 2, \tag{14}$$

$$with \ P = \bar{P} \ and \ S_0 \ given$$

where all variables and functions are as indicated earlier, except for the expectations operator on the value function, $\varepsilon\{V(S)\}$. The problem is characterized by a fixed exogenous level of phosphates $\bar{P}$, but recruitment fluctuates. Note that the inequality constraint requires escapement in any period to be less than or equal to the current level of stock,

regardless of the structural form taken by the recruitment function. This condition helps to define the set of feasible controls, ie. the range of values from which a constant optimal escapement solution can be selected.[3]

Expanding the objective function from (14), and applying the rules for taking the expectation of a function of a random variable yields:

$$\varepsilon\{V(S_t)\} = \rho\varepsilon\{\theta_1[\sigma S_t + R^i(S_t, \bar{P})]\} - \theta_2(S_t), \tag{15}$$
$$i = 1 \ or \ 2$$

where $\theta_1[\sigma S + R^i(S_t, \bar{P})]$ and $\theta(S)$ are the separable arguments of the profit function, with the former a function of a random variable. Expression (15) is the stochastic counterpart to (8) from the previous section and it can be solved for the steady state value of escapement $S*$ similarly to the deterministic case (see Footnote 1).

The welfare effect of a marginal change in the fixed level of phosphates $\bar{P}$ can now be determined for the stochastic case by drawing on the earlier deterministic comparative static analysis. If the demand curve for fish is perfectly elastic, the correct welfare measure is simply the change in producers' surplus, or $d\pi*/d\bar{P}$. Again making use of the envelope theorem, the desired value measure can be derived as the following partial derivative:

$$\frac{\partial \varepsilon\{\pi*[S*(\bar{P})]\}}{\partial \bar{P}} = \frac{\partial \varepsilon\{V[S*(\bar{P})]\}}{\partial \bar{P}} \tag{16}$$
$$= \rho\varepsilon\{\theta_1' R_P\}$$

Expanding the expectations expression on the right hand side of (16) we can take the relevant expectation. Recalling that optimal escapement is a function of the current phosphate concentration, this operation yields:

$$\varepsilon\{\theta_1' R_P\} = \varphi' \theta_1[\sigma S*(\bar{P}) + R^2(S*(\bar{P}), \bar{P})]$$
$$+ \varphi(\bar{P})\theta_1' R_P^2 + \Lambda' \theta_1[\sigma S*(\bar{P}) \tag{17}$$
$$+ R^1(S*(\bar{P}), \bar{P})] + \Lambda(\bar{P})\theta_1' R_P^1$$

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[3] Several conditions must be met to guarantee the validity of a constant escapement rule in the stochastic case. See Reed (1979) for the derivation of these and Knowler (1999) for a discussion of their significance in the present case.

Substituting (17) into (16) and noting that φ' $= f(P*)$ and Λ' $= -f(P*)$, where $f(P*)$ is the p.d.f. of $P*$ gives:

$$\frac{\partial \varepsilon\{\pi[S^*(\bar{P})]\}}{\partial \bar{P}} = \rho\Big\{\varphi(P)\theta_1' R_P^2 + \Lambda(P)\theta_1' R_P^1$$

$$+ f(P^*)\{\theta_1[\sigma S^*(\bar{P}) + R^2(S^*(\bar{P}),\bar{P})] \qquad (18)$$

$$- \theta_1[\sigma S^*(\bar{P}) + R^1(S^*(\bar{P}),\bar{P})]\}\Big\}$$

While complex in appearance, (18) is open to a relatively straightforward interpretation. The two initial terms inside the brackets on the right-hand side are a weighted sum of the deterministic response in profits to a marginal change in nutrients. This results from the inclusion of nutrients as an explanatory variable in the recruitment function. As I consider two alternative states of the world, i.e. with and without an ecosystem disturbance event, the weights comprise the respective probabilities governing each possible state. As in the purely deterministic case, this effect will be positive as the nutrient concentration rises, since $R_P > 0$ and I additionally have assumed $\theta_i' > 0$. Consequently, these two terms constitute the 'within regime' effect discussed earlier. Here it is assessed as an *ex ante* expectation, since it is not known in advance whether there will be an ecosystem disturbance event during time *t;* as a result, it is measured as the expected response in profits to a marginal change in nutrients.

The remaining terms on the right-hand side of (18) constitute the stochastic 'regime shift' effect arising from a marginal change in nutrients. It is composed of the difference in profits under the event versus non-event conditions, multiplied by the probability density function $f(P*)$, which measures the increased risk of encountering the threshold nutrient level $P*$ when the phosphate level increases slightly (or vice versa, if the reverse occurs). Thus, the stochastic formulation differs from the deterministic by incorporating the *ex ante* uncertainty about the position of the random threshold $P*$ and the likelihood of crossing it as nutrient levels are altered. The regime shift effect is negative in response to increasing enrichment, since $\theta' > 0$ and $R^1(S*,P) > R^2(S*,P)$, for any permissible value of $S*$.

From the above analysis, it can be seen that increasing nutrient levels may lead to immediate and tangible fishery benefits, since the 'within regime' effect results in higher equilibrium harvests. At the same time, enrichment creates a potentially offsetting increase in the risk of recurrence of an ecosystem surprise. It is not possible to determine which

effect will dominate without knowledge of the model's parameter values and the probability distribution governing the random variable $P*$. Such ambiguity in the theoretical results means that the sign of the aggregate welfare effect of a nutrient abatement policy under a stochastic optimal management regime cannot be determined *a priori*. This result may seem surprising in light of the often expressed belief that nutrient abatement is purely beneficial. It stems from the specification of the model, which recognizes the mixed blessing conferred on the marine system by nutrients.

5. AN EMPIRICAL APPLICATION TO BLACK SEA ANCHOVY

As a result of the indeterminacy of some of the key relationships explored in the previous section, establishing the effects of enrichment on the optimal management of fisheries within a semi-enclosed marine ecosystem requires empirical investigation. In this section, we produce valuation estimates for a representative small pelagic fishery that has been subject to nutrient enrichment and the type of stochastic marine ecosystem disturbance described above. We accomplish this by developing an applied bioeconomic model of the Turkish Black Sea anchovy fishery, drawing on a previous investigation of the open access situation governing this commercially important fishery (Knowler *et al.* 2000).

Figure 1 describes the relationships characterizing the Turkish anchovy fishery. The key relationship in the model is the recruitment function, which we have previously identified as the conduit through which nutrients (e.g. phosphates) have an impact on fishery productivity and hence on fishing profits.
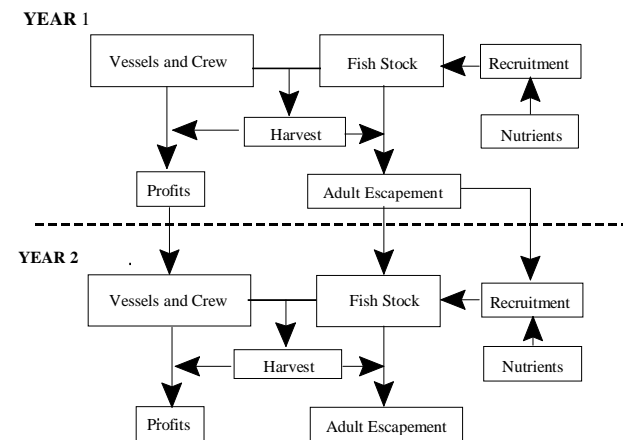

Figure 1 The Dynamics of Black Sea Fish Production (Knowler 1999)

Various authors have described a general deterioration in the Black Sea, a fairly typical semi-enclosed marine system subject to a variety of abuses (Mee 1992, Caddy 1990). Environmental and harvesting pressure are thought to have precipitated recruitment failures amongst small pelagics in the late 1980s, despite the boost to productivity provided by dramatically increasing inputs of nutrients. Perhaps the key development was the establishment of the exotic jelly fish, *Mnemiopsis leidyi*. While it was likely introduced as a result of ballast dumping, it is believed that high levels of nutrient enrichment may have played a role in opening up a niche for the species. The subsequent pattern of population explosions followed by periods of remission represent the type of stochastic disturbance modelled in the previous section (GESAMP 1997). Anchovy has been the main commercial fish species affected by the invading jellyfish, and phosphates have emerged as the nutrient of most interest, its levels showing a statistically significant and positive correlation with anchovy recruitment (Knowler 1999).

The three general functions contained in the model of the previous section -- two representing variants of the recruitment function [undisturbed, $R^1(S,P)$ and disturbed, $R^2(S,P)$] and the third a cost function – were specified as:

$$R^1(S_t, P_t) = P_t^\alpha S_t e^{-\beta_1 S_t}$$

$$R^2(S_t, P_t) = P_t^\alpha S_t e^{-(\beta_1 + \beta_2 D)S_t} \qquad (19)$$

$$C(X_t, S_t) = \frac{c}{q}[\ln X_t - \ln(X_t - S_t)]$$

As is evident in (19), the variants of the recruitment functionwere estimated using a structural change model rather than an explicit predator-prey approach, although the two need not be inconsistent. The rationale for this approach, the estimation of the relationships portrayed in (19) and other details concerning the empirical bioeconomic model are described in Knowler (1999).[4] The resulting parameters from the estimations, together with other economic and biological data employed in the empirical model, are presented in Table 1.

The parameters presented in Table 1, together with (11),

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[4] The cost function was derived by first estimating a catch function of the form $h = X(1 - e^{-qE})$ and then inverting this with E on the left-hand side, substituting $X-S$ for h and pre-multiplying the whole expression by the unit cost of effort, c (expressed as a cost per vessel per year).

the partial derivative of maximized profits with respect to a change in phosphates, make it possible to estimate the value of phosphates as an environmental input into fish production in the simple deterministic case. Inserting the relevant functional forms and parameter values into (11) produces the following annual estimates of the desired value measure $\partial\pi^*/\partial P$ under the two identified states of the world (all figures in US$ 1989/90):

- Enriched, but no *Mnemiopsis (*undisturbed) - US$ 713,000 per year per μM.

- Enriched, with *Mnemiopsis* (disturbed) - US$ 45,000 per year per μM.

Not surprisingly, the marginal valuations are positively signed, since increasing nutrients boosts the harvestable surplus for any ecological state, as long as $R_P > 0$. Additionally, the value of nutrients as an environmental input is greatest under the enriched but no-*Mnemiopsis* state (undisturbed) and lowest when *Mnemiopsis* events occur, since the aforementioned effect is strongest here.

Table 1
Parameter Values for the Empirical Model of the Turkish Anchovy Fishery (US$ 1989/90)

Parameters	Ecosystem Regime	
	Enriched, pre- or no-*Mnemiopsis* (undisturbed)	Enriched, with *Mnemiopsis* (disturbed)
price, p (US$/t)	90	90
effort cost, c (US$'000/year)	256	256
density depend. β_1, $(\beta_1 + \beta_2 D)$	0.000614	0.001624
catchability, q	0.0032	0.0032
survival rate, σ	0.78	0.78
phos., $\bar{P}$ (μM)	5.5	5.5
coeffic. on $\bar{P}$, α	0.117	0.117

Source: Knowler 1999

As noted in the previous section, a stochastic optimal management formulation can be used to analyse welfare effects when there is a 'mixed blessings' type of nutrient influence with deterministic and stochastic elements. If a probability distribution for the nutrient threshold $P*$ can be identified, and certain ancillary information about this distribution is known, then it may be possible to derive indicative valuation estimates for the stochastic model. For example, if $P*$ is an exponentially distributed random variable and P^j is the current fixed level of phosphates, the probability density function or p.d.f. is $\lambda e^{-\lambda P^j}$ and the cumulative distribution function is:

$$\int_{-\infty}^{P^j} f(P*)\,dP* = \begin{cases} 1 - e^{-\lambda P^j} & \text{for } P^j \geq 0 \\ 0 & \text{elsewhere} \end{cases} \quad (20)$$

where λ is the inverse of the mean value of the random variable described by the distribution.

While a range of possible values for the mean value of $P*$ (indicated as $\bar{P}*$) were considered, a valid constant optimal escapement solution required that the steady state escapement value be between 853,000 mt and 1,055,000 mt per year, a narrow range indeed. As this result considerably simplifies the analysis, further consideration was given only to those cases where the steady state escapement level fell within the permissible range. Only very low mean values for $\bar{P}*$ qualified, namely $\bar{P}* = 1$ µM and 3 µM.[5]

The welfare impact of a marginal change in nutrients in the stochastic case can be assessed by inserting the appropriate parameters, probabilities and optimal variable values for the two possible states (undisturbed and disturbed) into expression (16), the stochastic equivalent of (11). Keeping in mind that only $\bar{P}* = 1$ µM and 3 µM are considered, estimates of \$12,150 and -\$426,370 per µM, respectively, are obtained for this partial derivative.

These figures constitute the valuation of marginal changes in phosphates when viewed as an environmental influence on anchovy recruitment, but one comprising two offsetting effects. With $\bar{P}* = 1$ µM, the aggregate effect is dominated by the 'within regime' effect and small adjustments in phosphates affect welfare in the same direction, if only by a small amount. When $\bar{P}* = 3$ µM the 'regime shift' effect

is now stronger and the sign on the welfare effect is opposite to the direction of the change. Interestingly, there is a change in sign as the mean threshold rises. As $\bar{P}*$ increases, the steady state escapement value and expected producers' surplus rise too, since the likelihood of encountering $P*$ in any year is now reduced. This result is expressed as a heavier weighting of the undisturbed state in the expected producers' surplus so that an increased risk of a disturbance produces much greater potential losses under the 'regime shift' effect.

By comparison, the valuation of a marginal change in phosphates in the deterministic case, measured during the enriched, pre-*Mnemiopsis* or undisturbed state, was a sizeable \$713,000 per µM. In this case, only the 'within regime' effect for this particular ecosystem state was captured and so the welfare effect was large and always of the same sign as the change in phosphates.

6.   CONCLUSIONS

There is now increasing evidence that nutrient enrichment problems affecting the world's marine areas are complex and not amenable to the simple analytics applied to standard pollution problems. This observation is especially true for small pelagic fisheries that are not vulnerable to the same eutrophication damages that plague benthic species. Instead, nutrient enrichment effects are more complex, comprising deterministic and stochastic elements, as well as having beneficial and harmful aspects. To properly analyse the welfare effects of changes in nutrient levels, as may occur under proposed nutrient abatement policies, requires that this full range of complexity be incorporated into a valuation model. This paper takes on this task using a standard bioeconomic approach, modified for the presence of a nutrient influence on fish recruitment, and then extends this model to include a stochastic disturbance or ecosystem 'surprise'.

In the simple deterministic case, where only the direct and beneficial role played by nutrients is considered, the problem is one of valuing the change in nutrients as would be done for any environmental input into production. In the empirical case study involving Black Sea anchovy, this more conventional representation of the problem yielded marginal values for nutrient inputs of from \$45,000 to \$713,000 per µM of phosphates (US\$ 1989/90), depending on whether the Black Sea ecosystem is in a disturbed or undisturbed state. Here, the value of a marginal increase in nutrients is assumed to be positive, as would be the case with the influence of mangroves on shrimp production, for example. This effect was called the 'within regime' effect to reflect the absence of any possible shift or disturbance in ecological

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[5] In contrast, historic phosphate levels have ranged from below 1µM to as high as 12 µM with an average during the period immediately prior to the establishment of *Mnemiopsis* of about 5-6 µM (Cociasu *et al.* 1997).

conditions related to nutrient levels. Clearly, this suggests that nutrient abatement is costly, rather than beneficial, for a representative small pelagic fishery.

Theoretical modelling of the more complex 'mixed blessings' situation, where both the beneficial 'within regime' effect described above and a more insidious 'regime shift' effect are included, yielded ambiguous welfare results for the value of nutrient inputs. This result stems from the offsetting influences of these two effects and the possibility that either one may dominate. In terms of the empirical case study, the latter stochastic effect describes the risk of random outbreaks of the comb jellyfish *Mnemiopsis leidyi*, that reduce anchovy recruitment and the producers' surplus in the fishery.

Making a series of assumptions about how nutrients might be linked with *Mnemiopsis* outbreaks, experimental results for the value of nutrient inputs in this more complex situation were derived. Most importantly, it was found that for at least one set of assumptions, the benefit of marginally abating the phosphate concentration could be as high as US\$ 426,000 per µM. Thus, it was demonstrated that within a unified analytical framework, the 'regime shift' effect might well dominate the 'within regime' effect. This finding may be expected to have implications for nutrient abatement programs, where nutrients initially appear to be beneficial to certain fish stocks.

7.   REFERENCES

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