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The Economics of a "Mixed Blessing" Effect: A Case Study of the Black Sea

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SUMMARY

Nutrient enrichment of marine ecosystems is regarded as a pressing global environmental problem. For certain marine species it may be a mixed blessing, resulting in damaging ecosystem events, but contributing to primary productivity. Consequently, the impact of enrichment on fishery profits may be positive or negative. This paper 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. The deterministic model assumes a given ecological state in which nutrients contribute positively to pelagic fish production. The stochastic model recognizes that the planner may take into account the probability of potentially damaging shifts in ecological states due to nutrient enrichment. In this latter model, nutrient abatement has an indeterminate welfare effect, but under certain conditions a marginal change in nutrients generates positive aggregate benefits.

Keywords: Nutrients, Black Sea, *Mnemiopsis*, anchovy, eutrophication, stochastic, economics, valuation, bioeconomic, Turkey

JEL: Q2, Q20, Q22

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1. Introduction

Increasing concern has been expressed over the decline in marine fisheries worldwide due to overharvesting and the deteriorating situation in coastal and marine environments (Beverton 1992). A major obstacle to developing and implementing the necessary policies to address the problem is the absence of information about the benefits of marine habitat improvements. This is particularly the case with an important valuation issue, which concerns the influence of nutrient enrichment on commercial fish stocks. As this process often causes complex ecosystem responses, including changes in basic ecological relationships and states, the welfare impacts of nutrient enrichment on marine fisheries are difficult to predict, let alone value. To estimate these welfare effects, standard production fisheries models need to be modified to take into account the potential ecological influences of nutrient enrichment, some of which may not be fully predictable. The following paper develops one possible approach, and illustrates it with the example of nutrient enrichment impacts on the Black Sea anchovy fishery.

The economic implications of altering habitats for commercial fish stocks 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 marine habitat inputs to fisheries production or the destructive influence of pollution on resource stocks, as well as the evaluation of optimal policies for resource allocation. A number of other studies examine the complex interactions of fisheries and nutrient enrichment, recognizing that nutrient enrichment can be a ‘mixed blessing’, enhancing fisheries productivity by relaxing a nutrient constraint but also having more adverse consequences, such as fostering oxygen-suppressing algal blooms or invasions by exotic species (Boddeke and Hagel 1991, Caddy 1990 and Silvander and Drake 1989).[1] Few of these latter studies attempt to value the complex consequences of changing nutrient levels in economic terms when a mixed blessing effect is present. An exception is Turner *et al*. (1997), who study eutrophication and nutrient abatement policies in the Baltic Sea.

In this paper we use a bioeconomic model to analyse the welfare effect of nutrient abatement when there is no mixed blessing effect and compare this with the case where a mixed blessing exists. We concentrate on small pelagic fisheries and define the mixed blessing effect as an increase in ecosystem productivity due to nutrient enrichment, accompanied by the risk of a disturbance or shock to the ecosystem that would reduce this system productivity, either temporarily or in perpetuity. It is important to distinguish the deterministic and stochastic components of this mixed blessing effect. The deterministic element describes the direct influence of nutrients on fish recruitment as nutrient limitations are gradually relaxed, and for many small pelagic species this effect has been positive (Boddeke and Hagel 1991, Caddy 1990). More likely to have a negative impact are the occasional ecosystem disturbances cited above (e.g. algal blooms, biological 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, rendering nutrients a ‘mixed blessing’, and creating a challenge for the design of appropriate policies.

The next section presents a relatively simple deterministic spawner-recruit model incorporating only the direct and beneficial influence of nutrients on fish recruitment. The level of nutrients in a marine environment are modeled as a habitat input to fish recruitment. After solving for the steady state values in the deterministic model, we value these nutrient inputs using comparative statics

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[1] While our interest lies with marine applications, similar mixed effects can be found in terrestrial resource systems such as forests (e.g. the clearing of forest litter and fire prevention).

techniques and show that nutrient abatement is unlikely to be justified for small pelagic species. Subsequently, an approach for integrating the more complex and offsetting stochastic effect of nutrients is introduced and the deterministic model is reformulated in stochastic terms. We then value changes in nutrient levels under these more complex ecosystem conditions and confirm that a ‘mixed blessings’ type model could yield positive welfare effects from nutrient abatement. To demonstrate the approach empirically, indicative results for a case study of the Turkish Black Sea anchovy are presented for both the single state deterministic regime and for the more complex multi-state stochastic regime incorporating a mixed blessing effect. The latter regime adds recurring outbreaks of the comb-jelly *Mnemiopsis leidyi*, which invaded the Black Sea in the mid 1980s and both preys on and competes with anchovy.

2. A Deterministic Model with Nutrient Enrichment and No Ecosystem Disturbance

Initially, we develop a dynamic, deterministic bioeconomic model of a representative small pelagic fishery in discrete time and assume a constant ecological regime with no unanticipated ecosystem disturbances. The relationship between exploitable adult biomass X, harvest h and spawning biomass or ‘escapement’ S can be expressed as:

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

where t denotes the time period in years. 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 $\sigma > 0$, and $R(S,P)$ is the stock-recruitment relationship, which is not only a function of spawning biomass, but of nutrients P as well. Next period exploitable biomass X_{t+1} comprises surviving spawners and new recruits. If the recruitment function is dome-shaped, then $R_S > 0$ for $X < X_{MSY}$, and $R_S < 0$ for $X > X_{MSY}$, where *MSY* is maximum sustainable yield. We also assume that $R_P > 0$; rising nutrient levels increase food supplies for juvenile fish and enhance their chances of survival to recruitment age.

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

$$\pi_t \;=\; p h_t \;-\; C(X_t, h_t) \qquad (3)$$

where p is the real ex-vessel price of fish determined by a perfectly elastic demand curve and *C(X,S)* is a general cost function separable in X and S, with $C_X < 0$ and $C_h > 0$. Using (1), the variable h can be eliminated from (3), yielding the following statement for profits:

$$\pi_t \;=\; p(X_t - S_t) \;-\; C(X_t, S_t) \qquad (4)$$

Clark (1990) suggests (4) can be rewritten as:

$$\pi_t \;=\; \theta_1(X_t) \;-\; \theta_2(S_t) \qquad (5)$$

with 2_i and 2_i > 0.

If nutrients are treated as a fixed parameter, ie. $P =$ *&* , then the planner's problem under the assumption of deterministic optimal management can be expressed as:

$$\begin{aligned} &\max \sum_{t=0}^{\infty} \rho^t \pi(X_t, S_t) = \sum_{t=0}^{\infty} \rho^t [\theta_1(X_t) - \theta_2(S_t)] \\ &s.t. \quad X_{t+1} = \sigma S_t + R(S_t, \bar{P}) \\ &with \ 0 \le S_t \le X_t, \ and \ S_0, X_0 \ given \end{aligned} \tag{6}$$

In (6), D is the discount term, defined as 1/(1+*)^t, with * denoting the appropriate social discount rate. This type of problem can be simplified to the maximization of a value function *V(S)* which is a function of escapement, *S,* alone (Clark 1990). As a result, the optimization problem can be rewritten as:

$$\begin{aligned} &\max \sum_{t=0}^{\infty} \rho^t V(S_t) \\ &s.t. \ 0 \le S_{t+1} \le [\sigma S_t + R(S_t, \bar{P})] \\ &with \ P = \bar{P} \ and \ S_0 \ given \end{aligned} \tag{7}$$

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 value function shown as (8) is a partial analogue of the original profit function and was derived from the two separable components in expression (6). Through manipulation, the variable for fish stock, *X,* has been substituted out using the constraint in (6), and several accompanying constant terms have been dropped (Clark 1990). Since the variable *X* in the constraint in (6) is expressed in terms of period *t* + 1, the first term in (8) must be discounted back one period. The 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.[2] This yields the following implicit statement which is satisfied by the desired optimal escapement value S^*:

$$V'(S^*) = \rho(\sigma + R_{S^*})\theta_1'[\sigma S^* + R(S^*, \bar{P})] - \theta_2'(S^*) = 0 \tag{9}$$

Expression (9) can be rearranged to give a discrete time version of the well-known Golden Rule.

Determining the stability of the system at the steady state is relatively straightforward. The problem is simplified by the system's dependence on a single variable S for its solution and the existence of a most rapid approach path (MRAP) policy as optimal. If the exploitable biomass X is perturbed above or is equal to optimal escapement S^* at time t, excess biomass should be immediately harvested down to the optimal escapement level. If $X_t < S^*$, then system stability is ruled entirely by the underlying biological stability of the system in the absence of harvest, which is in turn governed by the condition, $-1 - \sigma < R_{S^*} < 1 - \sigma$, where σ is the adult fish survival rate.[3]

3. Valuing Changes in Nutrients in the Deterministic Model

So far we have assumed that the nutrient influence and other environmental conditions are constant under a non-fluctuating ecological regime. But our interest lies in the valuation of potential welfare effects arising from a change in nutrient levels. To conduct this analysis, we examine the comparative static effects on the steady state conditions of our model from a marginal change in the fixed level of nutrients **&** . Assessing the welfare effect of a marginal change in nutrients requires differentiation of the maximized profit function *B[S*(&)]*, defined at the constant optimal

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[2] If *V(S)* is quasi-concave, then the solution is 'bang bang' or a most rapid approach path to the steady state (Spence and Starrett 1975).

[3] Proof for the derivation of (9) as the stability condition is found in Clark (1976).

escapement $S*$ for a given nutrient level ***&*** . We can exploit the following relationship between maximized profits and the maximized value function *V[S*(**&**)]:*

$$\frac{\partial \pi [S^*(\bar{P})]}{\partial \bar{P}} = \frac{\partial V[S^*(\bar{P})]}{\partial \bar{P}} \qquad (10)$$

Proof of the validity of (10) is provided in Appendix 1.

Since the constant optimal escapement depends upon the exogenous level of nutrients, the maximized value function can be expressed as the following function of nutrients alone:

$$V[S^*(\bar{P})] = \rho \theta_1 \{\sigma S^*(\bar{P}) + R[S^*(\bar{P}), \bar{P}]\} - \theta_2 [S^*(\bar{P})] \qquad (11)$$

Recognizing (10) and applying the envelope theorem to (11), yields the following statement for the welfare effect of a marginal change in nutrients:

$$\frac{\partial V[S^*(\bar{P})]}{\partial \bar{P}} = \rho \theta_1^{\prime} R_P \qquad > 0 \qquad (12)$$

Expression (12) indicates that the welfare effect stemming from a marginal adjustment in nutrients is determined by the marginal profit θ_1' on the last unit of stock harvested times the additional harvest 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. Expression (12) is positive, since $R_P > 0$ and $2_1' > 0$. For a marginal change in nutrients under perfectly elastic demand and constant environmental conditions (no stochastic ecosystem disturbances), the welfare effects described here constitute the full economic impact.

However, pollution control policies are more likely to result in non-marginal changes in nutrient levels. Assuming such a policy is instituted, the initial nutrient level is designated as P_A and the post-change level is indicated by P_B, with $P_B < P_A$. If B $[S^*(P^j)]$ describes the maximized profit function for a given level of nutrients *j*, where $j = A$ or *B,* then the desired welfare measure for the gross benefits of a nutrient abatement policy is:

$$\Delta\pi^* = \pi[S^*(P_B)] - \pi[S^*(P_A)] \tag{13}$$

Expression (13) states that the welfare effect of a non-marginal change in nutrients is the difference between the maximized profit function before and after the change, with all inputs adjusted to their optimal levels. The welfare effect of a non-marginal change in nutrients can also be determined by integrating (12) over the interval P_A to P_B (Freeman 1993).[4] However, the integration requires knowledge of the path of S^*, which must be adjusted optimally throughout the procedure. Whether (13) is positive or negative for a nutrient abatement policy depends upon how S^* changes over its adjustment path. Appendix 2 shows that under nutrient abatement (13) will be positive if $R_S < 1 - \sigma$ and otherwise its sign is indeterminate. Interestingly, this condition constitutes the upper bound for system stability, shown earlier as (9).

For a planner contemplating nutrient abatement the implications of the analysis thus far are clear. While there may be many other benefits from such a policy, it should not be undertaken to benefit a small pelagic fishery that has been subject to nutrient limitations. Under such conditions, nutrient

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[4] The resulting expression equivalent to (13) makes use of the relationship between the maximized value function and the maximized profit function, as follows:

$$\Delta\pi^* = \Delta V^* = \int_{P^A}^{P^B} \rho\theta_1' \{\sigma S^* + R[S^*(P),P]\} R_P[S^*(P),P]\, \mathrm{d}P$$

abatement will always result in welfare losses to the fishery. This conclusion is based upon fixed, non-fluctuating environmental conditions characterizing the marine system and assumes that the underlying bioeconomic system is stable.

4. Extending the Model to Include a Stochastic Ecosystem Disturbance

The previous section showed that pelagic species may benefit from nutrient enrichment and that this effect can be valued using a deterministic bioeconomic model. We now consider the case where a nutrient-enriched marine ecosystem experiences random fluctuations or ‘surprises’ that harm fish stocks, and link the occurrence of these disturbances with ambient environmental conditions, such as the level of nutrients. Such a disturbance to the fishery is not only a random, or stochastic, event but also results in a change to the fundamental ecological conditions of the fishery. For example, nutrient enrichment may result in algal blooms or invasive outbreaks and these are likely to alter the underlying stock-recruitment relationship in the pelagic fishery. Under this new ecological regime, the management problem becomes one of selecting optimal escapement at the beginning of each time period in response to ambient nutrient concentrations but with uncertain knowledge about the marine system’s behaviour during the remainder of the period. Measuring the welfare effects of pollution control policies is now more difficult, especially if this uncertain system behaviour is linked in some way to nutrient concentrations. In this section we extend the deterministic model of the previous section to incorporate this type of stochastic influence and then consider whether the policy conclusions of the previous section still hold.

If disturbances are linked to underlying environmental conditions, then any change in these conditions can be modelled as the triggering mechanism that induces stochastic events. One means of modelling this process is to allow for the triggering of individual events when some random threshold level of environmental quality is exceeded. Under conditions of eutrophication, the current level of nutrient concentrations P_t is often used as a proxy for environmental quality

(Turner *et al.* 1997). In such a case, the desired threshold would be the nutrient level at which the marine system switches between its disturbed and undisturbed states. If a disturbance event leads to reduced fish recruitment for the current period, then the stock-recruitment relationship can be modified to reflect this, while retaining its undisturbed form during the intervals between events. The associated stochastic model would describe a regime comprising two alternating states, with shifts between these states triggered when environmental conditions exceed the random threshold level.[5] To capture the full effects of nutrient enrichment on pelagic recruitment in this more complex world this negative stochastic element can be incorporated into the deterministic model of the previous section.

To simplify the stochastic analysis, we assume that: (i) 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; (ii) an event's duration is determined by the persistence of disturbance conditions above the time-varying random threshold or trigger and that these disturbance conditions will hold for any period, *t*, in which the threshold is exceeded for that period; and, (iii) the planner is risk neutral and knows the relevant probability distributions and magnitudes of the two possible states of the world, but does not know whether an event will occur until after deciding upon the escapement level for that period.

Under these assumptions, a stochastic transition equation equivalent to (2) can be written as:

$$X_{t+1} = \sigma S_t + R_i(S_t, P_t), \quad where\ i = 1\ or\ 2 \tag{14}$$

where $R_i\,(S,P)$ refers to recruitment under state of the world i and is a function of spawning

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

biomass S and the nutrient concentration P. Two states of the world are recognized: either the marine system is between disturbance events and the recruitment function $R_1(S,P)$ prevails, or there is a disturbance event and $R_2(S,P)$ is the 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 of these two variables. As the system shifts between event and non-event conditions, the recruitment relationship governing the fish stock ‘jumps’ from one variant to the other, but retains the direct and positive impact of enrichment on recruitment via the variable P, with $R_P > 0$.

The stochastic variable in the analysis is the unknown threshold nutrient concentration at time t which may trigger a disturbance event. 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 identically and independently distributed over time. Drawing on Cropper (1976), the following expression describes the probability mass function governing the recruitment function:

$$\begin{cases} \Pr\{R_i(S_t,P_t) = R_1(S_t,P_t)\} \ = \ \Pr\{P^* > P_t\} \ = \ \int_{P_t}^{\infty} f(P^*)\,\mathrm{d}P^* \\ \Pr\{R_i(S_t,P_t) = R_2(S_t,P_t)\} \ = \ \Pr\{P^* < P_t\} \ = \ \int_{0}^{P_t} f(P^*)\,\mathrm{d}P^* \end{cases} \tag{15}$$

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

The first line in (15) shows the probability of an outbreak *not* occurring, which assumes that the threshold P^* lies within the interval P_t to ∞; that is, it lies above the current phosphate concentration P_t. The second line indicates the probability of an outbreak occurring and assumes that the threshold lies within the interval 0 to P_t ,and therefore, will be encountered in some time period, t. The probability mass function in (15) also implies that recruitment is determined jointly by the current level of nutrients P_t and the random variable P^*. Denoting the first expression in (15) as $\Lambda(P_t)$ and the second as $\phi(P_t)$, it follows that $\Lambda(P) = 1 - \phi(P)$, $\phi' = f(P^*) > 0$ and $\Lambda' = -$

$f(P^*) < 0$.

Setting up and then solving the stochastic problem can now follow the approach described in the previous section with only minor modification. Drawing on (7), the problem can be restated as:

$$\begin{aligned}&\max \sum_{t=0}^{\infty} \rho^t \epsilon\{V(S_t)\}\\ &s.t.\ 0 \le S_{t+1} \le \sigma S_t + R_i(S_t,\bar{P}),\ i = 1\ or\ 2,\\ &with\ P = \bar{P}\ and\ S_0\ given\end{aligned} \tag{16}$$

where all variables and functions are as indicated earlier, except for the addition of the expectations operator, ϵ, on the value function $V(S)$. 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 is one of several derived by Reed (1979) to guarantee a constant optimal escapement solution in stochastic models of this type. Appendix 3 describes these conditions and discusses their significance.

Expanding the objective function from (16) and applying the rules for taking the expectation of a function of a random variable yields:

$$\begin{aligned}\epsilon\{V(S_t)\} &= \rho\,\epsilon\{\theta_1[\sigma S_t + R_i(S_t,\bar{P})]\} - \theta_2(S_t),\\ &\qquad i = 1\ or\ 2\end{aligned} \tag{17}$$

where θ_1 $[\sigma S + R^i(S_t, \&)]$ and θ_2 (S) are the separable arguments of the profit function, with the former a function of a random variable. Expression (17) is the stochastic counterpart to (8) and it can be solved for constant optimal escapement S^* as in the deterministic case.

5. Valuing Changes in Nutrients in the Stochastic Model

The welfare effect of a marginal change in the fixed level of phosphates & can be determined in the stochastic 'mixed blessings' case by drawing on the earlier deterministic analysis. If the demand for fish is perfectly elastic, the correct welfare measure is simply the change in producers' surplus, or dB*/d&. Again relying on the relationship portrayed in (10) and applying the envelope theorem, the desired value measure is:

$$\frac{\partial \epsilon\{\pi^*[S^*(\bar{P})]\}}{\partial \bar{P}} = \frac{\partial \epsilon\{V[S^*(\bar{P})]\}}{\partial \bar{P}} = \rho\,\epsilon\{\theta_1^{\prime} R_P\} \qquad (18)$$

Taking the expectation on the right hand side of (18) and recalling that the constant optimal escapement can be expressed as a function of the current phosphate level & yields:

$$\begin{aligned}\epsilon\{\theta_1^{\prime} R_P\} = {} & \phi^{\prime}\theta_1[\sigma S^*(\bar{P}) + R_2(S^*(\bar{P}),\bar{P})] + \phi(\bar{P})\,\theta_1^{\prime} R_{2P} + \Lambda^{\prime}\theta_1[\sigma S^*(\bar{P}) \\ & + R_1(S^*(\bar{P}),\bar{P})] + \Lambda(\bar{P})\,\theta_1^{\prime} R_{1P}\end{aligned} \qquad (19)$$

Substituting (19) into (18) and rearranging gives the following expression for the welfare change arising from a marginal change in nutrients in the stochastic case:

$$\frac{\partial \epsilon\{V[S^*(\bar{P})]\}}{\partial \bar{P}} = \rho\Big\{\phi(P)\,\theta_1^{\prime} R_{2P} + \Lambda(P)\,\theta_1^{\prime} R_{1P} \;\; + f(P^*)\,\{\theta_1\,[\sigma S^*(\bar{P}) + R_2\,(S^*(\bar{P}),\bar{P})] \\ - \theta_1\,[\sigma S^*(\bar{P}) + R_1(S^*(\bar{P}),\bar{P})]\}\Big\} \tag{20}$$

While complex in appearance, (20) can be interpreted in a straightforward manner. Since nutrients are included as an explanatory variable in the recruitment function, the first two terms on the right-hand side measure the ‘expected’ direct response in profits to a marginal change in nutrients, analogously to the earlier deterministic analysis. As we consider two alternative states of the world (with and without an ecosystem disturbance event), it is a weighted sum where the weights comprise the 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 $\theta_i' > 0$.

The remaining terms on the right-hand side of (20) constitute the indirect stochastic effect arising from a marginal change in nutrients. It comprises the difference in profits under disturbed versus undisturbed 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. Thus, the stochastic formulation incorporates the *ex ante* uncertainty about the position of the random threshold P^* and allows for the possibility of encountering it as nutrient levels are altered. This indirect stochastic effect is negative in response to marginally increasing enrichment, since $\theta_i' > 0$ and $R^1(S^*,P) > R^2(S^*,P)$, for any permissible value of S^*.

In the absence of any unforseen and recurring ecosystem disturbance, the purely deterministic optimal management model is appropriate. As we demonstrated above, in this case there is little reason for the planner to adopt nutrient abatement from the standpoint of improving small pelagic fisheries. Decreasing nutrient levels would lead to immediate and tangible fishery losses, since this results in lower equilibrium harvests. In contrast, if the risk of a recurring ecosystem disturbance linked to nutrient conditions is present, then the fisheries model must be extended to include the risk. As we have just proven formally, the result is the ‘mixed blessing’ effect. Lower nutrient levels still decrease equilibrium harvests as before but now reduce the risk of recurrence of the disturbance, providing an offsetting influence and a potential rationale for abatement. However, it is not possible to determine which effect will dominate without knowledge of model parameters and any ancillary probability distributions, such as that governing the variable P^*.[6] In the next section, we derive an empirical application of both the deterministic and stochastic variants of our model employing the example of the Turkish Black Sea anchovy fishery.

6. An Empirical Application to Black Sea Anchovy

Various authors have described the deterioration in the Black Sea, a fairly typical semi-enclosed marine system (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 comb jelly *Mnemiopsis leidyi*, which preys on and competes with the most important commercial species, Black Sea anchovy. *Mnemiopsis* was likely brought by ship from its native U.S. East Coast and then introduced to the Black Sea via ballast dumping. However, it is believed that high levels of nutrient enrichment may have played a role in the species becoming firmly established in the Black Sea by the second half of the 1980s (Caddy, pers. comm.). The subsequent pattern of *Mnemiopsis* population explosions followed by periods of remission, possibly related to changing nutrient conditions in the Black Sea, represent the type of stochastic disturbance modelled in the previous section (GESAMP 1997).

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[6] Expression (13) describing the welfare effect of non-marginal reductions in nutrients is adapted readily to the stochastic case by expressing each of its terms as the corresponding expectation.

In our applied model, two distinct ecological regimes are analysed, corresponding to: (i) constant ecological conditions without *Mnemiopsis* present (1971-86), and (ii) a fluctuating regime of undisturbed conditions interspersed with periodic *Mnemiopsis* outbreaks (post 1986). Initially, we consider the purely deterministic formulation of the model and derive steady state solution values for the pre-*Mnemiopsis* period only. Subsequently, we use the stochastic 'mixed blessing' formulation of the model to estimate indicative steady state solution values for the post 1986 period, restricting our analysis to parameter assumptions that are consistent with a constant optimal escapement rule.

6.1 A Deterministic Model of Black Sea Anchovy without the Mixed Blessing Effect

Figure 1 describes the relationships characterizing the Turkish anchovy fishery prior to the entry of *Mnemiopsis* into the Black Sea. As this pre-*Mnemiopsis* period corresponds to stable ecological conditions in the Black Sea without any threat of disturbance to the anchovy fishery, it is consistent with the deterministic small pelagic fishery model of earlier sections. The two general functions in the latter model were the cost and recruitment functions. To specify the former, we start with a harvest function of the form, $h = X(1 - e^{-qE})$, where E is fishing effort measured as the number of vessels, and q is the 'catchability' coefficient. Inverting this function to express E in terms of X and h, the cost function is derived by pre-multiplying this expression by the unit cost of effort c. Inserting the cost function into the profit function (3) gives:

$$\pi_t = p h_t - \frac{c}{q}[\ln(X_t) - \ln(X_t - h_t)] \tag{21}$$

Eliminating h using the identity $h = X - S$ from (1), the profit function can be treated as separable in X and S, and expressed as the following two statements [see (5)]:

$$\begin{aligned} \theta_1(X) &= pX_t - \frac{c}{q}\ln X_t \\ \theta_2(S) &= pS_t - \frac{c}{q}\ln S_t \end{aligned} \qquad (22)$$

The anchovy recruitment function was specified as the following Ricker (1975) model incorporating nutrients (phosphates) as an argument:

$$R_i(S_t,P_t) = P_t^{\alpha} S_t \mathrm{e}^{-\beta_i S_t} \qquad (23)$$

where $i = 1$ or 2, and α and β are parameters. As well as adding phosphates as an argument, the standard Ricker curve has been modified to allow for two structural variants, one without the influence of *Mnemiopsis leidyi* ($i = 1$) and the other with this influence ($i = 2$), as described earlier. In this section we are only concerned with the former variant, since we assume *Mnemiopsis* has not yet entered the Black Sea. Substituting the functional forms from (22) and (23) into the value function from (8) and setting the first derivative equal to zero, ie. $V\ (S) = 0$, produces an implicit statement for the constant optimal escapement level S^*.

The parameters employed in the empirical model are presented in Table 1 and are taken from Knowler and Barbier (2000). Inserting these parameters from the first column into the fully-specified model allows calculation of steady state solution values for escapement S^*, adult biomass X^*, harvest h^*, fishing effort E^* and fishing profits π^* for the pre-*Mnemiopsis* ecological regime (see Table 2). Table 2 indicates that optimal anchovy escapement was 1.518 million metric tonnes (mt) and the associated equilibrium stock level X^* was 1.91 million mt, the difference representing the optimal annual harvest of 396,000 mt. The optimal number of fishing vessels was 72 and fishing rents were US$ 17.1 million per year. To ensure that the calculated optimal value of S^* is a unique global maximum, the value function $V(S)$ must be quasi-concave (Clark 1990). Figure 2 plots the value function for the pre-*Mnemiopsis* ecological regime and shows that the necessary condition is met. Furthermore, a check of the stability condition presented earlier as (9) verified that the steady state solution for the anchovy system under each variant of the recruitment function is stable.[7]

The optimal management results reported in Table 2 assume average ambient phosphate levels and a positive influence of phosphates on recruitment (see Table 1). As argued earlier, nutrient abatement under these conditions would have undesirable consequences for the Black Sea's small pelagic fisheries. Additional calculations provided in Table 2 bear out this observation for a counterfactual pollution control policy of 50% abatement of phosphates. The results confirm that abatement would have led to a substantial loss in economic rents during the pre-*Mnemiopsis* period.

6.2 Extending the Empirical Model to Include a Stochastic Mixed Blessing Effect

We can also develop a stochastic formulation of our applied model to analyse the 'mixed blessing' effect of nutrient influence on the Black Sea anchovy fishery. By specifying such a model empirically it is possible to determine: (i) the explicit 'positive' and 'negative' components of the mixed blessing effect on the optimal management of the fish stock arising from nutrient changes, assuming the existence of conditions meeting a constant optimal escapement rule; and (ii) whether the presence of such a mixed blessing effect alters the incentives for adopting nutrient abatement in comparison to the simple deterministic case analysed above.

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[7] The solution for the post 1986 period (with *Mnemiopsis*) displays stability but occurs on the downward sloping segment of the Ricker recruitment curve, which can be a potential problem (Clark 1990). Since the stock transition equation, $\sigma S + R(S,P)$, is monotonically increasing any potential problems are avoided.

The stochastic formulation outlined earlier requires a probability distribution for the nutrient threshold P^*. Several researchers have assumed an exponential distribution to describe a stochastic disturbance influencing a bioeconomic fisheries model (Reed 1988, Spulber 1982). To derive indicative results for the Black Sea anchovy model, we make a similar assumption concerning the distribution of the random variable P^*. If P^j is the current (constant) level of phosphates, then the probability density function of P^* is $\lambda e^{-\lambda P^j}$ and the cumulative distribution function (c.d.f.) is:

$$\int_{-\infty}^{P^j} f(P^*)\,\mathrm{d}P^* = \begin{cases} 1 - e^{-\lambda P^j} & for\ P^j \geq 0 \\ 0 & elsewhere \end{cases} \tag{24}$$

where λ is the inverse of the mean value of the random variable P^*, with this mean value denoted by $\&^*$. Using (24) to specify the probability expressions in (15), the probability mass function governing anchovy recruitment is:

$$\begin{cases} \Pr\{R^i(S_t,P^j) = R^1(S_t,P^j)\} = \Pr\{P^* > P^j\} = [1 - \phi(P^j)] = e^{-\lambda P^j} \\ \Pr\{R^i(S_t,P^j) = R^2(S_t,P^j)\} = \Pr\{P^* < P^j\} = (1 - e^{-\lambda P^j}) \end{cases} \tag{25}$$

To parameterise (25), we select a range of values for λ. Since λ is the inverse of $\&^*$, the mean threshold value for phosphates, we assume that λ would could be derived from historical values for phosphates in the Black Sea. According to Cociasu *et al.* (1997), these values have ranged from near zero to above 10 micro moles (µM) in the northwestern shelf area of the Black Sea where anchovy traditionally spawn. As an additional consideration, we wish to maintain a constant optimal escapement rule, but this applies only when the solution value for escapement lies between 853,000 mt and 1.055 million mt per year (see Appendix 3 for details). As working with a constant optimal escapement situation considerably simplifies the analysis, only estimates of $\&^*$ associated with this situation were allowed. This meant that only low values for $\&^*$ could be used and, as a result, we chose to assume $\&^* = 1$ µM or 3 µM. Taking an initial ambient phosphate level (P^A) of

5.5 µM, these estimates for &* yield probabilities for an outbreak in any year *t* of 0.996 and 0.84, respectively.

Table 3 shows the results of the indicative stochastic analysis for the two values of &* considered. Although the marine system fluctuates between two possible states of the world (without and with a *Mnemiopsis* outbreak), the model solves for a single optimal escapement value across both potential states, since the planner does not know whether an outbreak will occur in a given year until after escapement is set. Constant optimal escapement in the stochastic case is always lower than its value during the pre-*Mnemiopsis* regime, at 948,000 mt to 1.025 million mt versus 1.518 million mt, respectively.[8] This result occurs because the planner must factor in the possibility of an outbreak and ensure whatever escapement level is chosen it is still optimal in such a case. Thus, escapement cannot be set optimally for undisturbed conditions, even if these ultimately manifest. As a result, economic profits in the undisturbed state under the fluctuating post 1986 regime are lower than profits in the pre-*Mnemiopsis* period (see Tables 2 versus 3). Moreover, as &* rises the optimal escapement level and expected profits also increase, since the likelihood of encountering P^* in any year is now reduced and this is expressed as a heavier weighting of the non-outbreak outcome.

We can use the above applied stochastic model incorporating a ‘mixed blessing’ effect to analyse the welfare effects of potential nutrient control policies on the Black Sea anchovy fishery. Again we consider a 50% reduction in the ambient phosphate level, and only consider the cases where a constant optimal escapement rule was admissible, i.e. &* = 1 µM and 3 µM. The results of this simulation are presented in Table 3. It is immediately apparent that for &*= 3, the nutrient

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[8] When comparing optimal escapement for the pre-*Mnemiopsis* regime to the value for the later regime with *Mnemiopsis*, it may appear counterintuitive that the escapement level should be set lower in the face of perceived risk. This simply reflects the weighting of the two possible states of the world in the stochastic solution, with a much lower optimal level of escapement under outbreak conditions factored into the analysis.

abatement policy leads to an inadmissible constant optimal escapement solution; that is, it falls outside the allowable range defined above. For this reason, this case is disregarded and instead the focus is placed on the remaining possibility where **&*** = 1. Under the 50% phosphate abatement policy, constant optimal escapement rises modestly to 958,000 mt from 948,000 mt, but the overall effect of abatement is to raise expected profits from US$ 325,000 to US$ 607,000 per year, an increase of 87%. In contrast to the deterministic case, where a 50% phosphate abatement policy generates a welfare loss, the same policy applied in the case of a possible nutrient-induced stochastic disturbance to the anchovy fishery has the opposite effect. That is, once *Mnemiopsis* became established in the Black Sea, the presence of the mixed blessing effect may have led to positive welfare gains for the Turkish anchovy fishery from nutrient abatement.

The reason for the reversal in the welfare effect of a phosphate abatement policy once *Mnemiopsis* becomes established is clearly the result of the assumption that nutrients and outbreaks are linked. As portrayed in Table 3, economic profits in the undisturbed state decline by about 14% with abatement, and by an even larger amount when the system is subject to an outbreak. This negative effect of abatement on economic profits stems from the presence of P in the recruitment function and the assumption that $R_P > 0$. However, as the mixed blessing effect predicts, abatement also leads to a greater likelihood of the more productive *Mnemiopsis*-free state occurring, as reflected in the higher probability now attached to this state. Table 4 shows that the likelihood of no outbreak rises from 0.004 to 0.064 when **&*** = 1 μM . Accordingly, this indirect abatement effect on the economic profits in the anchovy fishery associated with a change in the risk of an outbreak is positive. Although the profitability under each state seen in isolation falls (see Table 3), the greater chance of a *Mnemiopsis*-free environment more than offsets, and as a result, positive aggregate abatement benefits ensue.[9] Assuming a link between nutrient conditions and the invader

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[9] This result contrasts with that of a marginal change, when defined at the same initial point where **&*** = 1. In the latter situation, the welfare effect was shown to be negative for a very small decrease in nutrients. Clearly, when integrating over the interval P^A to P^B to determine the welfare effect of a non-marginal change the welfare effect at the margin must switch signs so that the cumulative effect of abatement over the entire interval becomes positive.

Mnemiopsis exists, then the shift to a new ecological regime in the Black Sea in the mid 1980s may have warranted a renewed effort to reduce nutrient concentrations.

7. 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. Using a standard deterministic bioeconomic modelling approach modified for the presence of a nutrient influence on fish recruitment, this paper attempted to incorporate such complexity by extending the basic deterministic model to include a stochastic disturbance so that a 'mixed blessing effect' existed.

In the simple deterministic case with no mixed blessing effect, the policy problem is one of valuing the change in nutrients as would be done for any environmental input into production. The results from the theoretical analysis, confirmed later in our empirical case study, suggest that nutrient abatement is costly, rather than beneficial, for a representative small pelagic fishery. For the planner concerned with the Black Sea region , the lack of benefits for small pelagic fisheries from abating nutrients would have made this policy unattractive. Of course, the other many desirable benefits stemming from such a policy (e.g. benthic species, recreation, water quality) would need to be factored in to a broader analysis. Nonetheless, calls for nutrient reductions to assist recovery in the small pelagic fisheries were probably misplaced prior to the mid 1980s.

Incorporating both the beneficial effect described above and a harmful recurring ecosystem disturbance into the model creates the mixed blessing effect and nutrient abatement now yields less obvious welfare results. This result stems from the offsetting effects of the two influences and the possibility that either one may dominate. Making a series of assumptions about how nutrients might be linked with outbreaks of the Black Sea invader *Mnemiopsis leidyi,* as the stochastic ecosystem disturbance, experimental estimates of the expected benefits from nutrient abatement were derived. For at least one set of assumptions, the expected benefit of abating phosphates would be positive, in contrast to the earlier policy conclusion in the absence of a mixed blessing effect.

The analysis presented in this paper partially relies on a few key assumptions, such as the hypothesized link between nutrients and the recurring ecosystem disturbance. While a relationship of this nature seems likely, further research is required to verify it. Moreover, to retain the model's tractability, we concentrated on only those cases that met the stringent demands of an constant optimal escapement policy. The limited range of solution values reflects the extreme impact of the invader *Mnemiopsis* on Black Sea anchovy stocks, so that in other case studies where this influence is less pronounced, a wider range of solutions could be considered. Despite these limitations, we believe our findings have implications not only for nutrient abatement programs, but for a host of other similarly complex terrestrial and marine environmental problems.

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9. Appendix 1: The Value Function *V(S*)* and Welfare Measurement

Earlier it was asserted that the welfare effects of a marginal change in nutrients could be assessed by examining the response in the maximized value function $V[S^*(\&)]$ rather than directly employing the maximized profit function $\pi[S^*(\&)]$. In this appendix, this assertion is proved using a Lagrangean formulation of the problem. Recall the initial formulation of the planner's problem for a representative ecological regime portrayed in (6), with a profit function separable in X and S.

The standard Lagrangean expression associated with (6) is:

$$\mathscr{L} = \sum_{t=0}^{\infty} \left\{ [\theta_1(X_t) - \theta_2(S_t)] + \rho\lambda_{t+1}[\sigma S_t + R(S_t,\bar{P}) - X_{t+1}] \right\} \tag{A1.1}$$

The first order conditions for this problem are:

$$\begin{aligned} \frac{\partial \mathscr{L}}{\partial S_t} &= -\theta_2^{\prime}(S_t) + \rho\lambda_{t+1}(\sigma + R_S) = 0 \\ \frac{\partial \mathscr{L}}{\partial X_t} &= \theta_1^{\prime}(X_t) - \lambda_t = 0 \\ \frac{\partial \mathscr{L}}{\partial \rho\lambda_{t+1}} &= \sigma S_t + R(S_t,\bar{P}) - X_{t+1} = 0 \end{aligned} \tag{A1.2}$$

At the steady state, the time subscripts disappear and by substituting for λ and then eliminating X, it can be shown that:

$$\rho(\sigma + R_{S^*})\theta_1^{\prime}[\sigma S^* + R(S^*,\bar{P})] - \theta_2^{\prime}(S^*) = 0 \tag{A1.3}$$

which is the condition for a maximum of the value function *V(S),* where S^* is the optimal escapement value.

Furthermore, the welfare effect of a change in the constrained objective function from a marginal change in the parameter ***&*** is assessed as the following:

$$\frac{\partial \mathscr{L}}{\partial \bar{P}} \quad = \quad \rho \lambda_{t+1} R_P \qquad \text{(A1.4)}$$

As this expression includes the unobservable variable λ_{t+1}, it must be eliminated. Since only the steady state is of interest, we substitute for λ and eliminate X using (A1.2), yielding:

$$\frac{\partial \mathscr{L}}{\partial \bar{P}} \quad = \quad \rho \theta_1^{\prime} [\sigma S + R(S, \bar{P})] R_P \quad = \quad \frac{\partial V[S^*(\bar{P})]}{\partial \bar{P}} \quad > \; 0 \qquad \text{(A1.5)}$$

which is the same as (12) in the main text.

10. Appendix 2: Signing the Derivative d*S*/*d*P*

At the maximum of (8), the following statement describes the change in optimal escapement S^* in response to a marginal change in nutrients:

$$\frac{dS^*}{d\bar{P}} = \frac{\rho\,\theta_1' R_{SP} + \rho\,\theta_1'' R_P (\sigma + R_S)}{\theta_2'' - \rho\,\theta_1' R_{SS} - \rho\,\theta_1''(\sigma + R_S)^2} \qquad \text{(A2.1)}$$

Based on (5), it is difficult to have an *a priori* expectation for the sign of (A2.1), and upon inspection it is ambiguous in sign. The upward sloping portion of a domed recruitment function is characterized by R_S, R_P, $R_{SP} > 0$ and $R_{SS} < 0$ and the formal condition determining the sign of (A2.1) is:

$$\frac{dS^*}{d\bar{P}} \left\{ \begin{array}{ll} \textit{undefined}, & \textit{if } (\sigma + R_S) = \\ > 0, & \textit{if } (\sigma + R_S) < \\ < 0, & \textit{if } (\sigma + R_S) > \end{array} \right\} \sqrt{\frac{\theta_2'' - \rho\theta_1' R_{SS}}{\rho\,\theta_1''}} \qquad \text{(A2.2)}$$

The square root expression on the right-hand side of (A2.2) can be partially analysed by exploiting information about the functions $\theta_1(X)$ and $\theta_2(S)$. Since an optimal long run equilibrium solution will be characterized by $X^{*}\$\ S^{*}$, the following will characterize the derivatives of these functions: $\theta_1'(X) > \theta_2'(S) > 0$ and $\theta_1''(X) > \theta_2''(S) > 0$. As a result, the expression under the square root sign in (A2.2) will be greater than one, and so will its square root. Thus, for a positive sign on (A2.2), it is sufficient to have $(\sigma + R_S) < 1$ or, equivalently, $R_S < 1 - \sigma$. This was also the upper bound condition ensuring a biologically stable system without harvest, as noted in the main text. Thus, for the upward sloping portion of the recruitment curve, decreasing nutrients will reduce the optimal escapement level if the system is stable under no harvest. It then follows that recruitment must fall in such circumstances and so too will profits.

11. Appendix 3: Conditions for a Constant Optimal Escapement Rule in the Stochastic Case

In order for a constant optimal escapement rule to apply in the stochastic case, the following conditions must be met (see Clark 1985 and 1990; Reed 1979):

i. The current pre-harvest stock level X_t is known when current harvest h_t is established.

ii. The cost function can be expressed in the form $C(X_t) = k/X_t$, where k is a constant.

iii. The optimal level of escapement must be non-decaying or ‘self-sustaining’, regardless of the random fluctuations in stock growth. This condition is captured by the inequality constraint in (16) and can be restated as:

$$S^* \leq \frac{R^i(S^*, \bar{P})}{(1-\sigma)} \qquad for\ i = 1,2 \tag{A3.1}$$

iv. The underlying deterministic or ‘average’ stock transition equation must be strictly concave and increasing. For the class of S-shaped stock transition curves (as in the empirical analysis), the following condition must be satisfied:

$$S^* < \hat{S}, \quad where\ R_{SS}(\hat{S}, \bar{P}) = 0 \tag{A3.2}$$

For our model, conditions (i) and (ii) hold, since they pertain to assumptions already made about the availability of information or represent restrictions on the functional forms used in the later empirical analysis. For example, the conditions are shown to hold where the harvest function is of the Schaefer-Gordon variety and the stock transition relationship is of the Beverton and Holt or Ricker (upward sloping portion only) models. Conditions (iii) and (iv) define a range of optimal solution values that are consistent with a constant optimal escapement rule and can be applied empirically with little difficulty.

Table 1

Parameter Values for the Empirical Model of the Turkish Anchovy Fishery

(US$ 1989/90)

Parameters	**Ecosystem Regime**		
	Pre- *Mnemiopsis* (1971-1986)	*Mnemiopsis* Present (post 1986)	
		Undisturbed	Outbreak
anchovy price, *p* (US$/t)	90	90	90
fishing effort cost, *c* (US$'000/year)	256	256	256
anchovy recruitment parameter, $\$_i$	0.000614	0.000614	0.001624
coefficient on **&**, α	0.117	0.117	0.117
catchability, *q*	0.0032	0.0032	0.0032
anchovy survival rate, *F*	0.78	0.78	0.78
phosphates, **&** (µM)	5.5	5.5	5.5
social discount rate, δ	5	5	5

Source: Knowler and Barbier (2000)

Table 2

Steady State Values for the Turkish Black Sea Anchovy Fishery for the Pre-*Mnemiopsis* Ecological Regime, 1971-1986

(US$ 1989/90 per year)

Case Examined	**Escapement (S^*) (000 mt)**	**Recruitment (R^*) (000 mt)**	**Stock (X^*) (000 mt)**	**Harvest (h^*) (000 mt)**	**Effort (E^*) (vessels)**	**Profits (π^*) (000 US$/yr)**
Base Case , No Abatement (P^A = 5.5 µM)	1518.073	729.643	1913.74	395.667	72.381	17080.626
50% Abatement Policy (P^B = 2.75 µM)	1485.357	671.664	1830.243	344.886	65.248	14336.239
Impact of Abatement	-32.716	-57.979	-83.497	-50.781	-7.133	-2744.387

Table 3
Steady State Values for the Turkish Black Sea Anchovy Fishery for the Ecological Regime with *Mnemiopsis* Present, Post 1986
(US$ 1989/90 per year)

Value of &*	**Escapement** (***S****) **(000 mt)**	**Recruitment** (***R****) **(000 mt)**	**Stock** (***X****) **(000 mt)**	**Harvest** (***h****) **(000 mt)**	**Effort** (***E****) **(vessels)**	**Profits** **(π*)** **(000 US$/yr)**
Base Case, No Abatement (P^A *= 5.5 μ 9)*						
1. &* = 1 μM						
Undisturbed	947.560	646.481	1385.577	438.018	118.745	9023.012
Mnemiopsis Outbreak	947.560	248.268	987.364	39.805	12.859	290.486
Expected Value	947.560	249.895	988.991	41.432	13.292	326.174
2. &* = 3 μM						
Undisturbed	1024.554	666.735	1465.887	441.333	111.938	11063.711
Mnemiopsis Outbreak	1024.554	236.889	1036.041	11.487	3.484	141.888
Expected Value	1024.554	305.613	1104.765	80.211	20.824	1888.066
50% Abatement Policy (P^B *= 2.75 μ 9)*						
1. &* = 1 μM						
Undisturbed	958.365	598.933	1346.457	388.093	106.251	7728.033
Outbreak	958.365	227.512	975.036	16.671	5.389	120.738
Expected Value	958.365	251.256	998.780	40.415	11.837	607.056
2. &* = 3 μM						
Undisturbed	1133.605	636.180	1520.392	386.787	91.739	11325.603
Outbreak	1133.605	202.459	1086.672	-	-	-
Expected Value	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Note: (-) indicates a negative calculated value; (n.a.) is 'not applicable'

Table 4

Estimated Probabilities for the Occurrence of Alternative States with *Mnemiopsis* Present, for Base Case Nutrient Conditions and a 50% Abatement Policy

Value of &*	**Base Case, No Abatement (P^A = 5.5 µM)**	**50% Abatement Policy (P^B = 2.75 µM)**	**Change in Probability**
1. &* = 1 µM			
Undisturbed State	0.004087	0.063928	0.059841
Mnemiopsis Outbreak	0.995913	0.936072	(0.059841)
2. &* = 3 µM			
Undisturbed State	0.159880	0.399850	0.0239970
Mnemiopsis Outbreak	0.840120	0.600150	(0.0239970)

Figure 1

The Dynamics of the Black Sea Anchovy Fishery

During the Pre-*Mnemiopsis* Period

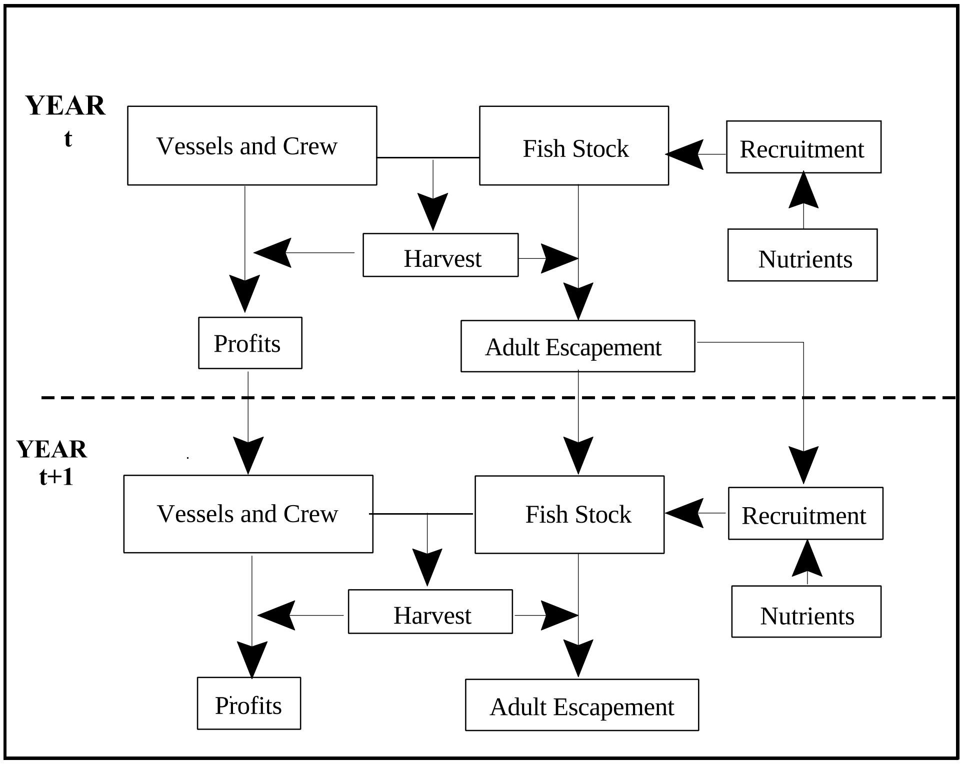
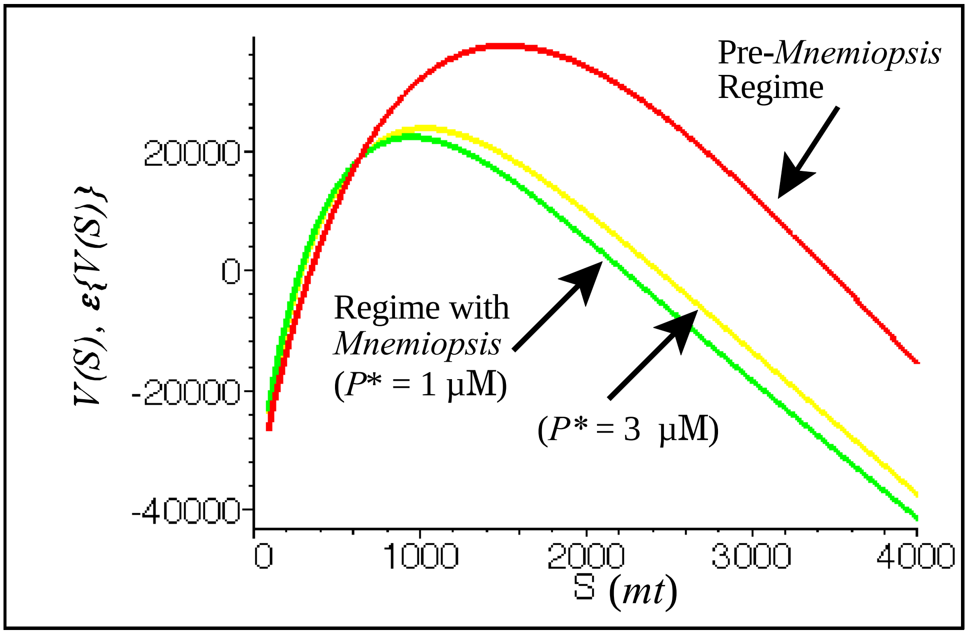


Figure 2

Value Function V(S) for the Turkish Black Sea Anchovy Fishery under a Pre-*Mnemiopsis* Regime and Expected Value Function ε{V(S)} for a Regime with Recurring *Mnemiopsis* Outbreaks (P* = 1 µM and 3 µM)



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