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Managing the Black Sea Anchovy Fishery with Nutrient Enrichment and a Biological Invader

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Abstract *Many marine systems are subject to high nutrient loadings together with invasions by exotic species. Devising appropriate management responses is an increasing concern and one that has received relatively little attention from researchers. This paper considers the Black Sea anchovy fishery, which has benefited from the relaxation of a nutrient constraint, but has suffered from competition and predation by an invading comb-jelly (*Mnemiopsis leidyi*). We examine alternative hypotheses about the mechanism triggering outbreaks of the invader (sea temperatures versus nutrients), and the severity of these outbreaks, to see whether a constant escapement policy might be optimal for this fishery. If nutrient levels serve as the triggering mechanism, we argue a mixed blessing effect may be present, so that the effects of nutrient abatement for the anchovy fishery are uncertain. We specify our model empirically and show that a constant escapement policy would be viable under a scenario of reduced impacts from outbreaks of the invader and that nutrient abatement could be beneficial if nutrients trigger outbreaks.*

Key words *Mnemiopsis leidyi*, nutrient abatement, stochastic bioeconomic model, biological invasion.

JEL Classification Codes O3, O41, Q2, Q20, Q22.

Introduction

Many researchers have expressed concern over a worldwide decline in marine fisheries due to overharvesting and deteriorating coastal and marine environments, the latter resulting from influences such as nutrient enrichment (Beverton 1992). Ironically, some fish stocks (mostly pelagic species) may benefit from the relaxation of a nutrient constraint over a limited range of nutrient levels (Silvander and Drake 1989). In addition, coastal and marine environments have been adversely affected by the presence of biological invaders, mainly the result of the accidental transport of exotic species into new habitats. For example, introductions of the zebra mussel (*Dreissena polymorpha*) and the Asian clam (*Corbicula fluminea*) into the United

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States, and a comb-jelly (*Mnemiopsis leidyi*) into the Black Sea, are thought to have occurred through ballast water released from ships (Knowler and Barbier 2000; Pimental *et al.* 2000). Once established, such invaders wreak havoc with marine systems and cause significant economic losses, but their behaviour is often subject to complex, non-linear dynamics (*e.g.*, thresholds).

Typically, environmental influences on commercial fisheries, such as nutrient enrichment and biological invaders, are modelled separately. In the case of the Black Sea marine environment, this would be appropriate if outbreaks of the invading comb-jelly, *Mnemiopsis leidyi*, which preys on and competes with commercially important anchovy, are linked to sea surface temperature rather than nutrient conditions (Shiganova *et al.* 2001). However, there is also conflicting evidence that outbreaks of *Mnemiopsis* may be linked to favorable feeding conditions resulting from elevated nutrient levels (Shiganova *et al.* 2001). Similarly, the commercial fish stock most affected by the invasion, the Black Sea anchovy, appears to have benefited more directly from elevated nutrient levels (Caddy 1990). If such linkages exist, then developing appropriate fisheries management responses to biological invaders and the design of nutrient abatement policies are more complex and should be considered together (Tahvonen 1991). This paper develops an approach that incorporates the stochastic behaviour of an invading species into a bioeconomic model of a commercially important fish stock subject to nutrient enrichment. We illustrate our model using the Black Sea anchovy fishery and the biological invader *Mnemiopsis leidyi*.

Various researchers have examined the effects of stochastic environmental influences on optimal fisheries management. Ludwig (1979) examined the case where environmental perturbations cause small deviations in stock recruitment from the deterministic situation, demonstrating that the optimal deterministic and stochastic strategies may differ only slightly. Reed (1979) examined a similar problem, concentrating on rules governing the optimality of a constant escapement policy in stochastic models of this type. Collapse and event risks were explored by Reed (1988) and Johnston and Sutinen (1996) for fisheries, and for the case of pollution control by Tsur and Zemel (1998). Learning and Bayesian updating in stochastic fisheries models were explored by Spulber (1982) and Walters (1981), the latter using a model where knowledge about competing recruitment hypotheses increased over time and recruitment was subject to an environmental disturbance. An overview of stochastic bioeconomic modeling is provided in Andersen and Sutinen (1984).

Fisheries scientists have recognized that nutrient enrichment can be a 'mixed blessing,' by relaxing a nutrient constraint but also potentially resulting in adverse consequences, such as fostering harmful environmental events (Boddeke and Hagel 1991).¹ For our purposes, we define the mixed blessing effect as an increase in ecosystem productivity due to nutrient enrichment, accompanied by the risk of an outbreak by a biological invader that reduces marine system productivity. Assuming the two influences occur simultaneously results in offsetting impacts on fisheries with no clear aggregate positive or negative effect.

Typically, ecosystem events involving a species with fluctuating population are triggered by some mechanism and may be subject to thresholds, as in a given level of nutrients or sea temperature. Beginning with Perrings and Pearce (1994), various authors have examined the role of thresholds in natural resource models [for a review, see Muradian (2001)]. For example, Cropper (1976) analyzed collapses related to catastrophic events, such as a nuclear accident, where the probability of collapse

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).

was related to concentrations of radionuclides above a random threshold. Increasingly, thresholds are being incorporated into models of the eutrophication of marine and freshwater systems (Naevdal 2001; Alaouze 1999). However, none of these studies model the economic and management consequences of an environmental disturbance when a mixed blessing effect may be present and where it involves a stochastic component.

In an earlier paper in this journal, Knowler, Barbier, and Strand (2002) assessed the potential benefits of nutrient abatement under open-access conditions using a deterministic model. In this paper, we use a stochastic bioeconomic model with an environmental threshold to address several questions. What type of escapement policy is likely to be optimal (*e.g.*, constant escapement), given the unique features of the Black Sea problem? Is nutrient abatement liable to be justified to benefit pelagic fish stocks if a mixed blessing effect is present? To address these questions, we assess the optimal fisheries management strategy under a variety of assumptions and examine the welfare effects of nutrient abatement when there is a mixed blessing effect and compare this with the case where no mixed blessing exists. In the latter case, we assume that outbreaks of the invader are triggered by alternative environmental conditions (*e.g.*, sea temperature), rather than the level of nutrients.

The next section provides an overview of the environmental problems characterizing our case study marine system, the Black Sea, as these motivate our initial modelling and later empirical application. Following this overview, we develop a stochastic spawner-recruit model that relies on two alternative hypotheses about the mechanism triggering outbreaks of the invader, *Mnemiopsis leidyi*. We derive a constant escapement solution for our model and consider whether such a rule might be optimal. We then derive the welfare specification for changes in nutrient levels under these more complex ecosystem conditions, and confirm that a mixed blessing model could yield positive welfare effects. To demonstrate the approach empirically, we calibrate the model using the Turkish Black Sea anchovy fishery, which has been subjected to recurring outbreaks of the comb-jelly, *Mnemiopsis leidyi*, since the mid-1980s. Finally, we discuss the policy implications of our analysis and investigate directions for further biological and ecological research, the need for which seems particularly acute in this case.

Environmental Management and the Black Sea Fisheries

The Black Sea is one of the most polluted and mismanaged inland or semi-enclosed seas in the world (Mee 1992; UNEP 1990; Caddy 1990). One of the most serious signs of environmental degradation has been the gradual reduction in the value and importance of Black Sea fisheries, historically serving as a source of protein for consumers, incomes for fishing communities, and export revenues for nations. Several decades ago, up to 26 species were of commercial interest, but now the number has dwindled to only six (Zaitsev 1992). While the commercial importance of individual species has varied over time, anchovies clearly dominated the catch, by weight, over the latter half of the 1960–95 period, benefiting from a shift in harvester interest and a rapid increase in nutrient levels in the Black Sea. Catches of anchovy fell dramatically during the late 1980s and early 1990s, apparently in response to overharvesting and the invasion of the Black Sea by the comb-jelly, *Mnemiopsis leidyi*, originating from the Northeast coast of the US (Travis 1993).

Initially, *Mnemiopsis*' entry into the Black Sea displayed behaviour typical of an invading species: there was an explosion in its population over the period 1987–90, as the ecosystem conditions were favourable (*e.g.*, eutrophication), and natural enemies and other forms of natural control were non-existent (GESAMP 1997). Other

events possibly influencing the initial outbreak of *Mnemiopsis* included high stock levels of zooplankton during the latter half of the 1980s, resulting from expanded catches of pelagic species that compete for the zooplankton as a food supply. Ultimately, the combination of high nutrient levels and high pelagic catches conspired to create an opening in the marine ecosystem for *Mnemiopsis* (Caddy 1997). After the initial outbreak phase, a second population explosion occurred several years later, suggesting the species exhibits the behaviour of a recurring, Type B invader (GESAMP 1997). With Type B invaders, population outbreaks occur periodically when conditions are right. For *Mnemiopsis*, a consensus is emerging that high sea temperatures in the late winter, together with food availability, are the key factors that trigger an outbreak, although their individual roles have yet to be fully clarified (Shiganova *et al.* 2001). Finally, a new development occurred in 1997 when the ctenophore, *Beroe ovata*, a natural predator of *Mnemiopsis*, invaded the Black Sea. This development, together with the much weaker outbreak of *Mnemiopsis* in 1994, has led to speculation of less severe outbreaks of *Mnemiopsis* in the future (Bilio and Niermann 2004; Shiganova *et al.* 2001).

Recognizing the influence of seasonal availability of food sources, the *Mnemiopsis* biomass normally expands from virtually nil in the spring to its annual maximum in the late summer/early fall, before contracting to just a few individuals over the winter period. Its initial population level each year appears to be determined by random environmental conditions (*e.g.*, sea surface temperature), rather than by the population level of the preceding year (Shiganova 1998). Studies of the feeding behavior of *Mnemiopsis* indicate it ingests prey in approximately linear proportion to prey abundance over a fairly wide range of population densities (Kideys 1994). *Mnemiopsis* preys directly on fish eggs and larvae of important commercial species (*e.g.*, anchovy), but it also preys on the food of adult fish, increasing the latter's mortality rate (GESAMP 1997). Thus, the fish stock suffers both from competition with and predation by the invader. Anchovy has been the main commercial fish species affected by *Mnemiopsis* (Kideys 1994).

The uncertainties associated with fluctuations in the biomass of *Mnemiopsis*, the hypothesized links between nutrients and the anchovy stock, as well as possible links between nutrients and *Mnemiopsis*, call for a carefully devised fisheries management strategy. While there are several possible strategies, one that may be particularly appealing is a constant escapement policy. For example, Steinshamn (1998) assessed several management policies when a fish stock is subject to cyclical and stochastic disturbances and found that under conditions of pure stochasticity (such as we model in this paper), a constant escapement policy performed best. Provided that adequate monitoring and adjustment takes place, such a strategy also may be simpler to apply and, therefore, more suitable when many countries must coordinate their management. This is not an easy task in a region such as the Black Sea catchment. As a result, the modeling carried out in the subsequent sections examines the optimality of a constant escapement policy.

Constant Escapement in a Stochastic Model with a Mixed Blessing Effect of Nutrients

In this section we develop a dynamic, stochastic bioeconomic model of a representative small pelagic fishery in discrete time and then solve it for the steady-state escapement level. If the demand for fish is perfectly elastic, the economic component of the model comprises the producers' surplus or economic profits, π , generated by the catch:

$$\pi_t = p h_t - C(X_t, h_t), \quad (1)$$

where p is the real ex-vessel price of fish, $C(X, h)$ is a general cost function with $C_X < 0$ and $C_h > 0$, and t denotes the time period in years. The relationship between exploitable adult biomass, X , catch, h , and spawning biomass or escapement, S , can be expressed as:

$$S_t = X_t - h_t. \quad (2)$$

Using equation (2), the variable h can be eliminated from equation (1), yielding the following statement for profits:

$$\pi_t = p (X_t - S_t) - C(X_t, X_t - S_t). \quad (3)$$

In keeping with our later empirical application, we assume $C(X, X - S)$ is separable in X and S , so equation (3) can be rewritten:

$$\pi_t = A(X_t) - B(S_t). \quad (4)$$

For the ensuing analysis, we confine ourselves to the region where π_j and $\pi_{j+1} > 0$.²

In constructing the biological component of the model, we assume that the fish stock is positively influenced by nutrient levels and subject to predation from and competition with a biological invader that has already become established in the marine system. Exploitable adult biomass in the next period is indicated by the following transition equation:

$$X_{t+1} = S_t + R(S_t, P_t), \quad (5)$$

where π combines the adult survival and growth rates from one period to the next, with $\pi = 0$, and $R(S, P)$ is the stock-recruitment relationship, which is not only a function of spawning biomass, but of nutrients, P , as well. Exploitable biomass in the next period, X_{t+1} , comprises surviving spawners and new recruits. If the recruitment function is dome shaped, then $R_S > 0$ for $S < S_{max}$, and $R_S < 0$ for $S > S_{max}$, where S_{max} is the escapement level associated with maximum recruitment. 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 nutrient-enriched marine ecosystem experiences random fluctuations or surprises that harm fish stocks, due to the presence of a biological invader, then we can devise a stochastic version of equation (5). We allow for various mechanisms that may trigger an outbreak of the invader and model the stochastic process formally as a random threshold in environmental conditions that, when exceeded during any time period, t , results in an outbreak of the invader. Since there remains uncertainty over the true environmental triggering mechanism amongst fisheries scientists, we consider sea temperature (T) and food availability (Shiganova *et al.* 2001). In the latter case, the current level of nutrient concentrations (P) is often used as a proxy for primary productivity and, therefore, food availability (Jorgensen 1992). In either case, the desired threshold would be the level of T or P at which the

² This should present no difficulties, since in our later empirical application this condition holds, except for small values of the variables X and S .

marine system switches from an undisturbed (no outbreak) to a disturbed (outbreak) state. If an outbreak leads to reduced adult survival and 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 exceeded the random threshold level.

To simplify the stochastic analysis, we assume that: (i) the invader has become established; (ii) recurring outbreaks of the invader modify the marine ecosystem similarly during each event, and this can be modelled as a temporary structural change in the adult survival rate and recruitment function of the exploitable fish stock; (iii) an event's duration is usually one season or year, and these disturbance conditions hold for any period, t , in which the threshold is exceeded during that period; and (iv) the planner is risk neutral and knows the relevant probability distributions and magnitudes under 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.

The above conditions lead to the following stochastic version of equation (5):

$$X_{t+1} = \alpha_i S_t + R_i(S_t, P_t), \text{ with } i = 1 \text{ or } 2, \quad (6)$$

where α_i and $R_i(S, P)$ refer to the adult survival rate and recruitment function under state of the world i , with the latter a function of spawning biomass, S , and nutrients, P . Two states of the world are recognized: either the marine system is between disturbance events and α_1 and $R_1(S, P)$ prevail, or there is a disturbance event and α_2 and $R_2(S, P)$ hold. Note that $\alpha_1 > \alpha_2$, and that $R_1(S, P) > R_2(S, P)$ over the entire domains of X and P for any values of these two variables. As the system shifts between no outbreak and outbreak 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 P , with $R_p > 0$.

The stochastic variable in the analysis is the unknown threshold at time t that may trigger an outbreak event. Denoting this random variable as \tilde{Z}_t , it lies within the interval $[0, \infty]$, has a probability density function $f(\tilde{Z}_t)$, and is identically and independently distributed over time. The threshold \tilde{Z}_t may be related either to the current T or to the current level of nutrients, P . Since we wish to consider both possibilities at this stage, we simply refer to the current value of the environmental influence related to the threshold as Z , recognizing that this could refer to T or P .

Drawing on Cropper (1976), the following expression describes the probability mass function governing the stochastic recruitment function in equation (6):

$$\begin{aligned} \Pr \{ \alpha_i S_t + R_i(S_t, P_t) = \alpha_1 S_t + R_1(S_t, P_t) \} &= \Pr \{ \tilde{Z}_t > Z_t \} = \int_{Z_t}^{\infty} f(\tilde{Z}_t) d\tilde{Z}_t \\ \Pr \{ \alpha_i S_t + R_i(S_t, P_t) = \alpha_2 S_t + R_2(S_t, P_t) \} &= \Pr \{ \tilde{Z}_t < Z_t \} = \int_0^{Z_t} f(\tilde{Z}_t) d\tilde{Z}_t \end{aligned} \quad (7)$$

$$\text{with } \int_0^{\infty} f(\tilde{Z}_t) d\tilde{Z}_t = 1$$

The first line in equation (7) shows the probability of an outbreak *not* occurring in period t , which assumes that the threshold \tilde{Z}_t lies within the interval Z_t to ∞ ; that is, it lies above the current value of the environmental influence, Z_t . The second line indicates the probability of an outbreak occurring and assumes that the threshold lies within the interval 0 to Z_t and, therefore, will be encountered in period t . The

probability mass function in equation (7) also implies that recruitment is determined jointly by the current level of the environmental influence, Z_t , and the random variable, \tilde{Z}_t . Denoting the first expression in (7) as (Z_t) and the second as (\tilde{Z}_t) , it follows that $(Z_t) = 1 - (\tilde{Z}_t)$, $f(\tilde{Z}_t) > 0$ and $-f(\tilde{Z}_t) < 0$.

Under this ecological situation, the management problem involves selecting optimal escapement at the beginning of each time period in response to ambient environmental conditions, here assumed to be fixed at $P_t = \bar{P}$, and the size of the fish stock. However, the planner does not know the marine system's behaviour for the remainder of the period. Solving this problem under the assumption of optimal management involves maximization of the discounted sum of expected annual utility (measured as industry profits) in equation (4), subject to the population dynamics for the fish stock in equation (6) and the condition, $0 \leq S_t \leq X_t$.

Since utility is assumed to be separable in X and S , Conrad and Clark (1987, p. 80) show how annual utility in equation (4) can be rewritten solely as the function $V(S)$, depending on S . This gives the following new expression replacing expected annual utility:

$$\{V(S_t)\} = \left[A [\tilde{Z}_t S_t + R_i(S_t, \bar{P})] - B(S_t) \right], i = 1 \text{ or } 2, \tag{8}$$

where $A [\tilde{Z}_t S + R_i(S, P)]$ and $B(S)$ are the separable arguments of the profit expression in equation (4), with the former a function of a random variable. Since the variable X was expressed in the original equation of motion [see equation (6)] in terms of period $t + 1$, the first term in equation (8) must be discounted back one period. This problem can be written now as the following maximization problem, with S as the choice variable:

$$\begin{aligned} \max J &= \sum_{t=0}^{\infty} \beta^t \{V(S_t)\} \\ \text{s.t. } 0 &\leq S_{t+1} \leq \tilde{Z}_t S_t + R_i(S_t, \bar{P}), i = 1 \text{ or } 2, \end{aligned} \tag{9}$$

where β is the discount term, defined as $1/(1 + r)$, with r denoting the appropriate social discount rate, and E_t is the expectations operator. The solution to equation (9) is found by setting $\partial \{V(S)\} / \partial S = 0$, which yields an implicit statement that is satisfied by the desired steady-state escapement value, S^* . Conrad and Clark (1987) further prove this solution is characterized by a most rapid approach path (MRAP) if the underlying utility function is separable, as assumed here, and if the function $V(S)$ is quasi-concave, as we later verify for the empirical case study. As a result, the solution to equation (9) is singular and governed by a conventional decision rule:

$$S_{t+1} = \begin{cases} S^* & \text{if } \tilde{Z}_t S_t + R_i(S_t, P) \leq S^* \\ \tilde{Z}_t S_t + R_i(S_t, P) & \text{if } \tilde{Z}_t S_t + R_i(S_t, P) > S^* \end{cases} \tag{10}$$

Since the stock transition relationship is a random variable, a number of additional conditions must hold in order for a constant escapement solution to equation (9) to be optimal in the stochastic case. For example, the inequality constraint in equation (9) requires escapement in any period to be less than or equal to the current exploitable stock; *i.e.*, $h_t \geq 0$, regardless of the structural form taken by the recruitment function. This condition is one of several derived by Reed (1979, p. 357), and later reworked by Clark (1990, pp. 346–49), that are required for a constant escapement solution to be optimal in stochastic models of this type (details are provided in an appendix).

Determining the stability of the system at the steady state; *i.e.*, under constant escapement, is relatively straightforward but important for analysing the comparative dynamics. The problem is simplified by the system's dependence on a single variable, S , for its solution and the existence of an 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. Clark (1976) showed that stability is governed in this case by the condition, $-1 - \lambda_i < R_{S^*} < 1 - \lambda_i$, where λ_i is the survival rate for adult fish in state of the world i . Furthermore, if a constant escapement policy is optimal, then the stock can always recover within a single period from random environmental events of known magnitude. Otherwise, a constant escapement policy would not be optimal.

Valuing the Benefits of Nutrient Abatement in the Stochastic Model

It should be clear from the preceding analysis that optimal management of the fishery will be linked to policies concerned with nutrient abatement. In this section, we explore this linkage and assess whether nutrient abatement is likely to be beneficial from the perspective of the small pelagic fishery in question. To value the potential welfare effects of a change in nutrient levels, we continue to assume the level of nutrients is fixed; *i.e.*, $P_t = \bar{P}$, and examine the comparative dynamic effects of a marginal but permanent change in \bar{P} at the steady state, occurring at $t = 0$. Since the optimal escapement depends upon the exogenous level of nutrients, the expected value function can be expressed as the following function of nutrients alone:

$$J^*(\bar{P}) = \sum_{t=0}^{\infty} \delta^t \{ V[S^*(\bar{P})] \}. \tag{11}$$

Applying the dynamic envelope theorem to equation (11) yields the desired statement for the welfare effect of a marginal change in nutrients (Kamien and Schwartz 1991, p. 171):

$$\frac{J^*(\bar{P})}{\bar{P}} = \sum_{t=0}^{\infty} \delta^{t+1} \{ \lambda_A R_P \}, \tag{12}$$

subject to the conditions governing a stochastic steady state solution (see Appendix) and local stability at the steady state.³ Expression (12) indicates that the welfare effect stemming from a marginal change in nutrients is determined by the discounted sum of the expected marginal profit on the last unit of catch times the additional catch 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 an additional period; *i.e.*, $t + 1$.

³ It also seems reasonable to assume we have an interior solution, as determined by the conditions outlined in the Appendix.

If T serves as the environmental threshold, \tilde{Z}_t , then we have $Z_t > T_t$ and $\tilde{Z}_t > \tilde{T}_t$, where \tilde{T}_t is the time-varying sea temperature threshold that triggers an outbreak of the invader. Taking the expectation on the right-hand side of equation (12) in this case:

$$\{ \Delta R_P \} = (T_t) \Delta R_{2P} + (T_t) \Delta R_{1P}. \tag{13}$$

Expression (13) indicates that the marginal effect of a change in nutrients is the weighted change in profits associated with the impact of abatement on recruitment in the fishery. As we consider two alternative states of the world (with and without an outbreak event), the weights comprise the probabilities governing each possible state. Since $R_S > 0$, and we are concerned with the region where $\Delta_j > 0$, expression (13) is positive. In other words, nutrient abatement leads to a reduction in the profitability of the small pelagic fishery regardless of which state of the world manifests in any year t .

Now we consider our second case, where the threshold that triggers an outbreak of the invader is related to the level of nutrients in the marine system. If P is associated with the environmental threshold, \tilde{Z}_t , then we now have $Z_t > \bar{P}$ and $\tilde{Z}_t > \tilde{P}_t$, where \tilde{P}_t is the time-varying nutrient threshold that triggers an outbreak of the invader. Under these assumptions, taking the expectation on the right-hand side of equation (11) yields:

$$\begin{aligned} \{ \Delta R_P \} = & (\bar{P}) \Delta R_{2P} + (\bar{P}) \Delta R_{1P} \\ & + f(\tilde{P}_t) \left[\Delta \left\{ {}_2S^*(\bar{P}) + R_2[S^*(\bar{P}), \bar{P}] \right\} - \Delta \left\{ {}_1S^*(\bar{P}) + R_1[S^*(\bar{P}), \bar{P}] \right\} \right]. \end{aligned} \tag{14}$$

While complex in appearance, equation (14) 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 previous case where T served as the threshold variable. As in the previous case, this effect will be negative under nutrient abatement.

The remaining terms on the right-hand side of equation (14) constitute the indirect stochastic effect arising from a marginal change in nutrients. It comprises the difference in profits under outbreak versus non-outbreak conditions, multiplied by the probability density function, $f(\tilde{P}_t)$, which measures the increased or decreased risk of encountering the threshold nutrient level, \tilde{P}_t , when the level of nutrients changes slightly. Thus, the stochastic formulation incorporates the *ex ante* uncertainty about the position of the random threshold, \tilde{P}_t , and allows for a change in the likelihood of encountering it as nutrient levels are altered. This indirect stochastic effect is positive in response to marginal abatement of nutrients, since $R_1 > R_2$ for any permissible value of S^* , and we continue to restrict the analysis to the region where $\Delta_j > 0$.

If outbreaks of the invading species are related to a temperature threshold, rather than a nutrient threshold, 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 catches. In contrast, if the risk of recurring outbreaks is linked to nutrient conditions, then the result is the mixed blessing effect referred to earlier. Lower nutrient levels still decrease equilibrium catches as before but now reduce the risk of an outbreak occurring, providing an offsetting influence and a potential rationale for abatement. However, it is not possible to determine which effect will

dominate without knowledge of the model parameters and the probability distributions governing the random threshold, \tilde{P}_t . In the next section, we apply our model to the Turkish Black Sea anchovy fishery to analyse possible environmental and fisheries management policies in the presence of the invading comb-jelly, *Mnemiopsis leidyi*, and nutrient enrichment.

Specifying the Stochastic Model of Black Sea Anchovy: Functional Forms and Parameters

In our empirical application, we consider a fluctuating regime of undisturbed conditions interspersed with periodic *Mnemiopsis* outbreaks (post 1986). We derive results for the stochastic model and test for the optimality of a constant escapement policy under no nutrient abatement and assume an independent policy of nutrient abatement. Using historical data on recruitment of anchovy, we also derive steady-state solutions for deterministic versions to our model, as reference points for the stochastic analysis. This approach allows us to examine various assumptions about parameters, to assess the conditions under which a constant escapement policy might be valid, and to determine how such a policy might differ from a deterministic stance.

The two general functions in our model are the cost and recruitment functions. To specify the former, we began with a number of specifications for the catch function, selecting one of the form, $h = X(1 - e^{-qE})$, where E is fishing effort measured as the number of vessels active in the fishery, and q is the catchability coefficient (Knowler, Barbier, and Strand 2002). 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) yields:

$$\pi_t = ph_t - \frac{c}{q} [\ln(X_t) - \ln(X_t - h_t)]. \quad (15)$$

Eliminating h using the identity $h = X - S$ from equation (2) and using equation (4), we can rewrite expression (15) so that it comprises the following two statements:

$$\pi_A(X) = pX_t - \frac{c}{q} \ln X_t \quad (16)$$

$$\pi_B(S) = pS_t - \frac{c}{q} \ln S_t.$$

Based on analysis contained in Knowler, Barbier, and Strand (2002), anchovy recruitment was specified using the Ricker model, with nutrients serving as an environmental influence (Ricker 1975):

$$R_i(S_t, P_t) = P_t S_t e^{-iS_t}, \quad (17)$$

where $i = 1$ or 2 and β_1 , β_2 are parameters. The influence of nutrients is captured using phosphates as a proxy measure. The choice of phosphates is somewhat at odds with the literature on this topic, which generally argues that nitrates are the limiting nutrient in coastal marine systems (Ryther and Dunstan 1971). Nonetheless,

Mee (1992, p. 281) points out that for the Black Sea “scientists have been debating whether nitrogen or phosphorous are the critical limiting nutrients in the sea for half a century.” Although both nutrient measures were included in initial estimations of the anchovy recruitment relationship, only the coefficient on phosphates was significant and, therefore, nitrates were subsequently dropped from the equation. As well as adding phosphates as an argument, the standard Ricker curve was modified to allow for two structural variants, one without an outbreak of *Mnemiopsis* ($i = 1$) and the other with this influence ($i = 2$), as described earlier.

Our initial set of parameters, $p, c, q, \beta_1, \beta_2, \beta_3, \beta_4$, and δ are taken from Knowler, Barbier, and Strand (2002), and are summarized in table 1. However, we included one modification to our parameter estimates to account for more recent information. The original estimation of the anchovy recruitment function was based on data describing the first outbreak of *Mnemiopsis* in the late 1980s. Several developments cause us to speculate that the impact of this outbreak on anchovy survival and recruitment might be greater than the impact of future outbreaks. First, the recent introduction of a predator of *Mnemiopsis*, *Beroe ovata*, into the Black Sea suggests that subsequent outbreaks may be reduced in magnitude for a given set of environmental conditions, since the natural mortality rate of *Mnemiopsis* has increased (Shiganova *et al.* 2001). Second, there is further evidence that anchovy may be adapting to *Mnemiopsis* by migrating to more protected areas to spawn, thereby increasing the survival rate of immature anchovy for a given population of *Mnemiopsis* (GESAMP 1997). Finally, even in non-outbreak years the population of *Mnemiopsis* does not fall to zero, so that some predation would exist (Shiganova 1998). In contrast, our recruitment parameters for the no outbreak situation were estimated using data for the years prior to the invasion by *Mnemiopsis* and, therefore, do not account for this continued presence of the invader. Given these considerations, we consider an alternative and perhaps more realistic case where the impact of *Mnemiopsis* on the anchovy stock is only 50% of that implied by the parameters taken from Knowler, Barbier and Strand (2002).

The stochastic element in our model is the link between environmental conditions (*e.g.*, sea temperature or nutrient levels) and fluctuations in the population of the invader, *Mnemiopsis*. While the true relationship is likely to be complex and involve several factors, we capture this uncertainty in the form of the random

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

Parameters	No <i>Mnemiopsis</i> Outbreak	<i>Mnemiopsis</i> Outbreak (Full Impact)	<i>Mnemiopsis</i> Outbreak (50% Impact)
Anchovy price, p (US\$/t)	90	90	90
Fishing effort cost, c (US\$'000/year)	256	256	256
Catchability, q	0.0032	0.0032	0.0032
Anchovy survival rate, β_i	0.792	0.75	0.771
Anchovy recruitment parameter, β_i	0.000614	0.001624	0.001119
Coefficient on \bar{P} ,	0.117	0.117	0.117
Phosphates, \bar{P} (μM)	5.5	5.5	5.5
Sea temperature ($^{\circ}C$)	3.2	3.2	3.2
Social discount rate,	5	5	5

Source: Knowler, Barbier, and Strand (2002).

threshold, \tilde{Z}_t . Since several researchers have assumed an exponential distribution to describe a stochastic disturbance influencing a bioeconomic fisheries model (Reed 1988; Spulber 1982), we use this approximation to the true but unknown distribution of \tilde{Z}_t . If Z_t is the current level of the environmental influence that triggers outbreaks, then the p.d.f. of the random threshold, $f(\tilde{Z}_t)$, is $e^{-Z(t)}$ and the c.d.f. is:

$$f(\tilde{Z}_t) = \begin{cases} 1 - e^{-Z_t} & \text{for } Z_t \geq 0 \\ 0 & \text{elsewhere,} \end{cases} \quad (18)$$

where \tilde{Z}_t is the inverse of the mean value of the random variable, \tilde{Z}_t .

We selected a range of values for Z_t and \tilde{Z}_t based on historical data for the two environmental variables, T and P . In the former case, Shiganova (1998) indicated that minimum sea temperatures in the Black Sea ranged from about 2°C to 4°C during the critical months of March/April (1988 to 1997), with an average of 3.2°C. During the most significant outbreak years (1989 and 1995), the minimum temperature exceeded 3.5°C, suggesting a possible average threshold value in this range.⁴ However, because of the uncertainties inherent in identifying mean threshold values, we considered values for the mean of the random threshold of 3.0°C, 3.5°C, and 4.0°C. Fixing the current T at its average for the period 1988 to 1997, we have $Z_t = \tilde{Z}_t - \bar{T} = 3.2^\circ\text{C}$. Additionally, we took the ambient level of nutrients (\bar{P}) to be fixed at its historical average value (see below). These assumptions for \bar{T} and \bar{P} , together with our assumptions about \tilde{T}_t , yielded probabilities for an outbreak of *Mnemiopsis* in any year t of 0.650, 0.599, and 0.551, respectively.

For the case where nutrients serve as the triggering mechanism for outbreaks of *Mnemiopsis*, we derive \tilde{P}_t 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, averaging 5.5 μM during the study period. For the purposes of our analysis, we considered values for the mean of \tilde{P}_t of 3 μM , 6 μM , and 9 μM . Taking an initial ambient phosphate level of 5.5 μM , these estimates for \tilde{P}_t yield probabilities for an outbreak of 0.840, 0.600, and 0.457, respectively.

Results for the Empirical Model of Black Sea Anchovy

We first derive results from solving our stochastic model under an assumption of a fixed level of phosphates equal to the historical average ($\bar{P} = 5.5 \mu\text{M}$) and assess the optimality of a constant escapement policy. We consider two cases: one where the impact of *Mnemiopsis* on anchovy is based on modelling of historic data for the initial outbreak in the late 1980s and another incorporating a reduced impact (at 50%) that relies on mounting evidence that future outbreaks may be much reduced (Bilio and Niermann 2004; Shiganova *et al.* 2001). Although the marine system fluctuates between two possible states of the world in either impact situation, the stochastic model solves for a single optimal escapement value across both potential states. This occurs because the planner does not know whether an outbreak will occur in a given year until after setting escapement. We then solve the model with a nutrient abatement policy in place and consider the impact on our optimal policies.

⁴ Shiganova *et al.* (2001, P. 433) state that, "*M. leidyi*, as most ctenophores, is annual and does not survive Black Sea winters if water temperatures decrease below 4°C."

Finally, we compare the results from our stochastic model and a deterministic version of the model, on the assumption that fisheries managers may rely (mistakenly) on such data to determine desirable targets for escapement in the future.

If the impact of *Mnemiopsis* in future outbreaks is similar to its initial outbreak in the late 1980s, then a constant escapement policy was not optimal for Black Sea anchovy under a variety of modelling assumptions (table 2). This result is not surprising, given the very severe impact of the invader on the recruitment of anchovy and the relatively high probability of invasion (0.457 to 0.840) under the range of mean threshold values we have modelled (subheadings *A* and *C* in table 2). Constant escapement policies are known to be suboptimal under such conditions, and a more conservative approach would be warranted (Walters 1981, Reed 1979). The non-optimality of a constant escapement policy applied regardless of whether sea temperatures or phosphates served as the triggering mechanism for outbreaks of *Mnemiopsis*.

If the impact of *Mnemiopsis* on the anchovy stock is less severe (50%), the results were quite different, as a constant escapement policy was now optimal (subheadings *B* and *D* in table 2). Optimal escapements ranged from 1.153 to 1.325 million t, which compared with estimates of historical escapements of 0.138 to 0.708 million t (Prodanov *et al.* 1995). Escapement and other solution values varied hardly at all, when comparing sea temperature to phosphates as the mechanism triggering an outbreak. In contrast, the expected annual value of profits from a constant escapement policy differed under each assumption (sea temperature versus phosphates), but this largely reflected differences in our selection of mean thresholds. Mean thresholds have a wider range in the case of phosphates, since measured levels of phosphates are more volatile than sea temperatures. Even though the impact of *Mnemiopsis* on the anchovy stock was assumed to be diminished when phosphates trigger an outbreak, the gap between profitability with and without an outbreak was striking: in years when *Mnemiopsis* did not experience an outbreak, profits were as high as \$16.724 million/year, dropping to as low as \$1.978 million/year under outbreak conditions (subheading *D* in table 2). Moreover, as the mean of \bar{P}_t rose from 3 to 9 μM , the optimal escapement level and expected profits also increased, since the likelihood of encountering \bar{P}_t in any year was now reduced and this was expressed as a heavier weighting of the non-outbreak outcome.

Expected annual utility must be quasi-concave to ensure that our calculated optimal values of S^* are unique global maximii (Conrad and Clark 1987). Assuming a 50% impact of *Mnemiopsis*, quasi-concavity was verified by plotting and checking the function $\{V[S^*(\bar{P})]\}$. Furthermore, a check of the stability condition discussed earlier verified that the steady-state solution was stable for the anchovy system under each threshold mechanism (sea temperature and phosphates) and each variant of the recruitment function (outbreak and no outbreak).

The optimal management results reported above assumed an average historical level of phosphates (see table 2). As argued earlier, policies to reduce the level of nutrients in the Black Sea have been agreed upon and it is our contention that management of the anchovy-*Mnemiopsis* system must be considered in light of this development. Our earlier analysis suggested that nutrient abatement would have undesirable consequences for the Black Sea's small pelagic fisheries if sea temperature was the mechanism that triggers outbreaks of *Mnemiopsis*. In contrast, we would hypothesize that the opposite finding could result if nutrients served as the triggering mechanism, due to the presence of the mixed blessing effect. Calculations were carried out to examine the impact of nutrient abatement, based on 20% and 50% abatement of phosphates (tables 3 and 4).

The analysis confirmed that nutrient abatement would lead to a substantial loss in economic rents if sea temperature was implicated in triggering outbreaks of

Table 2
Results for Stochastic Model for Varying Mean Threshold Values,
Assuming Full and 50% Impact of *Mnemiopsis* ($\mu = 5.5 \mu\text{M}$; US\$1989/90)

Mean Threshold ($^{\circ}\text{C}$ or μM)	System State	Probability	Escape, (S^*) ('000 mt)	Recruit.t (R^*) ('000 mt)	Stock (X^*) ('000 mt)	Catch (h^*) ('000 mt)	Effort (E^*) (vessels)	Profits (π^*) (\$'000/yr)	Expected Profits (\$'000/yr)
<i>A. Sea temperature as threshold ($T=3.2^{\circ}\text{C}$, $\mu = 5.5 \mu\text{M}$) – Full impact of <i>Mnemiopsis</i></i>									
4	No <i>Mnem</i>	0.449	1,175.066	697.181	1,627.833	452.767	101.852	14,675.005	-
	<i>Mnem</i>	0.551	1,175.066	212.773	1,094.073	-	-	-	-
3.5	No <i>Mnem</i>	0.401	1,143.593	691.747	1,597.472	453.879	104.452	14,109.334	-
	<i>Mnem</i>	0.599	1,143.593	217.934	1,075.628	-	-	-	-
3	No <i>Mnem</i>	0.344	1,107.798	684.985	1,562.362	454.563	107.445	13,404.773	-
	<i>Mnem</i>	0.656	1,107.798	223.748	1,054.597	-	-	-	-
<i>B. Sea temperature as threshold ($T=3.2^{\circ}\text{C}$, $\mu = 5.5 \mu\text{M}$) – 50% impact of <i>Mnemiopsis</i></i>									
4	No <i>Mnem</i>	0.449	1,281.521	712.233	1,727.197	445.676	93.266	16,234.677	8,581.633
	<i>Mnem</i>	0.551	1,281.521	372.872	1,360.925	79.404	18.787	2,337.007	-
3.5	No <i>Mnem</i>	0.401	1,259.260	709.492	1,706.826	447.566	95.035	15,952.039	7,887.815
	<i>Mnem</i>	0.599	1,259.260	375.637	1,346.526	87.266	20.939	2,493.658	-
3	No <i>Mnem</i>	0.344	1,233.644	706.078	1,683.124	449.48	97.087	15,598.863	7,106.813
	<i>Mnem</i>	0.656	1,233.644	378.697	1,329.836	96.192	23.464	2,650.629	-
<i>C. Phosphates (nutrients) as threshold ($\mu = 5.5 \mu\text{M}$) – Full impact of <i>Mnemiopsis</i></i>									
3	No <i>Mnem</i>	0.160	1,000.078	660.661	1,452.723	452.645	116.676	10,869.102	-
	<i>Mnem</i>	0.840	1,000.078	240.606	990.665	-	-	-	-
6	No <i>Mnem</i>	0.400	1,142.982	691.636	1,596.878	453.896	104.503	14,097.857	-
	<i>Mnem</i>	0.600	1,142.982	218.033	1,075.270	-	-	-	-
9	No <i>Mnem</i>	0.543	1,237.299	706.582	1,686.523	449.224	96.793	15,651.115	-
	<i>Mnem</i>	0.457	1,237.299	202.506	1,130.480	-	-	-	-
<i>D. Phosphates (nutrients) as threshold ($\mu = 5.5 \mu\text{M}$) – 50% impact of <i>Mnemiopsis</i></i>									
3	No <i>Mnem</i>	0.160	1,153.650	693.534	1,607.225	453.575	103.618	14,295.491	4,779.467
	<i>Mnem</i>	0.840	1,153.650	387.303	1,276.767	123.117	31.688	2,968.512	-
6	No <i>Mnem</i>	0.400	1,258.825	709.437	1,706.426	447.601	95.069	15,946.301	7,874.417
	<i>Mnem</i>	0.600	1,258.825	375.690	1,346.244	87.419	20.981	2,496.531	-
9	No <i>Mnem</i>	0.543	1,325.068	717.005	1,766.459	441.391	89.848	16,724.132	9,981.820
	<i>Mnem</i>	0.457	1,325.068	367.206	1,388.834	63.765	14.688	1,978.862	-

Note: Some figures may not add due to rounding.

Table 3
 Results for Stochastic Model for Varying Mean Threshold Values, Assuming Full and 50% Impact of *Mnemiopsis*, under a 20% Nutrient Abatement Policy ($\mu = 4.4 \mu\text{M}$; US\$1989/90)

Mean Threshold (°C or μM)	System State	Probability	Escape. (S^*) ('000 mt)	Recruit. (R^*) ('000 mt)	Stock (X^*) ('000 mt)	Catch (H^*) ('000 mt)	Effort (E^*) (vessels)	Profits (π^*) (\$'000/yr)	Expected Profits (\$'000/yr)
<i>A. Sea temperature as threshold ($T=3.2^\circ\text{C}$, $=4.4 \mu\text{M}$) – Full impact of <i>Mnemiopsis</i></i>									
4	No <i>Mnem</i>	0.449	1,166.144	677.760	1,601.346	435.202	99.107	13,796.817	-
	<i>Mnem</i>	0.551	1,166.144	208.719	1,083.327	-	-	-	-
3.5	No <i>Mnem</i>	0.401	1,135.011	672.397	1,571.325	436.314	101.649	13,246.126	-
	<i>Mnem</i>	0.599	1,135.011	213.682	1,064.94	-	-	-	-
3	No <i>Mnem</i>	0.344	1,099.647	665.747	1,536.667	437.020	104.57	12,561.672	-
	<i>Mnem</i>	0.656	1,099.647	219.262	1,043.997	-	-	-	-
<i>B. Sea temperature as threshold ($T=3.2^\circ\text{C}$, $=4.4 \mu\text{M}$) – 50% impact of <i>Mnemiopsis</i></i>									
4	No <i>Mnem</i>	0.449	1,273.044	692.886	1,701.136	428.092	90.589	15,337.467	8,049.264
	<i>Mnem</i>	0.551	1,273.044	364.300	1,345.817	72.773	17.372	2,102.337	-
3.5	No <i>Mnem</i>	0.401	1,251.012	690.168	1,680.969	429.957	92.318	15,062.724	7,388.069
	<i>Mnem</i>	0.599	1,251.012	366.931	1,331.461	80.449	19.476	2,254.494	-
3	No <i>Mnem</i>	0.344	1,225.676	686.791	1,657.527	431.851	94.323	14,719.845	6,644.369
	<i>Mnem</i>	0.656	1,225.676	369.838	1,314.834	89.158	21.943	2,406.782	-
<i>C. Phosphates (nutrients) as threshold ($\mu = 4.4 \mu\text{M}$) – Full impact of <i>Mnemiopsis</i></i>									
3	No <i>Mnem</i>	0.231	1,032.542	651.414	1,469.188	436.646	110.214	11,083.237	-
	<i>Mnem</i>	0.769	1,032.542	229.586	1,003.993	-	-	-	-
6	No <i>Mnem</i>	0.480	1,186.368	681.005	1,620.608	434.240	97.470	14,129.224	-
	<i>Mnem</i>	0.520	1,186.368	205.478	1,095.254	-	-	-	-
9	No <i>Mnem</i>	0.613	1,275.431	693.168	1,703.309	427.878	90.403	15,365.944	-
	<i>Mnem</i>	0.387	1,275.431	191.156	1,147.729	-	-	-	-
<i>D. Phosphates (nutrients) as threshold ($\mu = 4.4 \mu\text{M}$) – 50% impact of <i>Mnemiopsis</i></i>									
3	No <i>Mnem</i>	0.480	1,287.251	694.533	1,714.036	426.785	89.482	15,503.293	5,245.259
	<i>Mnem</i>	0.520	1,287.251	362.556	1,355.026	67.775	16.035	1,994.821	-
6	No <i>Mnem</i>	0.613	1,349.271	700.795	1,769.417	420.146	84.714	16,126.305	8,483.012
	<i>Mnem</i>	0.387	1,349.271	354.544	1,394.832	45.561	10.378	1,443.734	-
9	No <i>Mnem</i>	0.400	1,232.695	650.955	1,627.249	394.555	86.778	13,294.837	10,448.664
	<i>Mnem</i>	0.600	1,232.695	349.230	1,299.707	67.012	16.543	1,796.209	-

Note: Some figures may not add due to rounding.

Table 4
 Results for Stochastic Model for Varying Mean Threshold Values, Assuming Full and 50% Impact of *Mnemiopsis*, Under a 50% Nutrient Abatement Policy (= 2.75 μM ; US\$1989/90)

Mean Threshold (°C or μM)	System State	Probability	Escape. (S*) ('000 mt)	Recruit.t (R*) ('000 mt)	Stock (X*) ('000 mt)	Catch (h*) ('000 mt)	Effort (E*) (vessels)	Profits (π^*) (\$'000/yr)	Expected Profits (\$'000/yr)
<i>A. Sea temperature as threshold (T=3.2°C, = 2.75 μM) – Full impact of Mnemiopsis</i>									
4	No Mnem	0.449	1,146.994	638.424	1,546.843	399.849	93.460	12,060.707	-
	Mnem	0.551	1,146.994	200.445	1,060.690	-	-	-	-
3.5	No Mnem	0.401	1,116.597	633.214	1,517.558	400.961	95.880	11,541.159	-
	Mnem	0.599	1,116.597	205.007	1,042.455	-	-	-	-
3	No Mnem	0.344	1,082.155	626.798	1,483.864	401.709	98.655	10,898.218	-
	Mnem	0.656	1,082.155	210.113	1,021.730	-	-	-	-
<i>B. Sea temperature as threshold (T=3.2°C, = 2.75 μM) – 50% impact of Mnemiopsis</i>									
4	No Mnem	0.449	1,254.654	653.678	1,647.364	392.710	85.099	13,558.574	7,001.180
	Mnem	0.551	1,254.654	346.892	1,314.231	59.577	14.497	1,650.568	-
3.5	No Mnem	0.401	1,233.115	651.009	1,627.636	394.521	86.745	13,300.076	6,405.423
	Mnem	0.599	1,233.115	349.254	1,299.990	66.871	16.503	1,793.591	-
3	No Mnem	0.344	1,208.380	647.713	1,604.750	396.370	88.652	12,978.316	5,736.519
	Mnem	0.656	1,208.380	351.854	1,283.515	75.135	18.851	1,936.402	-
<i>C. Phosphates (nutrients) as threshold (= 2.75 μM) – Full impact of Mnemiopsis</i>									
3	No Mnem	0.400	1,116.008	633.108	1,516.987	400.979	95.927	11,530.65	-
	Mnem	0.600	1,116.008	205.095	1,042.101	-	-	-	-
6	No Mnem	0.632	1,267.078	655.134	1,658.660	391.582	84.155	13,698.651	-
	Mnem	0.368	1,267.078	182.198	1,132.506	-	-	-	-
9	No Mnem	0.737	1,337.474	662.279	1,721.558	384.084	78.890	14,371.809	-
	Mnem	0.263	1,337.474	171.544	1,174.649	-	-	-	-
<i>D. Phosphates (nutrients) as threshold (= 2.75 μM) – 50% impact of Mnemiopsis</i>									
3	No Mnem	0.400	1,232.695	650.955	1,627.249	394.555	86.778	13,294.837	6,393.931
	Mnem	0.600	1,232.695	349.230	1,299.707	67.012	16.543	1,796.209	-
6	No Mnem	0.632	1,338.239	662.346	1,722.232	383.992	78.833	14,378.026	9,438.246
	Mnem	0.368	1,338.239	336.965	1,368.747	30.508	7.044	942.420	-
9	No Mnem	0.737	1,387.050	666.235	1,764.779	377.729	75.264	14,727.908	10,962.295
	Mnem	0.263	1,387.050	330.690	1,400.106	13.056	2.928	425.541	-

Note: Some figures may not add due to rounding.

Mnemiopsis. For the 20% abatement policy, the loss in annual profits ranged from 6.2% to 6.5%, rising as the mean threshold temperature declined from 4.0 to 3.0°C. Implementation of a 50% abatement policy led to annual losses of as much as 19.3% of pre-abatement profits. Abatement also resulted in lower optimal escapement levels, although the differences were small.

Different results emerged when phosphates trigger outbreaks, and we again considered the reduced impact (50%) scenario. We have argued already that the relationship between nutrients and the anchovy fishery is complex, due to the mixed blessing effect discussed earlier. In our application, the indirect stochastic effect related to the triggering of outbreaks dominated the direct deterministic influence of nutrients on anchovy, so that abatement led to higher optimal escapement and expected profits in the fishery. For example, under the 50% phosphate abatement policy when the mean $\bar{P}_t = 6 \mu M$, constant escapement rose modestly to 1.34 million mt from 1.26 million mt, but the overall effect of abatement was to raise expected profits from US\$7.87 million to US\$9.44 million per year, an increase of 20%. This result was explained by the much-reduced probability of triggering an outbreak when phosphate levels were lower; *i.e.*, 0.600 with $\bar{P} = 5.5 \mu M$ versus 0.368 with $\bar{P} = 2.75 \mu M$, which had more impact on our solution than the reduced recruitment due to a lower level of nutrients and, therefore, decreased food supplies.

A final analysis was carried out to compare our stochastic results with deterministic versions of our model, based on average historical values for anchovy recruitment (Prodanov *et al.* 1995). Two deterministic cases were considered, the first based on average annual recruitment of anchovy over the period 1968 to 1993 (337,300 mt/year) and a second based on the period subsequent to the establishment of *Mnemiopsis* in the Black Sea (178,900 mt/year). We then solved our model, setting recruitment equal to these average historical values and estimated expected profits under alternative scenarios for the sea temperature and phosphates as triggering mechanisms, and for varying phosphate levels (base case plus 20% and 50% abatement). Only a reduced impact of *Mnemiopsis* (at 50%) was considered (table 5).⁵

The deterministic analyses produced estimates of optimal escapement of 1.10 million mt and 817,000 mt for the higher and lower average historical values for anchovy recruitment, respectively. These solutions were unchanged across all scenarios (table 5). In general, these escapement solutions are lower than those of the stochastic analysis, dramatically so in the case using lower average historical values for anchovy recruitment.⁶ This latter result is not surprising, since a manager considering only the historical recruitment values during the initial outbreak of *Mnemiopsis* would be excessively conservative in setting escapement in future periods, when there was the possibility of no outbreak. Even if an outbreak should occur, we have argued it is likely to be of less impact than the initial outbreak, so that escapement again would likely be set too low.

In comparing expected profits in the anchovy fishery, the deterministic policy led to significantly lower profits in all cases. However, based on recruitment data for the period after the establishment of *Mnemiopsis*, these were substantially lower under the more conservative deterministic policy. Clearly, a manager setting escapement on the basis of historical levels of anchovy recruitment, and ignoring the potential for outbreak versus non-outbreak conditions, would forego significant eco-

⁵ As with the stochastic modelling, assuming the full impact of *Mnemiopsis* on anchovy resulted in negative catches and, consequently, a constant escapement policy was inadmissible.

⁶ Our stochastic-deterministic analysis cannot be directly compared with results reported in other empirical stochastic bioeconomic studies where the deterministic version is the mean or average recruitment function, as our assumptions making use of historical data are somewhat different (see Conrad 1992; Reed 1979).

Table 5
Results for Deterministic Reference Model for Varying Mean Threshold Values and Ambient Phosphate Levels — Assuming 50% Impact of *Mnemiopsis* (US\$1989/90)

Mean Threshold (°C or μM)	Based on Data for 1968–93 Average R = 337.3 t/yr		Based on Data for 1987–93 Average R = 178.9 t/yr	
	Escapement (S^*) (‘000 mt)	Expected Profits (\$‘000/yr)	Escapement (S^*) (‘000 mt)	Expected Profits (\$‘000/yr)
<i>A. Sea temperature as threshold ($T=3.2^\circ C$, $\bar{P}=5.5 \mu M$)</i>				
4	1096.035	7575.872	817.446	2595.480
3.5	1096.035	7083.908	817.446	2384.287
3	1096.035	6509.593	817.446	2137.741
<i>B. Sea temperature as threshold ($T=3.2^\circ C$, $\bar{P}=4.4 \mu M$)</i>				
4	1096.035	7134.876	817.446	2348.129
3.5	1096.035	6663.135	817.446	2150.362
3	1096.035	6112.429	817.446	1919.491
<i>C. Sea temperature as threshold ($T=3.2^\circ C$, $\bar{P}=2.75 \mu M$)</i>				
4	1096.035	6266.620	817.446	1879.225
3.5	1096.035	5835.022	817.446	1707.938
3	1096.035	5331.178	817.446	1507.979
<i>D. Phosphates (nutrients) as threshold ($\bar{P}=5.5 \mu M$)</i>				
3	1096.035	4641.400	817.446	1335.751
6	1096.035	7074.245	817.446	2380.138
9	1096.035	8522.961	817.446	3002.052
<i>E. Phosphates (nutrients) as threshold ($\bar{P}=4.4 \mu M$)</i>				
3	1096.035	5009.436	817.446	1457.086
6	1096.035	7436.009	817.446	2474.372
9	1096.035	8728.973	817.446	3016.419
<i>F. Phosphates (nutrients) as threshold ($\bar{P}=2.75 \mu M$)</i>				
3	1096.035	5826.544	817.446	1704.574
6	1096.035	7894.316	817.446	2525.204
9	1096.035	8822.662	817.446	2893.634

conomic rents. In the more extreme case, using average historical values for recruitment from the post-*Mnemiopsis* period (1987 to 1993), these losses amounted to 70% of the potential economic rents available from the fishery.

Policy Implications and Conclusions

There is now increasing evidence that nutrient enrichment problems affecting the world’s marine areas are not amenable to the simple analytics used in standard pollution problems. For example, it might be assumed that reducing phosphates in the Black Sea would improve conditions for fish stocks, but we have shown this is unlikely for many small pelagic species. Instead, nutrient enrichment effects are more complex, such as when a biological invader that preys on or competes with the small

pelagic species is sensitive to a nutrient threshold. As a result, nutrient abatement may lead to benefits for the small pelagic fishery but in an indirect way. This ecological complexity needs to be incorporated into modelling that is used to develop policy. Using a stochastic bioeconomic modelling approach, we examined the consequences for developing fisheries management and optimal nutrient abatement policies under the aforementioned conditions, which we refer to as a 'mixed blessing' effect.

Our analysis has several important policy implications and is suggestive of some critical directions for future research. For example, a constant escapement policy might be seen as attractive, given the challenges facing fisheries managers in the Black Sea region, despite the need to take a cautious approach and to regularly update parameters. Notwithstanding this latter qualification, it is clear that the initial invasion of the Black Sea by *Mnemiopsis* had a dramatic impact on the anchovy stock. If recurring outbreaks of the invader are of a similar magnitude, a constant escapement policy is unlikely to be optimal.⁷ More realistically, recurring outbreaks of the invader *Mnemiopsis* may be of lesser magnitude than the initial outbreak and, therefore, are liable to be consistent with a constant escapement policy. Obviously, determining whether this observation is correct will be an important area for future research, once there are sufficient new data on the impact of *Mnemiopsis* on fish stocks.

Another important concern is clarification of the mechanism responsible for triggering outbreaks of *Mnemiopsis*, or at least delineation of the respective roles of sea temperatures and food supply (e.g., via nutrients). New scientific research is beginning to shed further light on this aspect of the marine relationships studied here, such as suggestions that the triggering mechanism could be multi-faceted and include influences from nutrients (eutrophication), overfishing, and longer-term climatic changes or regime shifts (Bilio and Niermann 2004). In our analysis, choice of triggering mechanism has relatively little impact on selecting optimal escapement of anchovy, but our analysis indicates there are potential economic implications associated with whether nutrients play an important triggering role or not. As a result, nutrient management measures under the Strategic Action Plan for the Black Sea require careful consideration (BSEP 1996). The Action Plan calls for substantial levels of coordinated nutrient abatement, as well as various restrictions on fish catches, amongst other measures. However, whether such plans will be successful, given the number of states and varying interests involved, is a different question and one that is outside the scope of this paper.

Even if nutrient abatement is successful, there are ancillary concerns. For example, reduced nutrients lead to fishery profits in the non-outbreak state that are always lower than they would be with no reduction in nutrients. Fishery profits decline by an even larger amount in the outbreak state, regardless of the triggering mechanism. This effect stems from the direct influence of phosphates (P) in the recruitment function and the assumption that $R_p > 0$. When the level of nutrients and the incidence of outbreaks are linked (due to the presence of a mixed blessing effect), nutrient abatement leads to a higher probability attached to the state of the world with no outbreak. A reduction in the risk of an outbreak has a positive effect on expected economic profits: although the profitability under each state seen in isolation falls, the greater chance of no outbreak occurring more than offsets; therefore, nutrient abatement leads to positive benefits. As a result, determining whether a link

⁷ Instead, policies would be needed that take into account the current level of the anchovy stock. Reed (1979) argued that when constant escapement was not optimal, the preferred optimal policy generally will require a larger escapement. We leave the elaboration and analysis of these policies to future research.

exists between nutrients and the invader *Mnemiopsis* has management implications that extend beyond the fishery itself, to the design of optimal nutrient abatement policies in the Black Sea and elsewhere. Again, newer evidence is suggestive that this is so but that other considerations may be important as well (Bilio and Niermann 2004).

The analysis must be regarded as limited in several ways. For example, we do not consider the role for adaptive management and potential updating as more is learned about the behaviour of *Mnemiopsis* in its new environment and of the response of the anchovy stock to its presence. Also, we have made numerous simplifying assumptions about ecological and biological relationships in order to make our model tractable, such as ignoring any direct role played by phytoplankton and zooplankton.⁸ Similarly, we assessed the optimality of a constant escapement policy using a relatively simple stochastic bioeconomic modelling framework. Alternative approaches exist, such as stochastic dynamic programming, numerical methods, or the simultaneous control framework described by Tsur and Zemel (1995). However, empirical challenges are liable to make such approaches of theoretical interest for the present. Improved modeling will require advances in our understanding of the severity of environmental events (such as invasions), the mechanisms that trigger such events, the linkages between different components of the system (*e.g.*, nutrients and environmental events), and the capacity of nations to respond to the pressing environmental problems of interest (*e.g.*, nutrient enrichment).

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⁸ Of course, indirectly we have considered planktonic influences as these operate in association with changes in primary productivity. For an analysis of some of these influences in the *Mnemiopsis*-anchovy system, see Knowler (2005), and for possible direct involvement in changes in the Black Sea, see Bilio and Niermann (2004).

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Appendix

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

- (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. Using Clark’s adaptation of Reed (1979), the inequality constraint in equation (8) must be restated for a constant optimal escapement solution as:

$$S \geq S^* \quad \min \frac{R_i(S^*, \bar{P})}{(1 - e^{-i})}, \quad i = 1, 2. \quad (\text{A.1})$$

- (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 Ricker recruitment model), the following condition must be satisfied:

$$S^* < \hat{S}, \quad \text{where } \hat{S} \text{ is defined at } R_{SS}(\hat{S}, \bar{P}) = 0. \quad (\text{A.2})$$

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, Reed shows that the conditions hold for the Schaefer-Gordon harvest function and the Beverton and Holt or Ricker (upward sloping portion only) recruitment 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.