The Effects of Pollution on Open Access Fisheries: A Case Study of the Black Sea

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Paper prepared for the 8th Annual Conference of European Association of Environmental and Resource Economics (EAERE), Tilburg University, The Netherlands, 26-28 June 1997.

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1. Introduction

Marine pollution, especially in coastal areas, has emerged as one of the leading environmental issues of our time.[1] While the dumping of toxic wastes and despoiling of coastal recreation areas often receive attention, one of the key problems is excessive nutrient loads accompanied by detrimental effects on commercial and sport fisheries. A number of economists have examined the theoretical implications of altering habitats for commercial fisheries or similar renewable resources (Thurman and Easley 1992, McConnell and Strand 1989, Swallow 1990, Barbier 1994, Barbier and Strand 1997, Tahvonen 1991), while others have attempted to model these effects empirically (Kahn and Kemp 1985, Swallow 1994, Lynne et al. 1981, Loomis, 1988, Fisher *et al*. 1991). Most of the latter studies concentrate on the valuation of coastal inputs to fisheries production and the evaluation of optimal policies for resource allocation. In contrast, this paper will focus on the long run implications of pollution abatement policies for open access fisheries.

In theoretical terms, coastal pollution imposes an external cost on fisheries when the costs of harvesting fish is increased.[2] Indeed, the unidirectional externality associated with pollution and

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[1] To find support for this conjecture one need only look as far as recent coverage of the problem in National Geographic and Scientific American, which suggests the issue has gained prominence beyond the usually limited circle of readership concerned with environmental matters.

[2] It is worth noting that nutrient pollution in coastal areas may up to a limited extent increase the productivity of the marine environment as primary productivity rises in response to a relaxation of a nutrient constraint. For discussions of this phenomena, see Lee *et al*. (1991).

fisheries is often cited as a prime example of such problems in standard economics works (Dasgupta 1982). To rectify the situation, the imposition of an appropriate tax on the polluter to internalize the external cost is usually prescribed.[3] Thus, by correcting for overproduction in the polluting industry and suboptimal harvesting of fish, a net welfare gain is made. Complicating such simplistic analyses are the property rights governing the fishery.

Where fisheries are subject to open access, all economic profits are dissipated at the long run equilibrium and welfare gains from improved resource allocations can only come from increases in consumers surplus (Freeman 1991). This implies that reducing pollution to bring about gains in the commercial fishery sector will benefit consumers alone. Of course, in the short run, there may be economic profits earned as the fishery adjusts to new levels of environmental inputs but these will fall to zero once the long run open access equilibrium is re-established. Moreover, one can imagine cases where the output of a fishery faces a perfectly elastic demand curve, as a result of export sales, for example, so that even long run welfare benefits accruing to consumers are non-existent. We are then left with few, if any, long run efficiency benefits attributable to improved fish habitat, except for intramarginal rents accruing to the more efficient vessels. Few of the empirical studies cited above have taken these rather surprising long run welfare implications into account.[4]

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[3] Interestingly, Strand and Bockstael (1990) demonstrate how the seemingly unidirectional nature of such externalities may in fact be an incorrect description. They show that if the costs of pollution abatement are passed on to the agricultural, the resulting price increases may shift demand for fish.

[4] McConnell and Strand (1989) provide a comprehensive treatment of the theoretical dimensions of the problem. They show that where the inverse demand curve is downward-sloping and shifts in response to a perceived improvement in fish quality as a result of environmental improvements, the net welfare effect of the environmental improvement may be negative.

Unless the absence of property rights is addressed, and fishing effort managed more optimally, there would appear to be few efficiency gains from policies aimed at reducing pollution of the coastal marine environment. Where the presence of transboundary fish resources or local political pressures prevent the imposition of property rights in the fishery, economists might be expected to find pollution abatement of questionable value from a traditional fisheries management perspective. This latter view is increasingly coming under attack for being overly concerned with the maximization of resource rent as the sole objective of fisheries management (Lawson 1984, Charles 1988). Limiting entry to the fishery may lead to the creation of larger resource rents but may have other less desirable socio-economic effects. For instance, many coastal fishing communities in both the developed and developing worlds are almost totally reliant on the fishery as an economic base. Income distribution and social safety net concerns may justify greater employment in the local fishing industry than efficiency considerations alone support (Charles 1988, Panayotou 1982). However, too often such arguments have been mounted at the political level in defense of un-sustainable, overharvesting of fish stocks. We argue that even where pollution abatement does not produce significant efficiency benefits, because property rights are lacking and demand is perfectly elastic, there may be a case for pollution abatement to support non-efficiency objectives in fisheries management as represented by higher sustainable levels of income and employment.

We address the question of open access fisheries and pollution abatement using the example of the Black Sea anchovy fishery. The anchovy fishery has been dominated by Turkish fishermen, who are not bound by the Varna Convention of 1959, which was intended to regulate fishing activity in the Black Sea (Reynolds 1987). While Turkey has made some effort to regulate minimum catch sizes and season openings, and there is evidence of informal agreements among fishermen (Knudsen 1995), conditions in the anchovy fishery are suggestive of an open access regime.

As a highly underdeveloped region by European standards, the six littoral countries involved have been historically reliant on the employment and incomes derived from Black Sea exploitation. Draining over half of the European continent, the Black Sea has received high nutrient discharges, chiefly via the Danube river, and suffered from a consequent problem of eutrophication. Of critical importance for the Black Sea's ecological decline has been the introduction of an exotic, predatory jellyfish (*Mnemiopsis leidyi*), thought to feed on anchovy and other fish larvae, as well as competing with adult anchovy for food. *Mnemiopsis* was likely introduced via ballast dumping by commercial shipping and originates from the northeast coast of the U.S. Its biomass is believed to be a function of several environmental factors, including nutrient loads (Mutlu *et al*. 1994), although there remains some uncertainty on this among natural scientists (GESAMP 1994). It therefore serves as an intermediate agent for the impact of eutrophication on certain fish stocks [see Ulanowicz and Tuttle (1992), for a similar example].

As the Turkish anchovy fishery constitutes a form of open access exploitation, and has an hypothesized association with nutrient loads, it proves highly suitable for our analysis. To be of interest from the standpoint of pollution abatement, modelling of the anchovy-*Mnemiopsis* system must link these nutrient loads with the Black Sea anchovy stock in a quantitative sense. Use of a bioeconomic model which integrates nutrient loads into the natural production function governing the growth of anchovy stocks is useful for this purpose. In effect, we treat the nutrient assimilation capacity of the marine environment as a form of habitat input into the population dynamics of the anchovy. Increases in nutrient loads in excess of this capacity serve to reduce the quality of that habitat, leading to poorer stock growth and ultimately to lower sustainable catches. While traditional static bioeconomic models of the fishery impose various equilibrium conditions to enable their solution, we do not take this approach. Instead, we develop a dynamic bioeconomic model and then solve for the steady state or long run equilibrium conditions contingent on a given level of nutrient inputs and economic parameters.

In the following sections we describe the Black Sea situation in more detail and then present an open access bioeconomic model of the anchovy fishery, incorporating both biological and economic aspects. Central to the approach is modelling of the influence of *Mnemiopsis* on anchovy recruitment, which in turn is postulated as a function of nutrient inputs to the sea. We solve for the steady state equilibrium of the anchovy system and then derive the comparative static effects of a change in pollution. To estimate the key parameter values determining the open access equilibrium, we estimate empirically the key bioeconomic relationships of the Black Sea anchovy system. We use the resulting estimates to calculate the impacts of various levels of pollution abatement on the equilibrium level of vessels employed, harvest and revenues. We conclude by discussing the general applicability of the analysis in light of the presence of property rights problems in many marine fisheries and the need to consider ‘second best’ management approaches.

2. Background: Pollution and Fisheries in the Black Sea

Degradation of the Black Sea is both an ecological and an economic problem. The main ecological problems of human origin are inflows of nutrients, resulting in eutrophication; the loss of higher trophic level predator species, which has altered food web structure; the introduction of exotic species, especially the jellyfish *Mnemiopsis leidyi*; and modifications in river flow regimes, which have affected the salinity of the Black Sea and had other effects. As a result, the Black Sea fishery is suffering from major reductions in catches, losses of key species as commercially exploitable populations and collapses more recently in previously important industrial fish stocks, such as European anchovy and Black Sea sprat.

Our chief concern here is with the discharge of nutrients into the Black Sea, which have contributed significantly to the problem. Caddy (1990) refers to the Black Sea as the “first semi-enclosed sea whose productivity has been decimated as a result of human activities, with the consequent nutrient enrichment having a major part.” (p.141) The major nutrients of interest are phosphorous, nitrogen and silica, discharged in various forms such as silicate, nitrates and phosphates. Beginning in the 1960s and early 1970s, there was a substantial rise in the discharge of these nutrients into the Black Sea. Humborg (1995) indicates that inorganic nitrogen loads in the Danube increased five fold over the period, while phosphates have doubled. When viewed on a wider European seas basis, total phosphorous loads per unit surface area are seen to be much higher for the Black Sea than for most other seas except the Mediterranean, and only slightly lower down in the list with total nitrogen (see Table 1). Polluters face incentives to dump their nutrients into waterways feeding the Black Sea and pay no or very little penalty for doing so.

The addition of nutrients to the Black Sea increased its primary productivity, but eventually led to surplus primary production and increased biological oxygen demand (BOD) as this surplus organic material decomposed. The resulting eutrophication of the Black Sea is evident in a changing mix of planktonic species, an increase in the frequency of plankton blooms and population explosions of jellyfish such as *Aurelia aurita* and the introduced species *Mnemiopsis leidyi* (Zaitsev 1992). Eutrophication problems are most severe on the shallow Northwest Shelf area of the Black Sea.

Fishing itself is also likely to have played a role in the decline of the Black Sea fisheries. No consensus exists as to the state of overfishing, since thusfar this influence has been difficult to disentangle from other factors, but it seems likely that during the 1960s and 70s overfishing contributed to the reduction of stocks of higher-valued species (Ivanov and Beverton 1985). Fishing effort was shifted from these more valuable, but now depleted species, to the smaller and less-valued pelagic species, especially anchovy and sprat. Heavy fishing pressure subsequently applied to anchovy likely contributed to the collapse in the stock in the late 1980s.

Steadily accumulating numbers of purse seine vessels in Turkey provide evidence of the increasing pressure on anchovy. Over the period 1975 to 1991, the total number of purse seiners rose from 22 initially to 215 by the end of the period (Turkish Statistics Agency). Combining purse seiners with trawlers and multipurpose vessels, the increase in gross tonnage in the industrial fishery over the period is almost four fold (Trabzon Institute surveys). To these numbers must be added a deepening of fishing capital resulting from the addition of various fish finding devices to the existing fleet. Turkish data show that the percentage of larger vessels having such devices rose from 12% in 1975 to 48% in 1991. Even after the stock collapse in 1989, construction of large steel fishing vessels in Turkey continued until at least 1991, aided by low cost capital (Black Sea Environment Programme, personal communication).

3. A Theoretical Model of Pollution-Fishery Linkages

In this section we develop an open access bioeconomic model of the Black Sea anchovy fishery incorporating habitat quality, as proxied by ambient nutrient levels. Such a model must integrate the key ecological relationships of interest, ie. fish stock growth and adjustment dynamics and physical links to nutrient concentrations, with the economic components of the system, the latter consisting of a production function and an effort adjustment relationship. In contrast to the optimal management problem, we model the behavioural response of fishermen as a function of the incentives for entry into and exit from the industry. Opsomer and Conrad (1994) have modelled the northern anchovy fishery of the eastern Pacific in a similar fashion but without environmental considerations. If the problem of interest was one of solving for optimal pollution levels, then the model could probably be restated as a pollution control problem (Keeler *et al.* 1972). However, this approach requires defining a damage function rather than a gross benefit function, which is more complex (Tahvonen 1991) and has other difficulties.[5]

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[5] For example, to optimize over pollution discharges requires that all potential benefits from abatement be specified. We are only concerned with the commercial fisheries benefits here and indeed the likelihood that all other benefits from reduced nutrient inflows could be quantified is rather low.

Previous theoretical modelling of renewable resources and pollution has tended to approach the problem from one of two directions. Some models have considered the impact of pollution on renewable resources productivity, explicitly incorporating population dynamics but treating pollution in a rather general way (Siebert 1982, Tahvonen 1991). Other studies have been more specific about the nature of the eutrophication process but have then sacrificed detail concerning the associated damages, generalizing in a way which prohibits explicit consideration of renewable resource effects and impacts on population dynamics in particular (Mosetti 1988, Garnaev 1990, Gatto et al. 1991a, 1991b). In the model presented below we are able to be more specific on both accounts.

We adopt a dynamic and discrete time perspective, as this more accurately describes the population processes of many fish species, as well as how fishermen respond to profit or other signals in deciding whether to enter the fishery from one season to the next. The general model consists of three difference equations which describe the change in each of three stock variables from one time period to the next. These relationships are: (i) an anchovy stock equation, (ii) a *Mnemiopsis* stock equation, and (iii) an effort adjustment (capital stock) equation. In turn, these functions make use of two others, an anchovy recruitment function and a standard fisheries production function. A description of the full system is provided below.

A typical fisheries model will employ a stock equation which describes changes in the stock (A) from period to period, often comprising a function for the net growth in the stock biomass (F)

from which is subtracted the annual harvest (*h*). Stock growth may depend on influences other than spawning stock size, such as the biomass of *Mnemiopsis* (*M*), as postulated here. Such a function adapted to Black Sea anchovy, incorporating a more general harvesting effect, would take the following form (subscripts refer to time periods):

$$A_{t+1} - A_t = F(A_t, h_t, M_t), \quad F_h < 0,\ F_M < 0. \qquad \textbf{(1)}$$

The partial derivative F_A is initially positive for values of $A < A_{MSY}$, where A_{MSY} is the maximum value of the growth function or maximum sustainable yield, and negative for $A > A_{MSY}$ (Clark 1976). Tahvonen (1991) provides a discussion of the assumptions behind the standard stock growth function incorporating pollution externalities.

We adopt a spawner-recruit type model to specify the function *F*, which is appropriate for short-lived species such as anchovy (Neher 1990). Following Clark (1976), we distinguish between growth originating from recruitment and that associated with the carryover of the prior period's biomass evading harvest, usually referred to as 'escapement'. Defining recruitment as R_t, we postulate that its value depends upon anchovy stock, A_t, and M_t, the biomass of the predatory *Mnemiopsis*.[6] Defining escapement as A_t - h_t, we need only be more specific about the harvest function, *h*. For empirical reasons, we adopt the standard Schaefer-Gordon production function, $h_t = qA_tE_t$, where *q* is the catchability coefficient ($q > 0$) and E_t refers to an aggregate fishing

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[6] In most spawner-recruit models, recruitment would be a function of escapement (A_t - h_t) instead of parent stock (*A*) alone. We adopt the simpler specification for analytical convenience in deriving theoretical results but use escapement in the empirical estimates presented later.

effort input, usually consisting of the joint labour and capital inputs tied up in active fishing vessels.[7] Thus, we rewrite (1) to indicate that anchovy biomass surviving both harvest and natural mortality isaugmented by recruitment to give the biomass in time *t+1*:

$$A_{t+1} = (1 - \eta)[A_t - qA_t E_t] + R(A_t, M_t), \quad R_M < 0 \tag{2}$$

where η is natural mortality, $0 < \eta < 1$ and the sign of R_A is similar to that of F_A, discussed above.

An interesting feature of the model is the inclusion of an equation describing growth in the biomass of *Mnemiopsis (M)*, the agent through which nutrients have an effect on anchovy recruitment. In its general form, we postulate a growth function (*G*) which depends on the previous biomass of the species as well as ambient nutrient concentrations in the Black Sea (*Z*):

$$M_{t+1} - M_t = G(M_t, Z_t). \tag{3}$$

As the life span of most *Mnemiopsis* is only one season, we use a Ricker-type curve to model its biomass in year *t+1* (Ricker 1975):

$$M_{t+1} = M_t \exp[\gamma_0 + \gamma_1 M_t + \gamma_2 Z_t], \quad \gamma_0 > 0,\ \gamma_1 < 0,\ \gamma_2 > 0 \tag{4}$$

One of the challenging components in the open access model is the description of fishermen’s

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[7] As the empirical analysis makes use of stock data derived from a virtual population analysis (VPA), we prefer to use a production relationship which is consistent with the assumptions used in the VPA. The VPA appears to impose a Schaefer-Gordon type production function.

behaviour. We must specify a process whereby fishing vessels (*E*) enter or exit from the industry, and this is typically expressed as a function of lagged financial profits, π (Conrad 1995). This specification yields an adjustment equation for fishing effort:

$$E_{t+1} - E_t = f(\pi_t), \quad f_\pi > 0 \tag{5}$$

The simplest form of the function *f*(π) is to assume profits are multiplied by a scalar coefficient of adjustment, ϕ, but other adjustment processes can be considered (Bjorndal and Conrad 1987). Obviously, a higher value of ϕ suggests that the adjustment to changes in profits is stronger than if this coefficient is lower-valued. We express π as the profits and resource rents generated by the harvest. We assume *p* is the real ex-vessel price for anchovy, determined internationally and therefore exogenous (perfectly elastic demand curve), and assume *c* is the real unit cost of effort. Thus, (5) can be rewritten as:

$$E_{t+1} - E_t = \phi[p_t h(A_t, E_t) - c_t E_t], \quad \phi > 0. \tag{6}$$

Both *p* and *c* are assumed to remain constant over time in real terms to allow analysis of the steady state comparative statics in the next section. Inserting the Schaefer-Gordon production function into (6) and rearranging, we arrive at a statement for the level of anchovy fishing effort in time *t+1*:

$$E_{t+1} = [1 + \phi(pqA_t - c)]E_t \tag{7}$$

Together, equations (2), (4) and (7) constitute a dynamic open access model of the Turkish Black

Sea anchovy fishery, incorporating the influence of *Mnemiopsis* directly in the anchovy stock dynamics and nutrients indirectly via the *Mnemiopsis* stock. We next determine the long run equilibrium of the open access system, and derive the comparative statics effects on this equilibrium of changes in nutrient concentrations.

4. Open Access Equilibrium and Comparative Statics

As a dynamic system, the anchovy-*Mnemiopsis* model may or may not meet the conditions for the existence of a steady state. Tahvonen (1991) derives these conditions for an optimal steady state in a pollution-renewable resources system not unlike the anchovy model described above, and shows that for the equivalent optimal control problem, a saddle point equilibrium may exist. It is possible to demonstrate the stability conditions corresponding to a steady state equilibrium for our open access problem with pollution but proving such conditions is not our main focus. For our purposes, we will simply solve for the steady state and analyse its comparative static properties. In some respects, conducting an analysis of a stable long-run open access equilibrium is a strong assumption in light of a history of dramatic changes in small pelagic stocks, such as the Peruvian and Black Sea anchovy, but one which can be relaxed in future research.

In equilibrium, let $A_{t+1} = A_t = A$, $M_{t+1} = M_t = M$, $E_{t+1} = E_t = E$, and also let $Z_t = Z^o$, i.e. some constant level of phosphate pollution which is exogenously determined. From (5) and (7) we get:

$$A = \frac{c}{pq}, \quad \text{for } E_{t+1} = E_t = E \tag{8}$$

and,

$$R(A,\ M)\ -\ A[(1\ -\ \eta)qE\ +\ \eta]\ =\ 0, \quad for\ A_{t+1}\ =\ A_t\ =\ A \tag{9}$$

Equation (8) is the standard open access condition that results from the assumption that any profits in the fishery will be dissipated in the long run. The condition tells us that the steady state anchovy stock is determined solely by model parameters, which is a convenient result and one which has been demonstrated before (Clark 1976). Equation (9) is the condition for a steady state anchovy stock. It indicates that for there to be no net biomass growth, recruitment must equal natural mortality, η, plus that portion of harvest that would have survived had it not been harvested, $(1 - \eta)qE$.

Rearranging equation (9) we get an expression for the steady state level of fishing effort:

$$E\ =\ \frac{R(A, M)}{A(1\ -\ \eta)q}\ -\ \frac{\eta}{(1\ -\ \eta)q}, \quad for\ A_{t+1}\ =\ A_t\ =\ A \tag{10}$$

Solving equation (4) for *Mnemiopsis* biomass at the long run equilibrium, and assuming $Z = Z^0$, we first get exp $[\gamma_0 + \gamma_1 M + \gamma_2 Z^o] = 1$, which implies $\gamma_0 + \gamma_1 M + \gamma_2 Z^o = 0$, and thus:

$$M\ =\ -\frac{(\gamma_0\ +\ \gamma_2 Z^0)}{\gamma_1}, \quad for\ M_{t+1}\ =\ M_t\ =\ M \tag{11}$$

Equations (8) and (10) are standard open access equilibrium conditions. Equation (10) is new, but because *M* is a linear (and increasing) function of Z^0, it leads to convenient results. Equation (8) is a vertical line in *A*-*E* space, shown in Figure 1, which represents the $E_{t+1} = E_t = E$ isocline. From (10), the slope of the $A_{t+1} = A_t = A$ isocline is:

$$dE/dA = \frac{R_A - [(1 - \eta)qE + \eta]}{A(1 - \eta)q} \tag{12}$$

Equation (12) is negative if the numerator is negative, which is unambiguously the case if R_A is negative. The latter is a reasonable assumption for the recruitment function over the range of anchovy stock values encountered in the comparative statics analysis.[8]

Still assuming that phosphorous levels, Z, are constant for now ($Z = Z^0$), the equilibrium of the system (E^*, A^*) is determined by the intersection of the isoclines described by (8) and (12), ie.

$$\begin{aligned} A^* &= \frac{c}{pq} \\ E^* &= \frac{pR(A^*, Z^0)}{c(1 - \eta)} - \frac{\eta}{(1 - \eta)q} \end{aligned} \tag{13}$$

Finally, define

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[8] Numerical analysis using the empirical model suggests that R_A is positive only for very small values of *A* and even where it is positive, *dE/dA* remains negative unless $R_A > [(1-\eta)qE + \eta]$.

$$\lim_{A \to A_{\min}} R(A, M) \to \eta A \;;\quad i.e.\; A_{\min} \; is \;\; `collapse' \;\; size.$$

In other words, the potential for collapse of the stock depends upon initial conditions and the resulting trajectory of the system as it adjusts towards a long run equilibrium. Once natural growth in the stock, ie. recruitment, is no longer sufficient to replace annual losses, here shown as natural mortality, the stock simply declines to extinction.[9] In Figure 1, Trajectory 1 leads to an open access equilibrium, while Trajectory 2 leads to collapse of the anchovy stock.

We can use the steady state results derived above to examine the effects of a change in pollution, Z^o, treated thusfar as fixed. From equation (11):

$$\frac{dM}{dZ} = -\gamma_2/\gamma_1 \tag{15}$$

and from (9):

$$R_A dA + R_m dM - [(1+\eta)qE + \eta]dA - (1 - \eta)qA\,dE = 0 \tag{16}$$

If prices and costs are held constant, which is consistent with our assumption of a perfectly elastic demand curve, and A^* is to the right of A_{min}, then dA*= 0 [see equation (8)] and:

$$dE^*/dZ^0 = \frac{\gamma_2 R_m/\gamma_1}{-(1 - \eta)qA^*} < 0 \tag{17}$$

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[9] Equally, we could define annual losses to include harvest as well, so that the collapse size of the stock would be defined by $\eta(A\text{-}h)$ in the limit.

The effect of a reduction in phosphorous pollution is to raise equilibrium fishing effort unambiguously. With the Schaefer-Gordon production function, this effect will result in a higher equilbrium harvest.

To summarize, if A^* is to the right of A_{min} and $dA^* = 0$, then just the $A_{t+1} = A_t = A$ isocline shifts up in Figure 1, as a result of reduced nutrient inflows, Z^1 $(Z^1 < Z^0)$. The new long run equilibrium is associated with higher values for both equilibrium fishing effort and harvest. When price does not adjust, there is no long run welfare improvement from pollution abatement in the efficiency sense.

4. An Empirical Open Access Model of Anchovy in the Black Sea

The Black Sea ecosystem is undoubtedly complex and as we have earlier noted, it has been subjected to a plethora of abuses. To empirically model its functioning in support of a single species, link this with the economy, and attempt to isolate the influence of nutrients alone on the this system, is certainly a challenge. The essential elements of such an empirical model are shown in Figure 2. The dynamics are accomplished through inter-temporal transition of three stock variables: i) the anchovy stock; ii) the *Mnemiopsis* stock; and, iii) the capital stock (purse seine vessels). Like previous biological models, we also specify and estimate a production relationship and recruitment function.

In some respects, our model is just a simplification of research already accomplished by others and we estimate the simpler relationships of Figure 2 to reduce the more complex structure provided by previous authors.[10] The production, prices and unit costs of production form the current period profits. We use our estimate of profit as a factor influencing the vessel construction for the subsequent period. The crucial environmental factors are addressed by estimating the effect of a general indicator of pollution, the phosphate concentration in Romania's Black Sea near Costanta, on the *Mnemiopsis* population. In turn, the *Mnemiopsis* population interacts with the level of anchovy recruitment - the jellyfish prey on anchovy in their larval stage.

Previous research describes in more detail each of the components of the model, giving functional forms, the data used and detailed descriptions of the estimates from a two-stage least square estimation of the model (Knowler, Strand and Barbier 1996). The resulting estimates for the coefficients for the system are reported in Table 2. The second column shows the estimates for coefficients in the anchovy stock equation [see equation (2)].[11] The carryover from the previous year's stock is about 0.30, which is consistent with earlier estimates for natural mortality in young anchovies, of about 0.7 - 0.8 (Ivanov and Beverton 1985). We include the harvest from all countries catching anchovy in calculating the carryover, not just the turkish catch. The average weight of a recruit is about 1.7 grams, as indicated by the coefficient on recruitment, not too

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[10] The data that is available on the Black Sea anchovy stocks comes primarily from virtual population analysis (Ivanov and Beverton, 1985; Prodanov *et al*. 1995). This type of analysis imposes a production technology on the vessels discussed later but provides estimates of the anchovy stock in each period. Because the evaluation of the environmental change rests crucially on having stock estimates, we are willing to accept the restrictions imposed on the fishing technology by the previous studies. Fisher *et al*. (1991) similarly use synthesized data in their modelling of salmon and water quality, while Dowlatabadi *et al*. (1994) provide a general rationale for the approach.

[11] For estimation purposes, it was necessary to modify equation 2 slightly to incorporate spawning or carryover biomass (A - h) as the independent variable, rather than adult stock, A, alone. As recruitment was also measured in numbers rather than as biomass we estimate a coefficent to convert from recruitment to a biomass value. This could have been accomplished using research estimates of weight-at-age but reliability of such estimates was uncertain.

dissimilar to measured weights. The high level of explanatory power and significance of the coefficients in the anchovy stock equation arises because the dependent variable was constructed from the independent variables in the virtual population analysis. Hence, the statistical tests are not traditional in any manner; the error arises because we have used slightly different functions to represent a deterministic relationship. The adjusted R^2, however, indicates a close correspondence between our simple estimated function and the more complex VPA model.

To use the estimated stock equation in a simulation, we need to predict anchovy recruitment and harvest. The recruitment of anchovies is predicted using a Ricker curve (Ricker 1975) modified for the influence of *Mnemiopsis*. Specifically, the number of anchovy recruits (R_t) is related to the anchovy spawning stock (SB_t) and *Mnemiopsis* (M_t) according to:

$$R_t = SB_t \exp[\beta_0 + \beta_1 SB_t + \beta_2 M_t], \tag{18}$$

where β_1 and β_2 are expected to be negative. This specification is consistent with methods proposed by Vaughan *et al.* (1984) for the introduction of sources of mortality in a recruitment function. A larger population of mnemiopsis will lower the recruitment of anchovy for each level of anchovy spawning stock ($R_M < 0$). As with several of the other equations in Table 2, equation (18) is transformed to a log-linear form for estimation. The estimated coefficients in the recruitment function conform to our expectations, with both signs negative (see Table 2). Each of the coefficients is significantly different from 0 at the 5 % level of significance. When the resulting recruitment function is simulated with no *Mnemiopsis* population and with the maximum observed population of *Mnemiopsis* in 1987, anchovy recruitment is about 40 % lower.

Estimation of the remaining equations for *Mnemiopsis* stock, fishing vessels (capital stock) and the production function conform with expectations, with the vital coefficient on phosphorous in the *Mnemiopsis* equation positive and significantly different from 0 at the 5% level of significance. The speed of entry and exit from the fishery is indicated by the adjustment coefficient, ϕ, in the capital stock equation [see equation (6)]. We estimate the adjustment coefficient at 0.012 (when annual profits are expressed in thousands of U.S. dollars per vessel), which suggests a very slow process when comparisons are made with previous estimates for other fisheries.[12] If vessels are slow to enter or depart the industry in response to profitability, this will have consequences for the speed at which the system attains a steady state. Using a transformed Schaefer-Gordon specification of the production function, the catchability coefficient, q, is estimated at 0.003.[13]

The performance of a integrated ecological-economic model can be evaluated in several ways, but here we choose to simply run a sample simulation of the system over a 20 year period, to demonstrate its potential usefulness. Table 3 provides the simulation results, assuming 1982 values for anchovy stock and fishing effort, as initial conditions, and for price, cost and

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[12] For example, Bjorndal and Conrad (1987) model the North Sea herring fishery and find a point estimate for the adjustment coefficient in the neighbourhood of 0.10, but cite a much lower figure of 0.02 estimated by Wilen (1976) for the North Pacific fur seal industry. The comparability of such estimates is not absolutely certain.

[13] Further refinement of the full anchovy system is planned. For example, both the capital stock and production equation estimates may suffer from autocorrelation, which would require corrective procedures, and several intercept terms were insignificant so that the relevant equations need to be re-estimated without intercepts. A much better (higher F and t statistics) recruitment function was estimated when *Mnemiopsis* was included as a mixed term, ie. multiplied, with spawning biomass, SB.

phosphorous load in the Black Sea, all of which are shown in Table 3. This year is chosen partly because it roughly coincides with the introduction of *Mnemiopsis* into the Black Sea. The simulation shows an initial increase and then prolonged decline in the anchovy stock, which eventually reverses itself if the simulation is extended a number of years. The *Mnemiopsis* stock rapidly increases after its introduction and converges to its steady state value by year 20. Given the trend in fishing effort evident in Table 2, and the rapid attainment of a steady state value for *Mnemiopsis,* the system appears to be following Trajectory 1 in Figure 1, passing from the upper right to the upper left quadrants during the period simulated. The 1982 initial conditions suggest that fishing effort already exceeded its steady state value, but that its slow response to profitability ensures that it continues to rise for several years, even though profitability is declining. This limit cycle effect is consistent with actual conditions, which saw the number of Turkish vessels double their 1982 total within just a few years and then decline quickly. For further detail on the simulations performed with the model and its disequilibrium aspects, see Knowler, Strand and Barbier (1996), and see Opsomer and Conrad (1994) for a discussion of the dynamics of a similar open access simulation model.

5. Comparative Static Effects of a Change in Nutrient Loads in the Black Sea

The steady state solution for the anchovy-*Mnemiopsis* system can be determined easily (assuming one exists) by inserting the appropriate coefficients from Table 2 and exogenous parameter values for price, cost and phosphorous concentration into the long run equilibrium expressions represented by (13). For this procedure we again employ the parameter estimates from the 1982 base year used in the simulation of the previous section. In particular, we set phosphorous at 5.0

μM, which compares to an average reading of about 4.0 over a 30 year period commencing in the mid 1960s (Cociasu *et al*., in press).

Our calculated long run equilibrium values are approximately 290,000 tonnes for the anchovy stock, 80 fishing vessels and an annual harvest of about 70,000 tonnes. At an ex-vessel price of US$ 155 per tonne in real 1989 dollars, the harvest would generate revenues of about US$ 11 million, again in real 1989 terms. These values can be compared to averages estimated from the time series data used in the econometrics (1972-93), of 742,000 tonnes for anchovy stock, 108 vessels and an annual harvest of 162,000 tonnes. At the height of the anchovy fishery in 1987, when Turkish landings of anchovy alone reached 350,000 tonnes, revenues using the 1989 real price would have topped US$ 50 million. The historic averages seem much higher than our equilibrium values, reflecting the sizeable stocks and high productivity of the fishery when it was initially opened up. However, by the end of the period, once stocks had collapsed, values were roughly in line with those implied by the long run equilibrium calculation. Of course, in noting this we have ignored differences in pricesand other parameters over the historic period.

Of interest is the potential for improving upon the estimated long run levels of effort, harvest and revenues by investing in pollution abatement. Here we confine ourselves to changes in equilibrium values and ignore short term gains from the adjustment to a new equilibrium when the parameters are modified. As we have so far considered only the open access case where demand is perfectly elastic, there can be no permanent welfare gain from an environmental improvement. We therefore restrict our assessment to the potential increases in non-efficiency indicators of the fishery, sure to be of importance to fisheries managers and local communities nonetheless, as we have already argued. We relax our assumption of perfectly elastic demand afterwards and consider the case where a permanent welfare gain to commercial fisheries may occur as a result of pollution abatement.

To determine the effects of a reduction in ambient phosphorous concentration (*Z*) on the anchovy fishery we first use the total derivative (17), which shows the response in fishing effort (*E*) to changes in the phosphorous load with no price adjustment. Inserting the appropriate parameters and partial derivatives into (17), defined again at their 1982 values, we find that a one unit reduction in phosphorous leads to an increase of about 17 purse seiners at the new equilibrium. Using the Schaefer-Gordon production function we can quickly determine that such a change in fishing effort yields an increase in steady state harvest of 14,500 tonnes per annum (recall there is no change in anchovy stock). Valued at the 1982 price (expressed in real 1989 dollars), the increased harvest generates additional revenues of US$ 2.25 million annually. Expressed in elasticity terms, the long run point elasticity for harvest with respect to phosphorous load is 1.04 (evaluated at 1982 parameter values). In effect, this implies something close to unit elasticity, ie. constant returns, for output with respect to habitat quality, where the latter is measured as the negative of ambient phosphorous concentration.

We can take our analysis further by considering possible policy scenarios for reducted nutrient loads delivered to the Black Sea. As an example, targets for reduction of the nitrogen and phosphorous loads discharged into the North Sea are in the range of 50%, as a result of negotiations among the riparian countries (Rodda, undated). Applying such a target to ambient phosphorous concentrations in the Black Sea, and using the 1982 values for parameters to derive steady state conditions (and a constant price), is instructive.[14] If we assume a negligible catch by other Black Sea countries, then the new long term equilibrium in the Turkish anchovy fishery would involve about 42 additional purse seiners, representing an increase of just over 50% from the steady state implied by 1982 parameters and an unchanged phosphorous level.[15] To get some sense of the employment impacts of the change, we can employ Dincer *et al.'s* (1995) estimate of 20 to 30 crew members required for an average Turkish purse seiner. At this manning level, the 50% reduction in phosphorous would result in a permanent increase in employment of 840 to 1260 on fishing vessels alone. Annual anchovy harvests would be approximately 36,000 tonnes higher and would bring in additional revenues totalling $US 5.6 million, at 1982 prices expressed in 1989 real terms. Assuming a crew share of one-third of total revenues (Campbell 1993), the income impact of the abatement measures is almost US$ 2 million.

6. Conclusions

On a global basis, the Black Sea fisheries are relatively insignificant, yielding only a few percent of the total marine landings world-wide. We have argued that under such conditions, environmental

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[14] We assume here that a 50% reduction in nutrient inputs to the Black Sea would result in an equivalent reduction in ambient concentrations in the sea itself. Lags in achieving this would be likely, given the stock of accumulated nutrients already present in the Black Sea system and the contribution from recycling of these. Nonetheless, as our focus is on long run equilibriums, we make the assumption for convenience.

[15] We evaluate the impact of the reduction in phosphorous at the steady state values of the variables implied by the initial phosphorous level (ie. 5 µM). As the targeted change in this level is non-marginal it might be preferable to evaluate the total derivate expression at some mid point value of the phosphorous parameter for each variable, say 3.75 µM. However, this was not done.

improvements affecting open access fisheries are unlikely to produce substantial welfare gains to consumers, except in local markets isolated or otherwise protected from international market conditions. Decision-makers concerned with the management of a polluted regional sea like the Black Sea may have little scope to influence the property rights governing national fishing fleets, which may be necessary if welfare improvements are desired. Nonetheless, our analysis shows that they still may wish to undertake pollution abatement to improve conditions in the regional fishing industry, while at the same time maintaining its sustainability. We demonstrate that policy targets for nutrient reductions applied to other semi-enclosed seas, if applied to the Black Sea, could lead to sustainable increases in employment in the thousands and increased revenues of tens of millions of U.S. dollars at current prices.

There may be another fisheries aspect to the pursuit of pollution abatement policies, one which is only cursorily treated in this paper. By allowing the marine system to accommodate a higher level of fishing effort at the long run equilibrium, without risk of fish stock collapse, pollution reduction policies may offer a form of protection to stocks. Given the uncertainty governing marine ecological processes, providing such protection might be argued to fall within the domain of ‘precautionary approaches’. Our results further hint that the problem facing coastal fish stocks in developing countries may be especially serious. As the opportunity costs of fishing fleets and labour is liable to be lower than in the more industrialized fishing countries (ie. a less ‘malleable’ capital stock), the responsiveness of fishing effort to profit incentives may be much slower. Thus, harvesting at unsustainable rates may be more prolonged, increasing the threat to fish stocks. Pollution abatement policies may be particularly important for these countries.

Any analysis attempting to model a complex ecological-economic system is liable to be imperfect, and ours is certainly no exception. For example, we have accounted for only the indirect effect of nutrients on anchovy, via the agent *Mnemiopsis*. Direct effects have been incorporated in a preliminary way in the anchovy model and appear to be significant. However, comparative statics analysis is complicated by such extensions. Further development of the model has also improved on the econometrics, but this has yet to be incorporated into the full system for simulation purposes. Planned extensions to the analysis include incorporation of a downward sloping inverse demand curve, to replace the perfectly elastic demand situation we have assumed in this paper. Such an extension would allow the estimation of welfare gains from pollution abatement, to accompany the non-efficiency benefits estimated here.

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Table 1
Riverine Loads of N and P to European Seas

Sea	Total Nitrogen (t/yr)	Total Phospho-rous (t/yr)	Surface Area of Sea (km^2)	Discharge per Unit Area, N (t/yr/km^2)	Discharge per Unit Area, P (t/yr/km^2)
Baltic Sea	454,000	32,400	412,560	1.10	.079
Barents Sea	29,100	6,830	1,425,000	.70	.005
Black Sea	340,000	60,000	500,000	.68	.120
Caspian Sea	126,000	5,020	436,000	.29	.012
Mediterranean Sea	1,042,000	358,000	2,505,000	.42	.143
North Atlantic Ocean	314,000	19,000	36,000,000	.01	.001
North Sea	920,000	48,000	750,000	1.23	.064
Norwegian Sea	31,000	2,000	1,340,000	.02	.001
White Sea	17,200	1,500	90,000	.19	.017

Source: European Environmental Agency 1995

Table 2
Preliminary Two Stage Least Squares Estimates for Anchovy System Parameters

	Anchovy Stock Equation	**Anchovy Recruitment Function**	***Mnemiopsis* Stock Equation**	**Vessel Adjustment Equation**	**Production Function**
Dependent Variable	X_{t+1}	$\ln (R_t) - \ln (SB_t)$	$\ln (M_{t+1}) - \ln (M_t)$	$E_{t+1} - E_t$	h_t/X_t
Explanatory Variables:					
Carryover Stock ($X_t - h_t$)	0.31 (6.24)				
Recruitment (R_t)	1.70 (21.10)				
Spawning Biomass (SB_t)		-0.00000063 (-1.78)			
Mnemiopsis Stock (M_t)		-0.062 (-1.67)	-0.46 (-1.75)		
Phosphorus (Z_t)			0.30 (2.36)		
Lagged Profits/ Vessel (π_t/K_t)				0.000012 (3.43)	
Effort (E_t)					0.003 (7.44)
Constant		0.19 (1.04)	0.25 (0.44)		
Observations, F-value, Durbin-Watson	20, 2990.7 1.41	20, 1.70 2.04	20, 3.27 2.15	15, 13.65 0.69	15, 55.30 1.20

Note: *t* statistics are in parentheses; the original vessel adjustment equation included a lagged profits squared term but this has been omitted here as its contribution to the forecasting power of the model was negligible.

Table 3
Simulation Results for the Anchovy-*Mnemiopsis* System Based on 1982 Initial Conditions and Parameter Values (all values are in real 1989 dollars)

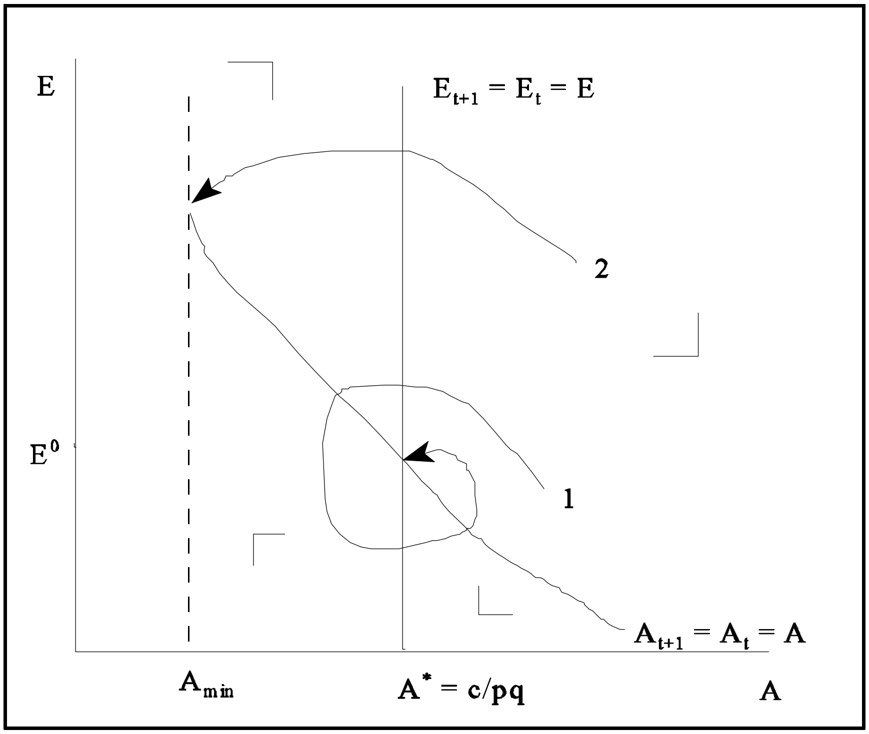
Parameters:

p = US$ 155 per tonne, ex-vessel
c = US$ 135,000 per vessel, per annum
Z (phosphorous) = 5.0 µM

Annual Simulated Values for Anchovy Stock, Recruitment, Fishing Vessels, Anchovy Harvest, *Mnemiopsis* Stock and Profits per Vessel

Year	Anchovy Stock (*X*)	Recruitment (*R*)	Purse Seiners (*E*)	Anchovy Harvest (*Y*)	*Mnemiopsis* Stock (*M*)	Profits per Vessel (π/*E*)
0	992000		106	315456	0.1	324380
1	1007407	469223	110	332120	0.55	331512
2	916850	416183	114	313207	2.46	289593
3	745654	328544	117	262498	4.57	210346
4	641248	289100	120	230599	3.22	162017
5	522526	232485	122	190953	4.22	107060
6	439029	197789	123	162132	3.49	68410
7	358671	160490	124	133339	4.03	31212
8	298581	134546	124	111336	3.63	3396
9	245222	110104	124	91469	3.93	-21303
10	204010	91969	124	75940	3.71	-40380
11	168869	75981	124	62614	3.88	-56647
12	141168	63664	123	52055	3.75	-69470
13	118000	53162	122	43217	3.85	-80194
14	99461	44870	121	36140	3.77	-88776
15	84070	37906	120	30279	3.83	-95900
16	71602	32310	119	25541	3.79	-101672
17	61257	27634	118	21627	3.82	-106461
18	52786	23824	116	18434	3.79	-110382
19	45735	20639	115	15790	3.81	-113646
20	39905	18013	114	13614	3.80	-116344

Figure 1
Open Access Equilibrium of the Anchovy-*Mnemiopsis* System for a Fixed Phosphorous Level (Z^0) and *Mnemiopsis* Biomass (M^*)



Trajectory 1. Leads to open access equilibrium

Trajectory 2. Leads to stock collapse

Figure 2: The Dynamics of Black Sea Fish Production