Endogenous Fishing Mortality in Life History Models:
Relaxing Some Implicit Assumptions

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Abstract

Life history models can include a wide range of biological and ecological features that affect exploited fish populations. However, they typically treat fishing mortality as an exogenous parameter. Implicitly, this approach assumes that the supply of fishing effort is perfectly inelastic. That is, the supply curve of effort is vertical. Fishery modelers often run simulations for different values of fishing mortality, but his exercise also assumes vertical supply and simply explores a series of these curves as different scenarios. The seemingly innocuous assumption of vertical supply conflicts with a large body of empirical work on behavior of fishermen and fishing fleets. Economists and fisheries scientists consistently find that fishing behavior is responsive to economic opportunities over time and space as well as across target species. Accounting for this phenomenon requires that fishing mortality be made endogenous. This paper demonstrates an approach to endogenizing fishing mortality in life history models by allowing the fish stock in the previous period and other behavioral drivers to enter into the equation that predicts fishing effort in the next period. The paper discusses conditions under which the standard approach is approximately accurate and when endogenous fishing mortality dramatically alters model predictions. An empirical application to the Gulf of Mexico gag, a species of grouper, illustrates the importance of endogenizing fishing mortality. Accounting for fishing behavior ultimately will improve predictions from management models and avoid fisheries management failures.

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Introduction

There is little doubt that human exploitation of the marine environment profoundly

affects marine ecosystems and the availability of fish for future generations (Botsford et al 1997;

Pauly et al. 1998; Jackson et al. 2001; Myers and Worm 2003; NRC 1999; UNFAO 2000; Pew

2003). The dilemma is what to do about it. The gut reaction of most scientists is to restrict

where, when, how, and how often we fish. But when our resource base continues to degrade in

spite of our best efforts, we are left wondering why. The answer is simple. Policies are put in

place, and humans adjust to them. When we constrain people in one activity, they do not simply

go away but instead engage in another activity. Policies that fail to recognize this fundamental

fact do little more than treat the symptoms of resource degradation without regard for the

underlying causes (Wilen 2006).

Among the most promising developments in marine conservation biology is our growing

knowledge about life history characteristics of fish and other marine species. Fisheries scientists

and managers have long considered age-dependent growth and mortality in modeling (Beverton

and Holt 1957), and recent studies have reinforced the importance of life history features for

marine conservation (e.g. Heppell et al. 2000). Larger individuals tend to produce more offspring

than smaller ones (Palumbi 2004), while individual offspring of older fish can be more viable

than those of younger fish (Berkeley et al. 2004). Many species of fish are hermaphroditic, and

there is theoretical support that harvesting pressure for sequential hermaphodites can lead to

sudden collapses in populations (Armsworth 2001). There is also some evidence that size-selective fishing pressure can induce evolutionary changes in fish populations over relatively short time horizons (Conover and Munch 2002).

To promote sustainable fisheries and ecosystems, managers have a range of policy instruments at their disposal, including limited entry programs, individual fishing quotas, gear restrictions, size limits, season closures, and marine reserves and other area closures. These policies often aim to protect organisms at different life stages. For instance, size limits may protect young, immature fish to give them an opportunity to reproduce; season closures may protect fish during spawning; and area closures may allow some fish to grow larger and produce more offspring. In spite of growing awareness about life history characteristics in fisheries management, we often fail to achieve conservation goals.

A great challenge and opportunity for marine conservation biology is to combine the insights from life history models with insights from economics and the social sciences about how humans behave in response to policy. What everyone would like to know is whether and under what circumstances policy interventions that target life stages are actually effective in achieving their goals. Although marine conservationists and fishing interests may not always agree on management objectives, no one has a stake in destroying the productive capacity of our oceans. When policies that aim to conserve fish populations fail to do so, fishing interests lose out. Similarly, when policies that aim to generate fishing profits fail to do so, they can exacerbate pressure on marine resources and ultimately cause conservation interests to lose out. A systematic consideration of biological and economic forces that interact with management offers a way out of this predicament.

Many management failures fundamentally stem from the lack of an interdisciplinary perspective. It is not path-breaking economic analysis to suggest that people fish more when prices are high, nor is it earth-shattering ecology to suggest that age-dependent fecundity is a determinant of population growth, but models rarely incorporate both forces. Life history models in particular ignore fishing behavior. Age-structured and stage-based modeling infrastructures are relatively advanced for incorporating new insights from ecology but relatively primitive for incorporating new insights from social and behavioral sciences. As a result, there is a disconnect between management models and the effects of management on fishing fleets. Fishery managers only indirectly control fishing mortality, and these indirect controls induce behavioral responses of fishermen and vessels that may reinforce management goals or undermine those goals (Wilen et al. 2002). Managers essentially plug one leak only to see another spring up somewhere else. Management models are unable to diagnose these behavioral responses because they assume direct control of fishing mortality. Thus, predicted success of certain policies becomes tautological, but actual outcomes are poorly understood and may be successes or failures.

Life history models of exploited fish populations typically treat fishing mortality as an exogenous parameter. This approach implicitly assumes that the supply of fishing effort is perfectly inelastic. That is, the supply curve of effort is vertical. Modelers run simulations for different values of fishing mortality, but this exercise also assumes vertical supply and simply explores a series of these curves as different scenarios. The seemingly innocuous assumption of vertical supply conflicts with a large body of empirical work; economists consistently find that fishing behavior is responsive to economic opportunities over time and space as well as across target species (Bockstael and Opaluch 1983; Holland and Sutinen 2000; Smith 2002; Eggert and Tveteras 2004). Accounting for this phenomenon is crucial for predicting the effectiveness of

conservation and fishery management policies and requires that fishing mortality be made endogenous. That is, fishing mortality must be dynamically linked in life history modeling such that the fish stock in the previous period and other behavioral drivers enter into the equation that predicts fishing effort in the next period, and the resulting stock post-fishing feeds into the predicted fishing effort in the following period. Only models that capture the dominant causal links in bioeconomic systems will be successful in predicting and avoiding management failures.

This paper builds on the work of Smith et al. (2006) to illustrate how traditional management models in fisheries go wrong and can compromise conservation goals by ignoring economic behavior. Specifically, the results show how fishing effort supply shifts at various times during the year in response to a seasonal closure in the Gulf of Mexico gag fishery and what a model without the economic behavior implicitly shows about fishing effort supply. In the next section, I describe the empirical model and how it differs from a standard matrix model of fish population dynamics. The following section reviews the empirical application in the Gulf of Mexico. Next, I present results and focus particularly on how a seasonal closure affects fishing behavior throughout an entire calendar year. In our discussion, I put forward one possible explanation for the seemingly paradoxical result: that total fishing effort actually increases in response to a seasonal closure. Finally, I draw some conclusions about the broader role of empirical bioeconomic modeling in marine conservation.

Model Description

The biological model is a standard age-structured life history model that incorporates several unique features to reflect stage transitions for a sequential hermaphrodite and a hockey-stick recruitment function (to reflect habitat limited recruitment). There are four life stages in the

model: recruits, immature females, mature females, and males. Surviving new recruits all become immature females. The number of surviving fish in each age class depends on natural and fishing mortality. Fish of each age grow according to a von Bertallanfy growth function. Fishable biomass (the fish stock from the point of view of fishermen) simply adds up the number of individuals in each age class above the size limit, applying allometric parameters to convert fish length to weight. Egg production by individual mature female is an increasing and convex function of fish length, while fertilization success is a concave function of the percentage of males in the population.

The distinction between a standard life history model (hereafter NOECON) and the model that accounts for fishing behavior (hereafter ECON) involves the manner in which the model treats fishing mortality. The basic approach follows Smith and Wilen (2003) but is customized for this application in Smith et al. (2006). NOECON incorporates fishing mortality as a fixed, exogenous parameter. As a consequence, if the fish stock increase, the rate of fishing mortality remains constant, and the total harvest of fish is simply scaled up according to fishable biomass. Moreover, when a seasonal closure occurs, the fishing mortality rate is simply scaled back according to the number of closed days. So, if there are 15 days out of 30 closed in a particular month, fishing mortality in the NOECON model is simply half what it would be if there were no closure. When put in this way, the standard management model sounds simplistic, and yet this is the way that management models are constructed. The ECON model, in contrast, makes fishing mortality a function of biomass and other factors that influence fishing effort. It not only accounts for the reduction in **potential** days fished under a seasonal closure, but also allows the data to determine how pronounced that reduction actually is.

The fishery data enter into the ECON model in two ways. First, there is a statistical routine to link fishing effort to catches (a production function). The parameters are estimated using nonlinear least squares. The parameter estimates of this routine are conditional on the how effort responds to stock, which is the second routine. Here, the model implements logistic regression (using maximum likelihood) to estimate fishing trips as a function of stock, weather, regulations, and monthly dummies (to capture outside opportunities). The estimates are conditional on the production function estimated in the first step. Thus, an iterative procedure is used to re-estimate each set of parameters until the entire parameter vector has settled down (based on relative Euclidean distance). See Smith et al. (2006) for more technical details about the biological and economic models.

Empirical Application

The case study in this paper is the Gulf of Mexico gag fishery. Gag (Myceteroperca microlepis) is a long-lived, slow-growing grouper that is a protogynous hermaprhodite. Between the 1970s and the 1990s, the percentage of male gag declined from 17% to 2% in Gulf of Mexico (Coleman et al. 1996; 2000). Gag is an excellent case study for three reasons. First, there is substantial policy variation in sample. In order to understand the effects of past policies empirically, policy changes need to take place in a time horizon over which we can measure outcomes. The Gulf of Mexico Fishery Management Council (GMFMC) provides this in-sample policy variation by forming two marine reserves, changing the size limit for gag, and implementing a seasonal closure during the gag spawning season. Second, I have built an extensive relational database of fisheries micro-data. The database contains U.S. NOAA Fisheries fishing logbook data (ten years of daily observations), Florida landings tickets, NOAA

weather buoys, online records of policy decisions of the GMFMC, county-level unemployment, and an original survey of reef-fish fishery captains that I conducted in 2005. This data set allows one to analyze economic substitution across space, time, and target species in response to policy changes. Here the focus will be only on inter-temporal substitution due to the technical challenges of integrating endogenous fishing mortality into a life history model, and the survey data will not be used. Third, a published empirically-based life history analysis exists for gag (Heppell et al. 2006).

In previous work, colleagues and I adapted the Heppell et al. (2006) model to incorporate inter-temporal behavioral responses to changes in the fish stock and the policy environment (Smith et al. 2006). Using an iterative econometric routine, we estimate behavioral parameters, a parameters from the fishing production function, and one key biological parameter (an initial condition on the shape of the initial abundance size distribution). See Smith et al. (2006) for additional technical details of the estimation. The focus of the current paper is to provide a heuristic explanation of how endogenous fishing mortality affects management outcomes using an analogy to supply curves and supply functions.

Results

Table 1 repeats the key qualitative findings in Smith et al. (2006). The message here is simple; all of the qualitative conclusions about the policy reverse when one accounts for behavioral responses of the fishing fleet. A standard management model (NOECON) predicts that a seasonal closure will reduce fishing effort, increase biomass, and also reduce pressure on large, older fish. The latter effect would thus address concerns about the gag sex ratio. Incorporating economic behavior (ECON), however, leads to the opposite conclusion for every

indicator. It is not surprising that economic behavior offsets some of the policy impacts, but in this case, behavior more than offsets the policy. The policy that aims to protect stocks actually harms them.

The dynamics of behavior are depicted in Figure 1. For the NOECON model, small fluctuations reflect only differences in number of days in each month (e.g. January has 31, but February has 28 or 29). The large dips illustrate the implied reduction in fishing effort during the seasonal closure. The ECON model nests all of these features and illustrates both short- and long-run dynamics of effort. Short dynamics reflect seasonal patterns in prices, openings and closings in the red snapper season, opportunities outside of fishing, and weather. Long dynamics reflect adjustments in the stock that are endogenously determined by fishing pressure.

Because the qualitative reversal in Table 1 is so surprising, it is worth exploring whether the model predictions, and not just the parameter estimates, are statistically significant. To this end, the point estimates of the biological parameters are fixed, and Figure 2 explores the sensitivity of model predictions about average biomass to the behavioral model parameters. Specifically, Figure 2 depicts 5,000 Monte Carlo simulations in which behavioral parameters are drawn from their empirical distribution (by taking the point estimate parameter vector and adding a vector of randomly drawn, independent standard normal variables multiplied by the Cholesky factorization of the covariance matrix). In all cases, the qualitative predictions of ECON and NOECON reverse; the seasonal closure increases average biomass in the NOECON model but actually reduces biomass in the ECON model. The histograms for the 'Closure' and 'No Closure' scenarios do not even overlap in either the ECON or NOECON models.

Figure 3 illustrates the implied average fishing effort supply curves for the ECON and NOECON model. Of interest here is the supply of fishing effort in response to the stock of fish.

One can think of the stock of fish as a 'price' and number of fishing trips as a 'quantity.' A supply curve is distinguished from a supply function in that the supply curve fixes all arguments of the supply function except price, which in this case is the level of biomass. The shaded box illustrates the region over which there is in-sample variation in gag biomass and fishing trips. In ECON, fishing mortality is endogenous and responds positively to the stock (the blue line). As such, there is some elasticity in the supply curve of effort. The NOECON model, in contrast, assumes exogenous effort supply (the green line). Thus, the NOECON supply curve is vertical, i.e. perfectly inelastic. The qualitative consequences for management are clear. Any increase in the biomass due to some management action will stimulate more fishing effort, and in the long-run, attenuate at least part of the increased stock. The extent of this attenuation will depend on the empirical application. My application in Figure 3 suggests that this attenuation will be substantial because the supply curve is relatively flat (elastic in the sample region), implying that effort will increase a lot in response to a stock increase.

Figure 4 shows how modeling fishing effort endogenously affects conclusions about seasonal closures. The gag spawning season spans January through April, and since gag aggregate to spawn, all other things being equal, one expects a concentration of fishing effort during the spawning season. The top panel shows the month of March. The shallow-water grouper closure is in effect from until March 15, so 15 out of 31 fishing days are eliminated. The assumed change in NOECON is thus a horizontal shift in the supply curve (solid green to dotted pink). However, the real change empirically is shown by the ECON model (solid blue to dotted red). To see what a difference this makes, a horizontal black line depicts the average biomass in sample. From this, one can see the short-run effort change in the ECON model. Thus, the real

reduction (ECON model) in fishing effort due to the closure during March is less than half of the assumed reduction in the standard management model (NOECON).

The story so far is that the ECON model shows how the policy is less effective than managers expected, but the story does not end there. The bottom panel depicts fishing effort response in April (still during the spawning season but after the seasonal closure). Because there is no seasonal closure in April, the NOECON model assumes that there is no change in fishing effort, and the exogenous effort supply curve does not shift. Empirically, however, effort supply does shift in the ECON model (blue to dotted red). Unlike in the top panel, effort supply in April shifts outward. That is, there is more fishing effort in April due to the closure in February and March. Economically, this is not surprising in and of itself. Some of the reduction in fishing effort from earlier in the year is displaced into later parts of the year.

Figure 5 repeats the analysis in Figure 4, but here the month of May is examined because it falls after the spawning season. As in the bottom panel of Figure 4, the NOECON model predicts that fishing effort will not respond to the seasonal closure. The ECON model, however, shows in increase in effort. The increase is less pronounced than the increase during April, but it exists nonetheless. At the margin, this effect is not surprising economically, though it runs counter to the way in which standard management models incorporate fishing effort. What is surprising is that the total effort increase aggregated over the year more than offsets the reduction of effort due to the closure (Table 1).

Discussion

Naturally, the immediate question to ask is why fishermen increase total effort in response to the seasonal closure. After all, Figures 3-5 show that supply of fishing effort is

upward sloping with regard to the fish stock, one of the key determinants of the profitability of fishing. This section develops a three-period model of effort supply for an individual fisherman. The goal is to show that the seemingly counterintuitive result of increased total effort can be explained by consumption smoothing combined with a subsistence constraint. At the onset, it is important to note a caveat: this explanation is not directly modeled in the empirical analysis. Thus, to formally test this explanation would require more statistical analysis and possibly additional data on incomes of fishermen and employment opportunities in other fisheries (and outside of fishing).

Previous analyses in the literature have focused on short-run profit maximization in response to management. For instance, Anderson (1999) shows that binding regulations reduce profits in the short run but can, in some circumstances, increase output. Though not modeled directly, he discusses individual preferences for leisure as another potentially important behavioral determinant. In a more recent paper, Anderson (2004) argues that motivations beyond profit maximization can lead to fishing strategies that target harvest or profit goals, and he shows that goal achievement can explain seemingly perverse economic behavior. I focus on labor-leisure tradeoffs in a utility maximization framework and find that binding regulations, while reducing utility, can increase or decrease total fishing effort. The implication is that seasonal closures can potentially induce a perverse behavioral response in many fisheries throughout the world. The empirical result in the gag fishery is just one example.

Suppose that fishermen derive utility in each period (t) from a composite consumption good (C_t) with price normalized to one and leisure (L_t). The three periods together constitute a calendar year, and for simplicity, assume away time preferences. The fisherman has a total time allotment in each period ($\overline{L}_t$) to divide between fishing effort (E_t) and leisure. Assume that

fisherman earn income (I_t) only from fishing. In each period, revenue is the product of the price of fish (p_t), the fish stock (X_t), effort exerted, and a cathability coefficient (q_t). Time-varying catchability explicitly captures productivity differences across periods. Costs are proportional to effort with a parameter c. Note that c includes operating costs like fuel and bait but does not include the cost of a fisherman's time, which is implicit in the labor-leisure tradeoff. Income from fishing can be written as:

(1) $\quad I_t = p_t q_t E_t X_t - c E_t = w_t E_t,$

where $w_t = p_t q_t X_t - c$. In a simple model structure like the one presented here, one can think of catchability differences also representing time-varying opportunity costs due to substitute economic activities or differences in typical weather conditions during periods that would affect an individual's pattern of fishing effort over time. Seasonal closures in each period constrain the individual's total effort in the period (E_t^{MAX}).

To characterize the situation of many owner-operator fishermen in industrialized countries as well as artisanal fishermen in developing countries, I introduce a subsistence constraint (C_t^{MIN}). For artisanal fishermen, C_t^{MIN} may represent the need to generate enough income to feed oneself and one's family. More likely in industrial fishing is that a minimum income is required in each period to make boat payments, dock rental fees, home mortgage payments, and other regular household expenses.

To add more realism, the model allows saving and borrowing in periods 1 and 2 (S_t). Essentially, fishermen can smooth consumption in the three periods by shifting their incomes across periods. However, the calendar year budget is binding. Debt service on borrowing across years—e.g. for a boat, home, or car—is implicitly folded into the subsistence constraint. Fishermen in this model can save or borrow in the short run to accommodate their labor-leisure

preferences or to meet subsistence requirements, but they cannot carry debts for non-capital purchases across years. The resulting utility maximization problem is:

(2) $\max \sum_{t=1}^{3} U(C_t, L_t)$

subject to:

$C_1 = w_1 E_1 - S_1$

$C_2 = w_2 E_2 + S_1 - S_2$

$C_3 = w_3 E_3 + S_2$

$C_t \geq C_t^{MIN}, \forall t$

$L_t = \overline{L}_t - E_t, \forall t$

$0 \leq E_t \leq \overline{L}_t, \forall t$

$E_t \leq E_t^{MAX}, \forall t$

This model is general enough capture spawning pre-closure, spawning post-closure, and post-spawning portions of a year through time-varying time allotments and catchability coefficients.

I illustrate the model in equation (2) with a numerical simulation. Suppose that the utility function is Cobb-Douglas with parameters 0.6 (for consumption) and 0.4 (for leisure). Without loss of generality, I vary w to represent catchability differences over time. Periods 1 and 2 take place during spawning, whereas period 3 takes place after spawning. I set $w_1 = w_2 = 1$ and $w_3 = 0.75$ to capture the increased catchability when fish aggregate to spawn. For simplicity, we set $\overline{L}_1 = \overline{L}_2 = \overline{L}_3 = 1$. This assumption can easily be relaxed to capture a situation in which the period after spawning is longer than either of the periods that divide the spawning season. This would match the empirical reality of the gag fishery. Gag aggregate to spawn during the first

four months of the year, but the season remains open the remainder of the calendar year. The results below also hold for situations in which time allotments vary across periods.

Assume that the regulator implements a seasonal closure in period 2 but not in periods 1 or 3. I explore how the extent of the closure affects fishing effort decisions for three different values of the subsistence parameter. For each case, we optimize the model using Matlab's nonlinear constrained optimization routine (FMINCON). The results are depicted in Figure 6.

The primary lesson from this numerical simulation is that total fishing effort can increase, decrease, or remain the same in response to a seasonal closure. Fixing all other parameters, the effect of the closure on total fishing effort aggregated across all three periods depends on the extent of the closure and the subsistence requirement.

In all three cases, the seasonal closure has no effect on total annual fishing effort if the constraint on maximum period 2 effort does not bind (reductions that are less than 50% of the period 2 season). Fishermen essentially can substitute within period to maintain their optimal labor-leisure tradeoffs. While this result seems obvious once stated, it illustrates how managers cannot count on effort reductions in response to marginal changes in seasons. In a real fishery, the desirability to substitute within a period will be limited by weather conditions and other economic opportunities. Still, if one imagines an extreme case—say a single day closure in a two-month period— it is difficult to believe that fishing effort will not find an opportunity to substitute into another one of the open days.

For the region in which reduced period 2 effort binds, the three cases diverge qualitatively. When $C_t^{MIN} = 0.4$, subsistence never binds. As a result, total fishing effort is always lower than the baseline. This case corresponds to the conventional wisdom that effort declines with a seasonal closure. Nevertheless, it is important to note that fishermen substitute

some effort into periods 1 and 3; the substitution is just not enough to make up for the effort

reduction in period 2. Substitution occurs because the marginal utility of consumption in period 2

with the closure is higher than the marginal utility of leisure in other periods that could be

foregone in order to redistribute income to period 2. Thus, the standard management model

assumption that effort decreases proportionally to a seasonal closure is untenable.

When $C_t^{MIN} = 0.6$, subsistence always binds. That is, consumption in each period is the

subsistence level. In this case, total effort increases as the restriction on fishing effort in period 2

tightens. This phenomenon is due to the fact that fishing is less productive in period 3. Thus,

fishermen must more than compensate for reduced effort in period 2 with increases in periods 1

and 3.

When $C_t^{MIN} = 0.5$, subsistence only binds once fishing in period 2 is restricted by more

than 80%. Between a restriction of 50% and 80%, total effort declines. After 80%, total effort

starts to rise and eventually reaches a level that is higher than the baseline.

Either of the cases in which subsistence binds closely mirrors the empirical output in

which the coefficients on the closure dummies are positive and large enough to increase total

fishing effort (Smith et al. 2006). Thus, a simple utility-theoretic model can explain why total

effort increases in response to a seasonal closure. The theoretical model in equation (2) produces

this result without any costs of short-run borrowing. If one considers the possibility that short-

run borrowing is costly for fishermen, the empirical result emerges as an even more likely

outcome. In order to meet long-term capital debt service, e.g. boat payment and home mortgage,

as well as basic household expenses, a fisherman may incur short-run credit card debt during the

seasonal closure. To repay this debt and the associated interest, the fisherman needs to generate

more revenues in the periods after the closure than would have been required without the closure.

This is exactly what happens empirically, though there is no way to test directly the effect of short-run subsistence constraints in the current empirical modeling framework.

Most economists, and probably most fisheries managers, might express discomfort with the idea that if you constrain people more, they will fish more intensively. It may be easier to accept a subsistence constraint in a developing country context, for instance. But, is this reasonable for U.S. fishermen? One piece of supporting evidence that is somewhat orthogonal to our empirical analysis is how fishermen respond to questions about fishing in bad weather. In a 2005 mail survey of Gulf reef fish captains (46% response rate out of all registered permit holders), I find that 80% of fishermen agree or strongly agree with the statement "Seasonal closures force fishermen to fish in bad weather." Thus, reef fish fishermen in their own claims support the notion that a seasonal closure changes their marginal values.

Empirically, seasonality in prices also supports the mechanism that is operating in this theoretical explanation. Averaged over our sample period, gag price is 6.8% higher during spawning season than post-spawning. For just 2003, the spawning season premium is 5.2%. Thus, gag fishermen, in relative terms, are losing more revenue with a seasonal closure during spawning than if there were a closure some other time during the year. If fishermen really are attempting to meet some income target, the empirical pattern of price will exacerbate the total effort intensification.

Conclusion

The long-term goal of this research is to refine our understanding of which species are vulnerable to overexploitation and extinction by recasting vulnerability as a bioeconomic phenomenon and not just a biological one. To what extent will marine reserves, seasonal

closures, size limits, and other policies actually protect species at risk once we fully account for the behavioral responsiveness of fishing fleets? This paper takes an important step towards answering that question by rejecting the reductionist approach of fishery management models in which humans are assumed to be unresponsive to changing economic conditions. Instead, fishing mortality is made endogenous. All fisheries are coupled systems with biological and economic components, but whether explicit modeling of the economics is of first- or second-order importance is likely to depend on a wide range of factors. When will biological intuition alone be sufficient for protecting critical life stages, and when will economic forces trump this intuition? In this particular application, the behavioral response of fishermen is enough to undermine the intended outcome of a seasonal closure. This appears to results from both a direct response to the policy itself and the elastic effort response to any policy that grows stocks. The science of marine conservation currently knows little about these issues in general, but my application illustrates that conservation and economic behavior cannot be separated *a priori*. To harness the power of life history modeling for future marine conservation, it is essential to fill this knowledge gap.

References

Anderson, L.G. 1999. The Microeconomics of Vessel Behavior: A Detailed Short-Run Analysis of the Effects of Regulation. *Marine Resource Economics* 14:129-50.

Anderson, L.G. 2004. Open-access Fishery Performance when Vessels Use Goal Achievement Behavior. *Marine Resource Economics* 19:439-58.

Armsworth, P.R. 2001. Effects of Fishing on a Protogynous Hermaphrodite. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 568-78.

Berkeley, S. A., C. Chapman, and S. M. Sogard. 2004. Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes melanops*. *Ecology* 85:1258-1264.

Beverton, R.J.H. and S.J. Holt. 1957. On the Dynamics of Exploited Fish Populations. London: Chapman and Hall (reprinted in 1993).

Bockstael, N.E. and J.J. Opaluch. 1983. Discrete modeling of supply response under uncertainty: the case of the fishery. *Journal of Environmental Economics and Management* 10:125-37.

Botsford, L.W., J.C. Castilla, and C.H. Peterson. 1997. The Management of Fisheries and Marine Ecosystems. *Science* 277: 509-15.

Coleman, F.C., C.C. Koenig, G.R. Huntsman, J.A. Musick, A.M. Eklund, J.C. McGovern, R.W. Chapman, G.R. Sedberry, and C.B. Grimes. 2000. Long-lived reef fishes: the grouper-snapper complex. *Fisheries* 25:14-21.

Coleman, F. C., C. C. Koenig, and L. A. Collins. 1996. Reproductive styles of shallow-water grouper (Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. *Environmental Biology of Fishes* 47:129-141.

Conover, D.O. and S.B. Munch. 2002. Sustaining fisheries yields over evolutionary time scales. *Science* 297:94-96.

Curtis, R. and R.L. Hicks. 2000. The cost of sea turtle preservation: the case of Hawaii's pelagic longliners. *American Journal of Agricultural Economics* 82: 1191-97.

Eggert, H. and R. Tveteras. 2004. Stochastic production and heterogeneous risk preferences: commercial fishers' gear choices. *American Journal of Agricultural Economics* 86:199-212.

Heppell, S.S., H. Caswell, and L.B. Crowder. 2000. Life Histories and Elasticity Patterns: Perturbation Analysis for Species with Minimal Demographic Data. *Ecology* 81: 654-65.

Heppell, S.S., S.A. Heppell, F.C. Coleman, and C.C. Koenig. 2006. Models to compare management options for a protogynous fish. *Ecological Applications* 16(1):238-49.

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R.E. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J.Tegner, R.R. Warner. 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science* 293: 629-637.

Myers, R.A. and B. Worm, "Rapid Worldwide Depletion of Predatory Fish Communities," Nature 423, 280-283, 2003.

National Marine Fisheries Service (1999), *Our Living Oceans: Report on the status of U.S. living marine resources*. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-F/SPO-41

National Research Council, *Sustaining Marine Fisheries*, Washington, D.C.: National Academy Press, 1999.

Palumbi, S.R. 2004. Why mothers matter. *Nature* 430:621-22.

Pew Oceans Commission. 2003. America's Living Oceans: Charting a Course for Sea Change. A Report to the Nation. Pew Oceans Commission, Arlington, Virginia.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres, Jr.1998. Fishing Down Marine Food Webs. *Science* 279: 860-863.

Smith, M.D. (2002), "Two Econometric Approaches for Predicting the Spatial Behavior of Renewable Resource Harvesters," *Land Economics* 78(4), 522-538.

Smith, M.D. and J.E. Wilen. 2003. Economic Impacts of Marine Reserves: The Importance of Spatial Behavior. *Journal of Environmental Economics and Management* 46: 183-206.

Smith, M.D., J. Zhang, and F.C. Coleman, 2006. "Structural Econometric Modeling of Fisheries with Complex Life Histories," Working Paper.

United Nations Food and Agriculture Organization. 2000. *The State of the World Fisheries and Aquaculture*. online at http://www.fao.org/DOCREP/003/X8002E/x8002e00.htm.

Wilen, J.E. 2006. "Why fisheries management fails: treating symptoms rather than the cause." *Bulletin of Marine Science* 78(3): 529-546.

Wilen, J.E., M.D. Smith, D. Lockwood, and L. Botsford. 2002. Avoiding Surprises: Incorporating Fishermen Behavior into Management Models. *Bulletin of Marine Science* 70(2), 553-575.
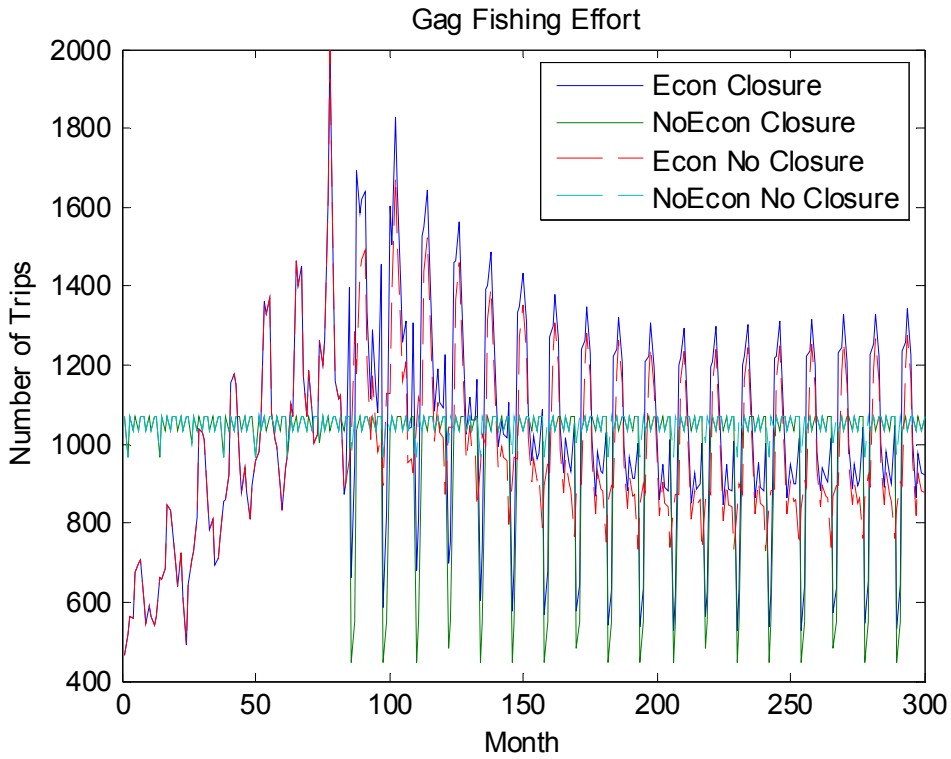
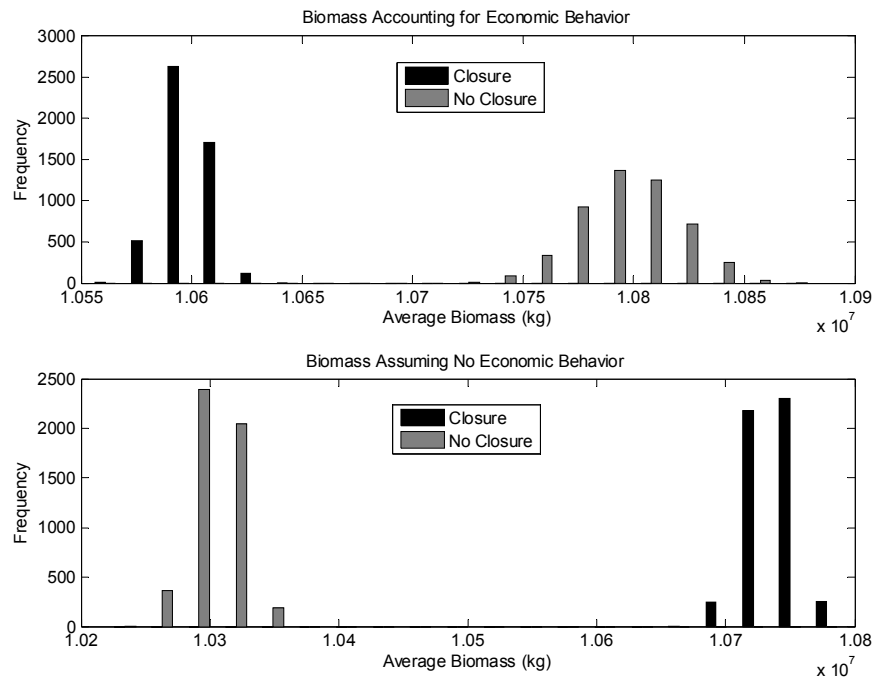**Figure 1 Dynamic Effect of the Seasonal Closure Policy – First 120 Months are In-Sample**
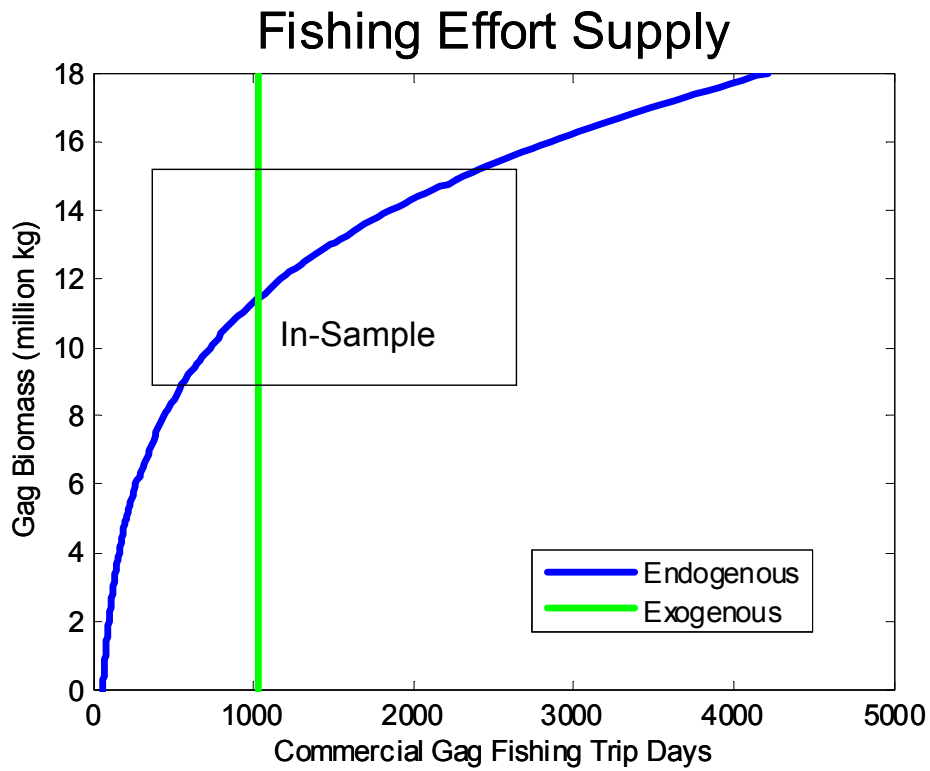
Figure 2 Biomass Sensitivity Analysis

Figure 3 Average Fishing Effort Supply in a Life History Management Model - With Endogenous Fishing Mortality Effort Supply is not Vertical
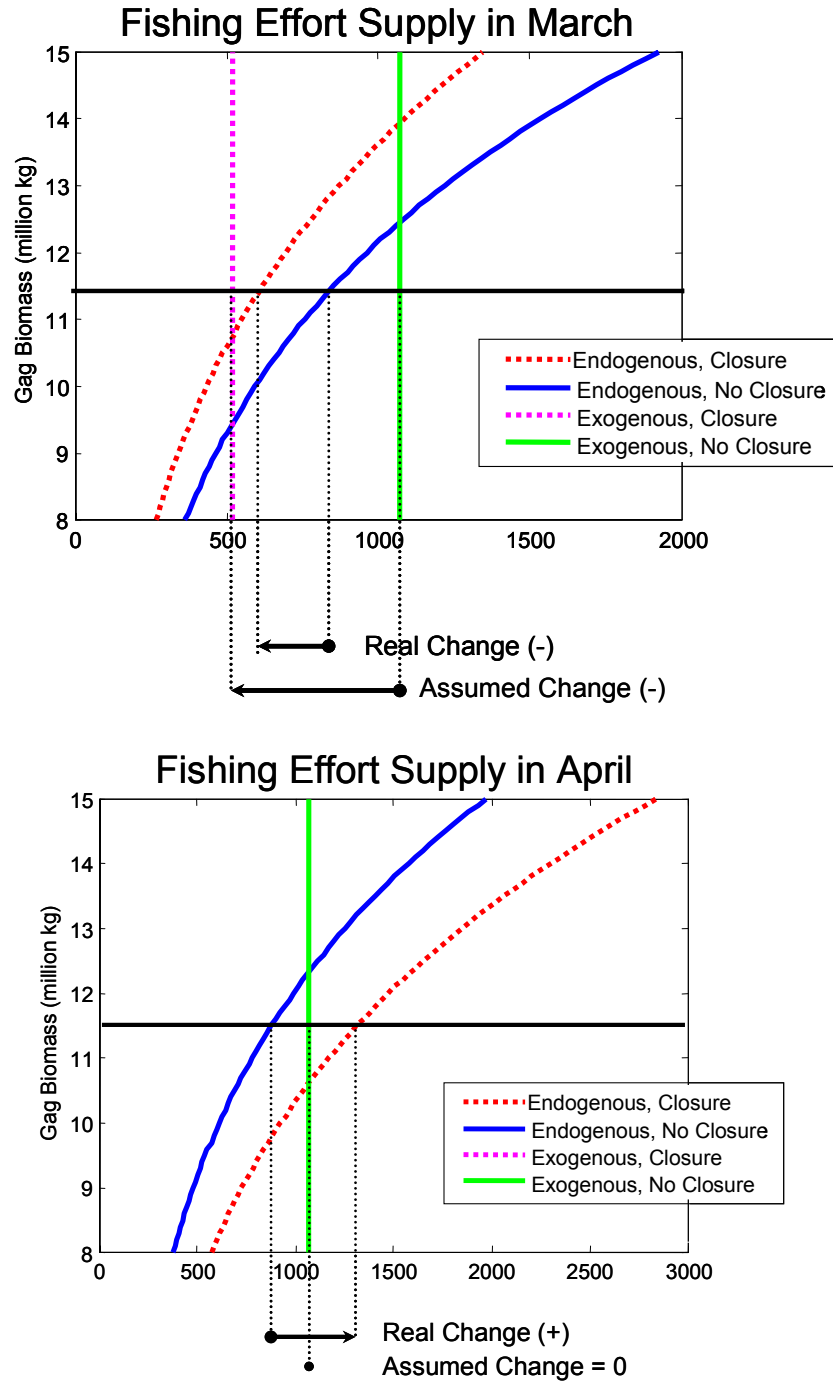
Figure 4 Fishing Effort Supply in a Life History Management Model During the Spawning Season – The x-axis reports predicted number of gag fishing trips in the month. The two panels show March (half of the month closed) and April (none of the month closed)
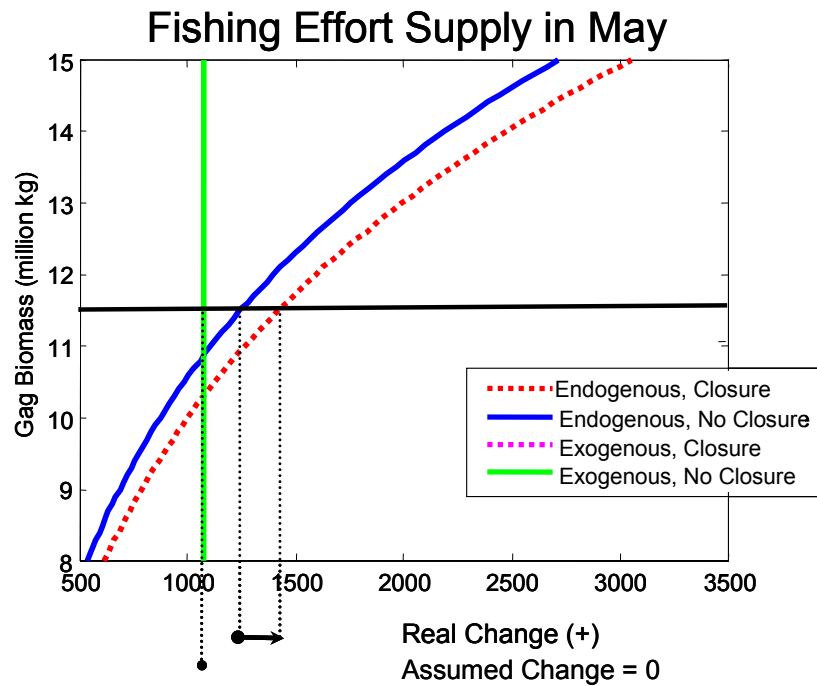
Figure 5 Fishing Effort Supply in a Life History Management Model After the Spawning Season – The x-axis reports predicted number of gag fishing trips in the month. The panel shows May (none of the month closed)
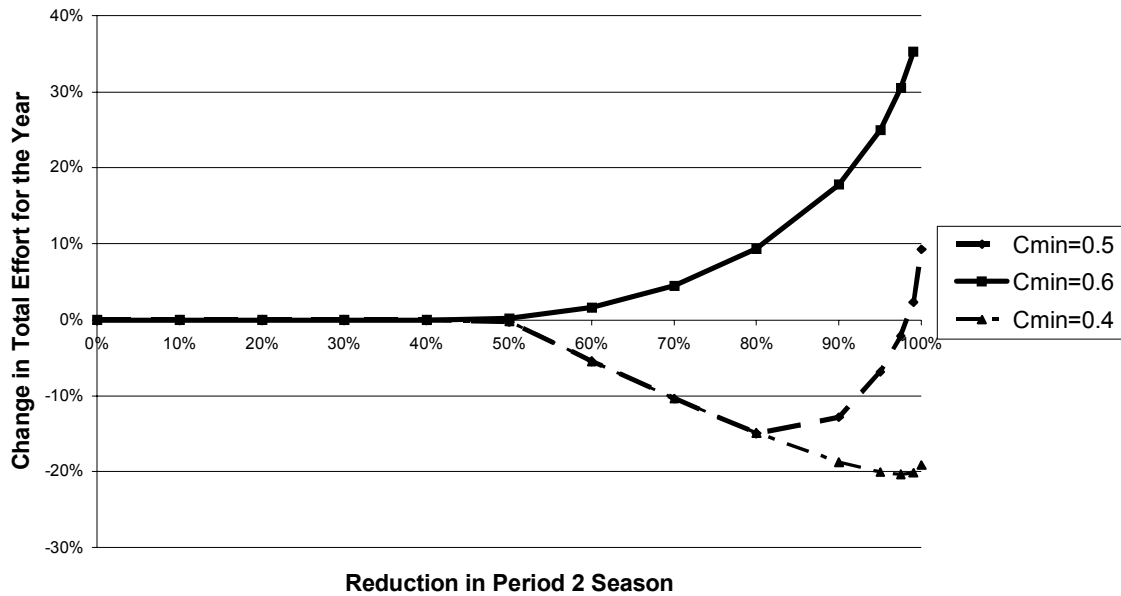
Figure 6 - A Possible Theoretical Explanation for the Empirical Results – Total Fishing

Effort in a Year Can Increase or Decrease in Response to a Seasonal Closure if Fishermen

Face Minimum Income Constraints

Table 1 - Bioeconomic Policy Simulation Using Point Estimates (from Smith et al. 2006)
Comparing 1-month Spawning Closure to No Closure
25 Years Total, 10 Years in-sample

	No Closure	Grouper Spawning Closure	Change	Qualitative Change
Modeling Economic Behavior				
Average Biomass (millions kg)	10.798	10.599	-0.199	-
Average Number of Big Fish (> 10 years)	66,160	64,387	-1,773	-
Total Catch (millions kg)	15.719	15.958	0.239	+
Total Trip Days	293,180	306,500	13,320	+
Weighted Catch Per Unit Effort	53.615	52.066	-1.549	-
Ending Percentage of Males (mature fish)	0.0616	0.0601	-0.002	-
No Economic Behavior				
Average Biomass	10.303	10.735	0.432	+
Average Number of Big Fish (> 10 years)	61,609	65,277	3,668	+
Total Catch	16.215	15.542	-0.673	-
Total Trip Days	315,650	296,980	-18,670	-
Weighted Catch Per Unit Effort	51.370	52.332	0.962	+
Ending Percentage of Males (mature fish)	0.0603	0.0633	0.003	+