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Size and Bag Limits in Recreational Fisheries: Theoretical and Empirical Analysis

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Abstract *Size and bag limits are among the most common forms of regulations for recreational fisheries. In this paper, we theoretically study and compare the short- and long-term impacts of these policies on individual anglers and fish stocks. Particular attention is paid to the issue of release mortality, which can have important consequences for policy effectiveness. Theoretically, we show the conditions under which these policies will be successful in achieving biological objectives. Implications for recreation demand analysis are discussed. We also study these policies using a simulation model of various policy combinations for the Gulf of Mexico red snapper fishery.*

Key words Fisheries management, size limits, bag limits, recreational fishing, simulation modeling.

JEL Classification Codes Q22, Q26, Q28.

Introduction

Limits on the total catch per day or trip (bag limits), and restrictions on the minimum size of fish that can be retained (size limits) are among the most widely utilized regulations in recreational fisheries. These policies are designed to reduce fishing mortality, improve fish stocks, and, in the long run, improve or sustain a quality fishing experience for anglers. To understand the effectiveness of these policies, one must recognize how they alter the incentives that anglers face. The incentives created by these policies will inevitably have secondary impacts that can either complement or offset the policy's direct effect. For example, a bag limit might not only reduce the number of fish retained on a given trip, but might also change the number of trips that anglers take during the year. In this paper, we explore the individual and fishery-wide implications of size and bag limits.

Size- and bag-limit policies, though widely used, have received only limited treatment in the economics literature. Anderson (1993) considers the implications of bag limits and Homans and Ruliffson (1999) evaluate how size limits affect a fishery. This paper provides a unifying economic framework for the analysis of recreational fishing behavior. The model is sufficiently flexible to allow the consideration of not only size and bag limits, either independently or together, but could

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also be used for the analysis of other policies that might be considered.

In addition to the theoretical framework, we study these regulations in an empirical context: the recreational red snapper fishery of the Gulf of Mexico. Using the General Bioeconomic Fisheries Simulation Model (GBFSM) (Gillig, Griffin, and Ozuna 2001), we analyze alternative policy mixes in the fishery. While the theoretical model can give insights into the short-term responses of anglers and some sense of how the policy might perform in the long run, the simulation model allows the prediction of long-term consequences of the policy in an environment in which changes in the fish stock depend on complex biological growth functions in which the stock's age structure plays an important role.

In both the theoretical and empirical analyses, we pay particular attention to the issue of discard mortality. Mortality of fish that are not returned can have important consequences for the effectiveness of fishery policy. For example, when size limits are used, all fish below the limit cannot be legally retained. If a substantial portion of these released fish die prematurely, this will diminish the policy's effect on total fishing mortality and the consequent long-term benefits for the fishery.

Because of the difficulty in measuring release mortality, there is a high degree of uncertainty surrounding its magnitude. However, the limited evidence that is available suggests that it might be substantial. In catch-and-release bass fishing tournaments, Wilde (1998) estimates mortality at about 26%. When compared to freshwater fisheries, release mortality in deepwater might be higher as fish are hooked at greater depths and pulled rapidly to the surface, suffering rapid pressure changes. Harley, Millar, and McArdle (2000) put discard mortality for recreational gulf snapper at between 15 and 35%. Burns, Koenig, and Coleman (2002) report preliminary findings of release mortality in red snapper of 50% or higher for fish caught deeper than 35 meters and 60 to 70% for those caught at 40 to 60 meters.

Most fisheries models have equated total fishing mortality with the number of retained fish. Anderson (1993), who we draw on extensively, admitted the possibility of a nonunitary survival rate, but did not explore in depth the implications that this might have. Hence, one of the contributions of this paper is to demonstrate the importance of considering the issue of release mortality when designing fishery policies.

The paper is organized as follows. In the next section, we provide a general model of angler behavior and discuss the system-wide implications of their behavior in an open-access regime. We then consider the theoretical implications of bag and size limits, both independently and jointly. After developing the theoretical framework, we demonstrate the potential implications of these policies in the context of the red snapper fishery in the Gulf of Mexico. We conclude with a summary of our findings and suggestions for future research.

The Model

The foundation of our analysis is a representative angler's utility maximization problem. Following the standard practice in the recreation demand literature, we assume that an angler's utility is a function of the number of days spent fishing, d, and a composite good representing other goods purchased, x_0. In addition, we assume that the angler's utility is affected by the quality of the experience on the fishing day, $q(\cdot)$, which is a function of the number of fish retained or "landed," l, the average size of the retained fish, s, and the time per day spent fishing, t. The angler faces costs per fishing day, c, and has a fixed income of m that is used to pay for fishing trips and other goods. By assuming a fixed cost per day, our model is directly applicable only to cases where the angler is considering one site, or cases in which all alternative sites are indistinguishable in terms of both cost and quality.

We maintain a number of simplifying assumptions. Our model is deterministic and static over the course of a fishing year so that all variables can be chosen exactly and catch can be predicted *ex ante*. We assume that the angler treats the biological condition of the fishery as constant over the course of the year so that all trips during a year are viewed as identical. Furthermore, we ignore the possibility that the angler may discount trips at the end of the year relative to those at the beginning of the year. In addition, to make our analysis more tractable, we treat all variables as if they were continuous.

The angler's utility, $U(\cdot)$, is a function of the days fished, d, the quality of a day of fishing, $q(l, s, t)$, and consumption of a numeraire good, x_0. In practice, anglers certainly make decisions throughout the year as conditions change and their budgets are used up. Provencher and Bishop (1997) present an empirical model that explicitly addresses these issues. However, as they indicate, incorporating the intertemporal dynamics of the angler's problem substantially complicates the analysis and may not always be desirable. To keep us focused on what we see as some of the most important issues in angler choices, our specification aggregates over time, treating the choices that determine d and q as if they are made at beginning of the year.

Throughout our analysis we make the following assumptions on the curvature. We assume that $\partial q/\partial t > 0$ at $t = 0$ and $\lim_{t \to 24} \partial q/\partial t = -\infty$ so that the quality of a fishing day is maximized by fishing somewhere between zero and twenty-four hours per day. All other variables are assumed to positively affect the angler's utility; *i.e.*, U_x, U_q, q_l, and q_s are all non-negative.[1] We assume that U is linear in x_0 and that U and q are concave in all other arguments; *i.e.*, U_{qq}, q_{ll}, q_{ss}, q_{tt} are all nonpositive. We refer to these monotonicity and concavity assumptions jointly as $\mathbf{c_1}$. At times, we will also assume ($\mathbf{c_2}$) that $q_{st} = q_{lt} = 0$, although the results that use this assumption would also be satisfied as long as these cross-partial derivatives are small relative to the first derivatives.

In the absence of regulations, the representative angler's decision problem is to choose d, t, l, s, and x_0 to maximize U subject to a budget constraint and the limit that landings cannot exceed the number of fish harvested. We write this problem:

$$\begin{aligned} &\max U\left[d, q(h, l, s, t), x_0\right] \text{ s.t.} \\ &c \times d + x_0 \le m \\ &l \le h(t; X), \end{aligned} \tag{1}$$

where h is equal to the catch per day, which is a function of the time spent fishing on that day, t, and the fish stock, X.

This specification unifies the frameworks of Anderson (1993) and Homans and Ruliffson (1999). Anderson considers, in detail, a model in which tradeoffs between l and d are made. Homans and Ruliffson focus on tradeoffs between l and s. Both papers pay particular attention to the case where the two inputs are substitutes. Here we consider the more general problem, in which anglers choose all these inputs and the variables might be either substitutes or complements. Our specification is consistent with "restricted-choice" models of recreation demand in which "the

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[1] The notation U_x refers to the partial derivative of the function U with respect to x.

decisionmaker is viewed as deciding on the number of trips within a planning horizon where diminishing marginal utility is associated with increasing frequency of trips" (Bockstael 1995, p. 658).[2]

Like Homans and Ruliffson, we assume angler utility is affected by the size of retained fish, though we use a slightly different approach. Those authors assumed that utility is a function of the minimum size of the retained fish.[3] In our analysis, we define s as the average size of the retained fish. While the value of s is largely determined by the biological conditions in the fishery, it can also be influenced if the angler chooses to discard a portion of his or her catch. In the absence of such discards, we assume that the angler's average catch would be $s = \underline{s}(X)$, where $\underline{s}(X)$ is the average size of the fish harvested as a function of the stock.[4]

The magnitude of many policy impacts will depend on the size distribution of the fish. Following Homans and Ruliffson (1999), we will occasionally assume (**u**) that the size distribution of fish caught, $f(S|X)$, is uniform (0,1). A fish of size 0 would be the smallest catchable fish, while a fish of size 1 would be the largest. Under this assumption, the average size of the fish harvested is 0.5. This assumption is made primarily to make our analysis much more tractable and does not affect any of our results qualitatively.

Angler Behavior in the Absence of Regulations

Because l, s, and t are arguments of the subfunction q, the angler's utility function is weakly separable, and his or her optimization problem can be solved using two-stage planning. First, for each day that a fishing trip is taken, the angler must choose t, l, and s, defining the quality of a given fishing trip. Second, over the course of the year the angler must choose d, the number of trips to be taken during the year, and his or her other expenditures, x_0.

One of the tradeoffs that an angler must consider is between the number of fish landed and the size of the catch. For any level of t, the angler's harvests $h(t; X)$ are fixed, but the angler can choose to increase the average size of his or her remaining catch by discarding smaller fish.

Figure 1 presents the angler's choice between l and s. The constraint, $s = S(l, h; X)$, indicates the feasible combinations of l and s given that the angler has spent t hours fishing and caught $h(t; X)$ fish. For example, if assumption **u** holds, then $S(l, h; X)$ will be linear from $\bar{s}(X) = 0.5$ if $l = h$ and approaching 1 as l goes to zero. More generally, the tradeoffs will be nonlinear, but as long as it is possible to increase s by decreasing l, the slope will be negative as in the figure. From the feasible set of combinations of s and l, the angler will choose that one which maximizes $q(l, s, t)$ as indicated by the tangency in figure 1.

As noted by Anderson (1993), in general it would be useful to have both l and h in $q(.)$ since this would allow the consideration of catch-and-release fisheries. Although our model is not completely satisfactory as an explanation of voluntary

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[2] Following Hellerstein and Mendelsohn (1993), we distinguish between "restricted-choice" models, which treat the decision as one being made at the beginning of the season, and "repeated-choice" models, in which an angler makes a choice each day about whether or not to take a trip.

[3] While having some attractive features from a modelling perspective, this specification can lead to some counterintuitive results. For example, under their specification angler welfare could fall if that policy leads to a reduction in size of the smallest fish caught, even if the policy simultaneously increased both total harvests and average size.

[4] In general, anglers can also influence the size distribution through gear choices. Here, we assume that the gear is held constant so that the angler views the size distribution as exogenous.

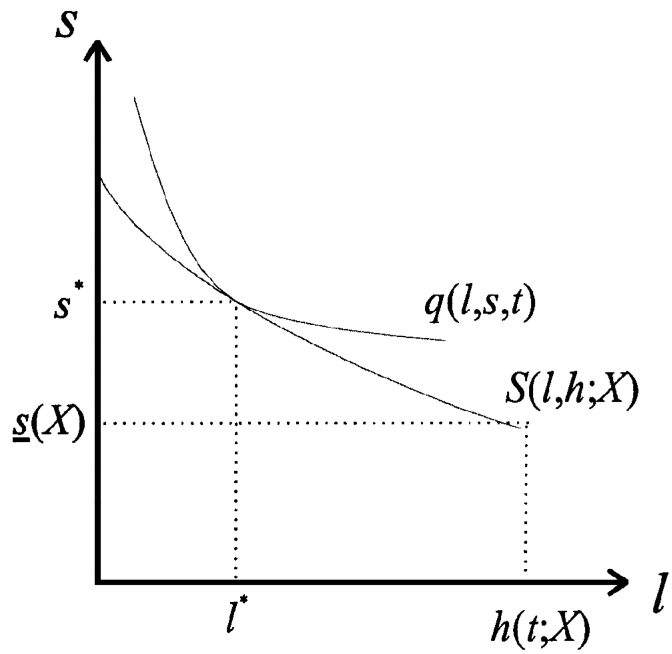

Figure 1. Tradeoffs Between the Number of Fish Landed and the Average Size

discards of all fish caught, it could be used to model the behavior of anglers who only seek to land large fish, characterized by a fisherman for whom the indifference curve is essentially horizontal. In contrast, anglers who only are interested in maximizing the total volume of the catch would have very steep indifference curves, so they choose to retail all fish no matter how small; *i.e.*, $l = h(t)$.

For an angler who discards part of his or her catch, the optimal levels of s and l are set at the tangency point where $q_l/q_s = -S_l$. If, however, $q_l/q_s > -S_l$, even when evaluated where $l = h$ and $s = \underline{s}(X)$, then a corner solution is optimal and the angler will choose to retain all fish, regardless of their size. We will call such an angler *quantity focused*, and the angler's landings and catch-size can be written as functions of $h(t)$, $l^*[h(t)]$, and $s^*[h(t)]$. In either case, the optimal quality of a fishing day can be written as a function of $h(t)$, $q(l^*, s^*, t) = q^*[h(t)]$.

Changes in t have two implications for the quality of a fishing day. First, t enters $q(\cdot)$ directly, eventually negatively as the length of the day approaches 24 hours. Second, t enters $q(\cdot)$ indirectly, increasing $h(t)$ and making possible higher levels of l, s, or both. Assuming q_{lt} and q_{st} equal zero, assumption $\mathbf{c_2}$, we can cleanly separate the marginal impact of changes in t into these two effects, $\partial q/\partial t = [(\partial l/\partial h) + (\partial s/\partial h)](\partial h/\partial t) + q_t = q_h^* h_t + q_t = 0$, where q_h^* is the marginal impact of h on q assuming optimal choices of s and l. For interior optima, the quality of a trip is maximized when $q_h^* h_t = -q_t$, as presented in figure 2.

Under the separable specification that we have assumed, anglers will seek to maximize q regardless of how many days are fished during the year. Hence, choices defining the levels of d and x_0 can be made contingent on the optimal level of q. From the first-order condition with respect to x_0, it follows that at the optimum, U_x equals the shadow price on the budget constraint. Dividing $U(\cdot)$ by U_x, we obtain a

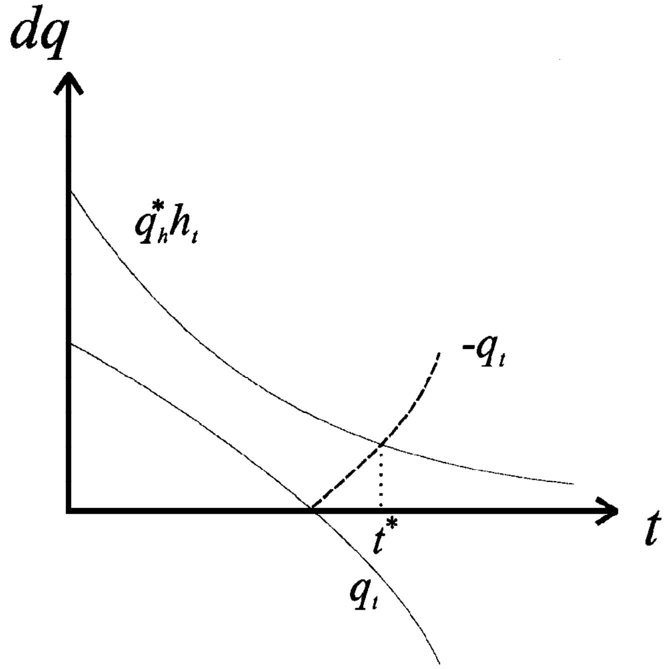

Figure 2. Marginal Changes in *q* with Changes in *t*

money-metric function, $u[d, q(l, s, t)]$, which indicates the total willingness to pay for *d* trips. The angler's optimization problem, therefore, can be written:

$$\max u\left[d, q(\ )\right] + u_0 x_0 \text{ s.t.} \tag{2}$$

$$c \quad d + x_0 \leq m$$

$$l \leq h(t; X).$$

When the assumptions $\mathbf{c_1}$ hold, analogous concavity conditions are also satisfied for *u,* and the optimal number of days fished, d^*, is defined by the first-order condition:

$$\frac{\partial u\left[d^*, q(\ )\right]}{\partial d} - c \equiv 0. \tag{3}$$

That is, the angler will take additional trips until the willingness to pay for an additional trip is equal to the travel cost.

Discard Mortality and Bioeconomic Equilibrium

We assume that natural growth, g, and natural mortality, m, are functions of the stock so that net natural growth can be written $G(X)$.[5] From year to year, the stock evolves according to the equation:

$$\Delta X = G(X) - \sum_i d_i l_i - \varphi \left\{ \sum_i d_i \left[h(t_i, X) - l_i \right] \right\}, \tag{4}$$

where i is the index of anglers active in a given year. The parameter φ is the rate of release mortality so that the final term in equation (4) is the total discard mortality. The bioeconomic equilibrium occurs when natural net growth equals fishing mortality; *i.e.*,

$$G(X) = \sum_i d_i \left[l_i + \varphi (h_i - l_i) \right]. \tag{5}$$

Since individual anglers ignore the stock externality, the equilibrium stock will be lower than would be economically optimal.

Regulations on an Open-access Recreational Fishery

We now consider the theoretical implications of bag and size limits in a recreational fishery. We look at the effect on angler welfare, fishing effort, and fishing mortality. Per-trip, annual, and long-term impacts are evaluated. We explore these policies separately and then compare those results with a joint policy in which both size and bag limits are used.

Policies that Improve Trip Quality

Many fishery policies are, in the long run at least, intended to improve the quality of anglers' fishing experiences. Since $\partial u / \partial d$ is the marginal willingness to pay for an additional fishing trip, we write $WTP = \partial u / \partial d$. The impact of a policy change that results in increases, q, can be identified by taking the derivative of equation (3) with respect to q^*:

$$\frac{\partial^2 u}{\partial d^2} \frac{\partial d}{\partial q} + \frac{\partial^2 u}{\partial d \partial q} = \frac{\partial WTP}{\partial d} \frac{\partial d}{\partial q} + \frac{\partial WTP}{\partial q} \equiv 0,$$

[5] In some cases, size and bag limit policies are designed to target specific cohorts of the fish population. In our theoretical model, we abstract from such targeted impacts, characterizing their impact as a homogeneous effect on stock. The simulation model we use in the final section of this paper does model the cohort-specific impacts.

which can be simplified to:

$$\frac{\partial d}{\partial q} = -\frac{\dfrac{\partial WTP}{\partial q}}{\dfrac{\partial WTP}{\partial d}}. \tag{6}$$

By the concavity of the utility function, we know that the denominator on the right-hand side of equation (6) is less than zero. Our first proposition follows:

> Proposition 1: Assuming $\mathbf{c}_1$, a policy that increases the quality of a fishing trip will lead to an increase (decrease) in trips taken if the WTP for additional trips is positively (negatively) affected by trip quality.

Although it might at first seem automatic that WTP would increase with q, this only holds if q and d are complements. However, it is also plausible that they might be substitutes. For example, q and d would be substitutes if anglers simply seek to maximize their annual catch so that improvements in the catch rate would increase q but decrease the number of trips taken per year. Furthermore, q and d might be substitutes at the margin, but not necessarily at all points on the demand curve. For example, an improvement in the catch rate could increase an angler's WTP for the first trips of the year while decreasing the WTP for trips later in the year. That is, changes in quality may cause the WTP curve to rotate rather than shift. Hence, for policy analysis it is important that estimates of recreation demand functions capture the effect of quality on both the function's height and its slope.

Proposition 1 has important implications for the effectiveness of policies. If q and d are complements, then a policy that reduces fishing effort per day, as is sought in bag and size limits, will be reinforced by additional declines in the number of fishing days desired. Alternatively, if they are substitutes, then the net effect of the policy will be dampened because the reduction in fishing per day will be offset by an increase in the number of trips taken.

Bag Limits

A bag limit is a mandatory restriction that places an upper limit on the number of fish that an angler can retain during a fishing trip, say $\bar{l}$. Excluding the possibility of direct cheating, which would lead to no change in harvest or fishing mortality, there are four possible ways that an angler can comply with the letter (though not necessarily the spirit) of a bag limit. First, an angler may comply simply by stopping his or her fishing when the bag limit has been reached. Second, the angler may discard smaller fish as they are caught to fill his or her limit with larger fish. Third, anglers can high-grade their catch by disposing of smaller fish caught early in the day when a later catch causes the angler to exceed the legal limit. We assume that high-grading leads to 100% mortality of discarded fish. Finally, anglers fishing as a group could share their limits so that a group of m anglers effectively face a joint limit of $m\bar{l}$ fish and adopt any of the previous approaches as a group.[6] Each of these re-

[6] This case will not be considered in detail but can be thought of as a linear extension of the model of a single angler.

sponses to the bag limit policy would have different consequences for total fishing mortality and the angler's net benefits per trip.

Simple compliance leads to a reduction in fishing mortality per trip by $h^* - \bar{l}$, but no change in s. This approach leads to a decrease in fishing time per day, and q and will cause a change in days per year depending upon the sign of $\partial WTP/\partial q$, as noted in Proposition 1. The effect on q of a strategy of simple compliance is demonstrated in figure 3 by the shift from l^*, s^* to $\bar{l}, s^*$. However, if q is increasing in s, simple compliance would not be optimal, and the angler's optimal response would be to improve the quality of a fishing day. This would be accomplished by discarding the smaller fish caught, increasing the average size to s^b, and moving the angler to the indifference curve labeled $q(\bar{l}, s, t)$. Unless stated otherwise, from here on we will assume anglers follow the second approach and comply with a bag limit by discarding their smallest fish.

If $F(x|X)$ is the cumulative size distribution of the fish caught, then the minimum size of the retained fish would be s', where:

$$F(s'|X) = (h - \bar{l})/h\,, \tag{7}$$

and the average size of the retained fish, s^b, would be:

$$s^b = \frac{h}{\bar{l}} \int_{s'}^{\infty} x \quad f(x)dx, \tag{8}$$

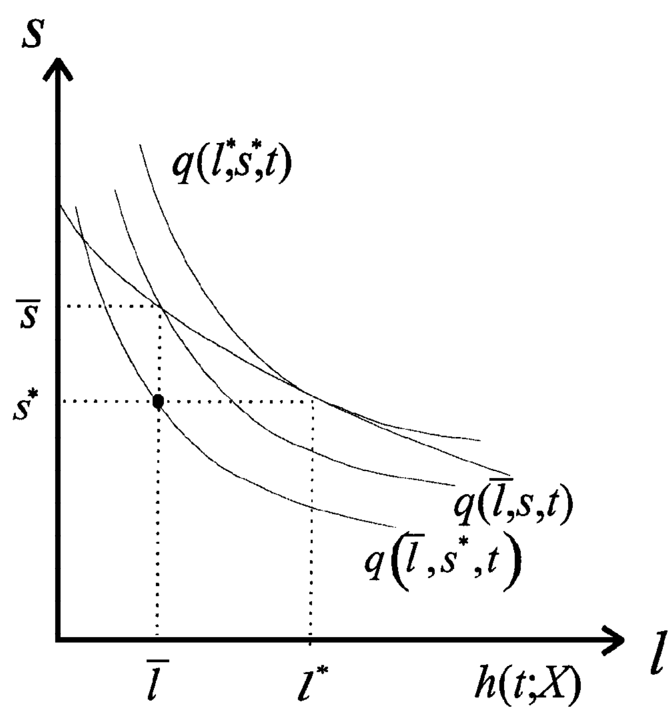

Figure 3. Tradeoffs Between the Number of Fish Landed and the Average Size under a Bag Limit Policy

where $f(\cdot)$ is the probability density function of the size of fish caught. Using assumption **u** that the size of the harvest is distributed uniformly (0,1), these simplify to $s' = (h - \bar{l})/h$ and $s^b = 1 - (\bar{l}/2h)$. Hence, under a binding bag limit, the angler's optimal landings are equal to $\bar{l}$, and s^b can be written as a function of $\bar{l}$ and $h(t)$. The optimal level of t will be achieved where:

$$\frac{\partial q}{\partial s}\frac{\partial s^b}{\partial h}\frac{\partial h}{\partial t} = -\frac{\partial q}{\partial t}, \tag{9}$$

and s^b is defined by equation (8).

A marginal reduction in $\bar{l}$ will affect the angler's quality maximization problem by increasing s and decreasing $\partial q/\partial s$. It follows that increasing harvests will increase q at a lower rate than in the unregulated fishery; *i.e.*,

$$\frac{\partial q}{\partial s}\frac{\partial s^b}{\partial h}\frac{\partial h}{\partial t} < \frac{\partial q^*}{\partial h}\frac{\partial h}{\partial t}.$$

This effect is represented in figure 4 in which the marginal benefit curve (the dashed line) kinks downward as a result of the bag limit. If $\mathbf{c}_2$ holds, then the bag limit does not affect q_t, and the downward shift in $q_h q_t$ will lead to an unambiguous decline in the optimal level of t.

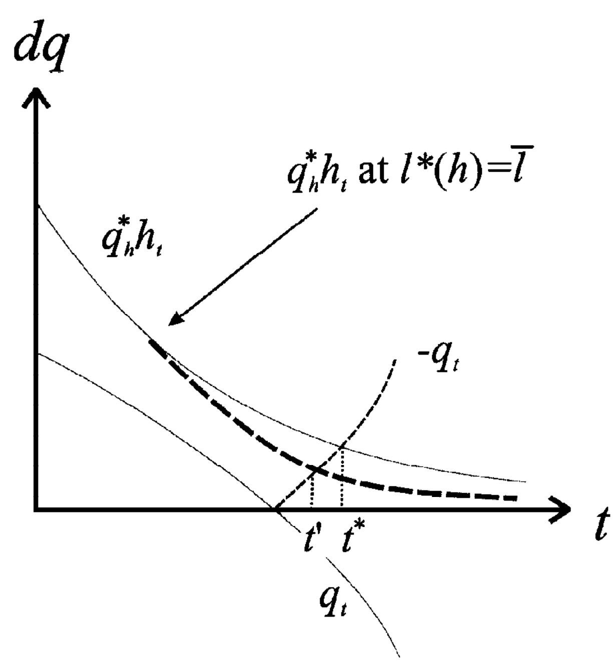

Figure 4. Marginal Changes in q due to Changes in t Under Bag Limit

PROPOSITION 2: Assuming $\mathbf{c}_1$ and $\mathbf{c}_2$, a bag limit will reduce the fishing time of an angler who discards smaller fish to comply with the regulation.

If $\mathbf{c}_2$ does not hold, then it is possible that the direct effect of time on q will also change, possibly decreasing the rate of decline in q as t increases, potentially offsetting the impact suggested in Proposition 2. For example, $\mathbf{c}_2$ would not be satisfied if q_t falls as the angler catches more fish. The effect of the bag limit on fishing time cannot be predicted *a priori* if $q_{tl} < 0$ or $q_{ts} > 0$.

From Propositions 1 and 2, it follows that if $\mathbf{c}_1$ and $\mathbf{c}_2$ hold and q and d are complements, then a bag limit will decrease both the time spent fishing per day and the angler's annual number of trips.

The biological impact of a bag limit depends on the release mortality rate, φ, and on how the regulation affects $h(t)$, l, and d. At one extreme, if $\varphi = 0$, then daily fishing mortality will unambiguously decline for a binding bag limit. At the other extreme, if $\varphi = 1$, or if the angler high-grades to satisfy the bag limit, the restriction will still cause a reduction in daily fishing mortality as long as t falls. In general, fishing mortality will decline if effort falls and will increase only if $h(t^*) - \bar{l} < \varphi[h(t') - \bar{l}]$. On an annual basis, the total fishing mortality can increase if the bag limit results in an increase in $d \cdot h$.

The long-term effectiveness of a bag limit is a function of the restriction's impact on total mortality. The short- and long-term consequences of a bag limit are summarized in table 1. For example, if q and d are complements, then the short-term impact of the policy is to diminish fishing mortality, though the impact is offset somewhat in the long-term as demand increases in response to improvements in the stock. However, when q and d are substitutes, both the short- and long-term consequences of the policy are uncertain, and it is possible for an unstable outcome to result. Although we view it as unlikely, it is possible for the bag limit to cause anglers to increase their trips over time as the stock falls, a situation that could even lead to the collapse of the fishery.

Table 1
Short- and Long-term Impacts of Bag Limits

		Short-term Effects			Long-term Effects (relative to short-term levels, not relative to pre-regulation levels)			
Relationship Between q & d	**c2** Holds	Fishing Time Per Trip	Trips Per Year	Harvests Per Year†	Stock Effect*	Harvest Per Trip	Trips Per Year	Effort/ Year
Complements	yes	↓	↓	↓	+	↑	↑	↑
Complements	no	?	↓	↓?	+	↑	↑	↑
Substitutes	yes	↓	↑	?	+ / –	↑ / ↓	↓ / ↑	?
Substitutes	no	?	↑	?	+ / –	?	↓ / ↑	?

† The symbol ↓? indicates that we expect the change to be negative, but it could be positive if $q_{tl} < 0$ or $q_{ts} > 0$.
* The notation +/– indicates that the stock effect might be positive or negative. The remaining columns are then divided if it is possible to distinguish the differential impacts of positive and negative changes in the stock.

Size Limits

The second policy that we consider is the use of size limits, where an angler can retain a fish only if it exceeds a minimum size. There are a number of characteristics of size limits that distinguish them from bag limits. First, bag limits affect only the most successful fishermen, while size limits tend to affect all participants in the fishery. Second, under a size limit an angler knows immediately whether a fish caught can be legally retained. Finally, the effect on total mortality is less certain since anglers may compensate for discarded fish by harvesting additional fish. Our attention is on this final aspect of the policy.

If the smallest fish that can be retained is of size $\underline{s}$, then $F(\underline{s})$ is the portion of the harvested fish that has to be discarded. Hence, $l^s \leq [1 - F(\underline{s})]h(t)$, and the average size of the retained fish will be $\underline{s}' \geq \int_{\underline{s}}^{\infty} s\, f(s)/[1 - F(\underline{s})]\, ds$. If assumption **u** holds, these terms are greatly simplified, for in this case $\underline{s}$ is also the portion of fish discarded so that $l^s \leq (1 - \underline{s})h$ and $\underline{s}' \geq (1 + \underline{s})/2$. We consider the case of an angler for whom $s^* < \underline{s}'$; *i.e.*, for whom the size restriction is a binding constraint.

The angler's quality maximization problem in this case is presented in figure 5. As is seen in the figure, prior to a change in *h*, a size limit will lead to a reduction in landings and a decline in *q*. In this case, however, it is more difficult to anticipate how the angler will change *t* in response to the policy.

Under a binding size limit, the angler's quality optimization problem is:

$$\max_t q\left\{\left[1 - F(\mathbf{s})\right] \ h(t), \mathbf{s}', t\right\},$$

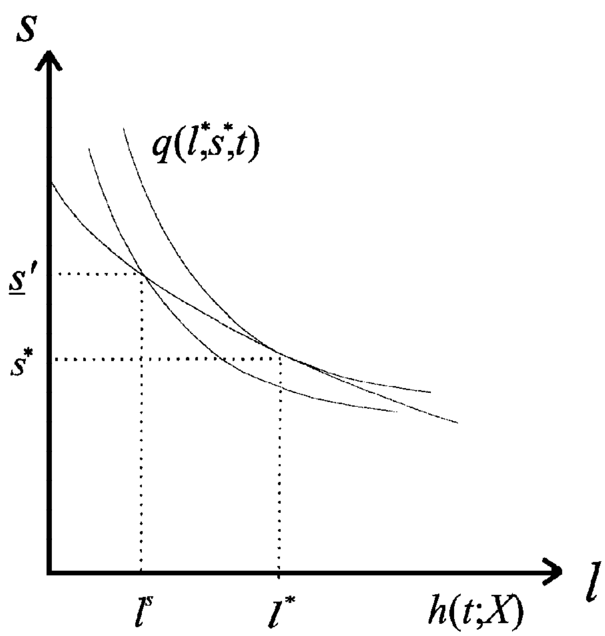

Figure 5. Tradeoffs Between the Number of Fish Landed and the Average Size Under a Size Limit

and the first-order condition to this optimization problem is:

$$q_1 \quad h_t\left[1 - F(\underline{s})\right] = -q_t. \tag{10}$$

In the case of a bag limit, under fairly weak conditions we can predict that its effect on daily fishing time is unambiguously negative. This is possible since the bag limit tends to increase s, diminishing the marginal utility of further increments to s and causing the curve in figure 4 to rotate downward. In contrast, under a size limit, its initial effect is to decrease l, since a smaller fraction of the harvested fish can be retained, increasing $\partial q/\partial l$ as seen in figure 5. Hence, although the term $[1 - F(\underline{s})]$ decreases in $\underline{s}$, the net effect on the left-hand side of equation (10) and the optimal level of t are not immediately clear.

Equation (10) indicates that an angler faced with a size limit will choose to stop fishing when the marginal improvement in q achieved by increasing l is equal to the marginal reduction in q caused by increments to t. Assuming $\mathbf{c_2}$, the right-hand side of equation (10) will not be affected by a marginal change in $\underline{s}$. Hence, the optimal level of t will decline if the left-hand side decreases; *i.e.*, if:

$$\partial \frac{q_l \quad h_t\left[1 - F(\underline{s})\right]}{\partial \underline{s}} < 0. \tag{11}$$

Simplifying equation (11) using $\partial F(\underline{s})/\partial \underline{s} = f(\underline{s})$ and $l = h[1 - F(\underline{s})]$, we see that an increase in the size limit decreases fishing time if:

$$\frac{-q_{ll}}{q_l}\, l < 1. \tag{12}$$

The left-hand side of equation (12) is analogous to a coefficient of relative risk aversion, a measure of how tightly concave q is in l, which we will refer to as r_q. If r_q is large, then as l is reduced this causes increasingly large declines in q. In other words, if $r_q > 1$, then as l declines because of a size limit, anglers are willing to make increasingly large sacrifices in time to maintain their landings.

> Proposition 3: Under assumptions $\mathbf{c_1}$ and $\mathbf{c_2}$, a marginal increase in the size limit will decrease daily fishing time if $r_q = (-q_{ll}/q_l)l < 1$.

Here we see that for policy analysis, it is important to understand the curvature of the function that determines the quality of a fishing day, a feature that merits attention in applied recreation demand analysis. Our attention to fishing time is motivated, in part, by the fact that this is a major contributor to fishing mortality if $\varphi > 0$. Under a size limit, an angler's annual contribution to total fishing mortality is equal to $d \cdot \{[1 - F(\underline{s})]h(t) + \varphi F(\underline{s})h(t)\}$. For $\varphi > 0$, fishing mortality is increasing in d and t, and decreasing in $\underline{s}$. For high levels of φ with $r_q > 1$, it is possible for the size restriction to actually lead to an increase in total mortality.

Table 2 presents the short- and long-run consequences of size limits. We see a sharp contrast between the possible outcomes here and those for bag limits presented in table 1. In this case, there is a much greater chance that the policy might actually have deleterious effects on the fish stock. If $r_q > 1$ and q and d are substitutes, we find that an increase in the size limit will actually cause an unambiguous increase in total fishing effort during the year and a subsequent increase in harvests.

The effect on annual landings cannot be predicted *a priori*, but if release mortality is sufficiently high, the policy might cause an increase in fishing mortality and, therefore, a decline in the fish stock.

Comparison of Size and Bag Restrictions

In principle, either bag limits or size limits can achieve any goal in terms of total landings. Questions remain, however, about which policy results in less fishing mortality and which is less costly. It turns out that in terms of their effects on fishing effort, bag limits are always at least as effective as size limits and are frequently preferred by anglers.

First consider the case of a size limit policy, $\underline{s}$, and a bag limit policy of $\underline{l}$, which are set so that they result in the same number of fish being landed in each policy. Recall that under either policy the angler's optimal choices involve equating the marginal benefits of increasing t, which makes possible increases in s or l, with the direct effect of t on q, which is negative at the optimum. These optima are defined by equations (9) and (10). The left-hand side of each equation is the indirect marginal benefit of increasing t and the right-hand side is the direct marginal cost. Let t^s be the optimal time under the size limit $\underline{s}$, so that equation (10) holds when evaluated at t^s. In order for the bag limit to yield equivalent landings, it must be that $\underline{l} = [1 - F(\underline{s})]h(t^s)$.

The two policies will yield identical outcomes only if equation (9) also holds when evaluated at t^s or, setting the left-hand sides of equations (9) and (10) equal, if:

$$\frac{\partial q}{\partial s}\frac{\partial s^b}{\partial h}\frac{\partial h}{\partial t} = \frac{\partial q}{\partial l}\frac{\partial l^s}{\partial h}\frac{\partial h}{\partial t}, \tag{13}$$

Table 2
Short and Long-term Impacts of an Increase in Size Restrictions

		Short-term Effects			Long-term Effects (relative to short-term levels, not relative to pre-regulation levels)			
Relationship Between q & d	$r_q < 1$ †	Fishing Time Per Trip	Trips Per Year	Harvests Per Year	Stock Effect‡	Harvest Per Trip††	Trips Per Year	Harvests Per Year
Complements	yes	↓	↓	↓	+	↓	↑	?
Complements	no	↑	↓	?	+ / –	↓ / ↑	↑ / ↓	?
Substitutes	yes	↓	↑	?	+ / –	↑ / ↓	↑ / ↓	↑ / ↓
Substitutes	no	↑	↑	↑	–?	↑	↑	↑

Note: Symbols are described in table 1.
† We do not present the case where $r_q = 0$, in which case time per trip would not change.
‡ The symbol –? indicates that the impact on the stock would be negative for a sufficiently high value of φ. For $\varphi = 0$, the policy can never cause an increase in fishing mortality.
†† We assume that a decrease in effort per year leads to a shift in the size distribution so that fewer undersize fish are caught and discarded, leading to a reduction in harvests per trip.

with both sides evaluated at t^s. Suppose that this does not hold, and instead that $q_s s_h^b h_t < q_t$ at t^s. In this case, the bag-limit constrained angler will choose to fish less than t^s. Hence, the bag limit would result in a lower level of harvests, lower fishing mortality if $\varphi > 0$, less fishing time, and an improvement in q. The nature of preferences for which anglers choose to fish less under a bag limit than under a size limit can be seen more clearly by considering the specific case when we assume **u**. As shown in the Proposition A1 in the appendix, assuming $\mathbf{c_1}$ and $\mathbf{c_2}$, quantity-focused anglers will always choose to fish less under a bag limit than under the equivalent size limit. Although we cannot show this point completely, the principle is that when anglers have a relative preference for l, bag limits tend to be more effective than size limits in reducing effort.

Now consider the alternative case, where $q_s s_h^b h_t > -q_t$; *i.e.*, the angler facing a bag limit would choose $t > t^s$ and retain fish that are larger than $\underline{s}$. This case would violate the assumption that t^s is optimal for the size-limit constrained angler, since it means that holding h constant the angler would prefer to retain fish that are strictly larger than $\underline{s}$. Hence, it is not possible for a size limit to lead to the same level of l but less time fishing than a bag limit. We summarize these results in the following proposition.

> Proposition 4: Assuming $\mathbf{c}_1$ and $\mathbf{c}_2$, for bag limit and size limit policies that lead to the same level of landings, the angler's fishing time per day, minimum size of retained fish, and the resulting release mortality will all be at least as great under a size limit as they are under a bag limit. Angler welfare will be at least as great under a bag limit as it is under a size limit.

Proposition 4 suggests that bag limits are preferred to size limits as a way to achieve a reduction in fishing mortality. We should point out, however, that our model ignores some reasons that are frequently given for size limits. Cohort-dependent growth and an interest in promoting trophy-sized fish are two factors that are often stated for the use of size limits, and such factors should not be ignored. Nonetheless, our analysis does suggest that size limits are a relatively ineffective way of reducing total fishing mortality, and this should also be taken into account in forming policies.

Joint Size and Bag Limits

In many fisheries, both bag and size limits are utilized. This combination of policies has some interesting consequences. In particular, in a fishery in which a bag limit already exists, the introduction of a size limit would mean that the angler would have to increase effort to reach the bag limit. Hence, if $\varphi > 0$, the addition of the size limit can actually induce an increase in fishing mortality.

In practice, the primary impact of the joint regulations may be to add a size restriction on anglers who are otherwise unrestricted because they fail to reach their bag limit. For anglers who are not currently reaching their bag limit, only the size limit regulation will be a binding constraint. Therefore, their response will be equivalent to that discussed above. The joint policy is most interesting when either constraint would be binding by itself.

We consider the case of an angler who would be bound by either a bag limit of $\underline{l}$ or a size limit of $\underline{s}$ when those regulations are imposed separately. Suppose the angler is initially constrained by a bag limit, $\underline{l}$, and chooses to discard all fish smaller than s'. A size limit, $\underline{s} > s'$, is then imposed. If the angler's effort does not increase, the bag-limit constraint would no longer be binding, as more fish must be discarded as a result of the size limit. If the angler reacts to the new restriction by increasing t, harvesting and discarding more fish, total fishing mortality can increase. The question is under what conditions will the angler respond by increasing effort.

Under a bag limit, the optimal amount of time spent fishing, t^b, is defined by the first-order condition, equation (9), $q_s s_h^b h_t = -q_t$. Holding t constant at t^b, the immediate effect of imposing a bag limit will be to increase s and decrease l, meaning that the bag limit will no longer be binding. From this point, the marginal benefit of increasing t is equal to the left-hand side of equation (10), $q_l \cdot h_t[1 - F(\underline{s})]$. If this marginal benefit is greater than $-q_t$, both evaluated at t^b, then the angler will increase his or her fishing time per day. This will hold if the left-hand side of equation (10) is greater than the left-hand side of equation (9), both evaluated at t^b; *i.e.*, if:

$$q_l \frac{\partial l^s}{\partial h} > q_s \frac{\partial s^b}{\partial h}. \tag{14}$$

Again we can obtain clearer results about the conditions under which this is true by assuming **u**.

> PROPOSITION 5: Under assumptions $\mathbf{c}_1$, $\mathbf{c}_2$, and **u**, a quantity-focused angler whose landings are bound by a bag limit, will react to the imposition of a marginally binding size limit by increasing his or her fishing time. If q_l is bounded from above, fishing time will eventually be reduced as the size limit increases.

The proof is provided in the appendix.

Proposition 5 is obviously much weaker than Proposition 4. Under most conditions, we cannot sign the change in fishing effort that would result from the addition of a size limit to a fishery already constrained by a bag limit. While the intuition would remain the same under more general size distribution, the proposition strictly holds only for the uniform case (**u**). The proposition does show us, however, that at least in some cases the addition of a size limit can cause an increase in fishing effort. If the angler's effort increases to the point where the bag limit is again reached, then for $\varphi > 0$, the size limit will cause an unambiguous increase in fishing mortality.

Summary of the Theoretical Model

The theoretical model that we have explored provides a general framework in which size and bag limit policies can be evaluated. The model leads to testable hypotheses that are stated as propositions. As emphasized in the tables, the implications of policies are strongly influenced by two characteristics of the angler's demand: whether fishing quality, q, and the annual number of days, d, are complements or substitutes; and by the curvature of $u(\cdot)$ and $q(\cdot)$. These results suggest important areas for emphasis in future empirical recreation demand modeling.

From the theoretical model, we find that because of the potential role of discard mortality, size limits may be less effective in reducing fishing mortality than bag limits. When imposed on top of a bag limit, a size limit could even lead to an increase in fishing mortality, though this holds only under quite special conditions. In the next section, we evaluate the relative effectiveness of size- and bag-limit policies in an empirical context.

Simulation of the Effectiveness of Size and Bag Limits in the Gulf of Mexico Red Snapper Fishery

To further explore the implications of size and bag limits, a variety of such policies were simulated for the Gulf of Mexico red snapper fishery using the General Bioeconomic Fisheries Simulation Model (GBFSM). GBFSM is a multi-region, multi-species fisheries model that was developed to predict how alternative management policies would affect fisheries (Grant, Isaakson, and Griffin 1981; Isaakson, Grant, and Griffin 1982). The model has been used extensively for analyzing the effects of management policies in the Gulf of Mexico (Blomo *et al.* 1978; Blomo *et al.* 1982; Gillig, Griffin, and Ozuna 2001; Grant and Griffin 1979; Griffin and Stoll 1981; Hendrickson and Griffin 1993; Griffin and Oliver 1991; Griffin *et al.* 1993).

GBFSM consists of two main parts: a biological submodel and an economic submodel. The biological submodel represents the recruitment, growth, movement, and mortality of shrimp and finfish. Shrimp and finfish mortality is due to both natural causes and fishing. In addition to harvests of both shrimp and finfish, effort targeted toward shrimp also leads to incidental bycatch of finfish. When a management policy is introduced in GBFSM, the model calculates the changes in days fished, number of vessels, and catch per unit of effort for both shrimp and finfish.[7] Based upon the biological effects of the management policy simulated, the economic submodel then calculates the impact on costs, revenues, and rent for commercial vessels and consumer surplus for recreational fishermen. Details of GBFSM's structure and its calibration can be found at http://GBFSM.tamu.edu.

In many ways, simulation of a policy using GBFSM is as close as an analyst might hope to get to an evaluation of the impact of policies in the real world. GBFSM was *not* developed to demonstrate the theoretical characteristics of any particular policy issue, but is instead a large-scale model in which relationships are based on empirical foundations, and the overall model is calibrated to closely replicate historical trends in the fisheries. In effect, the model is a numerical petrie dish that can be used by the analyst to evaluate the impact of fisheries policies by carrying out controlled experiments.

Of particular relevance here is the specification of the recreation demand function. Red snapper recreation is modeled based on the empirical analysis of Gillig, Ozuna, and Griffin (2000) and discussed in Woodward *et al.* (2001). The demand for red snapper fishing trips by the ith angler, y_i, is specified as:

$$\ln(y_i) = b_0 + b_1 P_i + b_2 Inc_i + b_3 l_i + b_4 l_i^2 + b_5 E_i + b_6 E_i^2 + b_7 B_i + \varepsilon_i, \qquad (15)$$

where P_i represents travel costs incurred by the ith angler to gain access to the resource in the Gulf of Mexico; Inc_i is the individual's household income in thousands of dollars; l_i refers to expected red snapper catch rates; E_i denotes the number of years an angler has fished recreationally; B_i is a dummy variable that is equal to one if an angler owns a boat; and ε_i is a gamma distributed error term.

The specification of the recreation demand model has some direct implications for the predicted impacts of the size- and bag-limit policies. First, as is common in

[7] The version of GBFSM used in this paper is parameterized to study the effects of management on the shrimp and red snapper fisheries of the Gulf of Mexico. The biological component of the red snapper model employs the Ricker stock-recruitment function so that as the spawning stock increases, the number of recruits increases up to a particular spawning stock level. Beyond this level, the number of recruits declines (Ricker 1975; Ortiz 1998; and Chavez and Arreguin-Sanchez 1991).

the literature, recreation demand was estimated based on the number of fish retained; no data were available on fish returned. Hence, it is implicitly assumed that all anglers are quantity focused. Secondly, the relationship between catch rates and annual demand is such that any increase in the catch per day will increase the number of trips per year. Therefore, it is implicitly assumed that fishing quality per day and days per year are complements in the angler's demand. Furthermore, anglers are assumed to follow a simple compliance response to bag limits. When their bag limit is reached, they stop fishing and do not discard fish prior to reaching their limit. Because of the specification, the short-term impacts of both bag and size limits on angler effort, and welfare are known *a priori*: the policies will reduce catch, effort, and per-angler welfare.

Figure 6 presents the immediate impact of 24 different policy combinations of size and bag limits: four bag limits (from two fish per day to no limit), combined with six size limits (ranging from a 10-inch minimum to a 20-inch minimum). As seen in the figure, for low-size limits the bag limit is the dominant factor in reducing landings. As the size limit is increased, however, fewer fish can be retained so that eventually the bag limit constraint does not bind, and total harvests are not affected by the bag limit.

The effect of these policies on fish stocks comes through two channels. First, fish stocks are affected by altering the number of fish caught and discarded. Second, the policies affect angler behavior by altering the catch per trip and thereby change the number of trips that anglers choose to take over time. This secondary impact is presented in figure 7, which shows the simulated number of trips taken over a 20-year time horizon for a variety of size limits without a bag limit. As seen in the figure, size limits of 18 and 20 inches have a strong impact on trips in the short term. This follows from the model's assumed relationship between the desired num-

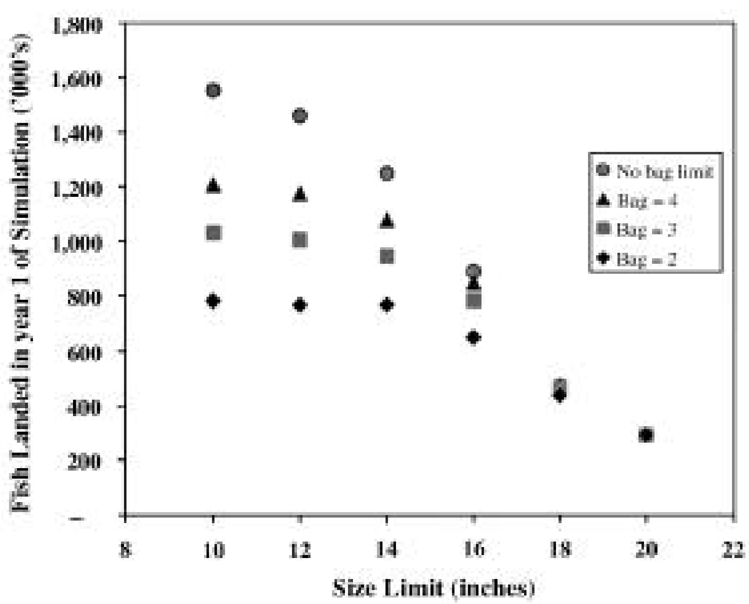

Figure 6. Fish Landings under Alternative Size and Bag Limit Policy Combinations

Note: first year of simulation.

ber of trips and the number of fish landed. Over time, however, more aggressive policies lead to a substantial increase in the spawning stock — increasing the stock by over 250% with a 20-inch size limit. This leads to an increase in catch per unit of effort, causing trips per year to increase. By the end of the simulated period, total trips are nearly back to their pre-regulation level.

While the short-term impacts of these regulations on fishing effort can be theoretically predicted, their impact on the fish stock cannot be determined, because it depends, in part, on the release-mortality rate. Here GBFSM offers substantially more realism than can be obtained in our parsimonious theoretical model. Release mortality is a function of not only the number of fish returned, but also the depth at which they are caught and returned. In figure 7, discard mortality is assumed to be at a "best guess" level of 10% for depths less than 5 fathoms, 20% for depths of 6 to 10 fathoms, and 33% for depths greater than 10 fathoms. GBFSM's biological model predicts total catch, the distribution of that catch, and how it is distributed among anglers of varying skill levels. It can, therefore, predict the number of fish caught, the size distribution of those fish, and the corresponding release mortality.

The primary purpose of simulation models, such as GBFSM, is to provide guidance to policymakers on policy choices. Inevitably, multiple objectives are relevant in this process. Some decisionmakers may place value on the biological condition of the fishery, while others may place more emphasis on economic indicators of the fishery's value.

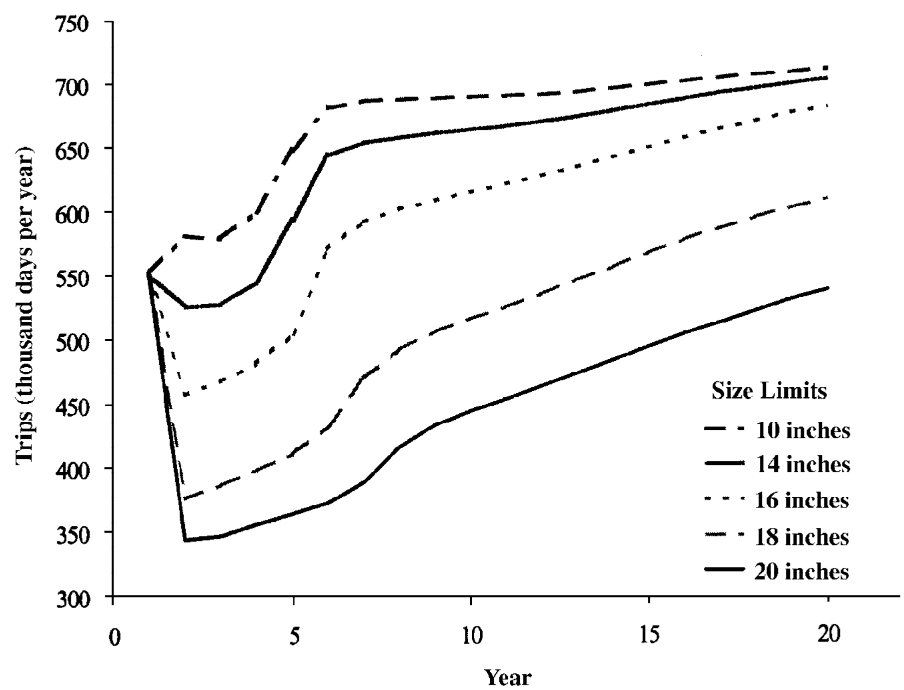

Figure 7. Trips Taken under Various Size-limit Policies in the Absence of a Bag Limit
Note: For any size limit, the addition of a bag limit policy uniformly reduces trips taken over the simulated time horizon with more aggressive policies (smaller bag limits), thus having a greater impact on trips taken.

Considering 24 different size- and bag-limit combinations, a wide range of outcomes is possible. Following Proposition 5, we know that for quantity-focused anglers there is a tendency for a size limit, at least on the margin, to increase fishing effort and discards. The biological impact of the policies combinations, therefore, is strongly influenced by release mortality. Since little is known about actual release-mortality rates, sensitivity analysis is carried out on these parameters over a range of possible values.

Figure 8 shows the tradeoffs between the spawning stock in year 20 and the present value of consumer surplus (7% discount rate) assuming that release mortalities are very low. If accurate, figure 8 would suggest that a wide range of efficient policies is available; virtually all the points on the frontier could be reached by various combinations of size and bag limits. However, the shape of the policy frontier changes dramatically in figure 9, where much higher levels of release mortality are considered. Here, we see that size limits are relatively inefficient, leading to outcomes on the interior of the feasible set. For example, in this scenario when there is a bag limit of two or three fish, an increase in the size limit not only reduces the fishery's economic value, but actually has negative consequences for the population as a result of the high discard rate. The contrast between figures 8 and 9 demonstrates the importance of research to improve our knowledge of release mortality and to take this variable into account when establishing fishery policies.

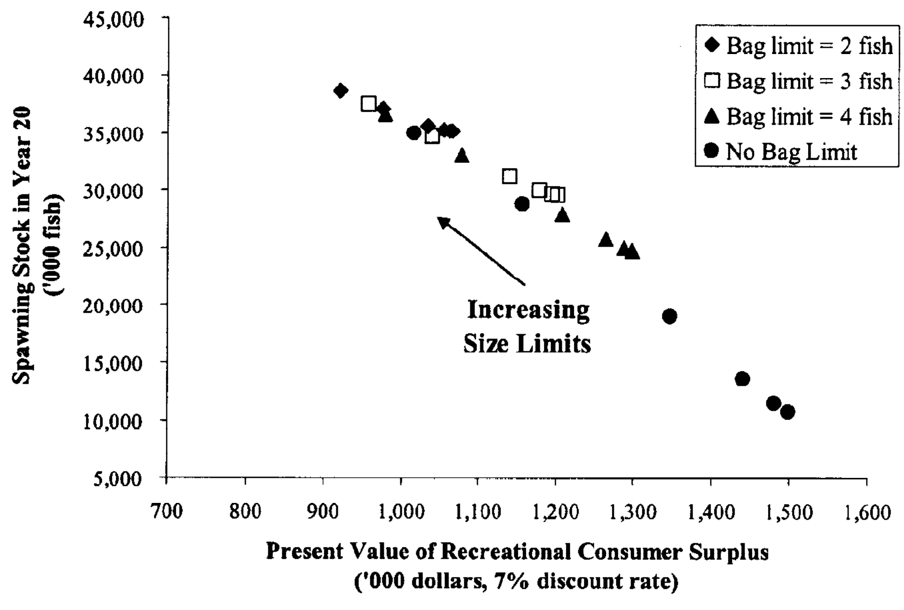

Figure 8. Consumer Surplus and Year-20 Spawning Stocks under Alternative Policy Options
Note: Mortality rates for fish caught at three depths: 0–5 fathoms, 6–10 fathoms, and more than 10 fathoms. Discard mortality rates: 1%, 1%, and 1%.

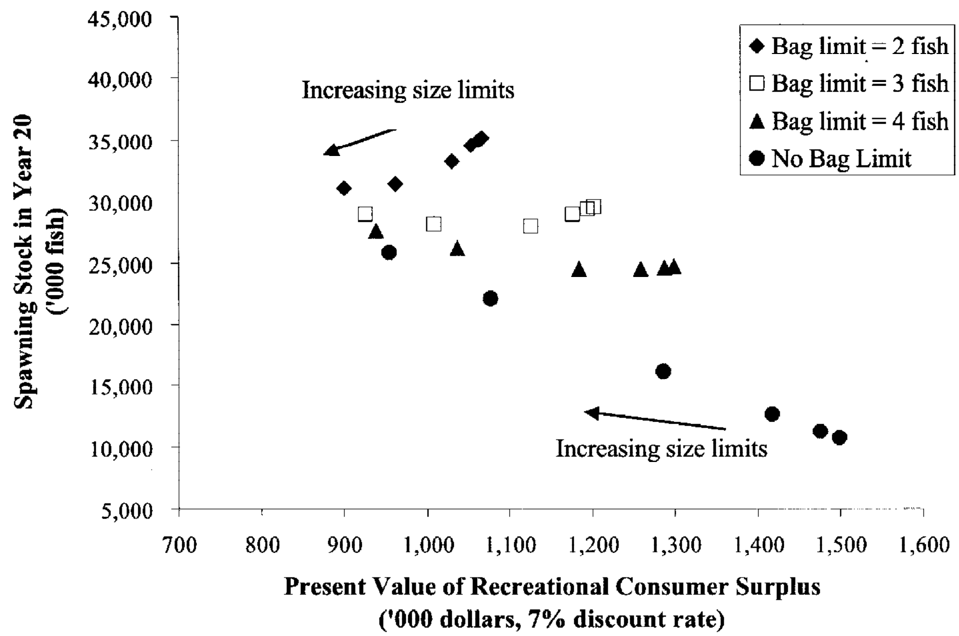

Figure 9. Consumer Surplus and Year-20 Spawning Stocks under Alternative Policy Options
(discard mortality rates: 33%, 46%, and 59%)

Conclusions

We have provided a unifying framework for the analysis of recreational fishing policies. Although the model is largely consistent with standard recreation demand models, it also includes some variables that are usually not captured in such models, including length of fishing days and discard rates. Policymakers would be aided by a better understanding of how anglers make tradeoffs between the size of the catch and the number of fish. Additionally, empirical tests of whether daily fishing quality and days per year are complements or substitutes are needed. We identify the conditions under which rankings of the two policies can be made. The next step will be to empirically test these conclusions.

We then evaluate alternative size- and bag-limit policies in the context of the Gulf of Mexico's red snapper fishery. As predicted in the theoretical model, the relative effectiveness of these policies is dependent on the rates of release mortality. When release mortality is high, size limits can be a very inefficient way to achieve either economic or biological goals. There remains, however, substantial uncertainty about release mortality rates, and scientific study of this issue is needed to help identify the optimal policy mix.

Certain caveats on our simulation results should be emphasized. First, we assume that anglers respond to bag limits through simple compliance, halting their fishing when their limit is reached. If anglers high-grade, share their limit with other anglers, or discard smaller fish during the day, then bag limits would lead to higher total catch and higher mortality. The simulation model could be made more general if empirical recreation demand analysis were carried out that captures the mix of angler responses considered in the theoretical section of this paper.

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Appendix: Propositions and Proofs

We define t^s as the optimal time under the binding size limit $\underline{s}$, and $\underline{l}$ to be the landings that would result; *i.e.*, $\underline{l} = [1 - F(\underline{s})]h(t^s)$.

> PROPOSITION A1. Assuming $\mathbf{c_1}$, $\mathbf{c_2}$, and $\mathbf{u}$, the optimal amount of fishing time for a quantity-focused angler will be less than t^s.

PROOF: Assuming $\mathbf{c_1}$ and $\mathbf{c_2}$, equation (13) states that the size and bag limits will both lead to same amount of fishing time if:

$$\frac{\partial q}{\partial s}\frac{\partial s^b}{\partial h}\frac{\partial h}{\partial t} = \frac{\partial q}{\partial l}\frac{\partial l^s}{\partial h}\frac{\partial h}{\partial t}, \tag{A.1}$$

with both sides evaluated at t^s. Writing $h(t^s)$ as h for notational convenience, under $\mathbf{u}$,

$$s^b = \frac{h-\underline{l}}{h} + \frac{\left(1 - \frac{h-\underline{l}}{h}\right)}{2} = \frac{1}{2} + \frac{h-\underline{l}}{2h} = \frac{2h-\underline{l}}{2h} = 1 - \frac{\underline{l}}{2h} \text{ and } \underline{l}^s = (1-\underline{s})h.$$

Note that $\underline{s}$ is a lower limit on the size of fish retained, while s^b is the average size of retained fish. The derivatives of s^b and $\underline{l}^s$ with respect to h can then be written, $\partial s^b/\partial h = \underline{l}/2h^2$ and $\partial \underline{l}^s/\partial h = (1 - \underline{s})$. Equation (A.1) can, therefore, be written:

$$q_s \frac{\underline{l}}{2h^2} h_t = q_l(1-\underline{s})h_t.$$

The right-hand side of this is equal to $-q_t$ at t^s by definition. Hence, $q_s s_h^b h_t < -q_t$ if :

$$q_s \frac{\underline{l}}{2h^2} < q_l(1-\underline{s}). \tag{A.2}$$

Simplifying using the fact that $(1 - \underline{s})h = \bar{l}$, (A.2) can be written:

$$\frac{1}{2h(t^s)} < \frac{q_l}{q_s}. \tag{A.3}$$

We now use the assumption that the angler is quantity focused, in which case $-S_l < q_l/q_s$, where S_l is the rate at which s can be increased as l is decreased holding harvests constant. Under **u**, $s = 1 - l/2h$, or $h = l/2(1 - s)$. Setting the total derivative of this curve equal to zero and solving for $-ds/dl$, we obtain $-S_l = (1 - s)/l$. For a quantity-focused angler under **u**, therefore:

$$(1 - s)/l < q_l/q_s. \tag{A.4}$$

The inequality in equation (A.3) holds, therefore, if its left-hand side is less than or equal to the left-hand side of equation (A.4); *i.e.*, if:

$$\frac{1}{2h} \le \frac{(1 - s)}{l}. \tag{A.5}$$

Under **u**, $s = \underline{s} + (1 - \underline{s})/2$ or $1 - s = (1 - \underline{s})/2$ and $l = (1 - \underline{s})h$. Substituting these into equation (A.5), therefore, we see that equations (A.5) holds with an equality, so that quantity-focused anglers will prefer the bag limit to a size limit.

Proof of Proposition 5

As shown in the proof of Proposition A1, under **u** $(\partial \underline{l}^s/\partial h) = (1 - \underline{s})$ and $(\partial s^b/\partial h) = -\bar{l}/2h^2$. Hence equation (14) can be written:

$$q_l(1 - \underline{s}) > -q_s\bar{l}/2h^2. \tag{A.6}$$

When evaluated at t^b, $(1 - \underline{s})h(t^b) < \bar{l} = (1 - \underline{s}^b)h(t^b)$, where $\underline{s}^b$ is the minimum size retained by the bag-limit constrained angler. Hence, equation (A.6) will hold if:

$$\frac{q_l}{q_s} > \frac{(1 - \underline{s}^b)}{2h(t^b)(1 - \underline{s})}. \tag{A.7}$$

For $\underline{s} = \underline{s}^b$, this will hold for a quantity-focused angler as seen in the proof of Proposition A1. However, as $\underline{s} \to 1$, the right-hand side of equation (A.7) goes to infinity. Hence, if $q_l < \infty$, it follows that the size limit will eventually lead to a reduction in t.