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Rent Dissipation in Chartered Recreational Fishing: Inside the Black Box

Joshua K. Abbott
School of Sustainability
Arizona State University
Joshua.k.abbott@asu.edu

James E. Wilen
Department of Agricultural and Resource Economics
University of California, Davis
wilen@primal.ucdavis.edu

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I. Introduction

A canvass of the resource economics literature of the last thirty years yields only a small number of applications of economic theory to the problems of recreational fishing, especially compared to the large number of contributions to commercial fisheries over this same era.[1] McConnell and Sutinen (1979) pioneered the application of bioeconomic models in the recreational context with a simple model in which angler demand was solely a function of the quantity of trips and the harvest per trip . They show the existence of a stock externality in free competition relative to the optimally managed system. Anderson (1993) expands upon this framework by endogenizing the discard decisions of anglers and incorporating a mechanism for entry and exit of potentially heterogeneous fishery participants. Bishop and Samples (1980) consider the issue of allocation of species that are shared between commercial and recreational fisheries. Homans and Ruliffson (1997) examine the implications of minimum size limits for achieving management goals and improving fishing quality while Woodward and Griffin (2003) take this analysis still further by considering the joint use of size and bag limits.

This neglect may be linked to the relatively short shrift given to the control of recreational fisheries by fisheries managers in the past. Recreational fisheries for many species have historically gone largely unchecked while commercial fleets targeting the same species (for instance, the Gulf of Mexico red snapper fishery) have seen their ability to harvest the same species dramatically curtailed. This asymmetry may be justified when recreational takes are

[1] By contrast, the empirical economic literature on recreational fisheries is far too extensive to fully catalogue here (c.f. Bockstael, et al. (1989), Criddle, et al. (2003), Gillig, et al. (2000, 2003), Haab, et al. (2000), Lee (2000)). However, this literature has shared the focus of the broader recreation valuation literature (Phaneuf and Smith, 2005) by focusing on welfare estimates of regional fisheries or the welfare impacts of changes in natural amenities. Relatively little focus has been placed upon the empirical assessment of rent dissipation in open access systems or the predictive modeling of demand in response to regulation, a notable exception being Scrogin, et al. (2004).

sufficiently small to be negligible for the purposes of stock management. However, it has become increasingly clear that recreational fish mortality, far from being insignificant, is often comparable to or greater than the commercial mortality for many species.[2] With fisheries managers scrambling to find solutions for the effective control of recreational mortality, economists have entered the policy arena promoting innovative rights-based policy prescriptions that are grounded in the past successes of economic prescriptions for the management of commercial fisheries but with allowances for the unique informational and transactions costs associated with the recreational case (Johnston, et al., 2007, Sutinen and Johnston, 2003).

Despite the possible merits of these proposals, there is nevertheless a sense that they may not be as immediately transferable to recreational settings as initially imagined. In the first place, our understanding of the mechanisms of the rent dissipation process under open access is imperfect at best. Experience from the rationalization of commercial fisheries has yielded many surprises that demonstrate the inadequacies of simple single-factor (i.e. effort) models in capturing the complexities of real-world rent dissipation (Wilen, 2005). Second, while the recreational for-hire sector may seem similar to commercial fisheries operations in many ways, there are key differences that may limit the simple transfer of knowledge and experience from commercial rationalization programs. These observations point toward the need for a more specialized theoretical foundation in order to predict the likely impacts of recreational fishery rationalization programs.

[2] A recent study suggests that 23% of the landings of "populations of concern" (those that are either overfished or experiencing overfishing) are accounted for by recreational harvest (Coleman, et al., 2004). This proportion exhibits significant regional variation – rising to 64% in the Gulf of Mexico.

As a first step along this path, we develop a bioeconomic model of optimal and open access management for a for-hire recreational fishery.[3] We restrict our attention to the for-hire sector for three reasons. First, charter and headboat trips are a substantial part of total fishing effort for many species and often contribute in a significant way to many coastal economies. Second, given the relative ease of observing fishing activities on for-hire vessels compared to solitary fishing trips (due to their limited and known ports of origin and the clustering of multiple anglers on a single vessel), they are widely considered as easier targets for regulation and are thus likely to be of some importance in recreational fisheries policy making over the near horizon. Finally, as we shall demonstrate, the interaction of consumer preferences with the supply behavior of vessel owners creates the potential for an array of fascinating distortions and feedbacks with great relevance for fisheries policy.

Our model rests upon elements of the bioeconomic framework pioneered by McConnell and Sutinen (1979) and Anderson (1993). However, their models focus on recreational demand whereas our model incorporates a realistic and flexible theory of the choice of inputs of the for-hire fishing firm. This synthesis of traditional bioeconomics with a production economics treatment of firm behavior is unique, both in commercial and recreational fisheries applications. Combining the supply and demand sides of the problem is necessary in order to examine the long run distortions arising under open access in a manner that reflects feedbacks between angler preferences and the decisions of vessel owners.[4] Understanding these distortions, in turn, allows

[3] The for-hire sector is composed of both charter and headboat vessels. A charter vessel is defined as a vessel for which a group of anglers pays a fixed rate for the exclusive use of the vessel for a trip whereas a headboat charges anglers individually for seats on the vessel. Our model applies to both types although we couch our analysis in terms of headboats.

[4] Huang and Lee (1976) develop a more general model of commercial fishery production in a bioeconomic context but do not apply their framework. Empirical production economists have criticized the classic bioeconomic model (Squires, 1987) but their has been no attempt, to the authors' knowledge, to reconcile the dynamic insights of the bioeconomic framework with the more realistic portrayals of fishing technology offered by production economists.

us to characterize the kinds of changes across different margins that would occur under various rationalization designs.

The second section of this paper describes the framework of our model and characterizes the optimally managed system. Section three contrasts these results with those obtained under an open access system. The fourth section addresses how the distortions of the previous section can be theoretically addressed through judicious choice of tax or quota instruments. The fifth section discusses the robustness of these suggested policy instruments to violations of our modeling assumptions and considers some real-world concerns for the "rationalization" of for-hire recreational fisheries. The sixth section concludes the analysis.

II. A Theory of For-Hire Recreational Fishing Under Optimal Management

We begin by assuming that vessel owners supply fishing trips of a fixed and exogenous length – say a day.[5] We assume that there is a population of identical anglers whose aggregated preferences for day trips on charter or headboat vessels conditional on their various quality attributes are encompassed by a marginal benefit function: $MB(D, H, L, S)$ where D is the number of angler-days of for-hire services demanded over the fishing season, H is the per-angler-day harvest of targeted fish, L is the amount of this daily harvest that is retained by anglers for landing, and S is a measure of fishing trip quality that is orthogonal with respect to the quantity or disposition of catch.[6]

[5] This is a convenient simplification despite the real-world differentiation of charter/headboat trips into at least two durations, half-day and day trips (with a few vessels offering overnight trips). This being said, day trips are by far the most common offering, particularly along the Gulf Coast (Sutton, et al., 1999).

[6] Although not explicitly included in our specification, demand is also influenced by other factors such as the prices of substitute recreation possibilities (e.g. the cost of fishing dockside without chartering a vessel) and prices of complementary goods.

Note that anglers' marginal willingness-to-pay for a day at sea is not only dependent upon the quantity of charter services previously consumed, but also upon the quality of these services. Quality may be a function of the daily catch rate, the chosen or imposed quantity of landings, and the non-catch aspects of trip quality, which include aspects of the trip such as the perceived safety and general upkeep of the vessel and the devotion of labor time toward non-catch related activities that enhance the experience of fishing (such as serving food or drink to passengers or filleting catch).[7] This formulation mimics that of previous authors (c.f. Anderson, 1993, Woodward and Griffin, 2003) who have posited that both catch and landings are important determinants of angler demand, but also embraces the findings of a wider social science literature that finds non-catch aspects figure significantly as well (Arlinghaus, 2006, Ditton and Gill, 1991, Fedler and Ditton, 1986). We assume the marginal benefit function is continuous and twice-differentiable with respect to all variables and satisfies the following properties:

$$MB_D < 0,\ \ MB_H > 0,\ \ MB_S > 0,\ \ MB_L(D,H,0,S) > 0,\ \ MB_{jj} < 0\ \ j = H,S,L \qquad (1)$$

where subscripts indicate the first partial derivative with respect to the subscripted variable. The first condition simply assumes the demand function for charter trips is downward sloping whereas the second and third state that the marginal willingness-to-pay for another day of fishing is strictly increasing in the quality aspects of the trip. We do relax these assumptions for the effects of landings, however, since it is plausible that, conditional upon the quantity of catch, individuals may face satiation. Accordingly, we make the minimal assumption that positive landings are a good for at least the first marginal unit of consumption.[8] The final condition

[7] Our assumption of identical preferences over catch, landings and non-catch quality can be easily relaxed by the introduction of a range of demand functions for various angler "types".
[8] This assumption precludes preferences for pure catch and release fishing. In this case, consumptive use of catch is no longer a good and so landings would fall out of the model.

simply imposes diminishing marginal returns on increases in harvest, landings and non-catch quality.[9]

As previously mentioned, the catch and non-catch aspects of trip quality are produced with multiple compensated and uncompensated factors of production. In the case of per-trip harvest, we assume that it is a continuous, differentiable and increasing function of the current stock of the target species, *X*, and a "catch effectiveness" argument, *q*, analogous to the catchability term commonly employed for analysis of commercial fisheries. Catch effectiveness is itself a function of a *Qx*1 vector of capital and labor inputs selected by the vessel owner, z_q, that serve to enhance the skill of fishermen.[10] For instance z_q may include the use of additional fishing rods for each angler to increase catch per unit effort, investment in engine horsepower to allow faster access to productive fishing grounds and greater fishing time, the use of chum to attract certain species, or the diversion of crew time to education on fishing techniques and the baiting of gear. In agreement with conventional production theory, we assume that each of these inputs has a positive and diminishing marginal effect on catch effectiveness.

In addition to these purchased factors, we also assume that the number of anglers onboard a given vessel, *N*, has a negative, continuous, differentiable and decreasing effect on the marginal effectiveness of effort – this to account in a generic fashion for a variety of possible intra-vessel congestion externalities (e.g. from entangled fishing lines). The mathematical summary of these properties of the catch quality production function, $H(X, q(z_q, N))$, are summarized as follows:

[9] Given our focus on aggregated demand, we do not entertain the possibility of "corner solutions" in demand (i.e. individual non-participation). Anderson (1993) exposits a model where free entry of anglers combined with heterogeneity yields an equilibrium where fishing benefits to anglers are dissipated, much as in the classical commercial fisheries model thus leading to partial exit of some anglers. While useful, this approach seems to lack a firm basis in consumer theory and also begs the question of what economic mechanism (if any) would guide angler demand so that some common minimal level of well-being is achieved across anglers in equilibrium.

[10] To simplify the formal analysis, we presume fishermen are equally skilled and that their per-trip catch is predetermined from their perspective. The implications of relaxing these assumptions are considered in the later discussion.

$$H_X > 0,\ H_q > 0,\ \frac{\partial q}{\partial z_q(i)} > 0\ \ \&\ \frac{\partial^2 q}{\partial z_q(i)^2} < 0\ \forall i = 1,...,Q,\ \frac{\partial q}{\partial N} < 0\ \&\ \frac{\partial^2 q}{\partial N^2} < 0 \qquad (2)$$

Non-catch quality is similarly dependent upon a $Mx1$ vector of inputs, z_s, which is subject to the same continuity, differentiability and concavity restrictions as previously stated for catch quality inputs. However, to account for the fact that some inputs that aid in the production of catch quality may actually reduce productive capacity for non-catch quality (and vice versa) we allow both "goods" and "bads" in the production relationship with sufficient curvature restrictions to ensure the overall concavity of the marginal benefit function with respect to all benefits. Note that all inputs are defined so that they are positive contributors to catch quality production. As with catch quality, we assume that non-catch quality is influenced by the number of passengers onboard a vessel in a negative and decreasing fashion so as to reflect negative attitudes toward crowding apart from its impacts on catch.[11]

In mathematical notation we assume $S(z_s, N)$ satisfies the following properties:[12]

$$\begin{aligned} &\frac{\partial S}{\partial z_s(i)} > 0\ \&\ \frac{\partial^2 S}{\partial z_s(i)^2} < 0\ or\ \frac{\partial S}{\partial z_s(i)} < 0\ \&\ \frac{\partial^2 S}{\partial z_s(i)^2} < 0\ \forall i = 1,...,M, \\ &\frac{\partial S}{\partial N} < 0, \frac{\partial^2 S}{\partial N^2} < 0. \end{aligned} \qquad (3)$$

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[11] Although convenient, such an assumption may not be true in general. Individuals may initially derive utility from the company of fellow anglers (apart from their effects on catch) with diminishing returns eventually leading to a threshold density where the marginal effect of an additional angler on the production of non-catch quality becomes negative. For the sake of mathematical tractability we assume that these preferences for "social" fishing are sufficiently weak or exhibited at such low angler densities as to be negligible.

[12] In our specification of the production processes of catch and non-catch quality we have assumed that the two processes are separable and thus represented by production functions. In reality, however, there may be significant jointness in production. We confront this issue in two ways. First, certain inputs are likely to contribute to the production of both forms of quality in a completely non-rivalrous fashion, such that their appearance in both production processes causes no problem. This is potentially the case for many characteristics of vessel capital such as deck size for which its usefulness in fostering catch (due to the dilution of congestion effects) is likely to in no way affect its contribution toward perceptions of non-catch quality. Secondly, for inputs that are clearly rivalrously consumed, a non-rivalrous relationship can be constructed by careful redefinition of inputs. For instance, labor inputs that can be utilized for either fostering catch or non-catch quality (but not both simultaneously) can be redefined as "catch related labor" and "non-catch related labor", thus subsuming the factor allocation decision within our analysis.

Given this structure of preferences and production relationships, we now consider the nature of costs to vessel owners. We assume that there is an endogenously determined number of identical vessels N_V. Each of these vessels faces three basic types of costs: 1) those that vary according to the number of trips, 2) avoidable fixed costs (costs that are invariant in the number of trips but are nevertheless avoidable without quitting the industry) and 3) fixed costs that are only avoidable by exiting the industry altogether (e.g. license fees, minimal vessel insurance, etc.) which we henceforth designate by Ψ. The first category may include expenditures such as labor and fuel while the second includes expenditures on capital inputs.[13] Note that inputs in each category can enter into the production functions for both catch and non-catch quality in a completely unfettered fashion.

Since part of our focus in this analysis is to investigate the use of inputs under optimal and open access scenarios, we work with the seasonal vessel expenditure function rather than the cost function resulting from quality-constrained expenditure minimization:

$$\begin{aligned} c(z_q, z_s, N, NumTrips, w, r) &= \left[(w_{VN}'z_{VN})N + w_V'z_V\right] * NumTrips \\ &+ \left[(r_{FN}'z_{FN})N + (r_F'z_F)\right] + \Psi. \end{aligned} \tag{4}$$

Note that seasonal costs are a function not only of inputs and their exogenous market prices (indicated by the vectors *w* and *r* for variable and fixed inputs, respectively) but also of the number of trips taken in the season and the number of anglers per trip.[14] Both the fixed and trip-variable cost components are partially comprised of costs that vary in a linear fashion with the number of passengers. For instance, a vessel owner may elect to allocate a given number of

[13] Since many aspects of vessel capital are best characterized as heterogeneous bundles of valued characteristics (e.g. horsepower, fuel capacity, length, tonnage) we adopt the language of hedonic pricing in our descriptions of capital inputs. Accordingly, the rental rates for a characteristic are interpreted as the first derivatives of the bid function with respect to the quantity of that characteristic (Rosen, 1974).

[14] We assume trips are reproducible at a constant variable cost when inputs and the numbers of passengers per trip are fixed. In the context of day-trips it seems eminently reasonable that the variable cost of taking a trip today should be independent of whether a trip was executed on the previous day.

fishing rods per angler. Such capital expenditures would be reflected in the vector z_{FN}. Alternatively, crew time spent in training and baiting gear for each passenger could be captured in the z_{VN} term. Finally, it may be that certain inputs enter both the portion of costs increasing in *N* and the portion without. For instance, the fuel costs associated with traveling a given distance from port (the endogenous variable input) could be parsed between the costs associated with a boat devoid of anglers and the extra per-angler costs due to increased payload.[15]

Having established the nature of both costs and benefits, we now require an expression linking the behavior of anglers and vessel owners to the evolution of targeted biomass through time. We employ the following standard relationship:

$$\dot{X} = g(X) - D^*\left(\phi\left(H(X, q(z_q, N)) - L\right) + L\right) \tag{5}$$

where D^* is the total number of fishing days demanded and ϕ is a discard mortality parameter indicating the fraction of discarded catch that dies before returning to the reproductive stock. The growth function $g(X)$ is assumed to be strictly concave and to prescribe zero growth at zero biomass and at a positive carrying capacity.

Having fully defined the notation of our problem we state the welfare maximizing objective:

$$\max_{D^*, L, N, N_V, z} \int_t^\infty e^{-\delta\tau} \left(\begin{array}{l} \int_0^{D^*} MB\Big(D, H\big(X, q(z_q, N)\big), L, S(z_s, N)\Big) dD \; - \\ N_V * c(z_q, z_s, N, NumTrips, w, r) \end{array} \right) d\tau \tag{6}$$

subject to (5), non-negativity constraints on the state and control variables and the following additional constraints:

[15] Note that the linearity of the expenditure function with respect to *N* does not mean that *optimized* costs possess a linear-in-*N* relationship. Given the endogeneity of both the number of passengers per trip and all inputs, it is possible for the allocation of inputs to vary as *N* varies – leading to a non-linear relationship in minimized costs.

$$L \leq H\big(X, q(z_q, N)\big), \;\; NumTrips \leq D_{MAX}, \;\; NumTrips = \frac{D^*}{N_V N} \qquad (7)$$

The first constraint simply limits landings to an amount weakly less than individual harvest.[16] The second constraint states that the number of trips taken by a vessel must not exceed the total number of available opportunities in a season, D_{MAX}. Note, however, that *NumTrips* is not included as a separate control variable in our statement of the problem. The rationale is found in the third constraint of (7). We assume, given the homogeneity of vessels in our model, that both passengers and trips are spread evenly across the fleet. Combining this assumption with the endogenously determined number of vessels and anglers per trip (and the constant variable cost of trips by a vessel) yields the per-vessel trip count indicated in (7).

The task of the social planner is to choose the time paths of fishing days, landings, angler density, the number of vessels and vessel inputs so as to maximize the discounted present value of the flow of net benefits. The constrained current value Hamiltonian, where we have substituted for the third constraint from (7), is:

$$\begin{aligned} H^{CV} &= \int_0^{D^*} MB\big(D, H\big(X, q(z_q, N)\big), L, S(z_s, N)\big)\, dD - N_V * c(z_q, z_s, N, \frac{D^*}{N_V N}, w, r) \\ &+ \lambda\big[g(X) - D^*\big(\phi\big(H(X, q(z_q, N)) - L\big) + L\big)\big] + \mu_1\big[H\big(X, q(z_q, N)\big) - L\big] \\ &+ \mu_2\left[D_{MAX} - \frac{D^*}{N_V N}\right]. \end{aligned} \qquad (8)$$

A glance at (4) and (8) reveals that the Hamiltonian (excepting the constraints) is linear in N_V. This linearity is particularly simple in that it plays no role in the equation of motion and only affects net benefits through a positive effect on fixed costs. The implication of this linearity

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[16] In reality individual landings may exceed individual harvest if fishermen are able to trade their catch with other passengers. In this case, the constraint could be modified to apply to the *sum* of individual landings and harvest. However, given our current assumption of identical preferences and skill across anglers (and non-stochastic catch), the individual and aggregate constraints are equivalent.

is that each vessel must be fully employed in every season for social welfare to be maximized. In other words, the second constraint in (7) must strictly bind.[17] Given that the second constraint in (7) must bind, a generalized version of the maximum principle (c.f. Caputo, 2005, p. 152) states that the necessary condition for the path of N_V through time can be found by taking the partial derivative of (8) with respect to N_V yielding:

$$N_V = \frac{D_{MAX}}{\left((r_{FN}'z_{FN})N + r_F'z_F + \Psi\right)}\mu_2. \tag{9}$$

Note the fundamental role of fixed costs in determining the optimum scale of the industry – the higher are fixed costs the lower the optimal number of vessels. Since fixed costs are increasing in the number of passengers, it is also the case that an increase in the optimum angler density will lead to a decrease in the number of vessels. Also, the longer the natural season, the greater the number of vessels since the fixed operating costs can be spread over a larger number of trips. Finally, the number of vessels is rising in the marginal valuation of an additional day for the entire fleet.

The necessary condition for the number of fishing days is:

$$\begin{aligned} &MB\left(D^*, H\left(X, q(z_q, N)\right), L, S(z_s, N)\right) - \left[(w_{VN}'z_{VN})N + w_V'z_V\right]\frac{1}{N} - \mu_2\left(\frac{1}{N_V N}\right) \\ &= \lambda\left[\phi\left(H(X, q(z_q, N)) - L\right) + L\right] \end{aligned} \tag{10}$$

[17] The proof for this assertion is intuitive and is easily arrived at by contradiction. Assume vessels are not fully employed. This would imply that angler demand could be diverted to a smaller number of vessels while maintaining the same angler density per trip. Benefits to consumers would remain constant while expenditures on variable costs would also remain the same due to the linearity of expenditures in the number of trips. However, fixed costs would decrease in this new state of affairs given the retirement of redundant vessel capital. Therefore it follows that any non-full-employment outcome is suboptimal. This result is an artifact of the lack of any adjustment costs of entry/exit in our model as well as the constant variable cost of trips. However, given our ultimate concern for long-run bioeconomic equilibria, the omission of adjustment costs is immaterial since excess capacity cannot persist indefinitely with finite costs of adjustment.

At an interior solution this condition states that the net marginal benefits from an additional angler-day (the increase in angler welfare minus the increase in variable costs as the fleet-wide number of trips is increased to accommodate the extra demand) are just offset at each point in time by the discounted capital value of the induced mortality. However, as broached in the previous paragraph, such an interior solution does not exist given the necessity of full vessel employment at the optimal solution. An increase in angler days at sea at a fixed angler density thus necessitates an increase in the number of vessels and an associated increase in fixed costs. This is easily demonstrated by simple rearrangement of (9) for μ_2:

$$\mu_2 = \frac{N_V}{D_{MAX}}\left((r_{FN}' z_{FN})N + r_F' z_F + \Psi\right). \tag{11}$$

The benefit of an additional day of available fishing time is simply the value of the reduction in vessel capital (i.e. the reduction in fixed costs) required to service demand at current angler densities. Therefore the third term in (10) reflects the industry-wide increase in fixed costs from the new vessel capital needed to service an extra angler day within the constraints of available fishing time provided that extra angler day were spread over all vessels equally (i.e. in a cost minimizing fashion) holding angler density constant.

The necessary condition for angler landings is:

$$\int_0^{D^*} MB_L(\cdot)\ dD - \mu_1 = \lambda D^*(1-\phi). \tag{12}$$

This condition simply implies that the net marginal benefits of additional landings must be offset by the full dynamic costs of the extra mortality from doing so. Note that if discards experience full mortality ($\phi = 1$) then there is no dynamic consequence to the allocation of catch between landings and discards and (12) becomes a static condition. It is possible, however, that catch is insufficient to satiate anglers' consumptive desires, in which case the entirety of harvest is landed and $\mu_1 > 0$.

The necessary condition for angler density is:

$$\int_0^{D^*} \left[MB_H(\cdot) H_q q_N + MB_S S_N \right] dD - N_V \left[(r_{FN}' z_{FN}) - (w_V' z_V) \frac{D^*}{N_V N^2} \right] + \mu_1 H_q q_N + \mu_2 \left(\frac{D^*}{N_V N^2} \right) = \lambda D^* \phi H_q q_N . \tag{13}$$

Interpretation of this expression is a bit complicated, but aided by substituting (11) into (13) (realizing that $\frac{D^*}{N_V N^2} = \frac{D_{MAX}}{N}$) and collecting terms:

$$\int_0^{D^*} \left[MB_H(\cdot) H_q q_N + MB_S S_N \right] dD + \frac{N_V}{N} \left[(w_V' z_V) D_{MAX} + (r_F' z_F) + \Psi \right] + \mu_1 H_q q_N = \lambda D^* \phi H_q q_N . \tag{14}$$

Note that the dynamic effect of an increase in angler density, the right hand side of (14), is negative, implying a *benefit* from an increase in angler density due to its adverse effect on an angler's harvest efficiency and thus fishing mortality. This implies that intra-vessel congestion should be driven beyond the point where the short run return to society is maximized. The short run marginal return (the left hand side of (14)) is intricate and can be examined piece by piece. The first term is always negative, reflecting detriments to angler utility from the effects of congestion. The cost effects of increased angler density consist of the reduction in variable costs due to a decrease in the overall number of trips required to service demand and a reduction in fixed costs (both avoidable and unavoidable) due to the reduction in vessel capital needed to satisfy demand while maintaining full employment for each vessel.

In the event that landings are constrained by harvest (i.e. $\mu_1 > 0$) there is an additional near-term cost of increasing angler density in that it reduces angler welfare due to reduced landings. This drives the optimal solution toward a lower density of anglers. In other words, *ceteris paribus*, a fishery with strong retention preferences (high quality food fish species) should have lower optimal levels of angler congestion than a technologically equivalent fishery characterized by weak retention preferences (e.g. tarpon or marlin).

In considering the necessary conditions for the choice of inputs, there are several stylized sub-cases to examine. An input can affect either catch or non-catch quality (or both) and can be a fixed or variable input and vary with the choice of *N* (or not). We work at the maximum level of generality, assuming that the input affects both catch and non-catch quality and that the factor has both *N*-varying and non *N*-varying aspects. For the case of a fixed input at an interior solution:

$$\begin{aligned}&\int_0^{D^*}\left[MB_H(\cdot)H_q q_{z(i)} + MB_S S_{z(i)}\right]dD - N_V\left[r_{FN(i)}N + r_{F(i)}\right] + \mu_1 H_q q_{z(i)} \\ &= \lambda D^* \phi H_q q_{z(i)}.\end{aligned} \tag{15}$$

The current net marginal benefits from an increase in an input must be balanced against the dynamic costs of the mortality due to increased catch effectiveness.[18] Additionally, if landings are constrained by harvest ($\mu_1 > 0$), then there is a further benefit to increasing factors that influence catch quality as doing so also increases landings.[19]

The necessary conditions for variable factors are as follows:

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[18] To ensure such interior solutions for all factors, we must supplement the properties of the catch and non-catch quality production functions (given by (2) and (3)) with additional "Inada conditions" that all inputs are essential and have an infinite marginal product as the quantity of the input approaches zero.

[19] The corollary to this statement is that vessels pursuing species for which preferences for landings are strong relative to the baseline "catchability" should optimally evidence a higher degree of catch-augmenting capital/labor investment compared to fisheries with similar natural catchability but weak preferences for landings.

$$\int_0^{D^*}\left[MB_H(\cdot)H_q q_{z(i)} + MB_S S_{z(i)}\right]dD - \left[w_{VN(i)}N + w_{V(i)}\right]\frac{D^*}{N} + \mu_1 H_q q_{z(i)} \\ = \lambda D^* \phi H_q q_{z(i)} \tag{16}$$

with a virtually identical interpretation to those for fixed factors. Factoring of this condition yields the following expression:

$$\underbrace{\left[\int_0^{D^*} MB_H(\cdot)H_q\, dD - \lambda D^* \phi H_q + \mu_1 H_q\right]}_{\chi_q^*} q_{z(i)} + \underbrace{\left[\int_0^{D^*} MB_S\, dD\right]}_{\chi_S^*} S_{z(i)} \\ = \left[w_{VN(i)}N + w_{V(i)}\right]\frac{D^*}{N}. \tag{17}$$

This equation closely resembles the standard profit maximization condition that the value of the marginal product of an input be equated to the marginal factor price, but with three key differences. First, our model works at the scale of the regional industry so that prices of outputs are not exogenous to the social planner maker. Second, the production processes under consideration are for the production of catch and non-catch quality at a given (but endogenous) level of trips so that benefits of quality change are measured with respect to shifts in the consumer demand function. Finally, χ_q^* and χ_S^* represent the optimal “prices” of catch and non-catch quality and reflect the full dynamic implications of these quality changes.

Calculating (17) for another variable factor *j* and forming the ratio of these conditions yields the following expression:

$$\frac{\chi_q^* q_{z(i)} + \chi_S^* S_{z(i)}}{\chi_q^* q_{z(j)} + \chi_S^* S_{z(j)}} = \frac{w_{VN(i)}N + w_{V(i)}}{w_{VN(j)}N + w_{V(j)}}. \tag{18}$$

If inputs are exclusive contributors to either catch or non-catch quality, this equation reduces to the standard cost-minimizing tangency condition between the expenditure frontier and the marginal rate of technical substitution. More generally, (18) is identical in form to the condition generated by a cost minimization problem subject to dual quality constraints with non-rivalrous inputs – only here the optimal prices of quality replace the usual Lagrange multipliers. This finding reflects how the family of conditions embodied in (16) jointly determines both the optimal quality levels and the cost-minimizing input combinations. Equation (18) shows that the relative combination of inputs is product of a mixture of two single-quality tangency conditions where the relative influence of catch or non-catch quality in influencing the mix of inputs is a product of their optimal marginal valuations.[20]

The costate equation for the dynamic optimization problem is:

$$\dot{\lambda} - \delta\lambda = -\int_0^{D^*} MB_H(\cdot) H_X \, dD - \lambda\left(g'(X) - D^* \phi H_X\right). \tag{19}$$

Considering this equation at the steady state ($\dot{\lambda} = 0$) yields the following solution for the costate variable:

$$\lambda_{SS} = \frac{H_X \int_0^{D^*} MB_H(D, H(X, q(z_q, N)), L, S(z_s, N)) \, dD}{\delta - g'(X) + D^* \phi H_X} \tag{20}$$

where for the sake of economy of notation it is understood that all control and state variables are evaluated at their steady state levels. Several observations are warranted here. First, the capital value of the fish stock is, predictably, inversely related to the discount rate of the social planner. Second, if harvest rates have no impact on marginal benefits ($MB_H = 0$) or if increases in fish stock stock density have negligible effects on catch rates ($H_X = 0$) then an extra unit of stock has no long run value and the user cost is zero. Third, the effect of a higher mortality rate of discards is to decrease the steady-state valuation of the fish stock due to the anticipated leakage

[20] We should note that analogous expressions to (17) and (18) can be derived for fixed inputs (and ratios of fixed and variable inputs) as well.

of fish capital from the system via the discard process.[21] Finally, the effect of increased angler demand on the valuation of the stock is ambiguous, depending upon the sign and magnitude of the derivative of the biological growth rate.

Having derived the necessary conditions for the optimal management of the fishery, we now contrast them with what we would expect in a perfectly competitive open access industry.

III. The Open Access Outcome

In competitive equilibrium the market determines the number of fishing days and landings (holding other variables fixed) so as to maximize the sum of short-run consumer and producer surplus:

$$\max_{D^*, L} \int_0^{D^*} MB\left(D, H\left(X, q(z_q, N)\right), L, S(z_s, N)\right) dD - N_V * c(z_q, z_s, N, NumTrips, w, r) \qquad (21)$$

subject to the aforementioned constraints on landings and the maximum number of trips per vessel where the vessels' choice of angler density, number of vessels and quality inputs are taken as given by anglers. The first order condition for D^* is as follows:

$$MB\left(D^*, H\left(X, q(z_q, N)\right), L, S(z_s, N)\right) - [(w_{VN}' z_{VN})N + w_V' z_V]\frac{1}{N} - \mu_2\left(\frac{1}{N_V N}\right) = 0. \qquad (22)$$

This expression differs from (10) in that the full user cost of the mortality from additional angler-days is missing from the right hand side. As a result, there will be excessive demand for days at sea by anglers in the competitive case relative to the social optimum.[22]

The analogous condition for *L* is:

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[21] The effect of the mortality parameter in our model on the costate variable is analogous (although not perfectly equivalent) to the role of depreciation in the literature on investment.

[22] In the event that vessels are fully employed in a competitive equilibrium (an unlikely event as we will later demonstrate), a fisherman desiring an extra day at sea would have to pay a discretely higher price than those immediately preceding him due to the necessity of covering the fixed costs of the marginal increase in vessel capital required to satisfy demand – thus the final term in (22).

$$\int_0^{D^*} MB_L(\cdot)\, dD - \mu_1 = 0. \tag{23}$$

Note that landings are determined without regard to the effects of the extra mortality on the future stock. Anglers either reach a satiation point in their consumptive use or are limited in their landings by the quantity of harvest. Therefore, the incentive to discard is excessive in a purely competitive system compared to the optimal situation in (12). The only exception occurs when there is full mortality of discards. In this case, all harvest is lost to the system regardless of whether it is retained and so landings decisions have no dynamic impact.[23]

The number of passengers per vessel and the factors of production are chosen by vessel owners and are driven to equilibrium values through competition in the market for fishing trips. We make no attempt to rigorously characterize the dynamic process by which such an equilibrium is achieved, choosing instead to focus on the properties of the equilibrium itself.[24]

Given that angler density influences angler perceptions of quality, vessel owners will seek to differentiate their services by altering the concentration of anglers on their vessel. Of course, we would expect this vessel's competitors to respond in kind, leading to an iterative process of quality competition. The competitive market equilibrium arising as the limit of this process is implicitly defined by the following condition (again realizing that $\frac{D^*}{N_V N^2} = \frac{D_{MAX}}{N}$ if $\mu_2 > 0$):

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[23] This finding that atomistic discard decisions may be socially optimal parallels the findings of Arnason (1994) in the commercial case.

[24] A fully developed dynamic explanation of the path to equilibrium would likely entail the consideration of the adjustment costs of investment in fixed factors and partial irreversibility of such investments (c.f. Clark, et al. (1979) and Gould (1968)).

$$\int_0^{D^*}\left[MB_H H_q q_N + MB_S S_N\right]dD - N_V\left[(r_{FN}'z_{FN}) - (w_V'z_V)\frac{D^*}{N_V N^2}\right] + \mu_1 H_q q_N + \mu_2\left(\frac{D_{MAX}}{N}\right) = 0. \quad (24)$$

In the case where landings are unconstrained, this condition says that quality competition will drive angler density down to the point where the foregone increases in angler benefits and reduced *N*-variable fixed costs from a reduction in density are just offset by the marginal costs of doing so, where these extra costs are incurred through an increase in the number of trips necessary to serve the available demand. In the event that landings are constrained by harvest, then a full accounting of the exploitable marginal benefits (i.e. the full marginal willingness to pay of anglers) of a decrease in density requires the third term in (24) to account for the value of increased landings. A comparison of (24) to (13) reveals that the competitive equilibrium once again fails to account for the dynamic implications of the choice variable. In this case a decrease in *N* imparts a long-run cost due to its accelerating effect on per-angler mortality – the implication being that the incentive in competitive equilibrium is toward a *smaller* number of anglers per vessel than is optimal. This result is particularly telling given the prevailing wisdom that open access competition encourages *excessive* congestion in commercial fisheries. This may be true for inter-vessel congestion (an arguably small effect for many recreational fisheries), but here congestion is assumed intra-vessel and consumer preferences for congestion avoidance are relayed to vessel owners through market demand, driving this surprising result.[25]

[25] Note that an extra cost of further lowering of *N* is revealed in (24) if the season limit constraint is binding on vessels in competitive equilibrium. This cost arises due to fixed costs from the increased vessel capital needed to service the surplus trip demand released by the lower angler density.

The determination of quality-augmenting inputs under competition is explainable via a similar sequential argument as made for angler density. The marginal condition that is satisfied in competitive equilibrium for variable factors is:

$$\int_0^{D^*}\left[MB_H(\cdot)H_q q_{z(i)} + MB_S S_{z(i)}\right]dD - \left[w_{VN(i)}N + w_{V(i)}\right]\frac{D^*}{N} + \mu_1 H_q q_{z(i)} = 0. \tag{25}$$

This condition is identical to that in (16) except for the now predictable result that decision making under unfettered competition fails to account for future mortality effects. Factoring (25) as in (17) reveals:

$$\underbrace{\left[\int_0^{D^*} MB_H(\cdot)H_q\, dD + \mu_1 H_q\right]}_{\chi_q^C} q_{z(i)} + \underbrace{\left[\int_0^{D^*} MB_S\, dD\right]}_{\chi_S^C} S_{z(i)} = \left[w_{VN(i)}N + w_{V(i)}\right]\frac{D^*}{N}. \tag{26}$$

Note that the valuation of the marginal contribution of catch effectiveness to the "value of marginal product" is overstated relative to the optimal case ($\chi_q^C > \chi_q^*$). The cost minimization tangency condition in (16) continues to hold, only now the relative preference given to catch quality in the quantity and composition of inputs is skewed toward excessive catch quality. In other words, equilibrium catch effectiveness will be too high under pure open access competition and some of the inputs that play a role in its production will see excessive use, notwithstanding the fact that input costs will be minimized at the competitive levels of catch and non-catch quality.

We now flesh out this insight for a couple of simple cases. First, consider the case where catch quality is a function of a single exclusive input. If we take the ratio of conditions (17) and (26) we find:

$$\frac{q^*_{z(i)}}{q^C_{z(i)}} = \frac{\chi^C_q}{\chi^*_q} > 1 \rightarrow z^C(i) > z^*(i) \quad (27)$$

given the assumption of diminishing marginal productivity of inputs. Note, however, that this increase in catch augmenting factors is not guaranteed to occur in general. When there are multiple catch-quality-exclusive inputs, the move from optimal management to competition may result in less of some inputs and more of others depending upon the nature of the catch quality production function.[26] Nonetheless, this combination of inputs must generate a higher level of catch quality than before such that the use of at least one input must exceed its level under optimal management.

In the case where an input affects non-catch quality exclusively a comparison of (26) to (17) reveals that the valuation of non-catch quality under competition and optimal management is identical. There is, therefore, no *direct* incentive for the distorted use of this input. However, indirect distortions may propagate due to possible substitution effects between catch and non-catch quality in angler demand. For instance, if the two components of quality are substitutes then the presence of excessive catch quality in pure competition will weaken demand for non-catch quality, lowering its equilibrium value and thus causing the use of at least one of its exclusive inputs to fall relative to the optimal input bundle.

In the case where some inputs contribute to both catch and non-catch quality, the situation is much more complicated. In the case of non-catch quality, there may be a tendency to substitute away from exclusive inputs and towards inputs that pay a "double dividend" by contributing positively toward catch quality.[27] This substitution is driven by the excessive price

[26] A sufficient (although not necessary) condition for expansion of all exclusive catch quality inputs is homotheticity of the quality production function.
[27] A corollary to this statement is that there will be a tendency to over-invest in catch-influencing inputs that act as "bads" in the production of non-catch quality, particularly if the two quality metrics are highly substitutable to

signal sent by the market for catch quality under perfect competition. The degree to which such behavior is evidenced in practice depends a great deal on the degree to which shared versus exclusive inputs are substitutable in consumer's perceptions of non-catch quality, the relative prices of these classes of inputs and the magnitude of the rift between the optimal and competitive "price" of catch quality.

These cases are indicative of a labyrinthine and theoretically ambiguous relationship between the distortions in the valuation of catch quality and potential feedback effects for equilibrium non-catch quality. Outcomes depend on a number of factors involving the degree of cost complementarities between the two forms of quality (which depends in turn on the nature and importance of shared inputs in their joint production) and the degree of substitutability of catch and non-catch quality in trip demand.

The determination of the number of vessels in long-run competitive equilibrium is characterized by the elimination of all supranormal rents from the system. Mathematically:

$$MB\left(D^{*}, H\left(X, q(z_q, N)\right), L, S(z_s, N)\right) * D^{*} - N_V * c(z_q, z_s, N, NumTrips, w, r) = 0 \qquad (28)$$

Assume that the optimally managed steady state would generate positive rents to the industry and now consider the "deregulation" of the system. Since anglers are no longer paying the implicit dynamic cost of their fishing-induced mortality, the number of trips demanded increases. Furthermore, the demand curve is shifted outward due to additional incentives on the part of vessel owners to compete along margins of catch quality. Given that each vessel under optimal management was operating at full seasonal capacity, it follows that the number of vessels in the fishery must increase under the competitive open access scenario. Fixed costs, downward

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consumers and these inputs are not easily substituted for in the production of catch quality. For instance, vessels may over-invest in noisy but powerful engines in order to increase fishing time. This would likely increase catch quality but diminish the aesthetics of the trip in a way that reduces angler welfare.

sloping demand and diminishing returns to increases in quality inputs eventually exhaust excess rents, however, and entry stops when the headboat trip price (the equilibrium price per angler-day) equals the average total cost per angler-day.[28] Note that there is no inherent mechanism in this rent dissipation process to ensure vessels will be fully employed at the long-run competitive equilibrium; indeed, it is likely that capital will lie idle for some portion of the season. The lower the barriers to entry (i.e. the lower are unavoidable fixed costs) the greater the tendency of vessels to enter the fishery at a given market price and thus the greater the amount of "idle capacity" within the system at equilibrium.

In summary, relative to optimal management, unfettered competition under open access will lead to excessive demand for fishing days. Vessel owners will place too few passengers onboard each trip and the number of vessels will exceed the optimal level and almost assuredly engage in too few trips per season. These vessels will be equipped with excessive catch augmenting capital given their number of passengers so that the harvest effectiveness of individual anglers is too high. Distortionary spillovers from catch-augmenting inputs to non-catch quality inputs are likely although the nature of this interaction is ultimately an empirical matter. The proportion of catch that is landed will be too high (except where discards face full mortality) while the amount of landed catch will be further augmented by the distortions in the effectiveness of angler effort. The overall consequences of these distortions are a reduced equilibrium biomass level, lowered rents for vessel owners and reduced total social surplus compared to the optimally managed case.

Interestingly, some of the foregone rents under competition are accounted for via transfers from vessel owners to anglers. Anglers do receive a greater number of days at sea and higher catch effectiveness (although not necessarily catch) in competitive bioeconomic

[28] We are, of course, assuming away any problems associated with the integer nature of the number of vessels.

equilibrium. However, they also face lower stock levels which may counteract or even outweigh these benefits. Furthermore, induced distortions in non-catch quality may tip the balance in favor of either regime without further empirical context for the model. In other words, it is far from clear that consumers of charter and headboat services would be better off under a rationalized system without some redistribution of the rents. This finding is of considerable importance for the political economy of the rationalization process and deserving of much more elaboration, both conceptually and empirically .

IV. The "Optimal" Corrective Policy

To mimic the necessary conditions of the efficient outcome in the steady state a policy or set of policies must explicitly or implicitly levy the following corrective taxes (where we have substituted out for D^* using (7) and scaled taxes to logical units and levying periods):

$$\begin{aligned} \tau_{D^*} &= \lambda_{SS}\left[\phi\left(H(X_{SS}, q(z_q, N)) - L\right) + L\right], \\ \tau_L &= \lambda_{SS}(1-\phi), \\ \tau_N &= \lambda_{SS} N \phi H_q q_N, \\ \tau_{z(i)} &= \lambda_{SS} N D_{MAX} \phi H_q q_{z(i)}, \quad \forall i = 1, \ldots, Q \\ \tau_{N_V} &= MB\left(N_V N D_{MAX}, H\left(X_{SS}, q(z_q, N)\right), L, S(z_s, N)\right) * (N D_{MAX}) \\ &\quad - c(z_q, z_s, N, D_{MAX}, w, r). \end{aligned} \tag{29}$$

The first tax can be thought of as a "user fee" for access to for-hire recreational fishing and is presented at the resolution of an individual angler-day. The optimal tax on days simply reflects the full mortality impact of the trip including both discards and landings. It is noteworthy that the importance of harvest (and by implication the importance of stock size, angler density and catch-augmenting inputs) in determining τ_{D^*} declines for stocks with low discard mortality. An interesting implication of this finding is that both the intensive and extensive margins of fishing mortality can be approximately controlled by a single post-trip levy on retained catch provided the survivability of discards is sufficiently high.

The tax on landings is denoted per angler-day and is proportional to the survivability of discards. If all catch dies regardless of its disposition, then no regulatory control on landings is warranted and the tax on angler-days collapses to a fee on harvest. This may be the case in many deepwater fisheries.

The instrument for angler density is envisioned as a per-head subsidy to be administered at the trip level for each vessel. This subsidy increases at an increasing rate with the optimal density. Furthermore, the subsidy per head goes to zero as the mortality of discards decreases. If there is no catch mortality apart from landings then there is no external dynamic implication to a skipper's choice of the number of passengers and the competitive market for angler days properly accounts for the remaining intra-vessel static externalities.

The taxes on catch-augmenting inputs are characterized as being levied on a seasonal basis per vessel (assuming that inputs are fixed over that horizon). They increase in the effectiveness of the factor in fostering catch and, as with the subsidy on angler density, the input tax declines to zero as survivability of discards increases. Without a direct dynamic externality from excess fishing power itself, mortality is controllable through a single levy on landings and the free market leads to the proper configuration of fishing inputs in long-run bioeconomic equilibrium.

The final tax is a seasonal levy per vessel that is designed to remove any rents available to the marginal entrant when evaluated at the optimal number of vessels. This "permit" fee could also be administered through the selling or leasing of transferable rights to participate as a charter or headboat in the fishery.[29] Note that the rationale for this instrument is not the same as that underlying the entry tax in the classic, single-input fisheries literature. This explanation has its root in the tendency of vessels in open access conditions to apply "effort" beyond the point that maximizes long-run resource rents. The other taxes in (29) account for analogous forms of this behavior in a multidimensional sense. The tax on entry in the current case is necessitated by a form of rent dissipation that arises due to the lack of cross-firm coordination in entry behavior under an external capacity constraint (the number of available fishing days). Without such a tax, there will likely be an excess burden of fixed costs in the industry.

Although the conditions in (29) may suggest the necessity of imposing *Q+4* corrective instruments to achieve optimal management, such is not the case. The analysis of the prior section foreshadowed this by demonstrating that the complex distortions in catch quality inputs have their common origin in the fact that the competitive value of catch effectiveness reflected to vessel owners is excessive under open access.

Consider the outcome of an open access for-hire market, but with corrective taxes on landings, discards (both administered on a per-angler basis) and the number of vessels[30]:

$$\max_{D^*, L, N, N_V, z} \int_0^{D^*} \{MB\big(D, H\big(X, q(z_q, N)\big), L, S(z_s, N)\big) - \tau_L L - \tau_{H-L}(H(\cdot) - L)\}\, dD - N_V * c(z_q, z_s, N, NumTrips, w, r) - \tau_{N_V} N_V \tag{30}$$

where the constraints in (7) are once again imposed. It is a simple exercise in algebraic substitution to demonstrate that each of the implicit tax conditions in (29) is satisfied (so that the

[29] The revenues from this instrument could be redistributed in a non-distortionary way back to industry or used to fund fishery research. Furthermore, this tax can achieve the safe effect on entry incentives if it is levied on only the *marginal* entrant into the fishery (so that this entrant is indifferent between participating or not) – a method that may enjoy significant practical advantages over wide-scale recapturing of rents.

[30] We assume in (30) that anglers bear the direct incidence of landings and discard fees while the tax on vessels falls upon vessel owners. Given the assumption of our theoretical model, alternative allocations will achieve the optimal equilibrium as well. The following section relaxes this unrealistic view and considers the question of how the target of the tax may alter outcomes.

regulated steady state competitive market mimics the optimal solution) as long as the fees are set as follows:

$$
\begin{aligned}
&\tau_L = \lambda_{SS} \\
&\tau_{H-L} = \lambda_{SS}\phi \\
&\tau_{NV} = MB\Big(N_V ND_{MAX}, H\big(X_{SS}, q(z_q, N)\big), L, S(z_s, N)\Big) * (ND_{MAX}) \\
&\qquad - c(z_q, z_s, N, D_{MAX}, w, r).
\end{aligned} \tag{31}
$$

Note that the $Q+3$ implicit taxes directed at inputs, angler density, landings and angler days are subsumed within two instruments on the level of discarded and retained catch. By targeting discard mortality (and, by extension, harvest), a single properly calibrated instrument is able to induce the optimal configuration of inputs. Furthermore, the combined fees on landings and discards cause fishermen to face (either directly through taxes or permit fees or indirectly through increased trip costs) the full dynamic cost of their fishing mortality when contemplating whether to make a trip.

As noted previously, the magnitude of fishing induced mortality is critical. Fisheries with either very high or low survivability rates of discards may be able to operate effectively under a single fishing mortality instrument. This potential for policy simplification is especially interesting given that survivability may itself be within the control of policymakers. For instance, it may be possible to institute relatively low-cost and easily-monitored standards for the handling and quick release of discards such that their mortality approaches zero. This would allow fishing mortality to be controlled by a single dockside fee on landings and could also foster considerable savings in monitoring, enforcement and administrative costs. This is especially important given the likely difficulties in monitoring and enforcing instruments focused on discards rather than those based on landings. Of course some deepwater fisheries will have inherently high mortality rates so that the distinction between the appropriate discard and landings taxes becomes negligible ($\tau_{H-L|\phi=1} = \tau_L$) and can be viewed instead as a composite "harvest" tax. It may, therefore, be desirous in such fisheries to divert limited monitoring and enforcement resources away from dockside to on-vessel efforts (such as human observers or electronic surveillance systems with random audits) to ensure that the full cost of harvest mortality is enforced.

V. Some Practical Considerations

The previous section deduced a number of properties of an efficiently managed recreational sector. We showed that efficiency could be achieved by using an extensive "price-based" incentive system that taxed or subsidized all relevant inputs in order to convey the correct signals to decision makers (both anglers and vessel owners) about the impacts of inputs on fishing mortality.[31] We showed that a parsimonious price-based system may also be used that directly alters the price of the two principle determinants of fishing mortality, namely discard and landings mortality. As we showed, mortality from both sources can be controlled either indirectly (by taxing all relevant inputs) or directly. This mirrors a common finding in the environmental economics literature, namely that pollution can be efficiently controlled by altering the prices of all inputs according to their marginal contribution to pollution, or by targeting pollution directly. A difference between our problem and pollution problems is that an additional instrument on entry is required to avoid open access dissipation of rents, even with corrective taxes on inputs or outputs.

[31] The implication of (29) is not that all the listed taxes/subsidies be *explicitly* levied. Doing so would result in redundant "double taxation" in one case. Specifically, given a tax on landings and all of the inputs of the harvest function, a separate tax on fishing days is not needed. Nonetheless, *Q+3* other inputs do require directed treatment.

Our findings to this point, while useful, raise important practical issues that are likely to arise in real-world fisheries. In particular they raise questions about regulatory design when the simplifying assumptions (complete certainty, homogeneity of anglers, absence of strategic behavior, etc.) fail to hold. We address some of these practical concerns in the context of two questions. First, who should bear the direct incidence of the landings and harvest taxes? Second, could catch effectiveness or its inputs be targeted by regulators instead of harvest?

V.1 Who Pays the Landings and Discard Taxes?

The previous section did not consider who bears the direct cost of the landings and discard taxes (or, equivalently, the extent of the market for discard and landings quotas). Indeed, in a model of perfect competition, complete and symmetric information and zero monitoring costs the direct incidence simply doesn't matter for efficiency. However, as Coase made abundantly clear, the assignment of rights in a world characterized by significant transactions costs is often of the utmost importance.

In the case of the landings fee, it appears sensible for anglers to directly bear the burden rather than vessels. First, a landings tax borne by for-hire vessel owners does not guarantee the proper behavioral response from customers since landings are individually chosen (assuming of course that they are not constrained by harvest). If monitoring and enforcement costs were sufficiently small, vessels would directly pass on their landings charge to anglers according to their individual landings, thus preserving the optimality of landings decisions. However, the costs of doing so in practice may be significant and one might anticipate instead that vessel owners would recoup their anticipated per-angler landings costs by an equivalent increase in the price of a trip. While the combination of this increase with a discard tax would send the proper marginal signal to fishermen in terms of the implicit tax on fishing days, it would fail to provide an effective check on their landings behavior since it is determined on an ex-ante basis. In the end, we would expect an equilibrium where landings exceed the level predicted by the optimal management model as well as a greater number of days at sea than prescribed under optimal management since demand would be shifted to the right relative to a scenario where landings are effectively constrained.

A second rationale for the direct imposition of landings fees on anglers is that it is robust to angler heterogeneity in landings preferences. Although we presumed identical preferences in our previous derivations, the results are easily generalized to allow for angler heterogeneity in a number of factors, including preferences for retaining catch and exogenous skill in capturing fish. It is simple to demonstrate that as long as this heterogeneity is accounted for in the derivation of λ_{SS}, the tax or quota system derived above allows each angler to retain catch according to their particular preferences while still doing so in an optimal matter.[32] "High retention" types retain a greater proportion of their catch than do "catch and release" types yet everyone pays the full social cost of the resulting mortality. Barring the existence of a perfect pass-through market for landings on vessels, the imposition of a landings penalty on vessel owners is unlikely to generate such an efficient distribution of landings across anglers. For instance, in an attempt to moderate expenditures on landings fees, vessels may establish blanket landings standards for all passengers. Such a system, while easy to monitor and enforce, will likely generate considerable inefficiencies and distributional issues by doing little to constrain

[32] This does not imply that regulators must perfectly observe individual heterogeneity; rather, they must possess knowledge of the distribution of heterogeneity in the population of anglers.

the landings of low retention types of fishermen at the expense of "meat hunting" high retention types.[33]

In the case of a tariff or quota on discards, the case for anglers bearing the burden seems less compelling. After all, per-angler harvest (the portion of the discard identity of harvest minus landings that is not controlled by an external instrument) in our model is an outcome of vessel owners' decisions, not anglers'. If all anglers utilize homogeneous gear provided by the vessel owner and fish equally assiduously, then there seems to be no efficiency gain from levying discard taxes on anglers. This observation is robust to the presence of exogenous variation in angler skill that makes certain fishermen more effective at catching fish than others, as harvest in this case remains predetermined from the perspective of the angler. However, the introduction of variable angler "effort" into the model (possibly combined with heterogeneity in the intensity of harvest preferences across anglers) clearly changes matters.[34] The argument parallels that employed for landings and hinge upon the ability of direct levies on anglers to influence their behavior in an efficient way that is encompassing of heterogeneity. Barring the low-cost development of a perfect pass-through market for discard fees on vessels, the direct levying of discard penalties is likely to have superior efficiency properties, although there may be compelling political deterrents to the establishment of such a system.[35]

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[33] A further advantage of individually-levied landings taxes or quotas is that they are robust to the sort of between-angler trading or purchasing of catch that is often experienced on vessels (but not explicitly modeled here) as long as the fees are levied at the dock after all trades have occurred. In this system fish will flow to those anglers with the highest willingness-to-pay and these fishermen will in turn face the full user cost of their retention decisions.

[34] Harvest is not likely to be purely predetermined from the viewpoint of individual anglers. Although key decisions affecting harvest are made at the vessel level (fishing location, angler density, etc.) there may be a number of behavioral "degrees of freedom" open to anglers. For instance, anglers may be able to supply some or all of their own gear, thus potentially increasing their harvest rate.

[35] Landings fees are likely to enjoy considerable political advantages over discard or catch fees given the likelihood that fishermen may view the ability to freely catch and release fish as a "natural right" whereas a charge for the retention of catch may seem more natural due to the fact that retention is consumptive in a more traditional, immediately tangible sense.

V.2 Could Controls on Catch Effectiveness or its Inputs be Employed Instead of Discard Fees?

Since the choices of vessel owners are the only determinants of harvest rates in our simple model, one might logically infer that a tax on catch effectiveness (i.e. a tax on some index of a vessel's productivity), if it could be reliably measured, would prove equivalent to a discard tax. This is not generally the case, however, as we shall see.

First of all, if we derive the optimal tax on *q* from a revision of (30) where the discard tax is simply replaced by a catch effectiveness tax ($\tau_q = \lambda_{SS}\phi H_q$), we find that some of the necessary implicit tariffs listed in (29) fail to hold for all functional relationships between catch effectiveness and harvest. Specifically, the first condition in (29) fails to hold except for the case where the following condition is satisfied:

$$H_q q = H(X, q),\ \forall q > 0\,. \tag{32}$$

In other words, the harvest function must be linear in catch effectiveness. This is a commonplace assumption, but if this condition fails then the implicit tax on trips is:[36]

$$\tau_{D^*} = \lambda_{SS}\left((1-\phi)L + \phi H_q q\right). \tag{33}$$

If $H_q q > H$ for all *q* (i.e. harvest is strictly convex in *q*), then the implicit tax on days is too high relative to that prescribed at the optimal solution, driving trip demand to too low a level – this despite the fact that catch-augmenting inputs are all optimally determined.[37] The imposition of a linear tariff on catch effectiveness fails to work in general for the reason that a *non-linear* tariff is required to account for the harvest-related mortality from additional fishing trips. A corrective tax or subsidy on fishing days is required in combination with the tariff on catch effectiveness to achieve the same outcome as the single levy on discards.

[36] Note that the tax on landings from (30) has been altered to $(1-\phi)\lambda_{SS}$ to compensate for the now-missing "subsidy" on landings implicit in the discard tax but missing in the catch effectiveness tax.
[37] The reverse applies for the case where harvest is strictly concave in catch effectiveness.

There are other practical reasons for avoiding taxation of catch effectiveness. First of all, the very nature of catch effectiveness is that it is difficult to measure, being composed of numerous inputs that are not easily observed by regulators. Furthermore, if such an index were established and taxes implemented in a manner based upon this index, then there would be an obvious incentive on the part of vessel owners to innovate so as to increase the effective catching power obtained for any value of the index. Finally, if harvest is in anyway malleable with respect to the decisions of anglers, then levies on catch effectiveness (or any input-targeted instrument) will leave these endogenous sources of mortality unchecked – a criticism that does not apply to a direct discard fee on anglers.

Rather than penalize catch effectiveness, per se, one could instead consider quantity restrictions on key inputs in the harvest process. However, such an approach suffers from all the prior criticisms of levies on catch effectiveness and is likely to face additional shortcomings as well. For instance, a restriction on the number of lines allowed per angler will increase the "virtual price" of this input (Neary and Roberts, 1980, Squires, 1994) leading to attempts by vessel owners to substitute away from the regulated input into non-regulated inputs. Barring a perfectly complementary relationship between the input and catch effectiveness, this attempt will succeed to some degree.[38] The possibilities for such substitution may be considerable and little understood on an *a priori* basis. Accordingly, barring an omnipotent knowledge of the production technology and factor costs faced by fishermen, regulators are likely to see their attempts to reign in catch effectiveness frustrated. The dynamic manifestation of this process may be a sequential game of "cat and mouse" between regulators and vessel owners – a pattern

[38]A restriction on fishing lines per angler may lead to the use of higher quality bait, increased chumming of the waters, more powerful vessels to maximize fishing time or even a countervailing reduction in the density of fishermen to enhance per-angler catch.

of behavior that can be observed in the histories of numerous managed commercial fisheries (Wilen, 2006).

VI. Conclusion

The adoption of market-based rationalization programs in commercial fisheries has been met by a great deal of success. Fisheries that once were compressed into short and intense “derbies” with excessive numbers of highly capitalized vessels are now conducted at slower paces that allow fishermen to maximize the value of catch rather than its volume. New rents have been generated both by producing higher valued products and by reducing excess inputs and reconfiguring production. Rights based systems such as ITQs give fishermen a stake in the health of the fishery, reducing the adversarial nature of fisheries regulation and management and generating stewardship incentives among participants. A question arising from these success stories is whether these same outcomes might be generated with similar programs in recreational fisheries. Currently the answer is not clear as there is no analogous body of experience for recreational fisheries.

In the absence of empirical experience, the alternative we pursue is to develop a conceptual structure with which to forecast the potential sources of rent dissipation in for-hire recreational fisheries and to gauge the likely consequences of various rationalization strategies. An important innovation in our approach is the detailed integration of the motivations and choices of the for-hire recreational sector within a traditional bioeconomic framework. Previous analyses of recreational fishing have focused on angler decision making without giving heed to the role of the suppliers of recreational trips. But understanding this supply behavior is essential to discovering how rents are dissipated and how, after rationalization, rents may be generated under new incentives. Importantly, we find that open access rent dissipation in the for-hire recreational sector operates in a manner subtly different from that in the commercial sector. In commercial fisheries, there is a direct link between harvest and revenue that motivates each vessel owner to increase fishing capacity in the drive to increase his/her share of the aggregate catch. In the recreational sector, vessel owners instead produce a multidimensional recreational service rather than mere harvest, although harvest and landings are obviously important drivers of the market for recreational trips. Vessel owners do not simply purchase more catch-producing inputs as in the commercial sector; instead, they offer recreational trips with various characteristics and prices, and anglers operate in the market to choose a recreational provider and number of trips according to utility maximization. It is the subtle interaction of angler preferences with open access competition among suppliers that leads to our predictions of rent dissipation, distorted inputs and excessive harvest and landings.

Efficient rationalization requires that the full mortality from discards and landings be incorporated within the institutional design. When the proportion of discard mortality lies between zero and one, it is necessary to induce both anglers and vessel owners in the for-hire sector to correctly account for their respective roles in influencing total fishing mortality. A useful and potentially policy-relevant result is that if both forms of mortality are appropriately priced, this induces efficient choices of all other fishing inputs, except the size of the fleet. A corollary is that with discard mortality, an efficient ITQ program must ideally have transferable permits for both discards and landings. However, if discard mortality lies at the extremes of the spectrum then a single mortality instrument will suffice. For example, if discard mortality is close to zero, an ITQ program on landings will be sufficient. Similarly, if the target is a high quality food species and anglers are strongly motivated by "putting food on the table", then landings are likely constrained by harvest so that only landing rights need to be traded (regardless of the mortality of discards for the species). These are fortunate situations from a management perspective because measuring landings at the dock is always easier than attempting to measure at sea discards. However, as discard mortality increases, so does the user cost of discards and so managers must increasingly focus their efforts on curtailing discards. This is especially important where a fish is primarily targeted for sport so that landings represent only small portion of total mortality. This is a very problematic situation that poses monitoring, measurement and enforcement difficulties that are yet to be solved in many long-standing *commercial* fisheries with significant discard mortality.

Although we have focused our attention on theoretically optimal policies in this paper, our framework is nevertheless quite useful in addressing the strengths and shortcomings of more limited and cost-conscious rationalization policies. For example, in lieu of the three-part tax (or quota) we have prescribed above, regulators could instead fix total angler days and allow vessel owners to purchase the rights to service these angler days in a quota market.[39] Such an approach is easily monitored and enforced and derives some clout from the first condition in (29) that shows how a properly calculated quota is capable of providing efficient incentives for anglers in determining the extensive margin of their fishing mortality. However, when applied exclusively without regard to the discards or landings associated with individual trips (the *intensive* margins of mortality), this policy will induce numerous slippages in per-angler landings, catch-augmenting and (possibly) quality-augmenting inputs, anglers per vessel and the equilibrium fleet size. The message of our modeling is that there are multiple margins across which rents may be dissipated in recreational fisheries. When a policy is targeted at only a subset of these

[39] Such a scheme is not a theoretical curiosity. A similar scheme has been in place in the New England commercial groundfish fisheries for several years to control fishing mortality after other methods were attempted and judged as failures.

margins, perverse incentives will often persist with respect to unconstrained inputs, a lesson that has been repeatedly borne out (if not always heeded) for commercial fisheries as well.

These observations only scratch the surface of the numerous issues involved in thinking about the rationalization of recreational sectors. While there are some similarities between the for-hire recreational and commercial cases, there remain significant differences that warrant further conceptual and empirical investigation.

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