Heterogeneity among agent types and second-best management for non-market ecological services

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Second-best management affects different agent types differently, and heterogeneity among agents may create instances when only second best management is feasible. Capital-theoretic bioeconomic modeling often has imposed representative agent assumptions that may not capture this heterogeneity. Interactions between agent heterogeneity and second-best management have received little attention. Such heterogeneity is particularly important when management actions do not directly affect extensive margin decisions. We employ a microparameter model in a dynamic bioeconomic model to incorporate agent heterogeneity and intensive and extensive margin decisions for a nonmarket good, recreational fishing. The model yields qualitatively different management recommendations when a representative agent is assumed than when heterogeneity is included using the microparameter approach.

Key words: entry-exit, microparameter; bioeconomics; recreational fishing; landing limits; optimal control.

Introduction

It is common to assume a representative individual in capital-theoretic bioeconomic modeling. This implies that individuals are homogeneous or that heterogeneities are unimportant. Furthermore, it is common to assume a social planner that directly controls, or can strictly enforce, interactions with the ecological system (e.g., the number of fish to harvest in a fishery). This may be problematic when considering non-market ecosystem services (e.g., recreational fishing) for two reasons. First, the value of non-market services are not coordinated in the market and do not obey the "law of one price." This means that least-cost individuals, as measured by travel costs or other common means, may not be the individuals that derive the most consumer surplus from fishing. Second, institutional constraints may prevent managers from choosing a first-best policy and directly controlling interactions with the ecological system (Dasgupta and Maler 2003). Such indirect management is inherently second-best. Whenever second-best management is considered it will affect different agent types differently, and heterogeneity among agents may create instances when only second best management is feasible. For example, first-best management in a recreational fishery with heterogeneous anglers requires choosing a management program that includes the number of anglers and which anglers participate (Anderson 1993). Schnier and Anderson (2006) provide empirical evidence for the importance of heterogeneity in the case of commercial natural resource extraction. There is a need to consider heterogeneity explicitly, and ignoring heterogeneity (i.e., focusing on a representative individual) may lead to qualitatively different results relative to the case when heterogeneity is considered.

Heterogeneity is of increasing interested in bioeconomic analysis. There is an increasing number of analyses that focus on the resource heterogeneity (e.g., Sanchirico and Wilen's 1999 and Smith and Wilen's 2003 applications to spatial heterogeneity). Random parameter models (e.g., Train 1998) are increasingly used in econometric studies to capture agent heterogeneity. In this paper we show how agent heterogeneity may be incorporated into a capital-theoretic bioeconomic problem using a micro-parameter or micro-unit model approach (Hochman and Zilberman 1979). This approach uses a distribution of agent types to incorporate heterogeneity. By integrating over the distribution is possible to scale up from the scale of an individual's decision to model aggregate demand for nonmarket recreational goods. This allows us to derive the social planner's objective function from individual utility maximization and thereby address issue associated with a lack of market coordination. Furthermore, the microparameter approach enables intensive margin decisions and extensive margin decisions to be modeled endogenously based on microeconomic theory. Kuhn-Tucker models have greatly expanded research on extensive margin decisions (i.e., corner solutions) (Phaneuf et al. 2000), but given their complexity, they have not yet been integrated with dynamic resource models. The microparameter approach provides a deterministic approximation to the Kuhn-Tucker model. The microparameter approach is easier to combine with dynamic resources models due to its deterministic nature. This enables the analyst to model the dynamic feedbacks from the ecological and policy sectors to individual behavior. Importantly, the approach enables the analyst to address second-best decisions when the number of (and which) participants can not be feasibly regulated.

We illustrate the microparameter approach by investigating the problem of setting daily landing (bag) limits in a recreational fishery, a common management instrument in recreational fisheries (Radomski et al. 2001). Prior research has mainly focused on the intensive margin, (e.g., Anderson 1983; McConnell and Sutinen 1978; Homans and Ruliffson 1999) or has used an exogenously defined entry-exit function (Swallow 1994) thereby ignoring an important feedback from the ecological to the economic system. Two exceptions are Anderson (1993), who focuses on first-best solutions, Woodward and Griffin (2003), who use a complex simulation model to examine welfare effects and account for extensive margin decisions. We focus on second-best solutions, where the number of anglers is not a choice for the social planner. In this case focusing on a representative angler or agent leads to qualitatively different results.

Bioeconomics of Recreational Fisheries

There is a long history of bioeconomic analysis for fishery management, but dynamic bioeconomic models of recreational angling are relatively rare. Most fisheries bioeconomics work focuses on commercial fisheries or commercial representations of recreational fisheries (Smith et al. 2008). Rational economic management is increasingly being embraced by fishery managers (Costello 2008; Hilborn 2007a,b). The scarcity of bioeconomic models of recreational fisheries is surprising given that recreational landings can exceed commercial landings for important species (Bartholomew and Bohnsack 2005). Recreational fisheries suffer from similar open access problems and stock externalities as commercial fisheries. Two potential reasons for the scarcity of work on recreational fisheries are their non-market nature and the public trust tradition, which serve as institutional constraints. Both of these suggest that second-best solutions are highly relevant.

Recreational fisheries managers and biologists are increasingly attempting to model angler behavior in a dynamic system (Cox et al. 2003; Post et al. 2003), perhaps do to a perceived neglect of recreational fisheries by economists. Of course, there is a large literature on recreational fishing in the environmental economics field relating to travel costs and contingent valuation (see Johnston et al. 2006 for a review). There is also a growing econometrics literature on modeling heterogeneity (e.g., Train 1998) and entry-exit decisions (Phaneuf et al. 2000). All of these are data intensive, and there is not an obvious and succinct way to combine them with dynamic biological models and provide a second-best theory of recreational fishery management.

McConnell and Sutinen (1979) and Anderson (1983; 1993) provide a framework for modeling recreational angler behavior based on microeconomic theory. Homans and Ruliffson (1999) and Woodward and Griffin (2003) have extended this work to examine structured fish populations and more complex policy instruments. Their models capture individual angler behavior and describe the general nature of the aggregated recreational fishing demand. Their models increase biological realism, but they do not address the details of summing over individual decisions to identify the total recreational angling effort or demand. Anderson (1993) focuses on first-best management with homo- and heterogeneous anglers. Woodward and Griffin (2003) aggregate over anglers in a simulation context, but do not provide a generalizable framework to sum over anglers to qualitatively understand extensive margin decisions. The interaction between extensive and intensive margin decisions has important implication for angler surplus, angler behavior, and the ultimately fish stock. Furthermore, angler surplus is not derived solely from landed fish in a recreational fishery. There is value in the act of fishing. Therefore, there is surplus even in an open access fishery that results from anglers' diminishing willingness to pay for increases in the quantity of fishing opportunities (Anderson 1983). Even for relatively simple deterministic models, the solution is not simply a matter of finding the number of least-cost anglers that produce the "optimal escapement" as in commercial fisheries (e.g., Clark 1980).

Angler Behavior Model

The individual angler

For illustrative purposes we assume that anglers vary in costs and assume all anglers have the same individual angling preferences and skills. Angler utility is $U = u(m, z(s, \theta)) + x$. Following Anderson (1983), u is a quasi-concave, increasing function of days fished, m, and the quality of the fishery, z, which is increasing in the fish stock, s, and a decreasing function of restrictions on keeping fish θ. Assume that $u_m(m, z(s,\theta)) > 0$, $u_z(m, z(s, \theta)) > 0$, $z_s(s, \theta) > 0$, and $z_\theta(s, \theta) < 0$, where subscripts denote partial derivatives. We also assume marginal utility is downward sloping with increases in fishing days, $u_{mm}(m, z(s, \theta)) < 0$, and that marginal utility is increasing fishing quality, $u_{mz}(m, z(s,\theta)) > 0$. The variable x is a composite numeraire good. Each individual has a budget constraint given by $I = x + cm$, where I is income and c is the individual's private unit cost of fishing. This differs across individuals. Using the budget constraint, we focus on the following affine transformation of utility, which is a measure of individual angler surplus due to the assumption of quasi-linear utility

$$(1) \qquad V = u(m, z(s, \theta)) - cm$$

Quasi-linear utility is a common assumption in the empirical literature that may have small effects on welfare estimates (Herriges and Kling 1999). In a recreational fishery, the individual angler has two choices, *i*) whether or not to fish in a given season, and *ii*) how many days to fish given that he chooses to participate (Anderson 1983; McConnell and Sutinen 1979). Anderson (1993) and Swallow (1994) recognize an additional choice of how many fish to keep because "catch and release" fishing is important in some recreational fisheries, though not in all (Bartholomew and Bohnsack 2005). Anglers gain utility from both the process of catching fish as well has gaining the fish for food or trophy. Assume that all else equal anglers would keep all fish caught and are worse off with increased restriction on the number of fish kept $u_\theta < 0$. Given this assumption we can focus on the proportion of fish that the angler is allowed to keep, $p \in (0, 1)$. An increase in p is a relaxation of θ.

An angler enters the fishery if $V \geq 0$. Given that an angler participates, he chooses the number of fishing days, m, to maximize utility. The optimal value of m solves

(2) $$u_m(m, z(s, p)) - c = 0,$$

and is written $m^* = m[z(s, p), c]$. The resulting surplus is $V^*(s, p, c) = u(m^*, z(s, p)) - cm^*$.

Aggregating anglers

To be able to couple the model of an individual angler's behavior to the dynamics of a fish stock, we have to be able to aggregate and determine the total number of anglers participating, and their total impact on the fish stock. Aggregated fishing related mortality (landings plus discard mortality) may have a large effect on the stock.[1] There are five ways the number of participating anglers could be modeled.

First, the number of anglers could be a management choice. Indeed, choosing the number of anglers would be necessary for first-best management. This problem is addressed by Anderson (1993).[2] This may be feasible for some fisheries; however in general the total number of participants is not restricted. Indeed, many fishery managers face incentives to maximize participation. Generally, we assume that a first-best solution, where the number of anglers is directly chosen, does not satisfy institutional constraints.

[1] Increasingly, there is also concern about how fishing alters stock structure (e.g., Wilberg et al. 2005). This aspect of managing fishery problems has been initially treated by Woodward and Griffin (2005).
[2] Anderson (1993) points out that if anglers are heterogeneous the social planner also needs to choose which anglers participate for first-best management.

A second approach is taken by McConnell and Sutinen (1979); exogenously setting the number of participating anglers.

The third approach sets the number of homogeneous anglers in open access such that all rents do to quality vanish (Anderson 1993). However, if anglers are assumed to be completely homogeneous, then the number of anglers can not be determined endogenously. If all anglers have identical preferences and costs, and anglers enter if they receive positive utility from doing so, then in open access all anglers will participate or none will participate depending on the quality of the fishery. Furthermore, all anglers fish the same number of days. Identical anglers make identical decisions on both the extensive and intensive margin. Hence, defining the pool of potential anglers defines the number of anglers participating. Similar issues have been identified in models of commercial fisheries (Clark 1980). As fishing improves we expect more anglers to participate. Additionally, we expect participating anglers to fish more days and gain a larger angler surplus.

Swallow (1994) uses a forth approach and defines an exogenous function of angler entry and exit into the fishery, based on empirical work by Andrew and Wilen (1998) that does not explicitly model individual level decisions. A variant on this approach is used by Woodward and Griffin (2005). They include extensive margin decisions in a complex simulation model with entry-exit rules. Yet, explicitly connecting the entry-exit decision to individual utility maximization decision is necessary to compute the marginal value of fishery improvements and understand how regulations may affect behavior and welfare.

We propose a fifth approach. To determine the total level of effort in the fishery, we recognize that each angler has a unique cost to fishing and think of c as a cost type. Each cost type is treated as a "micro-unit" (Hochman and Zilberman 1978).[3] Cost types are ordered in increasing order, such that the last cost type to enter the fishery is $\tilde{c}$. That is, $\tilde{c}$ is the cost at which the marginal angler is indifferent about entry and receives zero surplus.

(3) $$V^*(s,p,c) = u\left(m^*, z(s,p)\right) - \tilde{c}m^* = 0$$

This condition implicitly defines $\tilde{c}$ as the function $\tilde{c}(s,p)$, with $\tilde{c}_s(s,p) > 0$: a larger stock yields fishing quality improvements that induce entry by individuals with higher costs, increasing willingness to pay. Increases in the landing limit (relaxing regulations) encourages entry resulting in a larger set of cost types entering, $\tilde{c}_p(s,p) > 0$. Specifically, participating cost types will be in the interval $[0,\tilde{c}]$.

With a large number of potential anglers, we think of the cost types as being continuously distributed. Cost types, c, are distributed over the interval $[w,\infty]$. A density function ψ (with $w \geq 0$, if it is there is a minimal cost for a day of fishing $w > 0$; in the simulation model $w = 0$) is used to represent the distribution of these cost types. We take the approach of using a probability density function to represent the proportion of the total potential anglers, N, that participate. If N is the total number of *potential* anglers ($N = 1\times10^6$ in the numerical example), then the number of *active* anglers in the fishery, $n(s)$, depends on the size of the stock and regulations.[4]

(4) $$n(s,p) = N\int_0^{\tilde{c}} \psi(c)dc$$

[3] We include heterogeneity across anglers' cost of fishing, but recognize that anglers have heterogeneous preferences for fishing and heterogeneous skill levels resulting in different catch rates per anglers. The incorporation of these differences is left for future analysis. We discuss how this assumption may affect the optimal daily catch limit. This assumption enables to focus on the main contribution of the paper – demonstrating the importance of including heterogeneity in bioeconomic models if nonmarket demand using microparameter models. Hochman and Zilberman (1979) discuss how to incorporate multiple sources of heterogeneity in microparameter models.

[4] Defining the angler pool is not straight forward. However, as long as care is taken so that the distribution of c is taken into account, an appropriate angler pool can be defined.

Total angler surplus, B, is the sum of angler surplus received by all individual anglers at time t, and is also a function of salmon biomass and regulations.

(5) $$B(t) = B(s, p) = N\int_0^{\tilde{c}} V(s, p, c)\psi(c)dc$$

Total catch per unit time, $h(s,p)$, is derived similarly.

(6) $$h(s, p) = N\int_0^{\tilde{c}} m^* z(s, p)\psi(c)dc$$

In some recreational fisheries release or discard mortality may be significant (Bartholomew and Bohnsack 2005; Coggins et al. 2007). If there is discard mortality, where x is the proportion of discarded fish that subsequently die, the total fishing induced mortality is

(7) $$F(s, p) = N\int_0^{\tilde{c}} m^* z(s, p)\left[p + (1 - p)x\right]\psi(c)dc$$

Fish stock dynamics

To understand the dynamic nature of the system we couple our model of angler behavior to a population model for a fish stock. Given our focus on the effect of heterogeneity and entry-exit decisions, we focus on a simple model where fishing affects mortality, but does not affect the structure of the stock. We represent the stock dynamics as

(8) $$\dot{s} = sG(s) - F(s, p)$$

where G is a concave net growth function (e.g. the logistic growth function – Clark 2005). It is also convenient to introduce notation for the harvest per angler day. We follow the standard Shaffer model and write catch per unit effort (per m) as qs, where q is the catchability coefficient.

Management scenarios

Pure open-access, no regulations

Given our assumptions that, all else equal, anglers prefer to land the fish that they catch, we set $p = 1$. In this case there will be no release so the value of x is irrelevant.

In the case of homogeneous anglers Anderson (1993) states that each individual angler should solve condition (2) giving m^* for all anglers, and the net utility gain must go to zero giving n. The problem with this formulation is that there is no market to coordinate anglers. The simple case is where the implied $n > N$. In this case, all anglers, N, enter and continue to earn rents (Anderson 1933 address this case). Because recreational fishing is a non-market good, additional anglers can not be induced to enter the fishery. In our model, anglers do not consider rents to other anglers when they fish. For this reason the reverse case, $n < N$, makes little sense. If an individual angler would gain a positive benefit from entering at a given level of s, then the angler should enter. Furthermore, if all anglers are the same, then if one angler enters, they should all enter. Hence the formation $n < N$ does not correspond to microeconomic individual decision making. The only alternative to this is to choose N exogenously. But, if N is allowed to change with the stock size, then anglers must not be homogeneous.

Anglers must be heterogeneous to have anything other than knife's edge entry and exit. Exogenous entry-exit functions could be developed. Yet, to understand how a regulation affects behavior, entry-exit decisions must be based on microeconomic decision making, especially when a second-best policy that does not directly control entry and exit is considered. This may be handled with the micro-parameter approach. Equation (7) may be substituted into equation (8). Setting (8) equal to zero and solving for s gives the unregulated equilibrium stock size, s^{∞}.

This value of s^{∞} may be substituted into equations (4) – (6) to find the number of anglers participating, the aggregated angler surplus, and the total harvest.

Management with daily landing limits.

In the first-best case the manager chooses the daily landing limit, m^* for each angler, and n; nothing is left to the individual (see Anderson 1993 for a discussion of this problem). The more interesting problem is what happens when the manager must choose regulations within the bounds of an institutional constraint. We focus on the case when the social planner is constrained to only setting a daily landing limit. Assume that managers can perfectly institute a daily landing limit with zero management costs, and that $x = 0$. The daily landing limit is $\theta(t) = qs(t)p(t)$, where $p \in (0,1)$. It is more convenient to work in terms of $p = \theta/qs$.

The manager's problem is to maximize the discounted aggregated angler surplus over an infinite time horizon subject to equation (8) and initial conditions. For the homogeneous angler problem this is

$$\max_{p} \int_{t=0}^{\infty} n\left[u\left(m^*, z(s,p)\right) - cm\right] e^{-\rho t} dt \text{ s.t. (8) and } s(0)$$

where ρ is the discount rate. Recall that the actual number of anglers, n, is constant and equal to the number of potential anglers in N in the homogeneous angler case. Also, $F(s,p)$ in equation (8) is replaced with $qsnm^*$. The Hamiltonian for the problem is

$$H^1 = n\left[u\left(m^*, z(s,p)\right) - cm\right] + \lambda\left(sG(s) - qsnm^*\right)$$

where λ is the co-state variable. The Hamiltonian is a welfare measure. The right-hand-side (RHS) is net benefits to society from recreational angling conditional on a choice of p and the effects of the choice of p on changes in the fish stock. The co-state variable is assumed to be positive as this represents the shade price for the fish stock - an asset. For the first-order, $H_p^1 = 0$, and adjoint condition $\dot{\lambda} = \rho\lambda - H_s^1$, from the maximum principle (Conrad and Clark 1987) to lead to an optimal control the strong Legendre-Clebsch (LC) condition (i.e., $H_{pp}^1 < 0$) must be satisfied (Robbins 1967). This condition is a corollary to the maximum principle when the control variable takes an interior value.

(9) $$H_{pp}^1 = n\left[u_{pp} + m_{pp}^*\left(u_{pp} - c\right) + m_p^*\left(2u_{mp} + m_p^* u_{mm}\right)\right] - \lambda nqsm_{pp}^*$$

The sign of H_{pp}^1 is generally ambiguous. However, in a special case where the utility function results in a linear *individual* demand function for fishing services, i.e., $u_m(m, z(s, p)) = (z_1 + z_2 p)qs - ym$, which we consider in our simulations, $H_{pp}^1 > 0$.[5] Consider the first term; the one in the square brackets, and let this term equal Θ. In our special case only the third term of Θ is non-zero, and this term in >0 ($u_{pp} = m_{pp}^* = 0$). To see this, note that $u_{mp} = m_p^* u_{mm}$. Now consider the second term. In the special case this term is zero. Therefore, for the special case there is no optimal traditional optimal control. The optimal path in this case must be a sequence of extreme controls as in a Bolza type problem known as chattering (Clark 2005 pp.147-149) or sliding (Zelikin and Borisov 1994) controls (this can be shown to be the case numerically). Therefore, applying the necessary conditions associated with the maximum principle (i.e., the standard first order and adjoint conditions) to this problem would lead to a minimum if anything. These conditions may provide some more intuition as the state variable solution is the limit of the chattering sequence (Clark 2005).

[5] We consider this special case because it permits a corner solution even in the case when there is only one good or site to choose from. Specifically, our model provides a choke price as shown below.

Now consider the problem when the manager accounts for individual heterogeneity and extensive margin decisions. In this case the manager's problem is

$$\max_p \int_{t=0}^{\infty} B(s,p)e^{-\rho t}dt \quad \text{s.t. (8) and } s(0)$$

The Hamiltonian for this version of the problem is

$$H^2 = B(s,p) + \lambda\left(sG(s) - F(s,p)\right)$$

First, we verify the LC condition to determine if the maximum principle may lead to an optimal control path. This is done is two steps relating to the terms in H^2. Initially, H^2_{pp} appears rather complex, but greatly simplifies when condition (3) is accounted for. The second derivate of the first term in H^2 is

$$(10) \qquad B(s,p)_{pp} = N\left[\int_0^{\tilde{c}} \Theta\psi(c)dc - \psi(\tilde{c})\tilde{c}_p\tilde{c}\left(2m^*_p + m^*_{\tilde{c}}\tilde{c}_p\right)\right]$$

The first term on the RHS is suitable average of angler cost types. There is no reason that this could not be a representative angler, at least for a given stock size. Of course, the representative angler would have to change as the fish stock size changed. Assuming that the term in the round brackets is positive, as in our special case, the second term in the square brackets is < 0. Moreover, in our special case $B(s,p)_{pp} < 0$. Now consider the second derivative of the second term of H^2, which is

$$(11) \qquad -\lambda F(s,p)_{pp} = -\lambda N\left[\int_0^{\tilde{c}} qsm^*_{pp}\psi(c)dc + qs\psi(\tilde{c})\tilde{c}_p\tilde{c}\left(2m^*_p + m^*_{\tilde{c}}\tilde{c}\right)\right]$$

The first term on the RHS is a suitable average of angler types. As with the (10) presumably a suitable representative angler could be chosen to make this term equal to the second RHS term in equation (9). There is no guarantee it is the same value as the suitable average for the first term, and like the first term would change with changes in the fish stock. The second RHS in (11) term is positive. Assuming that the first RHS term in (11) is positive, then (11) is negative. Therefore, $H_{pp}^{2} < H_{pp}^{1}$. This implies that when heterogeneity is considered an interior optimal path may emerge. Indeed, in the special case the first RHS term in (11) vanishes. So that $H_{pp}^{2} < 0.$

Now that we have established that the maximum principle may yield an optimal path, and that the maximum principle does yield an optimal control in the special case. The first order condition is

(12) $\partial H/\partial p = \partial B(s,p)/\partial p - \lambda\,\partial F(s,p)/\partial p = 0$

A second condition, which must be satisfied along an optimal path, is the adjoint or arbitrage condition

(13) $\dot{\lambda} = \rho\lambda - H_{s}^{2}$.

Expressing this adjoint condition as a golden rule equation yields

(14) $\rho = \frac{\dot{\lambda}}{\lambda} + \frac{1}{\lambda}\frac{\partial B(s,p)}{\partial s} + \left(G(s) + sG_{s}\right) - \frac{\partial F(s,p)}{\partial s}$

The golden rule equation is a rate of return condition. It implies that the stock should be managed to provide a return equal to the social discount rate, ρ. The left-hand-side term, the social discount rate, is the marginal cost to society of forgoing harvests today and leaving more fish in the stock. The RHS is the marginal benefit of an increase in the stock. The first RHS term in equation (14) is a capital gains term, which is zero at equilibrium. The second RHS term is the marginal value of an increase in the stock size on the total angler surplus. This term is positive. The third RHS term is the stock's own rate of return and could be positive or negative depending on the stock size. The fourth RHS term is the marginal impact of an increase in the stock on mortality due to fishing mediated through angler behavior. This term is expected to be positive, *ceteris paribus*. If the second term is greater than the fourth term by a difference >ρ, then, at equilibrium, the third RHS term necessarily will be negative, implying a stock size greater than the maximum sustained yield level. In such a case a recreational fish stock managed for escapement equal to the maximum sustained yield level would be overfished from a bioeconomic perspective.

Condition (12) also implies

$$(15) \qquad \lambda(s,p) = B_p(s,p)/h_p(s,p)$$

Differentiating (12) with respect to time and substituting (13) and (15) gives an implicit function of $\dot{p}$, which may be manipulated to give $\dot{p} = \dot{p}(s,p)$. To find the optimal equilibria set $\dot{p}$ and $\dot{s}$ equal to zero and solve for $s = s^*$ and $p = p^*$.

Numerical Simulation

To complete our analysis we now turn to a numerical simulation based on the special case of $u_m(m, z(s, p)) = (z_1+z_2p)qs - ym$ and $G(s) = r(1-\Delta s)$. The linearity of u_m implies a choke, $(z_1+z_2p)qs$, at which an angler ceases to fish. The chock price is a function of fishing quality and the management policy. We specify a log-normal distribution for angler cost types.[6] Parameters and their values used on our simulation are listed in Table 1.[7] Values in the numerical simulation are chosen to represent a sport fishery that by common measures is over exploited; as such a fishery would be of high concern to managers (Post et al. 2002). Analyses were conducted using Mathematica 6.0 (Wolfram Research).

[6] Just and Antle (1990) recommend the log-normal distribution for micro-parameter models as a default.
[7] This calibration implies that the greatest marginal value comes from keeping fish. This is not true in all fisheries and affects the optimal daily catch limit. We have chosen this parameterization as realistic for some fisheries and to demonstrate the utility of modeling angler behavior using the microparameter approach.

For the numerical example, the unregulated equilibrium is compute numerically to be $s^{\infty} = 1.32 \times 10^6$ fish or 29% of the unfished stock size ($1/\Delta$). This stock size s^{∞} is then applied in equations (4), (5), and (6) to compute the number of anglers participating (591,563), the total angler surplus ($\$1.2 \times 10^7$), and the catch (974,437) in a given year at equilibrium. If the unregulated equilibrium is the initial condition, then the net present value of angler surplus at the unregulated equilibrium over an infinite time horizon is $B/\rho = 2.4 \times 10^8$.

Consider the second-best solution when the analyst assumes a representative angler. There can be no interior optimal control because the LC condition is > 0 for our functional forms. A sequence of control alternating between $p = 0$ and $p = 1$ is required. Numerically, we verify that such a sequence of control yields higher aggregated angler surplus than open access, $p = 1$, (which is greater than a complete closure of the fishery $p = 0$). The state variable solution from the first order and adjoint conditions is 2.58×10^6 fish (57% of the unfished stock size). This is the limit of the optimal sequence (Clark 2005). This is greater than the open access stock size and maximum sustained yield level, $1/(2\Delta)$.

Now consider the second-best solution when managers account for heterogeneity when choosing the efficient daily landing limit when $x = 0$. Given the parameters in Table 1, we apply the maximum principle and find a bioeconomic equilibrium for $s^* = 2.89 \times 10^6$ and $p^* = 0.38$. As expected, when the daily landing limit is chosen efficiently the stock size at equilibrium is larger than the open access case (64% of the unfished stock size). It is greater than the stock size that is the limit of the sequence of chattering controls in the representative angler case and greater than the maximum sustained yield level.

The value of p^* implies a daily landing limit of $\theta = 0.76$ fish/day. Of course, anglers can not catch non-integer values of fish, but such a limit may approximate weekly limits and is informative about the ability to use daily catch limits to manage a recreational fishery. Swallow (1994) makes a similar generalization in his theoretical study of daily landing limits. Fisheries biologist have suggested that daily catch limits would have to be quite low to have a biological effect (Cook et al. 2001; Post et al. 2002; Radomski et al. 2001). As expected, total angler surplus at equilibrium is higher (1.93×10^7) with more anglers participating (655,744) (Figure 1) and the average angler surplus is greater than in the open access case. It should also be emphasized that while total catch is greater, only 36% of the stock is harvested per year as compared to 71% in the open-access case.

We consider the effects on the capital fish stock and the approach path to the equilibrium. We linearize the $\dot{s}-\dot{p}$ system at the equilibrium and find one positive and one negative eigenvalue, indicating the equilibrium is a conditionally stable equilibrium (Conrad and Clark 1987). The saddle path to the equilibrium is identified (Figure 2). The phase-plane shows that at low stock sizes the proportion of the fish caught in a day that should be kept is low, i.e., the daily catch limit should be set at low levels, and increase monotonically to the equilibrium. Starting at high stock levels, the proportion of the fish caught in a day that should be kept is high, i.e., the daily catch limit should allow more fish to be kept, and decrease monotonically as the stock the approach equilibrium. The optimal daily catch limit increases the net present value of the total angler surplus to 4.68×10^8. This is much greater than the open access level.

When discard mortality is strictly positive ($x > 0$), the sign of H^2 is ambiguous, even in the special. For the parameters in Table 1 a sufficiently large value of x (approximately $x > 0.1$) results in the LC condition evaluating > 0. In such a case an interior control does not exist. Numerically, we evaluate a sequence of switches between $p = 0$ and $p = 1$, the resulting angler surplus in greater than open access (which is greater than a complete closure of the fishery). The stock size that is the limit of the sequence (the state variable solution) is between the open access and efficient bioeconomic equilibrium for $x = 0$. With discard mortality the efficient stock size will be smaller than with no discard mortality.

4. Sensitivity Analysis

Table 2 presents a summary of sensitivity analysis results for response variables at equilibrium or in the case of the net present value of angler surplus over an infinite time horizon starting at the unregulated equilibrium, with respect to a 5% increase in each parameter. The optimality of a daily catch limit is not affected by small changes in parameter values. Moreover, the optimal daily catch limits are less than unit elastic to each parameter, but are most sensitive to catchablity and to the parameter associated with the marginal value of catching, though not landing additional fish. This is particularly interesting because the model was calibrated such that landing an additional fish was three times more valuable than simply catching an additional fish. This indicates the potential importance of catch and release regulations (though release mortality merits explicit consideration). The sensitivity with respect to catchablity indicates the potential for gear regulations and the potential importance of angler heterogeneity in skill, though this is left to future investigations.

Carrying capacity, catchablity, the marginal value of additional days of fishing, and marginal value of catching an additional fish have the greatest impact on the net present value of angler surplus for the optimally managed fishery. But, biological parameters, catchablitiy, and the discount rate have the greatest impact on the net present value of angler surplus for the unregulated fishery. In the unregulated case increases in the average cost of fishing increase the value of the fishery. This potentially indicates an economic justification for the presence of regulatory fishing fees. The microeconomic parameter with the greatest affect on the value of the unregulated fishery is the marginal value of keeping an additional fish. The effect of parameter changes on stock sizes showed similar relationships.

Discussion

Incorporating heterogeneity shows the analyst that human behavior will adjust more sluggishly to marginal changes in the state of the world and policies, thereby leading to a saddle path (Liski et al. 2001). Incorporating heterogeneity reveals that adjustment is sluggish because it reveals that the system is buffered by two effects. The first effect relates to intensive margin decisions. Agents vary their intensive margin decision as the state of the world changes, which also happens with a representative agent model. But when heterogeneity is included in the model, all agents are not "forced" to make the same decision. The second, and perhaps more important, effect is the ability of agents to decide to enter or exit the system. In our example, the cumulative result is that the overall angler population is less sensitive to marginal changes in the state of the fishery and regulations. This may hamper rapid changes in the state of system, which may have implication for rapid conservation or invasive species control. But, it also means that by considering agent heterogeneity managers can devise more efficient management programs.

Management of ecosystem services (Daily et al. 2000) will often be second-best and many of these services are not traded in the market. There is a critical need for economist to play a role in understanding the allocation of such services. Policymakers are more likely to be interested in the nature of second-best management as often there are formal or informal institutions that constrain management. In many cases, limiting entry is not a viable policy option. A corollary to this research is when managers can not force compliance as is often the case with free-ride and weakest link problems. A similar formation may be useful for analysis of these problems. Moreover, managers may wish to restrict human impacts without explicitly excluding individuals. In such cases it will not be logically consistent to consider such policies without the inclusion of agent type heterogeneity. In this paper we have shown how agent type heterogeneity may be modeled by making distributional assumptions. Such models could open the door for increased consideration of second-best management for non-market goods.

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Table 1. Parameters used in the simulation model.

Parameter symbol	Definition	Value in the simulation
q	Catchability coefficient	7×10^7
z_1	Marginal effect on utility of catching fish	10
z_2	Marginal effect on utility of keeping fish	30
y	Marginal effect on utility of fish an additional day	10
μ	Average cost type	45
σ	Standard deviation of cost types	50.3
r	intrinsic growth rate	1.04
Δ	Inverse of the carrying capacity	$1/(4.56 \times 10^6)$
x	Discard mortality	0
ρ	Discount rate	0.05
N	Pool of potential anglers	1×10^6

Table 2. Sensitivity analysis: parameter values and the percent change in response variable at equilibrium for a 5% increase in each parameter; NPVAS is the net present value of angler surplus.

		Base line	Mean cost	Standard deviation of cost	z_1	z_2	y	ρ	r	k	q
Unregulated fishery	NPVAS ($\times 10^8$)	2.36	2.38	2.38	2.38	2.40	2.41	2.25	2.52	2.42	2.27
	(% change)		(0.6%)	(0.6%)	(0.7%)	(1.6%)	(2.0%)	(-4.8%)	(6.7%)	(2.6%)	(-3.9%)
	fish stock ($\times 10^6$)	1.32	1.35	1.32	1.31	1.35	1.28	1.32	1.35	1.33	1.24
	(% change)		(2.1%)	(-0.3%)	(-1.0%)	(2.0%)	(-3.0%)	(0.0%)	(2.0%)	(0.8%)	(-5.9%)
	% unfished stock	29.1%	29.7%	29.0%	28.8%	29.7%	28.2%	29.1%	29.7%	27.9%	27.4%
Fishery managed with optimal daily catch limits	NPVAS ($\times 10^8$)	4.68	4.57	4.73	4.92	4.92	4.85	4.48	4.82	5.09	4.92
	(% change)		(-2.3%)	(1.0%)	(5.1%)	(5.1%)	(3.7%)	(-4.1%)	(3.1%)	(8.9%)	(5.1%)
	proportion of fish kept	0.38	0.39	0.38	0.36	0.39	0.37	0.38	0.39	0.35	0.34
	(% change)		(3.5%)	(-0.3%)	(-5.7%)	(3.5%)	(-1.4%)	(0.4%)	(3.2%)	(-6.8%)	(-10.2%)
	fish stock ($\times 10^6$)	2.89	2.87	2.89	2.94	2.88	2.87	2.88	2.88	3.07	2.94

(% change)		(-0.6%)	(0.1%)	(1.9%)	(-0.3%)	(-0.6%)	(-0.2%)	(-0.4%)	(6.3%)	(1.9%)
% unfished stock	63.7%	63.3%	63.7%	64.9%	63.5%	63.3%	63.6%	63.4%	64.5%	64.9%
catch limit	0.76	0.78	0.76	0.73	0.79	0.75	0.76	0.78	0.75	0.73
(% change)		(2.8%)	(-0.3%)	(-3.9%)	(3.2%)	(-2.0%)	(0.2%)	(2.8%)	(-0.9%)	(-3.9%)
Percent increase in NPVAS through management	98.1%	92.4%	98.9%	106.8%	105.0%	101.4%	99.4%	91.4%	110.2%	116.7%

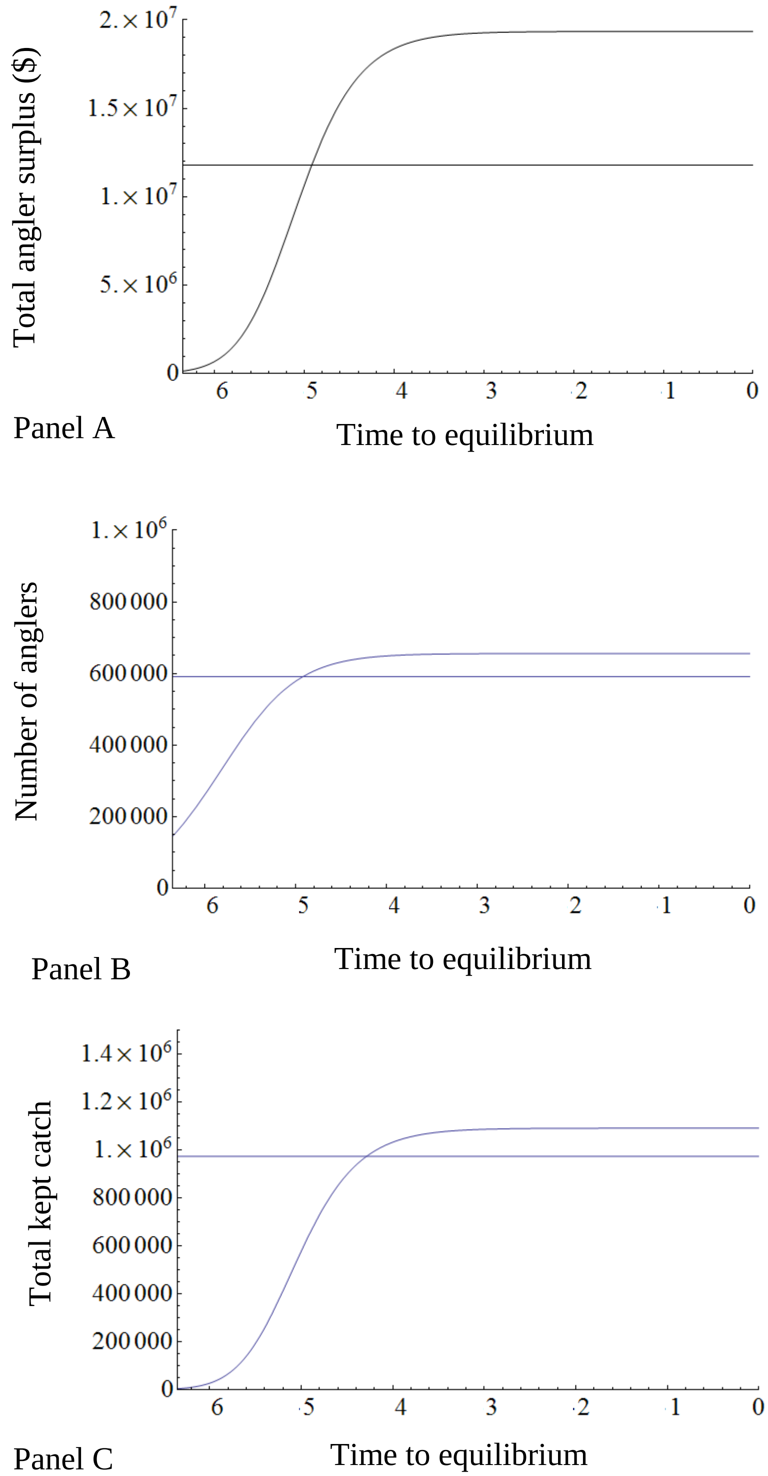

Figure 1. Illustration of the intertemporal tradeoffs following the saddle path from the open access equilibrium to the optimal equilibrium for angler surplus (panel A), participating anglers (panel B), and landed catch (panel C). The flat lines represent the open access equilibrium.

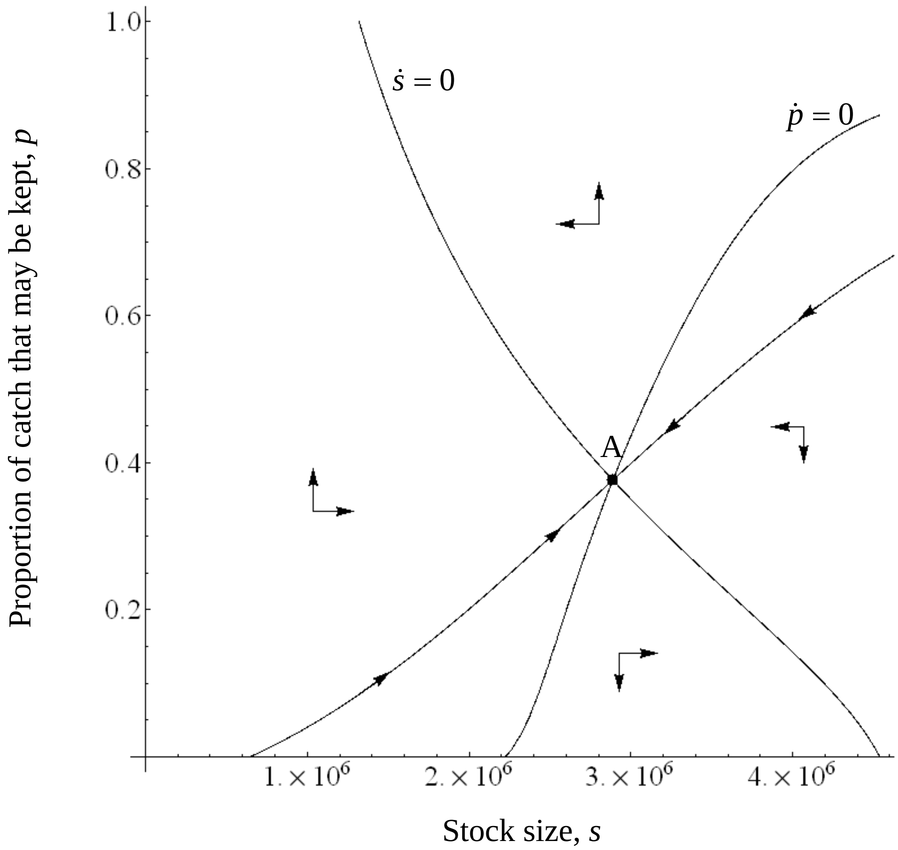

Figure 2. Phase plane showing the optimal proportion of catch that may be kept, the daily optimal daily catch limit is computed *pqs*, where *q* is the catchablity. Point A indicates the optimal equilibrium. The separatrices are indicated with arrows pointing to the equilibrium. Phase arrows indicated the local dynamics.