The Bioeconomics of Resource Rehabilitation: A Commercial-Sport Analysis for a Great Lakes Fishery

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ABSTRACT. *We construct a fishery model which simulates: (a) stochastic population fluctuations and (b) harvest shifts between commercial and sport user groups. This model then assesses, for both commercial and sport harvesters, the bioeconomic impact of an ongoing rehabilitation plan for the yellow perch fishery of Green Bay, Lake Michigan. Overall economic gains from this plan are positive, with sport anglers reaping sizeable benefits, while commercial harvesters lose moderately. Using probing exercises which approximate economic optimization, the efficient allocation of harvest between sport and commercial user groups is also explored. Uncertainties about sport effort levels greatly influence this optimal allocation.*

I. INTRODUCTION

Applied dynamic models are proficient at describing the conceptual underpinnings of fishery economics. They are less adept, however, at portraying bioeconomic realism. Unrealistic biological methods are partly to blame. Simply put, most works have used single-equation, deterministic models to simulate the complex, highly stochastic population dynamics of fish stocks (Clark, Edwards, and Friedlaender 1973; Spence 1973; Henderson and Tugwell 1979; Collins et al. 1980; Gallastegui 1983; Conrad and Adu-Asamoah 1986; Hagan and Henry 1987; Bjørndal 1988; Cook 1988; Conrad 1989; Deacon 1989). Biologists have questioned the predictive powers of these models (Beddington, Bokin, and Levin 1981; Hall 1988). Another concern is that, thus far, no applied bioeconomic study has formally explored the optimal allocation of catch between commercial and sport user groups.[1] Commercial-sport catch allocation is a key policy issue in fishery management today (Edwards 1990).

This study advances the realism of applied bioeconomic modelling—and hence its policy relevance—by building a complex model which simulates: (a) stochastic population dynamics and (b) harvest shifts between commercial and sport user groups. This model then assesses a rehabilitation

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[1] A partial exception might be McCarl and Rettig (1984), who build a Salmon fishery bioeconomic model which contains both sport and commercial sectors. They calculate economic surplus for various sport-commercial catch allocations, and so appear to be searching for the optimal division of harvest. Their results, however, are based on an analysis of a hypothetical salmon restoration project (developed by the National Marine Fisheries Service). Hence, most of their economic parameters appear to be fixed at plausible values (as opposed to being formally derived by empirical methods). Loomis (1988) builds an applied bioeconomic model of an Oregon salmon fishery with both commercial and sport sectors, but the catches for both sectors are assumed to equal fixed percentages of the total catch. He does not explore the efficiency ramifications of varying these fixed percentages. Carter and Radtke (1986) and Hushak, Morse, and Apraku (1986), focusing on Oregon salmon and Lake Erie yellow perch and white bass, use input-output analysis to explore how changes in sport-commercial harvest allocation affects income and employment in nearby local communities. They do not assess economic surplus changes.

plan, initiated in 1983 by the Wisconsin Department of Natural Resources (WDNR), for the yellow perch (*Perca flavescens*) fishery of Green Bay, Lake Michigan. Our initial goal is to determine the economic impact of the WDNR rehabilitation plan for both commercial and sport harvesters. Using probing exercises which are designed to approximate economic optimization, we then explore the efficient allocation of catch between sport and commercial fishers. Finally, we outline several empirical techniques which may aid bioeconomic model building in other fisheries.

In promoting these goals, we are building on Milliman, Bishop, and Johnson (1987) and Bishop et al. (1990), who explored the economic impact of the 1983 WDNR plan without a formal bioeconomic model. Their results, while impressionistic, suggested that sport anglers would benefit greatly from the plan, while commercial users as a group would break even. Their finding about commercial users is modified in the current paper, and results from the probing exercises are added. In addition, we explore the impact of sport effort uncertainty on the economic gains generated by both the 1983 WDNR plan and economic optimization. Johnson et al. (1990) concluded that, with respect to achieving important biological goals, this uncertainty makes little difference, i.e., the 1983 WDNR plan will be successful for a wide spectrum of sport effort levels. This paper examines whether this finding is valid from an economic viewpoint.

We proceed by providing an overview of the Green Bay yellow perch fishery in Section II. To illustrate bioeconomic realism, Section III provides a detailed description of our model. We then assess the economic gains induced by both the WDNR rehabilitation plan and the probing exercises in Section IV. Major findings and future research directions are summarized in Section V.

II. OVERVIEW OF THE GREEN BAY YELLOW PERCH FISHERY

Although most North American commercial yellow perch are currently harvested from Lake Erie, historically Green Bay was also a large producer, averaging 525,000 kilograms (1.16 million pounds) annually from 1936 to 1964 (Milliman et al. 1987). Gill nets and drop nets were the primary commercial gears during this time period (which remains true today).[2] An active sport fishery for Green Bay perch also existed prior to 1964, although its catch rate was not documented (Kraft 1982).

In 1965 the Green Bay perch fishery suffered a partial collapse (Figure 1), with commercial harvests falling to an annual average of 204,000 kg (413,000 pounds) for the period 1965–82. Sport catches also declined by an unknown amount. Intense commercial fishing pressure, pollution, and an increase in alewife abundance (an exotic fish species which may harm perch populations) are probable culprits (Kraft 1982). During the 1965–82 time period, a closed season during spawning (April 9–May 20) and a minimum legal size limit of 191 millimeters (7.5 inches) were the major commercial regulations. Commercial entry barriers were minimal; harvesters paid only a modest license fee. The only sport catch regulation was a daily bag limit of 50 perch, which probably mattered little after 1964 due to relatively low angler catch rates (Kraft 1982). These regulations constitute the *baseline policy* of the analysis. Absent the 1983 rehabilitation policy (to be described shortly), this policy is assumed to continue beyond 1982.

In 1983 the WDNR responded to the post-1964 drop in biological productivity by imposing two additional commercial catch restrictions: (a) a total commercial catch quota, adjusted annually, with each individual fisher harvesting a fixed percentage of this quota; and (b) a longer closed season for drop nets only (April 9–July 1, instead of April 9–May 20). This latter restriction was imposed in an attempt to reduce the mortality of sublegal perch (fish under 191 mm) which often die in drop nets in late

[2] A drop net works by forcing fish, via a single barrier net ("lead") resting on the lake bottom, to swim into a bag-shaped trap at either end of the barrier net (Kraft 1982). The fish are recovered by lifting the traps every 3–5 days.

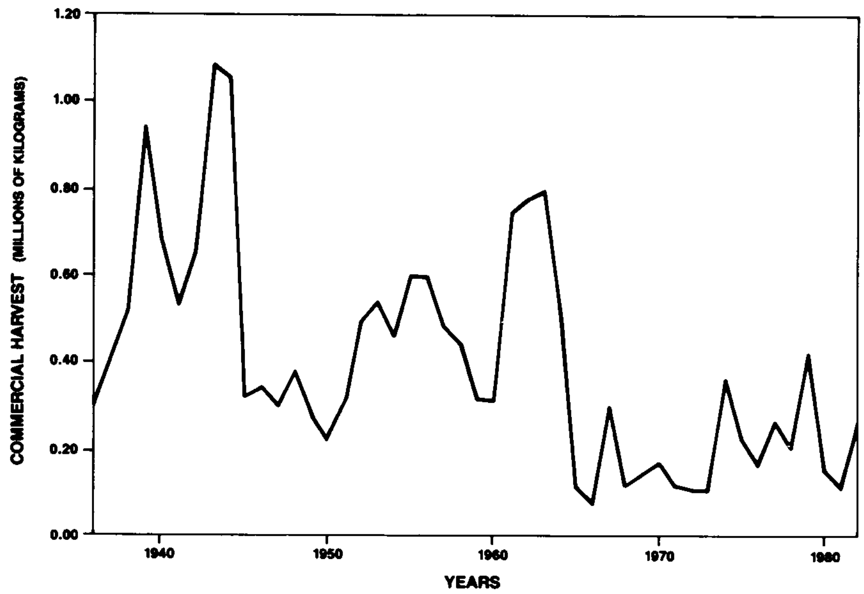

FIGURE 1

Annual commercial harvests of yellow perch (in kilograms) from the Wisconsin waters of Green Bay, Lake Michigan, 1936–82.

May and June (WDNR 1982). These regulations constitute the *rehabilitation policy* of the analysis. The twin goals of this policy were (a) to increase long-term perch abundance (and thus both sport and commercial catch) and (b) to enlarge the percentage of total catch harvested by sport anglers from its pre-1983 amount of 15 percent to 30–40 percent (WDNR 1986). With respect to the first goal, the WDNR believed that the catch restrictions would enhance fish abundance by increasing both the number of recruits (although highly variable, recruitment is believed to be positive-density dependent over a wide range of stock size) and the yield per recruit (by allowing fish to reach an older age before being caught) (WDNR 1982). To facilitate the second WDNR goal, no restrictions were placed on sport catch. Hence, under the 1983 WDNR plan, the major "biomass investors," and thus risk-takers, were the commercial fishers.

The economic gains from the rehabilitation policy, net of its regulatory costs, are in two forms: (a) greater producer rents due to larger commercial harvests and lower fishing costs (to be preserved by individual, transferable catch quotas, which act as entry controls); and (b) angler surplus gains due to both increased sport catch and a larger size of fish caught.[3] These possible gains are estimated by our bioeconomic model, which is described below.

III. THE GREEN BAY YELLOW PERCH BIOECONOMIC MODEL

Model Overview

The model contains four components—Biology, Harvest, Management, and Economics—which are linked as follows (Figure 2). Under the baseline policy, the Harvest component applies sport and commercial effort to the perch population, whose structure (the number and size of fish) is calculated by the Biology component. This effort-biomass interaction determines the resulting harvest. The Econom-

[3] It will be argued in Section 3 that consumer surplus changes associated with the commercial harvest are probably slight, and so they are not estimated.

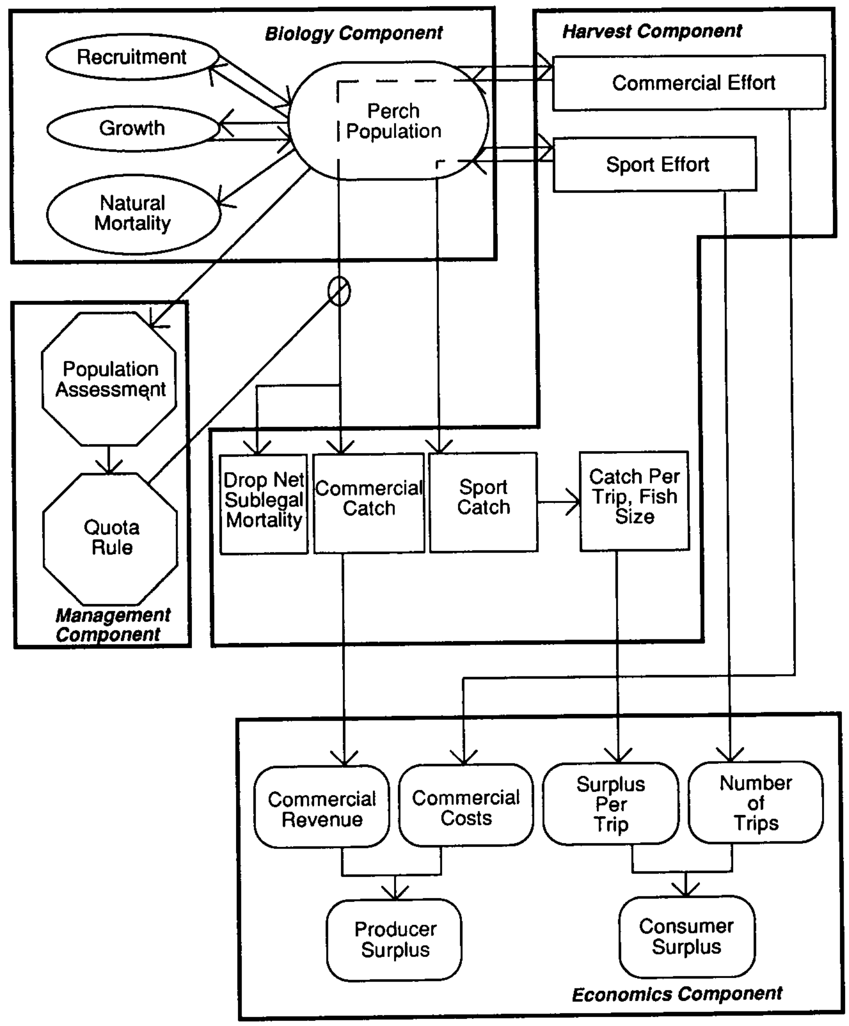

FIGURE 2

Overview of the Green Bay yellow perch bioeconomic model.

ics component, using both catch and effort data, then estimates the annual economic gains (producer and consumer surplus) from this harvest. These calculations are repeated annually as the fishery moves through time, with the catch and associated economic gains generated by the current effort-biomass interaction being a partial function of past interactions. Under the rehabilitation policy, these component linkages are the same, except that the Management component limits commercial harvest (and thus commercial effort for a given population structure) to a particular level each year.

Each component is described in more detail below.

Biology Component

Space limitations preclude us from providing more than a broad overview of the Biology component. A complete description can be found in Johnson (1989).

In this component, the perch population is structured by sex, length, and age (with five age classes in all), and has density dependent functions for recruitment and growth. The rate of natural mortality is assumed to be independent of age and time.

For each sex in a given model year (January 1–December 31), the model tracks population dynamics by age class, denoted by a ($a = 1, 2, \ldots, 5$), across nine intrayear time periods, denoted by t ($t = 1, 2, \ldots, 9$). The length of each t (which range from 15 to 139 days) is set in order to best predict intrayear population dynamics (Johnson 1989). For example, the summer time periods are shorter than other periods because the rapid growth of fish in these months can produce substantial changes in their vulnerability to commercial fishing gear. For each year, the initial number of fish entering age class 1 at time period 1 is calculated by a stock-recruit relation (to be described shortly). Age class 5 represents the accumulation of all fish older than age 4.

For each sex, the difference equation describing intrayear population dynamics for each age class a as it moves from time period t to $t + 1$ is:

$$N_{t+1,a} = N_{t,a} - \left(\sum_{g} J_{t,a,g}\right) - S_{t,a} - A_{t,a} \qquad [1]$$

where N is fish numbers, J is total legal catch mortality, S is total sublegal catch mortality due to drop nets, A is fish lost due to natural mortality, and g is gear type (sport, gill net, or drop net). Equation [1] also tracks interyear population dynamics, which involves changing from year class a to year class $a + 1$ at the beginning of a new year:

$$N_{1,a+1} = N_{9,a} - \left(\sum_{g} J_{9,a,g}\right) - S_{9,a} - A_{9,a} \qquad [1a]$$

Equation [1] then repeats the intrayear dynamics for $N_{1,a+1}$ in this new year.

We describe each mortality source. Legal catch mortality $J_{t,a,g}$ (fish greater than 191 mm) is:

$$J_{t,a,g} = \left[N_{t,a} \cdot \frac{F_{t,a,g}}{Z_{t,a}}(1 - e^{-Z_{t,a}})\right] P_a \qquad [2]$$

where $F_{t,a,g}$ is the instantaneous capture rate by fishing (not mortality rate, since some of the sublegal fish released will live), Z is an instantaneous total "withdrawal" rate (to be described in more detail shortly); and P_a is the proportion of catch which is of legal size for a given age class a. The bracketed term is thus the total number of fish captured by fishing for a given age class a, which is then adjusted by P_a to determine legal catch mortality. Sublegal catch mortality $S_{t,a}$ (fish less than 191 mm) due to drop nets is thus:

$$S_{t,a} = \left[N_{t,a} \cdot \frac{F_{t,a}}{Z_{t,a}}(1 - e^{-Z_{t,a}})\right] (1 - P_a) \cdot SM \qquad [3]$$

where $(1 - P_a)$ is the proportion of catch which is sublegal by age class a, and SM is their drop net mortality rate (proportional), which was estimated to be 55 percent from experiments in which sublegal mortality due to these nets was directly observed (Johnson 1989). The equations for $F_{t,a,g}$ and $Z_{t,a}$ are:

$$Z_{t,a} = \left(\sum_{g} F_{t,a,g}\right) + M_t \qquad [4]$$

$$F_{t,a,g} = q_g \cdot E_{t,g} \cdot T_{g,1} \qquad [5]$$

where M_t is the instantaneous rate of natural mortality in equation [4]. Since $F_{t,a,g}$ is an instantaneous capture rate for fishing, it follows that technically Z is a total instantaneous "withdrawal" rate (not a total instantaneous mortality rate, since some of the sublegal fish captured by F are released and then live).[4] In equation [5], F can also

[4] Since Z is not an instantaneous total mortality rate in our paper, it follows that the standard population dynamics equation (Ricker 1975):

$$N_{t+1,a} = N_{t,a}(1 - e^{-Z_{t,a}}) \qquad [a]$$

cannot be used. Instead, our Z is used to calculate be interpreted as a production function for capturing fish. The parameter q is catchability for a given gear type (the odds that a fish will contact the gear type), E is the amount of effort by gear type, and T is the selectivity of a given gear type and length l (the odds that a fish of a given length, once contact has occurred, is entrapped). Estimates of selectivity T by length l for both commercial gears were supplied by previous studies (cited in Johnson 1989), while Johnson (1989) estimated sport fishing selectivity from angler survey data collected by the WDNR during 1983–85. Values of q for each gear type were estimated by simulating the fishery's 1978–85 biological evolution a number of times with the model's Biology and Harvest components (the latter component to be described shortly), with different q values for each simulation. Data inputs for these simulations were 1978–85 effort levels and $N_{1,1}$ fish counts, plus the initial 1978 perch population structure (with the biological data drawn from WDNR population assessment exercises). The q coefficients that generated the best fit between the simulation results and the actual 1978–85 evolution were retained by the model (Johnson 1989). The q and T coefficients are assumed to be constant across the baseline and rehabilitation regimes.[5]

Finally, natural mortality $A_{t,a}$ is:

$$A_{t,a} = N_{t,a} \cdot (M_t/Z_{t,a}) \cdot (1 - e^{-Z_{t,a}}) \qquad [6]$$

where M equals 0.56 as estimated from an analysis of 1978–85 year-class changes (Johnson 1989). Note that all fish "withdrawn" due to natural mortality end up dying—no adjustment by proportional constants is necessary.

The number of age-one fish entering the fishery at the start of each year ($N_{1,1}$) is calculated by a Ricker stock-recruit function (estimated from 1978–85 data—Figure 3) (Johnson 1989):

$$N_{1,1} = 2.3164D_{yr-1}(e^{-0.0777D_{yr-1}+s}) \qquad [7]$$

where D_{yr-1} is the number of eggs deposited by spawning females in the previous year. The parameter s is a normally distributed random variable (mean = 0, standard deviation = 0.654) and generates a lognormal distribution of $N_{1,1}$, thought to be common for many fishes (Garrod 1983). Note that the number of age-one fish has varied by almost thirty-fold during this eight-year time period (Figure 3). This variability can have a significant impact on stock dynamics and hence the net economic gains from harvesting.

In the model, D_{yr-1} is calculated by using a length-fecundity equation to estimate egg deposition per average-sized spawning female in a given age class (with females becoming fecund at 150 mm). These estimates are then multiplied by the number of spawning females in each age class (Johnson 1989). Summing these year-class egg deposition estimates yields D_{yr-1}. A random number generator provides s. The resulting distribution of $N_{1,1}$ approximates the recent historical $N_{1,1}$ record in this fishery (Johnson 1989). This estimate is divided into males and females (assuming a 1:1 ratio) and then entered into the appropriate equation [1] for each sex at the start of each year.

The model determines growth (increase in length per fish) for each sex and age class by first calculating the maximum possible annual growth increment. This annual increment is then adjusted downward as pop-

separately the number of fish "withdrawn" due to natural causes and fishing. We will show momentarily in equation [6] (main text) that all fish withdrawn due to natural causes die. However, the fishing withdrawals must be adjusted by proportional constants P_a and SM in order to exclude the sublegal fish which survive after being captured by commercial nets (see equations [2] and [3]). (Clark [1983] also uses fishing capture rates and proportional constants when calculating fishing mortality.) This adjustment yields legal and sublegal fishing mortality. The natural and fishing mortality losses are then combined in equation [1]—our equivalent of equation [a]—to arrive at total mortality.

[5]In fact, regulatory changes may result in gear modifications (and thus influence T) or intrayear temporal shifts in effort (which may change q). Due to data limitations, we could not calculate separate q and T values for the baseline and rehabilitation regimes. The model does fit the actual 1978–85 evolution of the Green Bay perch fishery closely, when both regimes were in effect (baseline for 1978–82, rehabilitation for 1983–85) (Johnson 1989). This suggests that the model's q and T values work well under both regimes.

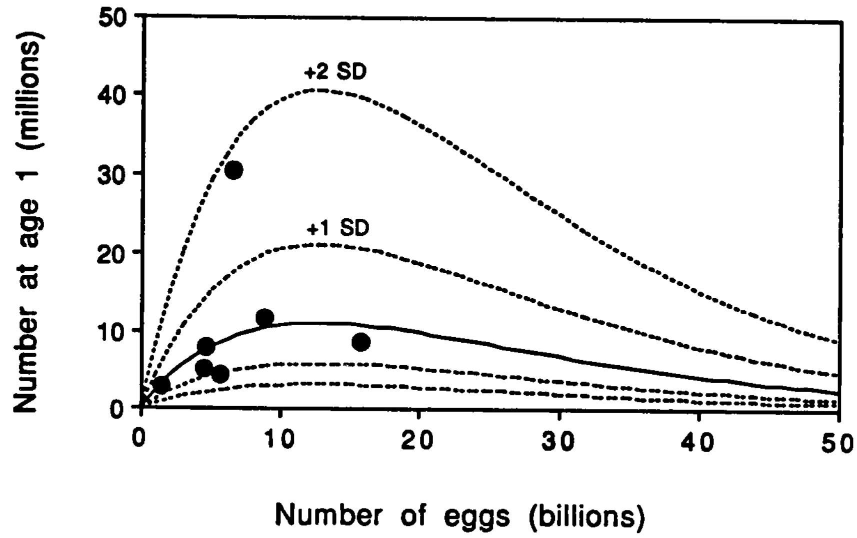

FIGURE 3

Annual 1978–85 relationship between egg deposition and the number of $N_{1,1}$ fish (dots), the estimated Ricker curve (solid line), and the estimated standard deviations around this curve (dashed lines).

ulation density (the number of fish aged one and older) increases. The downward adjustment relationship was calculated from 1978–85 data on population density and fish growth (Johnson 1989). This modified annual growth increment is then spread across the nine time periods of the year in a manner which approximates the expected pattern of fish growth over this time.

Since fish growth is variable, it follows that recruitment (when fish become vulnerable to commercial and sport fishing pressure) is a function of fish size, not age (Johnson 1989). This size is 190 mm for gill nets, 150 mm for drop nets, and 140 mm for sport fishing.

Harvest Component

The Harvest component determines the amount of effort and resulting catch (in weight) under the baseline and rehabilitation policies. Effort is in three forms: (a) the number of gill nets lifted (each 1,000 feet long), (b) the number of drop nets lifted, and (c) the number of sport fishing trips (with each trip generating 2.8 hours of fishing, based on WDNR creel census results).

Baseline commercial effort was inferred from recent historical baseline data. We postulate that gill net effort (but not necessarily drop net effort) is a positive function of both dockside price and harvestable biomass size (in weight). Unfortunately, baseline data on biomass size is available only for the 1978–82 time period (Johnson 1989). This impedes the estimation of a complete simultaneous supply-demand system under baseline conditions, which ideally should be used to forecast baseline effort. As a fallback measure, and to preserve degrees of freedom, we instead regressed baseline effort during the 1978–82 time period against the biomass of harvestable fish B_{160} (weight of fish longer than 160 mm at the start of the year). The demand conditions during this time period may roughly match post-1982 conditions, since dockside prices were generally high (which approximates the expected high post-1982 baseline prices). These regressions are (standard errors in parentheses):

$$E^G = 9{,}062 + \underset{(9.87)}{12.22}B_{160}, \quad R^2 = .32 \qquad [8]$$

$$E^D = 17{,}110 + \underset{(6.29)}{2.78}B_{160}, \quad R^2 = .05 \qquad [9]$$

where E^G and E^D are annual gill net and drop net effort levels. None of the regression coefficients were statistically significant at the 90 percent level of confidence (not an unexpected result given the small sample size). Note that the coefficient on B_{160} in equation [9] for drop net effort is small. This is plausible because drop nets, once in place, are difficult to move and so may remain in the water when stock abundance—and thus catch—declines (Johnson 1989). Thus E^D is set at 17,920 lifts (the 1978–82 annual mean) for all years under the baseline scenario. In contrast, as suggested by the size of the B_{160} coefficient in equation [8], the effort level of gill nets (which are much easier to move) appear to adjust to biomass levels. Hence equation [8], using B_{160} estimates obtained from the Biology component, is used to forecast E^G.

Using fish length and number data (provided by the Biology component), the model then computes the number and length of fish caught by E^G and the fixed amount of E^D under baseline conditions. A length-weight equation (estimated from 1978–85 length-weight data) then converts fish numbers into weight (in kilograms) (Johnson 1989). These weight and effort data are then transferred to the Economics component (to be described shortly), which calculates discounted producer rents under the baseline policy.

Commercial effort levels under the rehabilitation policy are determined as follows. For a given commercial quota, the Harvest component, drawing upon the number and size of fish per age class as provided by the Biology component, calculates the total amount of effort (gill net and drop net) needed to catch this quota. Gill net and drop net effort are fixed at 49 percent and 51 percent of this total effort (the mean distribution of effort for the 1985–87 time period) (Johnson 1989). The effort data, plus the harvest in weight, are again sent to the Economics component for use in economic surplus calculations.

In contrast to commercial fishing, few historical data are available on sport catch, which impedes the design of a sport effort forecasting method. We postulate that sport CPUE (catch-per-unit-of-effort), by increasing sport surplus per trip, leads to greater trip numbers. Our model is unable to estimate the sport CPUE in advance, but perch biomass (in weight) can be predicted. We thus forecast sport effort from the total weight of fish longer than 150 mm (B_{150}) at the beginning of each year (those fish most likely to be caught by anglers). Sport effort levels (E^S) for the years 1983, 1984, and 1985 (the only reliable sport effort data available [personal communication, B. Belonger, WDNR, Marinette]) were regressed against 1983–85 estimates of B_{150} (Figure 4):

$$E^S = -2.60 + 659B_{150}, \quad R^2 = .98. \qquad [10]$$

This equation—denoted as the "standard" sport-effort equation—is used to predict sport effort under both baseline and rehabilitation policies. Since it is based on only three data points, we will use two additional equations (also shown in Figure 4): (a) a "high" sport-effort equation (effort is highly sensitive to biomass size), where the slope is increased by 50 percent and the intercept is adjusted so that the new line crosses the mean of the 1983–85 observed data; and (b) a "low" sport-effort equation (effort is only moderately sensitive to biomass size), where the slope is decreased by 50 percent and the intercept is again adjusted so that the new line crosses the 1983–85 means.[6]

After sport effort E^S has been estimated by equation [10], the Harvest and Biology components jointly determine the total sport catch, the catch per trip, and the average size of fish caught. These data are again transmitted to the Economics component in order to calculate total angler surplus per year.

[6]Both the standard and high sport-effort equations assume that sport effort responds significantly to both increases and decreases in biomass. The 1983–85 data suggests that this assumption holds when biomass is increasing. No hard data exists on sport effort changes when biomass is decreasing, but Brian Belonger (WDNR fish manager for Green Bay) believes that sport effort might fall significantly if biomass suffered a major decline (B. Belonger, loc. cit.). Thus, given our current knowledge of the fishery, the standard and high sport-effort equations are plausible.

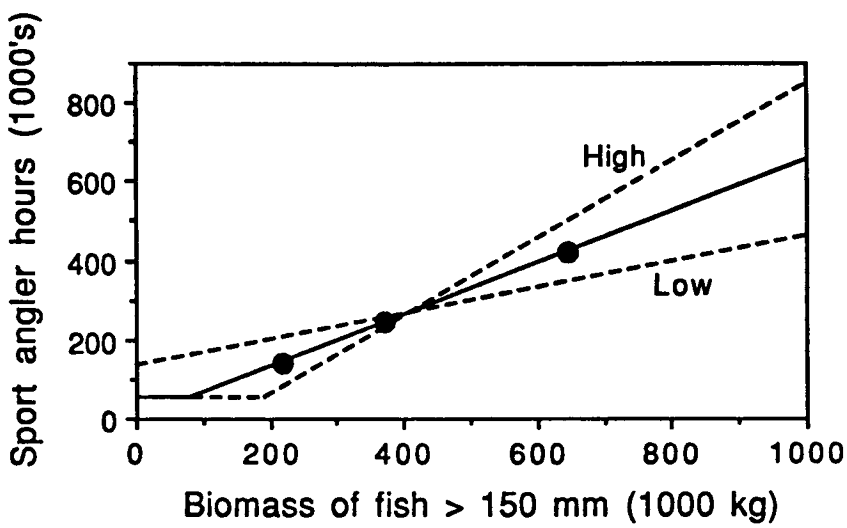

FIGURE 4

The relationship between the annual number of hours spent sport fishing (with 2.8 hours equalling one trip) and the total weight of fish longer than 150 mm (in kilograms) for the years 1983–85.

Management Component

The WDNR sets the commercial quota in a current year based on data generated by a WDNR population assessment exercise carried out in August and September of the previous year. Subject to some restrictions (to be discussed momentarily), the management component uses the following quota rule to simulate this WDNR procedure:

$$Q_{yr} = 0.29 \cdot B_{160,yr-1} \qquad [11]$$

where Q_{yr} is the commercial harvest quota in year *yr*, and $B_{160,yr-1}$ is the previous year's biomass (in weight) of fish longer than 160 mm as estimated by a simulated version of the WDNR population assessment survey (Johnson 1989). Equation [11] was inferred from actual quotas set by the WDNR from 1983–86 (Figure 5). The year 1984 is an outlier, probably because the WDNR, when setting this quota, did not take into account a slowdown in population growth which occurred in that year due to high stock levels (Johnson 1989). However, quotas in the other three years closely fit our rule.

The WDNR placed constraints on quota setting (Johnson 1989). They sought to change the quota in 50,000 pound increments, with the maximum annual increment equalling 150,000 pounds. Hence Q_{yr} was rounded to the nearest multiple of 50,000 and was changed by no more than 150,000 in a given year.

Economics Component

This component forecasts the economic surplus for commercial and sport users across time under both the baseline and rehabilitation policies (net of regulatory costs), and then expresses these estimates in 1983 present value terms, the year when the rehabilitation plan began.

Commercial fishing revenues. Prices were forecast from the following dockside demand equation for Green Bay perch (estimated from annual 1958–82 data via single-equation estimation, with standard errors in parentheses):

$$\begin{aligned} \operatorname{Log} P = & -13.878 - \underset{(0.047)}{0.203} \cdot \operatorname{Log} Q^{GB} \\ & - \underset{(0.125)}{0.653} \cdot \operatorname{Log} Q^{LE} + \underset{(0.211)}{0.332} \cdot \operatorname{Log} P^{O} \\ & + \underset{(0.876)}{2.312} \cdot \operatorname{Log} POP \quad R^2 = 0.961 \qquad [12] \end{aligned}$$

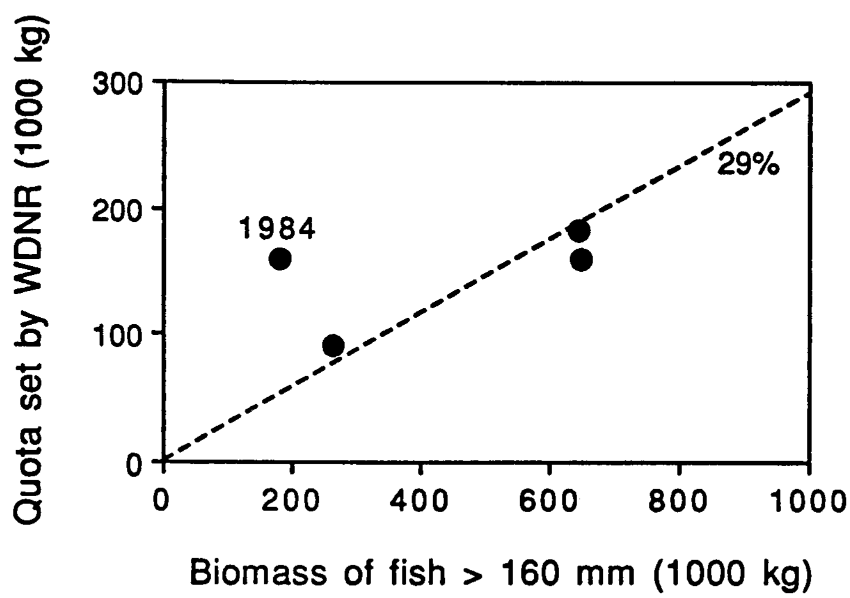

FIGURE 5

The relationship between the size of the WDNR commercial quota and the weight of fish longer than 160 mm (in kilograms) for the years 1983–86.

where P and Q^{GB} are the Wisconsin dockside price and catch in pounds of perch (mostly Green Bay); Q^{LE} is the remaining North American perch harvest (mostly Lake Erie); P^O is the price of ocean perch, a restaurant substitute (Lesser 1978); and *POP* is the Wisconsin population, which consumes the majority of North American perch (Milliman 1985). The specific estimation process, which included correcting for first-order serial correlation, is covered in Milliman (1985). The price data are in 1983 dollars. All coefficients have the expected signs and are significant at the 90 percent level or better using one-tailed t-tests. The reasons for single-equation estimation, the Green Bay dockside market definition, and the log-linear functional form are as follows:

- Fish size data from Griffith (1979) and Belonger (1980) strongly suggest that virtually all perch beyond the minimum legal size were being harvested in both low and high price years during the 1958–82 time period. Additional effort prompted by even higher prices, then, would result in (at best) a small increase in output, suggesting a (near) vertical supply curve. Vertical supply in turn allows for demand estimation with a single equation.
- A comparison of monthly U.S. Lake Erie dockside prices with those in Green Bay during the 1972–83 time period revealed that the former were significantly lower than the latter (Milliman 1985). In part, this may be due to the high buyer concentration in the Lake Erie area (Lesser 1978). (In contrast, buyer concentration appears to be low in Green Bay [Milliman 1985]). Talks with industry participants also suggested that Green Bay and Lake Erie were distinct submarkets (Milliman 1985). Thus we define our exvessel market as Wisconsin (which is mostly Green Bay catch), and the Lake Erie harvest is entered as a separate independent variable in the demand equation.[7]

[7] In downstream markets (after the fish have been filleted), Lake Erie catch is often shipped to Wisconsin (Milliman 1985). However, we are primarily interested in the dockside market which encompasses the com-

- Talks with industry participants revealed that: (a) when the Lake Erie harvest is large, the impact of the Green Bay harvest on Green Bay dockside prices is very slight; but (b) when the Lake Erie harvest is small, then the Green Bay harvest size can have a noticeable impact on price (although this impact remains modest) (Milliman 1985). Hence, a linear specification is incorrect for the Green Bay submarket, since for a given change in Q^{GB}, the resulting Green Bay price change is not a function of Q^{LE}. However, a log-linear form does allow this price impact to vary with Q^{LE}, and so was adopted.

We calculated post-1982 prices by plugging future estimates of the Wisconsin population, Lake Erie harvests, ocean perch prices, and the Green Bay harvest (from the Harvest Component) into equation [12]. Milliman (1985) describes how the exogenous variables were forecasted. Price is then multiplied by the Green Bay harvest to obtain the (undiscounted) commercial fishing revenues for a given year and policy.

Commercial fishing costs. Data collected in 1983 from lengthy face-to-face interviews with commercial fishers were used to calculate commercial fishing costs. Due to the controversial nature of the WDNR rehabilitation plan at that time, however, many fishers were unwilling to discuss these costs (Milliman 1985). The quality of record-keeping also appeared to vary greatly among fishers. Due to these constraints, thirteen cooperative operators with good cost records were selected nonrandomly for interviewing. These fishers caught 39.4 percent of the total harvest for the 1983–84 fishing season. Their associated costs-per-unit-of-effort (which included the opportunity cost of fishing time, assumed to be the minimum wage) were estimated to be \$14.01 for gill nets and \$6.23 for drop nets (Milliman et al. 1987). Since most operators fished for perch exclusively, allocating costs across different fisheries was not a concern.

Total annual commercial fishing costs are estimated by multiplying the effort level for each gear (obtained from the Harvest component) by the relevant cost-per-unit-of-effort. Both cost figures are subtracted from total revenues, yielding undiscounted commercial economic surplus for a given year.

Sport fishing surplus values. In 1986, a sample of 600 anglers was randomly drawn from a larger pool of sport fishers who were contacted on site, during the preceding year, by WDNR and university-employed creel census clerks. These 600 anglers were then contacted by a mail survey; 91 percent of the deliverable surveys were returned. The survey revealed that the sport fishery was primarily local in character, with 97 percent of the trips being one day in length, and that most anglers either fished from a boat (53 percent) or ice fished (35 percent). On the day they were contacted by the creel census clerks, anglers caught and kept an average of 14 fish with a mean length of eight inches.

To estimate the Hicksian surplus for Green Bay sport fishing, the respondents were asked to answer a dichotomous-choice, contingent valuation question (see Bishop, Heberlein, and Kealy 1983; Hanemann 1984; and Boyle and Bishop 1988). Before answering this question, anglers were asked to report their expenditures for items such as gas, food and beverages, lodging, and bait for the trip they took when contacted by the creel census clerk. These costs averaged \$15 per trip, with a range of \$0 to \$280. Subsequently, trip expenditures were used as the payment vehicle in the valuation question by asking anglers if they would still have made the trip if these expenses were a specified, randomly assigned dollar amount higher than actual trip expenses.

A logit model was estimated using maximum likelihood procedures from the answers to the contingent valuation question

mercial fishers (fish sold in the round, before filleting). According to an Ohio fish wholesaler, some round fish are occasionally shipped to Wisconsin. This occurs in high production years for Lake Erie, when local processors have a surplus of fish (Milliman 1985). These appear to be infrequent shipments, however.

(standard errors in parentheses):

$$Pr(yes) = [1 + \exp(\underset{(0.420)}{2.0445} - \underset{(0.017)}{0.023} \cdot FN - \underset{(0.046)}{0.039} \cdot FS - \underset{(0.022)}{0.106} \cdot X)]^{-1} \quad [13]$$

where $Pr(yes)$ is the probability that a respondent will answer yes to the dichotomous-choice valuation question given the number of perch kept (FN), the average size of the perch in inches (FS), and the dichotomous-choice dollar amount (X). The sample size for estimating this equation was 250, since not all respondents were asked to answer the trip valuation question.

While FN and FS are important policy variables, neither are significantly different from zero at the 10 percent level. Their estimated standard errors are probably inefficient due to the high multicolinearity between the two variables (simple correlation coefficient = .547, which is significantly different from zero at the 10 percent confidence level). A short equation, without FN and FS, was estimated to test whether these two variables collectively add to the predictive ability of the equation. The resulting chi-square statistic is 6.11 with two degrees of freedom, indicating that the standard null hypothesis (FS, FN coefficients = 0) can be rejected at the .10 level. Thus, the equation reported above is used by the model.

The estimated Hicksian surplus per trip, derived by setting FN and FS at their mean values and integrating over X (see Hanemann 1984 and Boyle and Bishop 1988), is \$25.80 in 1986 dollars or \$23.45 in 1983 dollars. In 1983 dollars, the marginal value of an extra fish kept is \$0.18 and the marginal value of an extra inch in the average fish size is \$0.27. The extra fish value is plausible, since the catch per trip was at historically high levels in 1985 (when anglers took the trips being evaluated); hence, additional fish might not have been highly valued by anglers at that time. Similar reasoning may explain the low incremental value associated with increasing fish size.

The aggregate Hicksian sport surplus is obtained by first plugging values for FN and FS (obtained from the Harvest component) into equation [13] and then integrating over X to derive a conditional, per-trip expected value. This per-trip value is then multiplied by the total number of angler trips (also obtained from the Harvest component), yielding the aggregate Hicksian surplus.

Consumer surplus changes for final perch consumers. As will be shown in Section IV when the results are presented, the mean commercial harvest under rehabilitation is approximately one-third less than the mean baseline harvest. Since the price elasticity of demand for Green Bay dockside perch is high (-4.91, from equation [12]), consumer surplus changes induced by rehabilitation appear to be slight, and so are not formally calculated.

Regulatory costs associated with rehabilitation. The annual incremental regulatory costs of the WDNR rehabilitation policy were estimated to be \$70,241 in 1983 dollars (\$32,861 for stock assessment and \$37,380 for enforcement) (Milliman 1985). These costs are discounted, summed across all years and then subtracted from the rehabilitation surplus benefits.

The discount rate and time horizon of the analysis. Since a consensus on the appropriate discounting policy for government projects does not yet exist (Scheraga 1990), we use several plausible rates. Hartman (1990) and Lind (1990) suggest that often the government borrowing rate can serve as a discount rate (with uncertainty to be handled by expected return calculations). We use 2.84 percent, the average annual interest rate (in real terms) paid on three-month U.S. Treasury securities for the years 1979–88 (Council of Economic Advisors 1989). From the vantage point of commercial fishers (the major "biomass" investors), an appropriate borrowing rate might be the rate paid when taking out a second mortgage on one's home (Milliman 1985). Long-term data are only available for interest rates charged on first-time mortgages, which in real terms was 5.59 percent nationally from 1979 to 1988 (Council of Economic Advisors 1989). Conversations with several Green Bay banking officials revealed that, as a rule of thumb, Green Bay second-time mortgages were one-half of a point above the national first-time mortgage rate during the 1983–85 time period (Milliman 1985). As a rough approximation, then, a discount rate of 6.09 percent (5.59% + 0.50%) was calculated. Finally, a 10 percent discount rate, often used by the U.S. Government, is also employed to observe the sensitivity of the results to changes in this parameter. All values are discounted back to 1983, when the rehabilitation plan began.

The time horizon of the WDNR rehabilitation scheme is uncertain due to two factors. First, Great Lakes ecosystems have exhibited substantial instability over the past century (Francis et al. 1979); second, policy goals may shift. For example, the WDNR may decide to allocate a greater catch share to sport anglers in future years. In the current analysis, we utilize four time horizons: 5, 10, 15, and 20 years. Due to the uncertainties mentioned above, a time horizon beyond 20 years would have little credibility in this fishery.

Our simulation results follow.

IV. SIMULATION RESULTS

One hundred simulations, each 20 years in length (1983–2002), were run under both the baseline and rehabilitation policies. For comparison purposes, the same random number sequence for generating counts of $N_{1,1}$ fish was used for both policies. The initial population structure for January of 1983 (inferred from 1983 WDNR population assessment data) was also used for all simulations.

The annual means for various biological and harvest indicators when the standard sport-effort equation is used are shown for both policies in Figure 6. As sought by the WDNR, both stock size (indicated by female stock) and older fish numbers (indicated by the fish aged four and older) increase under the rehabilitation plan (upper graph, Figure 6). Sport harvest increases greatly, which is also a WDNR goal, but the rehabilitation commercial catch is two-thirds of the baseline catch after year 5, which is at odds with the official WDNR goal of increasing the commercial catch (lower graph, Figure 6).[8] While the sport harvest is larger under the 1983 WDNR plan, sport harvest variability as measured by the associated standard deviation (the vertical lines at five-year intervals for sport catch, lower graph in Figure 6) has also increased. In contrast, commercial harvest variability has fallen. It appears that the WDNR plan, by restricting both commercial catch and its annual change, has transferred catch variability from the commercial sector to the sport sector.[9]

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[8] A large 1982 year class, which was part of the initial 1983 population structure, is responsible for the unusually high numbers of fish in 1985 under both the baseline and rehabilitation policies (upper graph, Figure 6). These high fish numbers in turn generated large sport and commercial catches under both policies in 1985 (lower graph, Figure 6).

[9] We also ran the biological model in the absence of commercial and sport effort (but with stochastic recruitment) in an attempt to assess the model's stability and robustness. The number of adult female fish (a good proxy for stock size) stabilized after year 15 within the 3.7–4.0 million range (compared to 3.2–3.4 and 2.2–2.3 million under the rehabilitation and baseline policies), and the number of fish aged 4 and older stabilized after year 15 at 3.3–3.7 million (compared to 1.1–1.3 and .07–.12 million under the rehabilitation and baseline policies). Since both total stock size and older fish numbers are stabilizing, it follows that the younger fish population—ages 1–3—is also stabilizing. These results are plausible, since less fishing pressure should increase both stock size and the number of older fish (particularly the latter, since older fish are highly vulnerable to commercial nets). However, all of our model parameters were estimated under conditions of intense fishing, and so many would probably change in its absence (particularly the natural mortality rate). Hence these results are of uncertain validity (even though they appear to cast favorable light on the model).

The robustness and stability of our complex, empirically based model might be better assessed under the conditions which were used to calibrate it, e.g., intense fishing, which occurs under both the rehabilitation and baseline policies. Note that both female stock size and the number of fish aged 4 and older also stabilize under these two policies (see upper graph, Figure 6 plus the data listed immediately above). Relative to the baseline policy years of 1978–82, the model also predicts that sport catch, the catch per unit of effort for the commercial gears and the number of older fish will all increase under the rehabilitation policy, while total commercial catch will decline. Post-1985 biological and harvest data indicate that these trends are occurring in the fishery (Johnson 1989; B. Belonger, loc. cit.). (Note: We cannot compare 1983–85 data to these

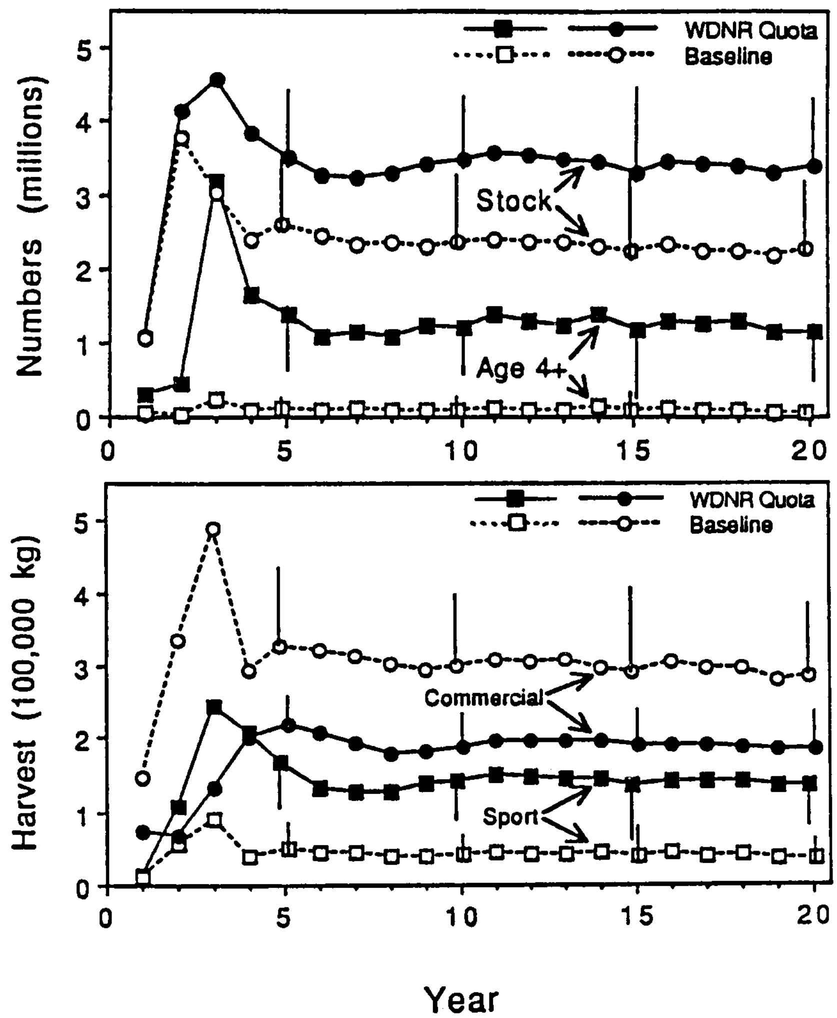

FIGURE 6

The upper graph illustrates the annual mean number of females longer than 150 mm, which is a good proxy for total stock size (signified by circles; closed for the rehabilitation policy, open for the baseline policy). The number of fish aged four and older is also shown in this graph (signified by boxes; closed for rehabilitation, open for baseline). The lower graph illustrates mean annual harvests for commercial fishers (signified by circles; closed for rehabilitation, open for baseline) and sport fishers (signified by boxes; closed for rehabilitation, open for baseline). The means were estimated from 100 simulations, each 20 years in length, which used a standard sport-effort equation. The vertical lines at five-year intervals for each type of data equal one standard deviation.

Relative to the baseline economic surplus, the discounted surplus changes induced by rehabilitation by discount rate and time horizon are shown in Table 1. All change estimates, which are in 1983 dollars, are positive. Gains increase with a longer time horizon, but are substantial even after

model predictions, in part because this data was used to calibrate the model, and also because 1983–85 was a period of transition between the baseline and rehabilitation policies.) This result suggests (although of course it does not prove) that the model can provide credible predictions about stock dynamics for the rehabilitation policy.

TABLE 1

Relative to the baseline economic surplus, mean discounted changes in surplus induced by the 1983 WDNR rehabilitation policy, by discount rate (2.84%, 6.09%, and 10%) and time horizon (5, 10, 15, and 20 years). Surplus changes as a percentage of total baseline surplus are listed in parentheses under each estimate. Mean surplus changes are based on 100 simulations with a standard sport-effort equation and are in 1983 dollars (millions). The incremental regulatory costs associated with the rehabilitation policy have been subtracted from each estimate.

	Time Horizon (Years)			
Discount Rates (%)	5	10	15	20
2.84%	+5.0 (+36%)	+10.9 (+44%)	+16.7 (+48%)	+21.7 (+51%)
6.09%	+4.5 (+35%)	+9.3 (+42%)	+13.3 (+46%)	+16.2 (+48%)
10.00%	+4.1 (+34%)	+7.9 (+41%)	+10.6 (+45%)	+12.2 (+46%)

five years. Gains also increase with a lower discount rate, but often only slightly. Table 2, for a 2.84 percent discount rate and 5-, 10-, 15-, and 20-year time horizons, generates a distributional picture of these gains. Sport anglers experience major gains, while commercial anglers suffer moderate losses. Note that the standard deviations associated with the mean difference in surplus between the two policies for each user group (lines 4, 9, 14, and 19, Table 2) are small relative to their associated means. This suggests that stock variability induced by stochastic recruitment does not modify this distributional result. Although not reported here, this also holds for other discount rates (6.09 percent and 10 percent).

Sensitivity Analysis on Sport Effort Levels

Since recreational gains are so substantial, we vary the sport effort equation (which was inferred from only three data points) in order to assess the sensitivity of our results to changes in this construct.

Results with the two alternative sport effort equations (shown in Figure 4) are presented in line one of Table 3 with a 2.84 percent discount rate. Relative to the standard results, the mean economic gains fall significantly with the low sport-effort equation, but they still remain positive. The gains with the high sport-effort equation increase greatly relative to the standard results. It appears that the sport-effort specification has a major impact on the magnitude of rehabilitation benefits, but not on their sign.

Exploring Optimal Catch Allocation Between Commercial and Sport User Groups

The complexity of our model impedes formal optimization. We facilitate this step by assuming that the optimal quota rule is linear in form:

$$Q_{yr}^{*} = a + b \cdot B_{160,yr-1} \qquad [14]$$

where Q_{yr}^{*} is the optimal quota for commercial catch in year *yr*. We search for this optimal rule by varying the *a* and *b* values and observing the resulting total economic surplus—the *a* and *b* combination which maximizes total surplus is judged to be optimal. This process is done for all three sport effort equations. Here we are assuming that, due to political pressures and high regulatory costs, the WDNR is unable to impose meaningful sport catch controls.

The results of this approximate optimization process are shown on line two in Table 3. With the standard and high sport-effort equations, eliminating the commercial fishery (a, b = 0) maximizes economic gains. Further, with a high sport-effort equation, the additional surplus induced by commercial closure is not insignificant, e.g., relative to baseline surplus, commercial closure generates incremental gains

TABLE 2

Mean discounted surplus in 1983 dollars (in millions) under the baseline and rehabilitation policies by user group, and the standard deviation associated with the mean difference in surplus between the two policies, also by user group, for the 5-, 10-, 15-, and 20-year time horizons and a 2.84% discount rate. The parentheses list surplus changes as a percentage of baseline surplus for each user group. A standard sport-effort equation is used, and the dollar figures have not been adjusted for regulatory costs.

	User Group	
Policy and Time Horizon	Commercial	Sport
5-Year Time Horizon		
Baseline	3.5	10.2
Rehabilitation	2.3	16.8
Δ from Baseline	−1.2	+6.6
Standard Deviation of Δ	0.25	0.34
% Δ from Baseline	(−34%)	(+65%)
10-Year Time Horizon		
Baseline	6.5	18.5
Rehabilitation	4.8	31.7
Δ from Baseline	−1.7	+13.2
Standard Deviation of Δ	0.43	0.77
% Δ from Baseline	(−26%)	(+71%)
15-Year Time Horizon		
Baseline	9.0	25.7
Rehabilitation	7.1	45.2
Δ from Baseline	−1.9	+19.5
Standard Deviation of Δ	0.61	0.97
% Δ from Baseline	(−21%)	(+76%)
20-Year Time Horizon		
Baseline	11.3	31.7
Rehabilitation	9.2	56.6
Δ from Baseline	−2.1	+24.9
Standard Deviation of Δ	0.71	1.20
% Δ from Baseline	(−19%)	(+79%)

TABLE 3

Relative to the baseline economic surplus, mean changes in discounted surplus when the sport effort specification is low, standard, or high. Discounted surplus changes induced by three policies are shown: (a) the 1983 WDNR rehabilitation plan; (b) economic optimization, assuming that the optimal quota rule is linear; and (c) commercial fishery closure. The surplus changes are based on 100 simulations, a 20-year time horizon, and a 2.84% discount rate, and are adjusted for regulatory costs. For a given sport effort specification, the extent to which surplus gains induced by the optimization and commercial closure policies exceed those generated by the WDNR rehabilitation plan are shown in percentage terms in parentheses.

	Sport Effort Specification		
Policy	Low	Standard	High
WDNR Rehabilitation Policy Gains	+11.5	+21.7	+30.2
Economic Optimization Gains	+11.9	+26.8[a]	+40.2[a]
% Increase Over Rehabilitation Gains	(+3%)	(+24%)	(+33%)
Commercial Closure Gains	+10.2	+26.8	+40.2
% Increase Over Rehabilitation Gains	(−11%)	(+24%)	(+33%)

[a]Optimization results in commercial closure.

which are 33 percent higher than those induced by the rehabilitation policy. In contrast, with a low sport-effort equation, optimization incremental gains exceed rehabilitation gains by only 3 percent, with the average annual commercial harvest decreasing from 190,081 kg (57 percent of total catch) to 120,245 kg (46 percent of total catch) in years 11–20. Commercial closure with the low sport-effort equation actually reduces surplus gains slightly relative to the rehabilitation policy (compare line four to line one in Table 3). In short, it appears that the optimal allocation of harvest between commercial and sport user groups is crucially affected by the specification of the sport effort equation. Concurrently, the economic case for the commercial fishery may rest on this specification.[10]

These results are tentative for several reasons. Some quota rules may generate perch population structures which differ radically from the status quo, while our model probably performs best when assessing moderate changes. If greater economic gains are possible with a nonlinear quota rule, then our estimated optimization gains are also understated, all else equal.

V. MAJOR FINDINGS, QUALIFICATIONS AND FUTURE RESEARCH DIRECTIONS

Major Findings

Our major empirical results are as follows:

- The mean overall economic gains from the 1983 WDNR rehabilitation policy, net of regulatory costs, are positive for various discount rates, time horizons, and sport effort specifications.
- The major winners of this policy change are sport anglers, while commercial fishers lose under all simulations. As a percentage of baseline producer rents, commercial losses are the highest at five years, but then fall with longer time horizons. Variability (as measured by the standard deviation associated with the mean difference in surplus between the two policies for each user group) does not modify this distributional result. Hence, commercial fisher opposition to the 1983 WDNR policy change appears to have been economically rational.
- However, relative to the baseline policy, the 1983 WDNR plan increases catch variability for sport anglers, while reducing it for commercial users.
- Probing exercises with a linear quota rule suggest that the optimal allocation of harvest may be 100 percent sport and 0 percent commercial if the sport effort specification is standard or high. Further, with the latter equation, the economic gains from this allocation could be significant. However, with a low sport-effort specification, the estimated optimal catch allocation is 54 percent sport and 46 percent commercial, with net gains declining slightly if the latter sector is closed. Hence, while Johnson et al. (1990) concluded that this uncertainty made little difference when promoting important biological goals, we reach the opposite conclusion from an economic viewpoint.

Qualifications

Several qualifications are in order:

1. Johnson et al. (1990), using different values for various recruitment and fish growth parameters, obtain economic results similar to those reported here when comparing the rehabilitation and baseline policies. Nevertheless, the predictive capability of our bioeconomic model (like any other) is subject to considerable uncertainty. Important biological parameters, such as the relationship between population density and fish growth, should be periodically checked for accuracy. Other helpful model refinements would include: (a) devel-

[10] The Table 3 results are for a 20-year time horizon, but results for shorter time horizons would be similar, since the surplus gains induced by the three policies listed in this Table are spread relatively evenly across time.

oping a more detailed prediction model for sport effort (which would simulate interrelationships between sport effort, sport surplus per trip, and fish abundance, ideally within a utility maximizing framework for anglers), and (b) directly measuring surplus gains per trip for the marginal sport trips generated by commercial closure. With respect to (b), this marginal trip value is probably lower then the model's trip value (which was estimated from anglers already fishing under the WDNR rehabilitation policy), since nonparticipating anglers probably benefit less from perch fishing. If this surplus divergence is large, then our model would overstate sport gains from commercial closure.[11]

2. Our model may systematically overstate the incremental producer surplus losses induced by the rehabilitation policy. Specifically:

- Our effort cost estimates are based on open access (pre-1983) conditions, when fishers probably raced to place nets in choice fishing locations. Racing incentives, and thus fishing costs, are probably lower under the rehabilitation policy because fishers possess quotas which guarantee each of them a set amount of the total commercial harvest. Our model would miss this cost reduction.
- The more cost efficient fishers would probably accumulate quota rights, which can be bought and sold. Our model would again miss these cost savings.
- Finally, since quota shares make individual catches more secure, fishers may attempt to allocate catch towards high-price periods. The efficiency gains from this temporal shift in catch would be missed by our model.

3. Continuing from point (2) above, if producer surplus under the rehabilitation policy is understated, then our model may also understate the losses associated with commercial closure. Hence, commercial closure should be approached cautiously, even if sport effort is highly sensitive to biomass conditions (as with the high sport-effort specification). Three additional points also argue for caution:

- While commercial closure may increase total fish numbers, it may also curtail fish growth by a greater amount than estimated by our model, very possibly leading to a large population of small, stunted perch. The quality of sport fishing, in turn, may be harmed.
- Commercial closure may significantly affect dockside prices for perch (in contrast, the more modest reduction in commercial harvest under the 1983 WDNR policy change is likely to have a small impact). This implies that measurable losses in consumer surplus may occur with commercial closure.
- Finally, commercial closure may harm the cultural milieu of the Green Bay area, which historically has been a major commercial fishing port on the Great Lakes. Results from the 1986 angler survey cited earlier suggest that many sport fishers would oppose commercial closure for this reason.

Summary and Future Research Directions

In conclusion, we find that resource rehabilitation generates economic as well as biological gains for the Green Bay yellow perch fishery; that the economic gains are primarily due to higher sport catch; and that determining the optimal catch division between sport and commercial users may hinge on clarifying the relationship between sport effort levels and fish abundance. Our finding that a larger sport catch is economically beneficial may encourage managers in other fisheries to explore similar harvest shifts. Finally, several of our modelling techniques (developing and then optimizing with the WDNR quota rule, predicting sport effort from biomass conditions) may aid model building elsewhere.

Along with those mentioned previously, several other issues require additional re-

[11] The possible dangers of using average instead of marginal values when valuing additional fishing trips are discussed in McCarl and Rettig (1984).

search. When estimating F (our instantaneous fishing rate), data limitations forced us to assume constant T (selectivity) and q (catchability) parameters, when in fact regulatory changes may result in gear modifications (thus affecting T) or temporal shifts in effort (thus affecting q). Developing modelling techniques which measure these changes would be helpful. Future researchers could also develop applied bioeconomic models with sport controls (such as strict daily bag limits) as well as commercial regulations. Because we optimized with respect to commercial catch only, we may have understated the potential economic gains from managing the Green Bay perch fishery. Finally, while recruitment was stochastic in our model, other bioeconomic parameters are also subject to unpredictable changes. Following the adaptive management approach of Walters (1986), researchers could incorporate monitoring activities into their applied bioeconomic models with the explicit goal of detecting non-recruitment parameter changes. Policy modifications prompted by these parameter shifts could also be simulated. Progress on these issues would enhance both the realism and policy relevance of applied bioeconomic modelling.

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