Relative Effects of Mixed Stock Fisheries on Specific Stocks of Concern: A Simplified Model and Brief Case Study

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ABSTRACT: An algebraic model is presented that allows comparison of changes in total catch, stock-specific catch, and stock-specific harvest rate for various fisheries harvesting the same stock of concern under conditions of change in the stock's abundance. The model operates without detailed estimates of each fishery's complete stock composition and without ongoing assessment of each component stock's biomass or population size. Rather, observations or assumptions of the proportional contribution (ρ_x) of the stock of concern to each fishery's total catch, combined with presumptions of change in that stock's abundance (θ_x), are sufficient to illustrate proportional changes in catch and harvest rate under management prescriptions for constant harvest rate and for constant total catch. Results indicate that mixed stock fisheries, especially those with low ρ_x from a particular stock, are only slightly affected by and exert very small influence upon changes in abundance of that stock, even if total harvests remain constant. In contrast, single stock fisheries with high ρ_x are more directly affected by and exert more substantial influence upon changes in the stock's abundance. Because the presence of other stocks in a mixed stock fishery dilutes its relationship to any stock in particular, such a fishery may not need to be managed nearly so precisely as another fishery for which a common stock supports the bulk of the harvest.

INTRODUCTION

The harvest of specific stocks of fish in mixed stock fisheries often generates questions of both biological and social concern. This is especially true when 1 or more of the stocks taken in an otherwise robust fishery is in decline. Conflicts exacerbate when the stock has other potential users, disputes focusing on appropriate sharing of management restrictions to help reverse the stock's decline. The attendant technical debate generally centers around the accuracy and precision of estimates of the stock's contribution to the fisheries and the effect of the harvests on the stock in question. Social debate can often range much further.

Obtaining accurate information on relative stock contribution to most mixed stock fisheries and evaluating a fishery's impacts on the component stocks are not easy tasks. At a minimum the origin of contributing stocks taken (e.g., determined by tagging experiments, scale-pattern analysis, or genetic stock identification) and their respective catches must be known. To evaluate the impact of the fishery on each stock, however, requires even more — that is, detailed knowledge of each component stock's respective total annual biomass or population size. And if stock identification is not available each year, then to estimate catches and impacts over time, some indication of each stock's ongoing relative vulnerability to the fishery is required.

Rarely is all this information available, largely because this type of comprehensive data gathering is very expensive. Facing these constraints, managers and research biologists often need to fashion and defend some enterprising assumptions about stock composition, relative vulnerability, and annual stock size in order to estimate harvest or harvest rate, or to set prescriptions for harvest controls on component stocks. In a regulatory context such tacit uncertainty can lead to public perception that technical guidance is lacking at a time when decisions must be made.

This paper presents an alternative model, not nearly so data-intensive, with which to anticipate the relative potential impacts of various fisheries on a stock facing population decline. Specifically, this algebraic model factors out the need for most of the data inputs normally associated with estimating stock composition and calculating stock-specific harvest rates. To illustrate use of this model, a case study is presented of 2 Pacific herring *Clupea pallasi* fisheries in Alaska that purportedly harvest fish from the same stock: the Dutch Harbor food/bait fishery and the Nelson Island

sac roe fishery in relation to spawning biomass of the Nelson Island stock.

There have been a number of attempts to characterize the relation of a mixed stock fishery to its various component stocks (Ricker 1958; Paulik et al. 1967; Hilborn 1976, 1985), but these have focused primarily upon calculation of optimum or maximum exploitation rates and rely upon some detailed estimates of individual stock-recruitment parameters. As a practical matter, such data often are not available (Healey 1982). For many management questions, more simplified approaches may well be sufficient.

METHODS

The model relies upon estimates or assumptions of (1) the proportion of the fishery's total catch (ρ_x) composed of fish from the stock of particular interest, x, and (2) the change in population size (θ_x) exhibited by that stock between one period or year to the next. Model outputs describe (1) yearly percentage changes in total catch (θ_c) and in stock-specific catch ($\theta_{c,x}$) if fishing intensity were to remain constant, and (2) yearly percentage changes in harvest rate ($\theta_{\mu,x}^*$) on the stock and its catch ($\theta_{c,x}^*$) if the fishery's total catch were to remain constant. In the face of a particular stock's anticipated, presumed, or observed decline, values for θ_c, $\theta_{c,x}$, $\theta_{\mu,x}^*$, and $\theta_{c,x}^*$ give readily understandable measures of the stock's importance to the mixed stock fishery, the potential impact of the fishery on that stock, and the relative impacts on affected fisheries. Such comparisons can be useful in evaluating management and regulatory decisions necessary to address stock declines, especially in the face of uncertain or frequently unavailable data. This process might also placate legitimate concerns over fairness among multiple users.

Parameters and Definitions

The only inputs required are measurements or assumptions of ρ_x and θ_x. Other parameters, such as total and stock-specific catches and total biomass or population size for the stock in question, can be input, but they are not necessary to derive rates of change in total catch, harvest rate, and stock-specific catch.

Let C_x be a fishery's catch of stock x and C_y be a fishery's catch of all other stocks combined, so that total catch is $C = C_x + C_y$. Let N_x be the abundance of stock x, so that harvest rate is $\mu_x = C_x \cdot N_x^{-1}$. The proportion of stock x in the total catch is $\rho_x = C_x \cdot C^{-1}$.

The catch of a single stock in a mixed stock fishery in year 1 is

$$C_{x,1} = C_1 \, \rho_{x,1} \, . \qquad (1)$$

The harvest rate in year 1 is

$$\mu_{x,1} = \frac{C_{x,1}}{N_{x,1}} \, . \qquad (2)$$

The proportional change in stock abundance between years 1 and 2 is

$$\theta_x = \frac{N_{x,2} - N_{x,1}}{N_{x,1}} \quad \text{or} \quad N_{x,2} = (\theta_x + 1) \, N_{x,1} \, , \quad (3)$$

where $N_{x,2}$ is the stock size in year 2 and $N_{x,1}$ is the stock size in year 1.

For simplicity and to focus attention, the model assumes that between years 1 and 2 stock x is the only stock to change biomass or population size. The model also assumes that other aspects of vulnerability (e.g., migratory pathways and timing, gear efficiency, etc.) for all stocks in the fishery remain constant.

Constant Harvest Rate

If in year 2 the fishery's overall intensity were to remain the same as in year 1, then respective harvest rates on all stocks, including x, would remain the same, $\mu_{x,1} = \mu_{x,2} = \mu_x$. The catch of stock x would thus decline by the same factor as the stock's size declined. Using equation (3),

$$C_{x,2} = \mu_x N_{x,2} = C_{x,1} (\theta_x + 1) \, . \qquad (4)$$

Given that abundance, harvest rates, and thus catches from other stocks remain constant, the total fishery catch of all stocks would decline by the numerical amount that catch of stock x declined:

$$C_2 = C_1 - (C_{x,1} - C_{x,2}) \, . \qquad (5)$$

Model output, in terms of the rate of change in stock-specific catch and under conditions of constant harvest rate, is simply equivalent to the proportional change in stock size, as derived from equation (4):

$$\theta_{c,x} = \frac{C_{x,2} - C_{x,1}}{C_{x,1}} = \theta_x . \qquad (6)$$

The rate of change in total catch under constant harvest rate is

$$\theta_c = \frac{C_2 - C_1}{C_1} . \qquad (7)$$

This equation can be simplified using relationships in equations (5), (4), and (1), such that

$$\theta_c = \rho_{x,1} \theta_x . \qquad (8)$$

This percentage change in total fishery catch (θ_c) under constant harvest rate or fishing intensity results from the change in 1 component stock's abundance and the fishery's consequent change in catch effected by that stock alone.

Whereas individual stock harvest rates remain constant, changes in total catch and stock-x catch change the proportion of stock x in the total catch. Thus, in year 2

$$\rho_{x,2} = \frac{C_{x,2}}{C_2} . \qquad (9)$$

Constant Total Catch

If in year 2 the fishery were to increase in intensity to make up for the lower availability of fish from stock x, thus keeping total catch in year 2 the same as in year 1, then respective harvest rates on all stocks would increase. The increased harvest rate on stock x is of particular concern.

The increase in total fishery catch from C_2 to make $C_2^* = C_1$ would equal the number of stock-x fish not caught under constant harvest rate (see equation (5)):

$$C_2^* - C_2 = C_{x,1} - C_{x,2} = C_1 - C_2 . \qquad (10)$$

However, the stock composition of this incremental increase in total catch would not be solely from stock x. In fact, the increment ($C_2^* - C_2$ or $C_1 - C_2$) would display the same stock composition as the rest of the catch in year 2. Consequently, the total number of fish taken from the stock of concern would be the original amount calculated under constant intensity plus the

product of $\rho_{x,2}$ times the increment in total catch needed to make up for the shortfall, or

$$C_{x,2}^* = C_{x,2} + \left[(C_1 - C_2) \rho_{x,2} \right]. \qquad (11)$$

The new harvest rate on stock x would then be

$$\mu_{x,2}^* = \frac{C_{x,2}^*}{N_{x,2}} . \qquad (12)$$

Model output, in terms of change in harvest rate on stock x with total fishery catch remaining constant between years 1 and 2, is

$$\theta_{\mu,x}^* = \frac{\mu_{x,2}^* - \mu_{x,1}}{\mu_{x,1}} . \qquad (13)$$

This output equation can be simplified to relate change in harvest rate directly to ρ_x and θ_x by first defining $\mu_{x,2}^*$ from equation (12), then using relationships outlined in equations (11), (9), (4), and (3):

$$\mu_{x,2}^* = \frac{C_{x,1} C_1}{N_{x,1} C_2} . \qquad (14)$$

Therefore, $\theta_{\mu,x}^*$ from equation (13) can be derived from equations (14) and (2):

$$\theta_{\mu,x}^* = \left(\frac{C_1}{C_2} \right) - 1 . \qquad (15)$$

Equation (15) can then be expressed in terms of $\rho_{x,1}$ and θ_x by substituting values from equations (5), (1), and (4):

$$\theta_{\mu,x}^* = \frac{-\left(\rho_{x,1} \theta_x \right)}{1 + \left(\rho_{x,1} \theta_x \right)} . \qquad (16)$$

This percentage change in harvest rate under constant total catch results from decline in abundance of stock x and subsequent intensification of the fishery on the entire mixture of stocks to maintain the same year 1 total catch level in year 2.

Corresponding change in catch of stock x if total catch remained constant is

$$\theta^*_{c,x} = \frac{C^*_{x,2} - C_{x,1}}{C_{x,1}}. \qquad (17)$$

This can be simplified similarly to the derivation of equation (14). $C^*_{x,2}$ from equation (11) can be rewritten as

$$C^*_{x,2} = \frac{\left[C_{x,1} (\theta_x + 1) C_1 \right]}{C_{x,2}}. \qquad (18)$$

Therefore, using equation (16)

$$\theta^*_{c,x} = \frac{\theta_x - \left(\rho_{x,1} \theta_x \right)}{1 + \left(\rho_{x,1} \theta_x \right)}. \qquad (19)$$

The change in stock-x catch under conditions of constant total catch, in the face of population decline, results from intensification of the fishery on the entire mixture of stocks modified directly by a reduced abundance of stock x.

RESULTS

The model derives 4 equations based solely upon an estimate of the proportion of total catch contributed by a stock of concern and an estimate of percentage change in that stock's abundance.

Assuming constant fishing intensity, thus constant harvest rates, the rates of change in stock-x catch and total fishery catch are modeled by

$$\theta_{c,x} = \theta_x \text{ and } \theta_c = \rho_{x,1} \theta_x .$$

Under a different management prescription to keep total fishery catch the same from year 1 to year 2 (denoted with symbol *), proportional changes in stock-x harvest rate and catch are modeled as

$$\theta^*_{\mu,x} = \frac{-\left(\rho_{x,1} \theta_x \right)}{1 + \left(\rho_{x,1} \theta_x \right)} \text{ and } \theta^*_{c,x} = \frac{\theta_x - \left(\rho_{x,1} \theta_x \right)}{1 + \left(\rho_{x,1} \theta_x \right)} .$$

Although these equations are valid for both increases and decreases in stock size, results here are described primarily with regard to stock decline. Figures 1 and 2 depict the relationships of θ_c and $\theta^*_{\mu,x}$ to proportion of catch (ρ_x) at various levels of decline in stock x (θ_x).

Results are fairly intuitive for fisheries in which stock x composes the entire catch ($\rho_x = 1.0$). When fishing intensity is constant from year to year (Figure 1), total catch will decline by the same proportion as the stock size reduction ($\theta_c = \theta_x$). Changes in harvest rate resulting from keeping total catch constant (Figure 2) are also straightforward. If the stock declines by half, then the harvest rate on that stock would double ($\theta_x = -0.50$; $\theta^*_{\mu,x} = 1.0$). If the stock were to decline by only 25%, then the resulting harvest rate would have to increase by 33% ($\theta_x = -0.25$; $\theta^*_{\mu,x} = 0.33$) in order to maintain the same total catch.

Not so intuitive are the effects on total catch and harvest rate when the stock does not compose all of the fishery catch ($\rho_x \neq 1.0$). Simply because a component stock declines by a certain proportion does not mean that impacts on or effects of a mixed stock fishery and a single stock fishery are the same. For example, if a prescribed management objective were to prevent any increase in harvest rates (i.e., maintain constant fishing intensity; Figure 1) of various fisheries on a stock that declined 50% ($\theta_x = -0.50$), reductions in total catch in a fishery for which $\rho_x = 1.0$ would be by half ($\theta_c = -0.50$). However, total catch for a fishery with $\rho_x = 0.1$ would only be reduced by 5% ($\theta_c = -0.05$). This latter result occurs because a 50% decline in stock x affects only the original 10% that stock previously contributed to the fishery; abundance of other contributing stocks remains unchanged.

Similarly, that same mixed stock fishery with low ρ_x would not exert much additional pressure on the declining stock, even if fishing intensity increased to keep total fishery catch constant (Figure 2). Increase in harvest rate for a fishery with $\rho_x = 1.0$, in the face of $\theta_x = -0.50$, would be 100% ($\theta^*_{\mu,x} = 1.0$), whereas $\theta^*_{\mu,x}$ for a mixed stock fishery with $\rho_x = 0.1$ in the face of the same stock decline would only be about 5% ($\theta^*_{\mu,x} = 0.053$). In other words, the harvest rate of the single stock fishery would double, whereas the harvest rate of the mixed stock fishery would increase only a few per-cent. The latter result is derived from the fact that any incremental increase in harvest intensity, required to keep total catch constant and make up for the shortfall in availability of the declining stock, would be exerted against the entire mixture of stocks present, not just on the specific stock of concern.

Percentage change in stock-specific catch under conditions of constant harvest rate are simply equivalent to changes in population size ($\theta_{c,x} = \theta_x$) and are not dependent upon the contribution of the stock to total fishery catch. Under conditions of constant total
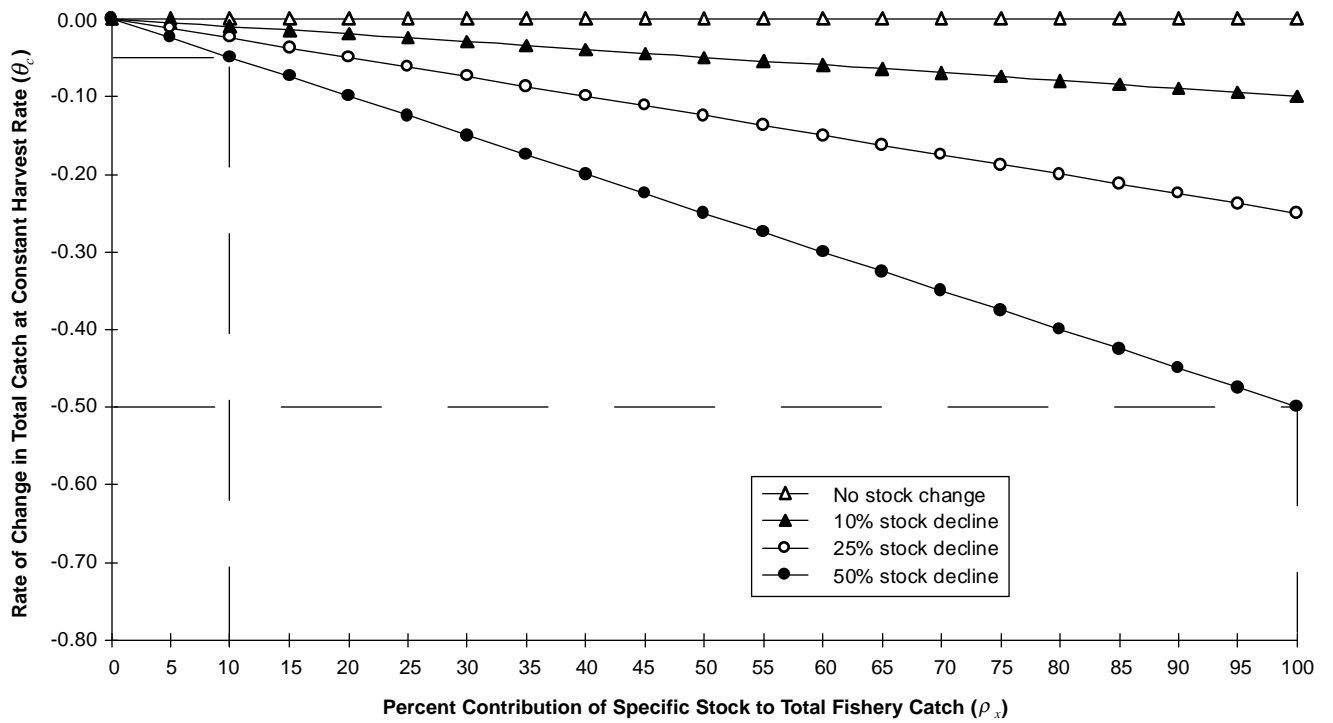
Figure 1. Change in total catch needed to keep harvest rate on a declining stock constant, as related to the stock's previous contribution to the fishery. Dashed-line examples shown are for ρ_x of 0.1 and 1.0, with $\theta_x = -0.50$.
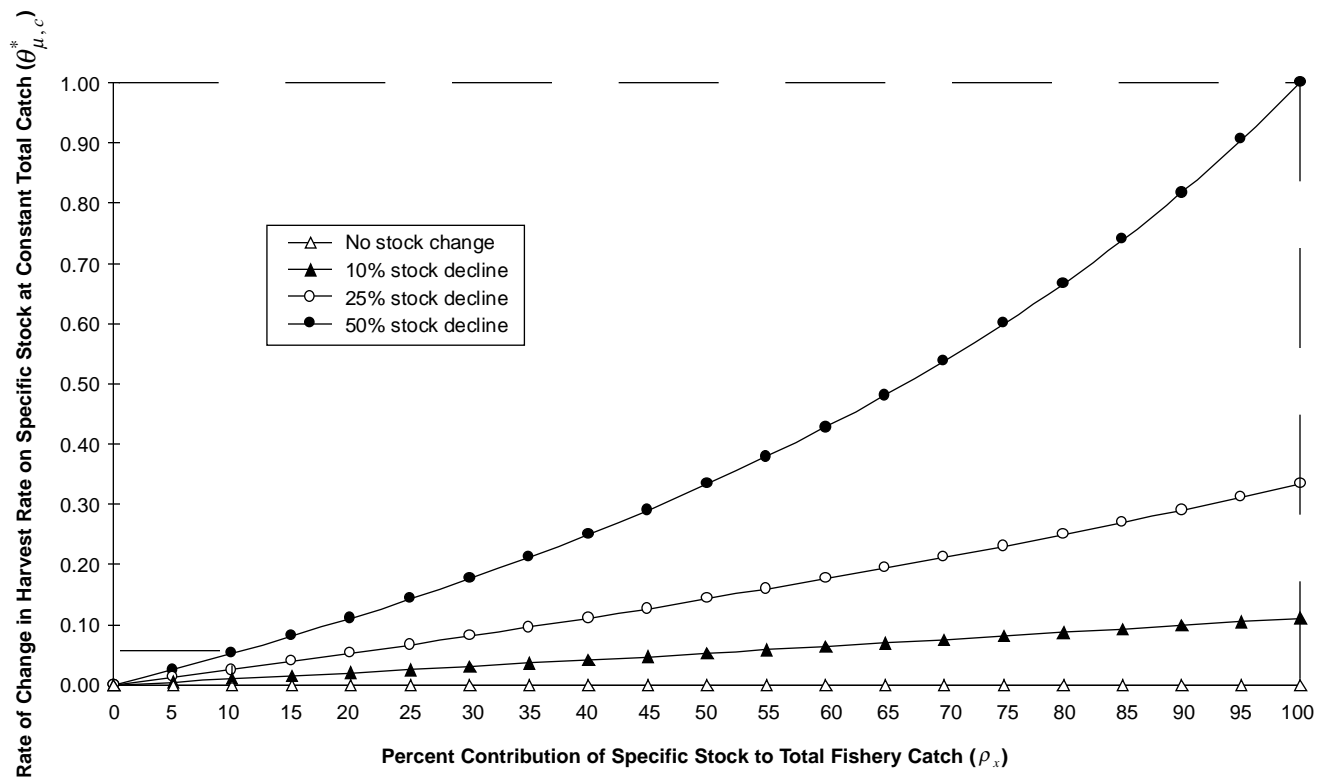

Figure 2. Change in harvest rate on a declining stock, given total fishery catch remains constant, as related to the stock's previous contribution to the fishery. Dashed-line examples shown are for ρ_x of 0.1 and 1.0, with $\theta_x = -0.50$.

catch, however, changes in stock-specific catch are directly influenced by ρ_x. Figure 3 depicts $\theta^*_{c,x}$ showing much greater accommodation to reduced population size by fisheries with low ρ_x; there is almost no accommodation by those fisheries in which stock x is the major contributor.

Although attempting to maintain constant harvest rates is a common fishery management objective, it is actually total catch that is adjusted to accomplish this objective. Figure 4 depicts the difference in changes to stock-specific catch under imaginary conditions of reducing total catch to keep harvest rate constant and under more static conditions of maintaining a constant total catch for various fisheries of differing ρ_x. This figure illustrates a large difference in effect on stock x for those fisheries with high ρ_x, indicating that some management control of total catch may be necessary. But for mixed stock fisheries in which the stock contributes only a small proportion of the total catch, there is little difference in effect between allowing the fishery to continue previous total catch levels and attempting to fine-tune that fishery's total catch so that an individual harvest rate and stock-specific catch exactly match changes in the contributing stock size.

CASE STUDY

In Alaska annual catch quotas for single stock herring fisheries are generally established under a constant harvest rate strategy (Funk and Harris 1992) based upon annual estimates of spawning biomass. In western Alaska about 6 apparently discrete spawning stocks support distinct sac roe fisheries, from the Alaska Peninsula and Togiak through the Yukon-Kuskokwim delta and further north to Norton Sound. A herring food/bait fishery near Dutch Harbor, in the Aleutian Islands, presumably takes a mixture of the western Alaska spawning stocks and is managed under a total catch quota calculated each year based upon preseason estimates of the large Togiak spawning biomass in Bristol Bay.

In the late 1980s and early 1990s, several of the western Alaska stocks were in decline, notably those spawning at Nelson Island. Funk et al. (1991) describe the limited information available on stock composition of the Dutch Harbor food/bait fishery. Based upon presumed migratory routes, timing of fisheries, some scale-pattern analyses, and respective biomasses of western Alaska stocks, they estimated that the Nelson Island stock may contribute approximately 2–3% of
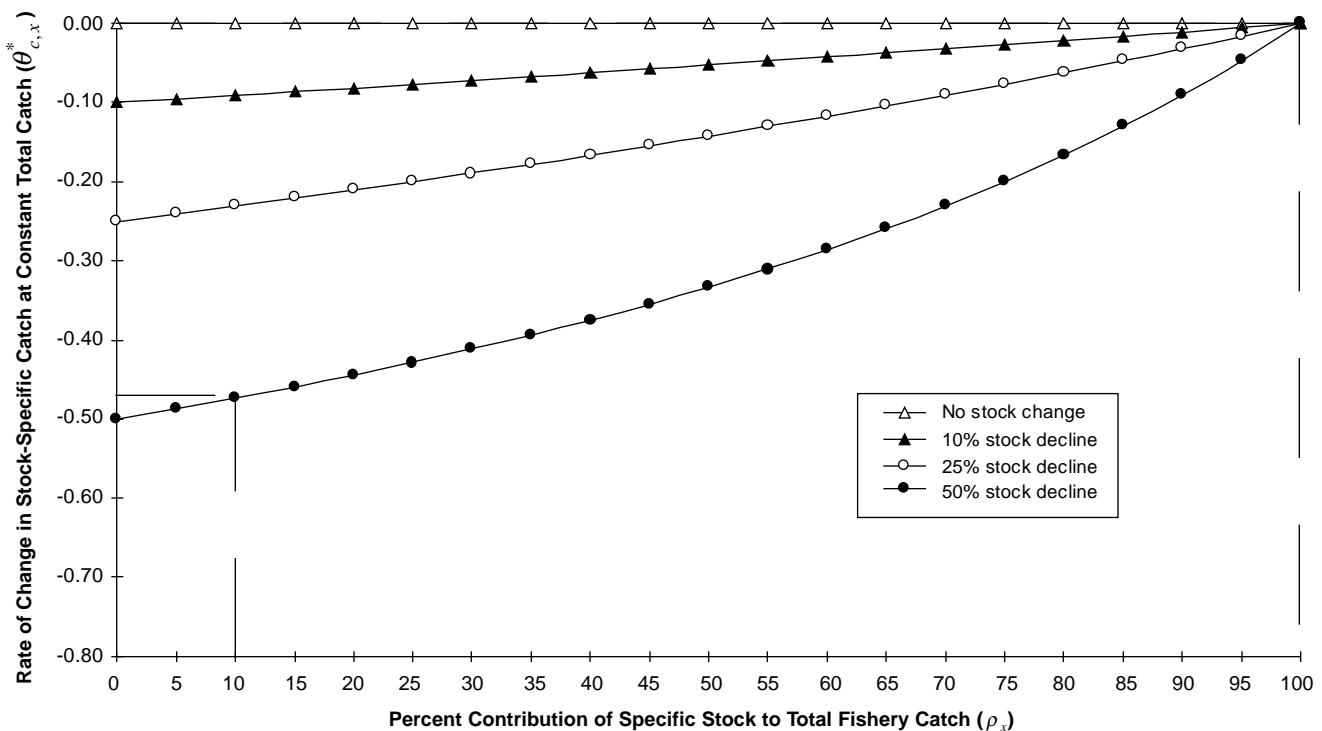

Figure 3. Change in stock-specific catch on a declining stock, given total fishery catch remains constant, as related to the stock's previous contribution to the fishery. Dashed-line examples shown are for ρ_x of 0.1 and 1.0, with $\theta_x = -0.50$.

the Dutch Harbor harvest. Funk (1991) and Funk and Harris (1992) report spawning biomass estimates for the Nelson Island stock of 2,705 tons in 1990 and 2,385 tons in 1991, a Dutch Harbor harvest of 820 tons in 1990, and a Nelson Island allowable harvest of 205 tons in 1990 (actually, no commercial harvests were taken at Nelson Island due to lack of a market). Although the model requires only values for ρ_x and θ_x, all of these estimates are used (Table 1) to more clearly illustrate hypothetical changes in this case study.

Though the stock decline was not very substantial (11.83%, for a θ_x rounded to -0.12), the differences in ρ_x for the Dutch Harbor and Nelson Island fisheries (0.03 and 1.0, respectively) result in some definite differences in their potential responses in catch and harvest rate. If, under assumptions of this model, the Dutch Harbor fishery were to have maintained the same harvest rate in 1991 as in 1990, then its total catch (820 tons) would need to have been reduced by only 3 tons, for a θ_c basically indistinguishable from zero (i.e., no change). For the Nelson Island fishery to have maintained a constant harvest rate, its total catch (205 tons) would need to have been reduced by 12% (24 tons), for a θ_c = -0.12, which is readily distinguishable from zero.

If both fisheries were to have been allowed to maintain their total catch for 1991 the same as for 1990, then harvest rate of the Dutch Harbor fishery on the Nelson Island stock would not have noticeably increased, by about 0.3%, for a $\theta^*_{\mu,x}$ indistinguishable from zero, whereas the Nelson Island harvest rate would have increased by about 13%, for a $\theta^*_{\mu,x}$ of 0.13.

Regarding changes in stock-specific catch, letting the Dutch Harbor fishery maintain a constant catch level between years ($\theta^*_{c,x}$ = -0.12) was pragmatically equivalent to attempting to adjust total catch to keep harvest rate absolutely constant ($\theta_{c,x}$ = -0.12). In either case the Dutch Harbor catch of Nelson Island herring would similarly adjust to reduced abundance of the stock.

However, for the Nelson Island fishery, under constant total catch, $\theta^*_{c,x}$ is zero whereas attempting to achieve a consistent harvest rate would require a substantial correction ($\theta_{c,x}$ = -0.12). Thus, to achieve the same objective, in this case constant harvest rate, the total Nelson Island catch must be reduced about 12%, but there would be no practical reason to alter the total mixed stock Dutch Harbor fishery catch.

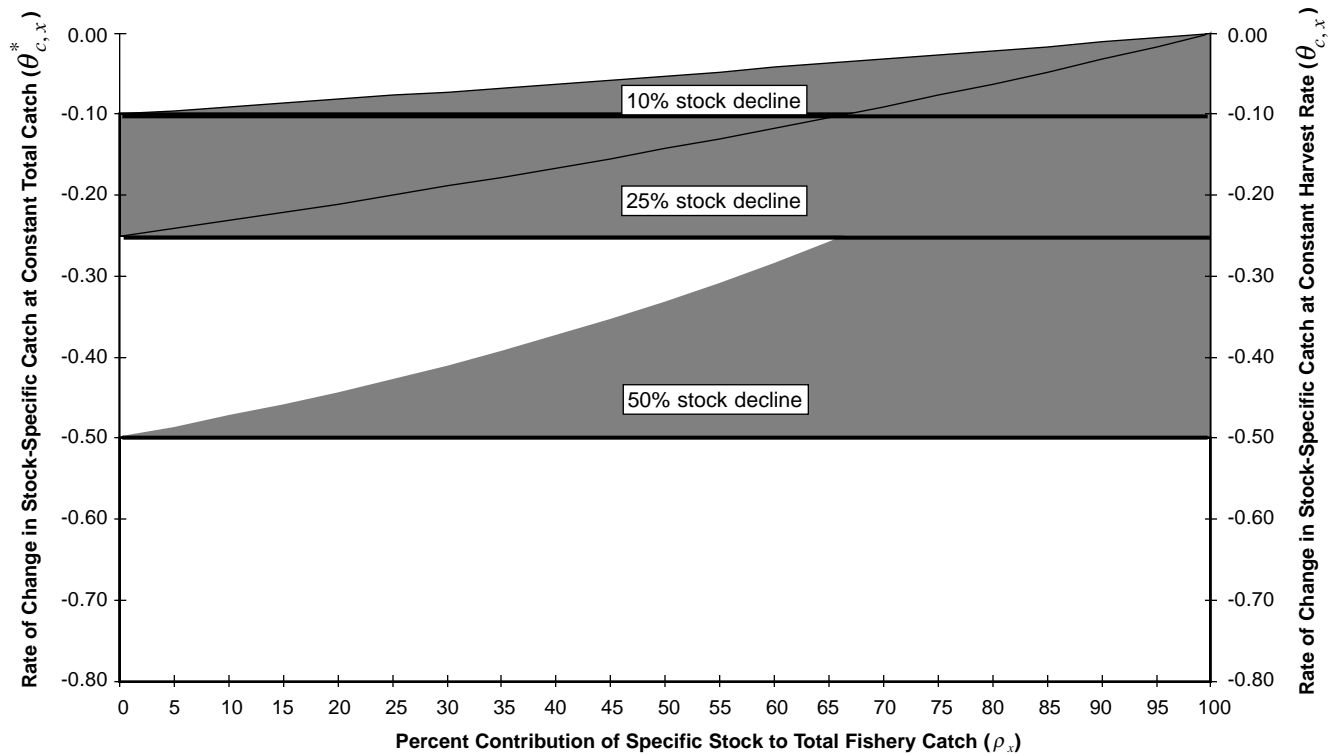For Dutch Harbor at low ρ_x there is little difference between strategies of constant harvest rate and

Figure 4. Difference between changes in stock-specific catch (filled areas), given total fishery catch remains constant (upper sweeping boundaries), compared to constant harvest rate (dark, lower horizontal lines), at various rates of stock decline.

Table 1. Model worksheet and illustration for Dutch Harbor food/bait fishery and Nelson Island sac roe fishery on the Nelson Island herring stock, 1990 and 1991.

	Model Parameters	Dutch Harbor Fishery		Nelson Island Fishery	
		Tons of Fish	Rates and Percents	Tons of Fish	Rates and Percents
Inputs					
Initial conditions:					
1990 stock size (tons)		2,705		2,705	
1990 total fishery herring catch		820		205	
Initial proportion of fishery catch composed of stock in question	ρ_x		0.03		1.00
Resulting tons of fish from stock harvested in fishery		25		205	
Resulting fishery harvest rate on stock of concern			0.91%		7.58%
Proportional change in stock size, from 1990 to 1991	θ_x		-0.12		-0.12
Illustration					
For constant fishing intensity (harvest rate) in 1991:					
Stock size in 1991		2,385		2,385	
Tons of fish to be taken from stock in 1991, at same fishing intensity		22		181	
Decline in total fishery catch		-3		-24	
Resulting total fishery catch		817		181	
1991 proportion of stock in the fishery catch			2.65%		100.00%
Proportional change in total catch			-0.35%		-11.83%
Proportional change in stock-specific catch			-11.83%		-11.83%
On to constant harvest level (total catch) in 1991:					
Increase in harvest to make up deficit		3		24	
Resulting total fishery catch		820		205	
1991 proportion of stock in the fishery catch			2.65%		100.00%
Additional fishery harvest of stock of concern		0		24	
Total 1991 harvest of stock of concern		22		205	
Resulting harvest rate on stock of concern			0.91%		8.60%
Proportional change in harvest rate			0.36%		13.42%
Proportional change in stock-specific catch			-11.52%		0.00%
Output (calculated solely from ρ_x and θ_x)					
Constant harvest rate between 1990 and 1991:					
Proportional change in total catch	θ_c		0.00		-0.12
Proportional change in stock-specific catch	$\theta_{c,x}$		-0.12		-0.12
Constant total catch between 1990 and 1991:					
Proportional change in harvest rate	$\theta^*_{\mu,x}$		0.00		0.13
Proportional change in stock-specific catch	$\theta^*_{c,x}$		-0.12		0.00

Table 2. Effect of raising ρ_x for the Dutch Harbor food/bait fishery and intensifying θ_x for the Nelson Island herring stock.

	Parameter	Dutch Harbor Fishery	Nelson Island Fishery
Inputs			
Initial proportion of fishery catch composed of stock x	ρ_x	0.06	1.00
Proportional change in stock size	θ_x	-0.50	-0.50
Output			
Given constant harvest rate:			
Proportional change in total catch	θ_c	-0.03	-0.50
Proportional change in stock-specific catch, given constant harvest rate	$\theta_{c,x}$	-0.50	-0.50
Given constant total catch:			
Proportional change in harvest rate	$\theta^*_{\mu,x}$	0.03	1.00
Proportional change in stock-specific catch	$\theta^*_{c,x}$	-0.48	0.00

constant catch, but for Nelson Island at high ρ_x there is a substantial difference. The proportion of the Dutch Harbor fishery composed of Nelson Island spawning stock is so low that a moderate stock decline has little or no bearing on the mixed stock fishery (or the fishery on the stock), yet impacts to and response required of the local Nelson Island fishery are much more substantial.

The model can be used to examine more extreme situations as well. The Nelson Island stock can potentially fluctuate widely between years (Hamner and Kerkvliet 1994), more than the 12% decline noted between 1990 and 1991. Moreover, the contribution of Nelson Island herring to the Dutch Harbor catch might conceivably be higher than estimated by Funk et al. (1991). By changing population decline to $\theta_x = -0.50$ and doubling the proportional contribution of Nelson Island herring to the Dutch Harbor fishery ($\rho_x = 0.06$), then model outputs can be recalculated to compare more extreme effects of the Dutch Harbor fishery on the Nelson Island herring stock (Table 2). Even assuming more impact to this stock by mixed stock catches at Dutch Harbor, it is the local Nelson Island fishery that must be adjusted in response to the stock's decline; adjusting catch in the Dutch Harbor fishery would still be inconsequential (Figure 5).

Although managers may be more immediately concerned with declining stocks, this model can also be used to examine relative benefits to various fisheries gained through increases in abundance. Using inputs from the example above, but rather than declining in half, assume the Nelson Island stock doubled ($\theta_x =$

1.0) as it did between 1991 and 1992 (Hamner and Kerkvliet 1994), then θ_c for Dutch Harbor would be 0.06 compared to a θ_c for Nelson Island of 1.00; $\theta^*_{\mu,x}$ for Dutch Harbor would be -0.06; and $\theta^*_{\mu,x}$ for Nelson Island would be -0.50. Figure 5 illustrates these conditions as well: little difference in stock-specific catch between strategies of constant harvest rate and constant catch for Dutch Harbor but substantial gains for the Nelson Island fishery under constant harvest rate rather than constant catch. Consequently, doubling of the Nelson Island stock biomass would hardly be felt in the Dutch Harbor fishery, while total catch at Nelson Island could double without increasing its harvest rate. Thus the benefits and costs of single stock fluctuations apply much more directly to single than to mixed stock fisheries.

Finally, although not derived entirely from the model's simplified equations, the model can illustrate the effect of applying strict proportional reductions on total mixed stock catch in fisheries of low ρ_x in the face of a single stock decline. In the case of a 50% reduction in biomass ($\theta_x = -0.50$), in year 2 there would be no discernible difference in harvest rate ($\mu_{x,2} = 0.91\%$ to $\mu^*_{x,2} = 0.92\%$) or stock-specific catch ($C_{x,2} = 12.30$ tons to $C^*_{x,2} = 12.49$ tons) for the Dutch Harbor fishery (at $\rho_x = 0.03$) under either harvest strategy. Yet, loss to the fishery as a whole ($C^*_2 - C_2$) would be 1.5% of total catch (>12 tons) if total catch were reduced to keep harvest rate absolutely constant.

If the quota was reduced by half under a mistaken impression that a 50% reduction, rather than a 1.5% reduction, in total catch at Dutch Harbor must be im-

posed to match a 50% decline in the Nelson Island stock, then the costs would even further exceed the benefits. Applying consequent $\rho_{x,2} = 1.52\%$ to the reduced quota (410 tons) would give a stock-specific catch savings of <6 tons of Nelson Island herring out of the reduced population size of 1,353 tons (i.e., a 0.4% "savings") at a cost of 410 tons (50%) of total catch to the Dutch Harbor fishery. In this case, almost 70 tons of catch at Dutch Harbor would be forfeited for each of the 6 tons of Nelson Island stock saved. Yet, these savings would be an insignificant contribution to the Nelson Island stock's total biomass.

DISCUSSION

Ricker (1958), in an early evaluation of a mixed stock fishery and its several component stocks, noted:

> *Most of the conclusions arrived at from the analyses above could, I believe, be reached by "intuition" or common-sense reasoning, without actual computation... The value of these calculations and others similar is mainly to provide objective models which can be cited in justification of a particular regulation. What is common sense to one man may seem ridiculous to another. The calculation of benefits and losses under prescribed conditions is the only way to resolve such arguments.*

Sometimes regulatory questions must address comparison of 2 or more fisheries upon a shared stock of fish, rather than a single fishery upon 2 or more stocks. Just such a debate surrounded management of the Dutch Harbor and Nelson Island herring fisheries and occupied the Alaska Board of Fisheries from the mid 1980s through the early 1990s. In the face of decline in the Nelson Island stock, the board wished to share the management burden across both fisheries in some comparable manner but found little technical information available to assist them.
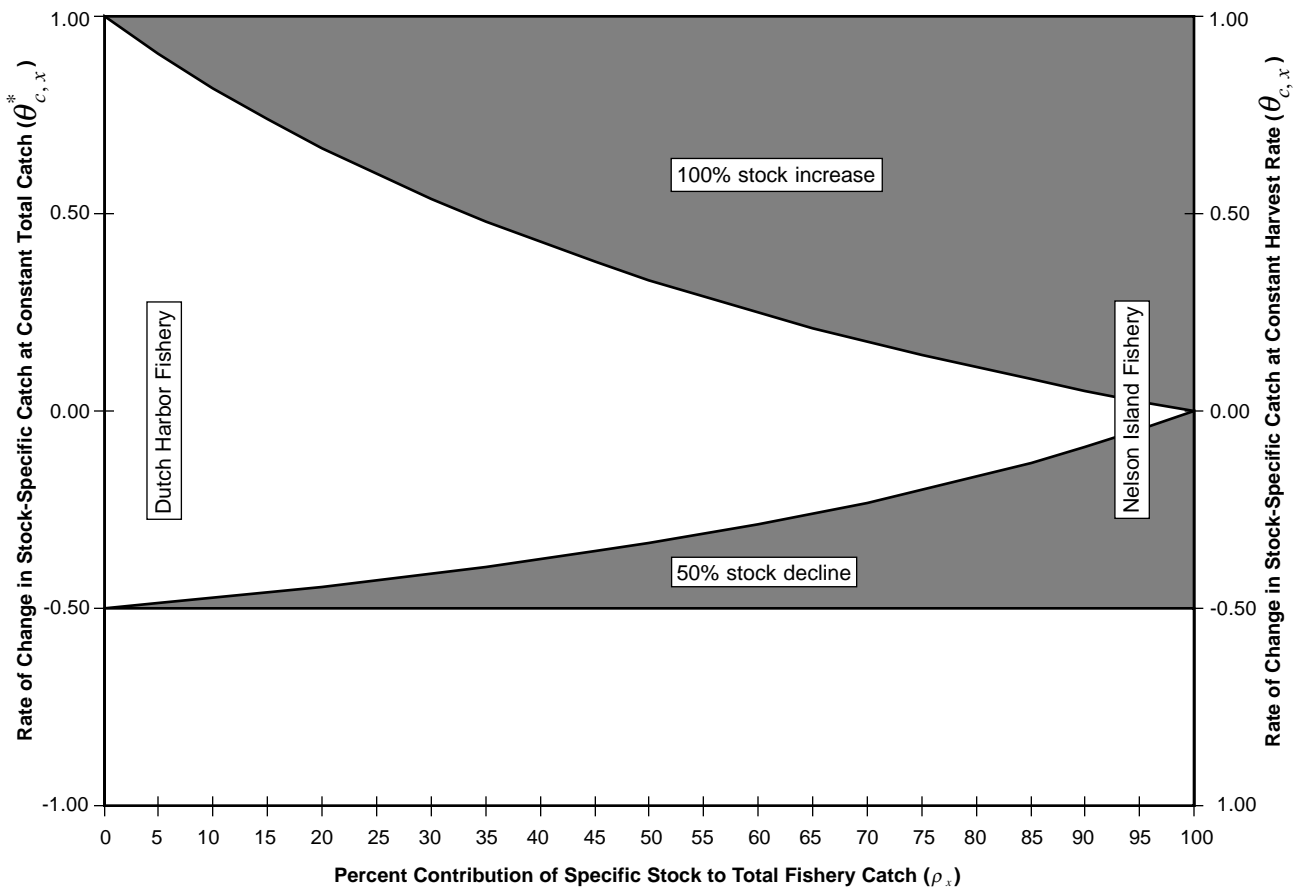

Figure 5. Comparison of potential changes in catch of Nelson Island herring in Dutch Harbor and Nelson Island fisheries, given total fishery catch remains constant compared to constant harvest rate; $\theta_x = -0.5$ and $+1.0$.

This paper presents a simple method to compare the relative effects of different fisheries on a common stock of concern. Results indicate that a mixed stock fishery, for which a specific stock contributes only a small portion of the total harvest, may have little relative effect on the stock, even if it is in substantial decline and total harvest of the fishery remains unchanged. Catch reductions or changes in harvest rates need not be the same among fisheries sharing a stock of concern in order to effect similar responses by the fisheries or to exert similar influence upon the stock. For example, not all fishery catches would need to be cut in half to maintain a consistent harvest rate on a stock that declines by 50%. The algebraic model and brief case study developed here illustrate that, in the face of changes in abundance (θ_x), the proportional contribution (ρ_x) of a stock to a fishery's harvest dramatically influences that fishery's total and stock-specific catch and the effects of that fishery (e.g., harvest rate) on the stock.

Various scenarios within the case study illustrate the robustness of the model. Initial assumptions need not be especially accurate, so long as there is a substantial difference in the ρ_x of fisheries being compared, which is usually the case between mixed stock fisheries and more stock-specific ones. Of course, this model presumes that only the single stock of concern fluctuates in abundance from year to year. While this is seldom strictly true in the real world, such an assumption can be valid as long as there is not substantial covariance in the abundance of contributing stocks. It would be possible to expand this model to allow for an increase or decrease in aggregate abundance of stocks other than x. Generally, if such θ_y were to be positive while stock x declined, then the differences between fisheries of low and high ρ_x would be even more pronounced than described here. Conversely, if θ_x and θ_y were both negative, then the differences between fisheries would be less distinct.

Many times the data needed to conduct a detailed examination of various fisheries' relationships to fluctuating stock abundance are simply not available, yet management concerns must still be addressed. This model illustrates a rather apparent, but sometimes overlooked, notion that the proportion of total catch contributed by a particular stock affects the responses of fisheries to the stock's decline.

Specifically, fisheries that rely heavily upon the stock of concern have a much more direct relationship to any fluctuations in the stock, whereas such influences and effects are diluted by the presence of other stocks in a mixed stock fishery. If the proportion (ρ_x) is quite small, then the effects on stock x of a constant catch or a constant harvest rate policy would be nearly identical, but the difference between such policies on total catch of the mixed stock fishery could be substantial.

This model can be used for a number of fishery types, whether they are quota-based or exploitation rate-based, such as those for herring, groundfish, and shellfish. Extension of this model to escapement-based salmon fisheries is discussed separately (see Lloyd 1996 in this issue) because salmon fisheries are generally managed upon fixed annual escapements, with allowable catch and harvest rates both fluctuating greatly depending upon harvestable surpluses.

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