North American Journal of Fisheries Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ujfm20

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Peter W. Lawson [a] & David B. Sampson [b]
[a] Oregon Department of Fish and Wildlife, 2040 Southeast Marine Science Drive, Newport, Oregon, 97365, USA
[b] Oregon State University, Coastal Oregon Marine Experiment Station and Department of Fisheries and Wildlife Hatfield Marine Science Center, Newport, Oregon, 97365, USA

Available online: 09 Jan 2011

To cite this article: Peter W. Lawson & David B. Sampson (1996): Gear-Related Mortality in Selective Fisheries for Ocean Salmon, North American Journal of Fisheries Management, 16:3, 512-520

To link to this article: http://dx.doi.org/10.1577/1548-8675(1996)016<0512:GRMISF>2.3.CO;2

North American Journal of Fisheries Management 16:512–520, 1996

Gear-Related Mortality in Selective Fisheries for Ocean Salmon

PETER W. LAWSON

Oregon Department of Fish and Wildlife
2040 Southeast Marine Science Drive, Newport, Oregon 97365, USA

DAVID B. SAMPSON

Oregon State University
Coastal Oregon Marine Experiment Station and Department of Fisheries and Wildlife
Hatfield Marine Science Center, Newport, Oregon 97365, USA

Abstract.—In ocean fisheries for Pacific salmon *Oncorhynchus* spp., there can be several forms of gear-related mortality. Much research effort has been directed at estimating mortality rates for salmon that are hooked and then released. Also potentially important but not easily measured is mortality of fish that escape from the hook before being brought to the boat or fish that are removed from the hook by predators, so-called "drop offs." In selective fisheries in which some hatchery-bred fish are marked for retention and unmarked fish legally must be released, the actual mortality rate suffered by unmarked fish depends on the harvest rate for the marked fish, the accuracy of mark recognition, and the proportion of marked and unmarked fish when fishing begins. This paper develops a model for evaluating gear-related mortality in selective fisheries and explores the potential importance of several sources of mortality. Mortality rates for unmarked fish are generally lower than the apparent harvest rates but increase rapidly as harvest rates increase. In the overall mortality of unmarked fish, drop-off mortality could be as important as hook-and-release mortality.

In traditional ocean fisheries for Pacific salmon *Oncorhynchus* spp., mixtures of wild and hatchery fish are generally harvested. In the ocean off California, Oregon, and Washington, which is managed by the Pacific Fishery Management Council (PFMC), landings quotas are used to achieve exploitation rates calculated to allow sufficient spawners for certain naturally reproducing salmon stocks (PFMC 1995). Recent restrictions designed to conserve wild stocks of chinook salmon *O. tschawytscha* and coho salmon *O. kisutch* also limit access to hatchery stocks. A solution proposed to avoid this problem involves marking all hatchery salmon and requiring that fishers retain only marked fish (Pacific States Marine Fisheries Commission 1992; Pacific Salmon Commission 1995). This form of so-called selective fishery is an attractive alternative to the present restrictive policies because fishers can apparently keep hatchery fish, wild ones will go free, and fishers can return to full fishing seasons without harming the wild stocks. However, in selective fisheries, the unmarked stocks can suffer mortality from encounters with fishing gear. The magnitude of this form of mortality is poorly known and may be difficult or impossible to determine experimentally. In this paper, we use modeling techniques to explore the potential importance of several sources of gear-related mortality in a selective fishery.

Encounters with gear can take several forms. Most obvious and most easily measured are fish that are hooked, brought to the boat, and then released. Mortality rates of such fish have been estimated in many studies on the west coast of North America. Reviews are provided by Wright (1970), Ricker (1976), and Horton and Wilson-Jacobs (1985), in a joint report prepared by the Washington Department of Fisheries and Wildlife and the Northwest Indian Fisheries Commission (1993), and by Muoneke and Childress (1994). Estimated hook-and-release mortality rates for Pacific salmon ranged widely, from less than 5% to more than 70%.

Additional complexity arises because some fish will be hooked and released more than once. Mortality rates possibly increase with repeated gear encounters, although having been hooked previously, a fish is possibly less likely to be hooked again.

In addition to hook-and-release mortality, several other forms of gear-related mortality may occur. For example, gear may remain embedded in fish that escape and reduce their rate of survival. Hooked salmon may be more vulnerable to some kinds of predators because their movements are restricted by the fishing line. Ricker (1976) identified escapees and fish removed from troll lines by predators as two classes of fish that are not measured in hooking mortality studies but that suffer mortality as a result of fishing. Together, these two classes of fish constitute "drop-offs."

One of the most difficult problems in managing fisheries is in assessing "noncatch mortalities" (gear-related mortalities other than landed catch). Compared to measuring catch and escapement for which the fish are in hand to be counted, noncatch mortalities are neither directly observable nor measurable. It is not feasible to estimate experimentally the magnitude of factors such as mortality rates of fish that are hooked but not brought to the boat. Although we may never know actual mortality rates, we can perform sensitivity analyses with fishery models to alert us to the likely importance of these mortality factors in different types of fisheries. Fisheries could then be conducted to minimize the risk of high, unquantifiable noncatch mortalities.

There have been previous attempts to include noncatch mortality in fishery models. Clark et al. (1980) and Clark (1983) incorporated hooking mortality in a model of several freshwater fish species, including two salmonids, to evaluate the effects of size limits on species with complex population dynamics. Noncatch mortality was included in the harvest model described in Hunter (1985), which is the basis for the current U.S. West Coast coho salmon management. Although this model captures much of the complexity of these fisheries, including factors such as hook-and-release and drop-off mortality, it does not adequately reflect the basic interactions in selective fisheries between stock composition, harvest rates, errors in mark identification, and mortality from gear encounters. These interactions are best explored with a model with an easily understood structure so that the effects of parameter values and assumptions can be considered intuitively as well as examined systematically.

In contrast to traditional mixed-stock fisheries, in which all stocks encounter gear and suffer mortality at equal rates, in selective fisheries the stock composition and gear encounter rates change throughout the course of the fishery. The model we developed mimics this dynamic feature of selective fisheries. The harvest policy in this model applies the quota management system currently used by the PFMC to a selective fishery scenario. We assume that the fishery is sufficiently short that natural mortality during the fishing season is negligible.

The model includes two stocks, one marked and one unmarked, and treats the fishing process in accord with the following sequence of events. Fish in the combined pool of marked and unmarked stocks encounter fishing gear at random. These fish have a probability of dropping off, and those that drop off have a probability of dying. Fishers catch fish that do not drop off and examine them for marks. They retain those fish that appear to be marked and release those that appear to be unmarked. Released fish have a particular probability of dying, which may depend on the number of times they were previously released. The fishing season stops when the harvest quota is reached, where the quota is based on a predetermined target harvest rate or escapement goal for the marked fish.

The selective fishery model we describe, like that of Clark et al. (1980), is a straightforward extension of the standard fishery catch equation. Although the model is reasonably simple, it requires numerous variables and parameters (Table 1).

TABLE 1.—Variables and parameters for the selective fishery model.

Variable or parameter	Description
M	Initial number of marked fish
U	Initial number of unmarked fish
C	Cumulative number of fish caught and retained
H	Apparent harvest rate; $H = C/M$
λ	Instantaneous rate coefficient for encounters by a fish with the fishing gear
α	Drop-off probability: the probability that a hooked fish escapes before being brought to the boat
β	Drop-off mortality rate: the probability that a fish that drops off dies from being hooked; the model assumes that β does not change after each encounter with the gear
δ	Release mortality rate: the probability that a released fish dies after its first release
Δ	Release mortality increment: the fractional increase in δ with each successive release
γ	Mark recognition rate: the probability that fishers properly identify a fish as being marked or unmarked; the probability that a fish is misidentified is $(1 - \gamma)$
p_M, p_U	The probability that a marked or unmarked fish has a fatal encounter with the fishing gear; $\mu = p_U$
D_M, D_U	The cumulative number of marked or unmarked fish that die

Model for a Selective Fishery

There is a fish population that consists initially of a mix of M (marked) and U (unmarked) individuals. Marked and unmarked fish are assumed to act independently, and both encounter fishing gear at the same rate. However, fishers can legally retain only the marked fish. Each marked and unmarked fish encounters the fishing gear as a simple Poisson process (Parzen 1962) with rate parameter λ. This parameter determines how rapidly fish are harvested and sets the basic time scale for the fishery. As in a simple catch process model (Sampson 1988), one would normally assume that the encounter rate was proportional to the number of gear units in the fishery.

Let α denote the probability that a fish escapes the gear after encountering it; let β denote the probability that an escaped fish subsequently dies from gear-related injuries; let γ denote the probability that a fish brought to the boat is correctly identified as marked or unmarked; and let δ be the probability that after being released, a fish subsequently dies from injuries sustained during capture and release. For simplicity, we assume that fish do not suffer higher mortality rates if they are caught and released more than once. If release mortality rate (δ) depends on each fish's previous encounters with the gear, the analysis requires a historical accounting for each fish and is much more complicated.

We describe γ as the mark recognition rate, but it also accounts for the probability that fishers deliberately release marked fish or illegally keep unmarked fish. For simplicity, we assume that marked fish are as likely to be mistaken for unmarked fish as unmarked fish are to be mistaken for marked fish.

The probability that an encounter with the gear results in death depends on whether a fish is marked or unmarked. For a marked fish, the probability that an encounter is fatal is

$$(1-\alpha)\cdot\gamma + (1-\alpha)\cdot(1-\gamma)\cdot\delta + \alpha\cdot\beta; \quad (1)$$

the first term accounts for fish that are brought to the boat and kept. The second term accounts for fish that die after being brought to the boat and released because they are mistaken for unmarked fish, and the third term accounts for fish that die after escaping the gear. For an unmarked fish, the probability that an encounter is fatal is

$$(1-\alpha)\cdot\gamma\cdot\delta + (1-\alpha)\cdot(1-\gamma) + \alpha\cdot\beta; \quad (2)$$

the first term accounts for fish that die after being brought to the boat and released, the second term accounts for fish that are brought to the boat and kept because they are mistaken for marked fish, and the third term accounts for fish that die after escaping the gear.

Given that fish encounter the gear as a simple Poisson process, the mortality of marked and unmarked fish operates as a simple death process (Parzen 1962). For each marked fish, the probability of dying during time span t is given by

$$p_M(t) = 1 - \exp(-\lambda\cdot t\cdot\{(1-\alpha)\cdot[\gamma + (1-\gamma)\cdot\delta] + \alpha\cdot\beta\}), \quad (3)$$

and for each unmarked fish, the probability of dying during t (mortality rate μ) is given by

$$p_U(t) = \mu = 1 - \exp(-\lambda\cdot t\cdot\{(1-\alpha)\cdot[\gamma\cdot\delta + (1-\gamma)] + \alpha\cdot\beta\}). \quad (4)$$

The numbers of marked and unmarked fish that die during t because they encounter the fishing gear are binomially distributed random variables. The number of marked fish that die on average is

$$E[D_M(t)] = M\cdot p_M(t), \quad (5a)$$

and its variance is

$$V[D_M(t)] = M\cdot p_M(t)\cdot[1 - p_M(t)]. \quad (5b)$$

Similar equations apply for the number of unmarked fish. Observe that the number of marked fish that die is independent of the initial number of unmarked fish, and vice versa.

Only a fraction of the fatalities result in retained catches. For the marked fish, the fraction retained is

$$\frac{(1-\alpha)\cdot\gamma}{(1-\alpha)\cdot\gamma + (1-\alpha)\cdot(1-\gamma)\cdot\delta + \alpha\cdot\beta}, \quad (6)$$

and for the unmarked fish, the fraction retained is

$$\frac{(1-\alpha)\cdot(1-\gamma)}{(1-\alpha)\cdot\gamma\cdot\delta + (1-\alpha)\cdot(1-\gamma) + \alpha\cdot\beta}. \quad (7)$$

Let the apparent harvest rate (H) be the ratio of the retained catch over the initial number of marked fish. We describe H as the apparent harvest rate because, in addition to the fish that were correctly identified as marked, the retained catch may include unmarked fish that were incorrectly identified as marked.

$$H(t) = \frac{(1-\alpha)\cdot\gamma}{(1-\alpha)\cdot[\gamma + (1-\gamma)\cdot\delta] + \alpha\cdot\beta}\cdot p_M(t) + \frac{(1-\alpha)\cdot(1-\gamma)}{(1-\alpha)\cdot(\gamma\cdot\delta + 1 - \gamma) + \alpha\cdot\beta}\cdot\mu\cdot(U/M). \quad (8)$$

Under the harvest policy in this model, the fishing season continues until the retained catch is a certain target fraction of the initial size of the marked fish population.

Observe in equation (8) that the apparent harvest rate is independent of the initial stock mixture (U/M) when there is perfect mark recognition ($\gamma = 1$). However, when fish are misidentified ($\gamma < 1$), the apparent harvest rate is a function of the initial ratio of marked to unmarked fish. Also, when the population is mostly marked fish (U/M is small), the apparent harvest rate is dominated by marked fish, accounted for in equation (8) by the first term. When the population is mostly unmarked fish, the converse is true.

If marked and unmarked fish have different probabilities of being correctly identified, then the equation for the apparent harvest rate is

$$H(t) = \frac{(1-\alpha)\cdot\gamma_M}{(1-\alpha)\cdot[\gamma_M + (1-\gamma_M)\cdot\delta] + \alpha\cdot\beta}\cdot p_M(t) + \frac{(1-\alpha)\cdot(1-\gamma_U)}{(1-\alpha)\cdot(\gamma_U\cdot\delta + 1 - \gamma_U) + \alpha\cdot\beta}\cdot\mu\cdot(U/M); \quad (9)$$

γ_M denotes the probability of correctly identifying a marked fish and γ_U denotes the probability of correctly identifying an unmarked fish. In the remainder of this paper, we consider only the simpler case of $\gamma_M = \gamma_U = \gamma$.

Eventually all of the marked and unmarked fish die, and in the limit, as t approaches infinity, p_M and μ both approach unity and the apparent harvest rate approaches its maximum value:

$$H_\infty = \frac{(1-\alpha)\cdot\gamma}{(1-\alpha)\cdot[\gamma + (1-\gamma)\cdot\delta] + \alpha\cdot\beta} + \frac{(1-\alpha)\cdot(1-\gamma)}{(1-\alpha)\cdot(\gamma\cdot\delta + 1 - \gamma) + \alpha\cdot\beta}\cdot(U/M). \quad (10)$$

When there is imperfect mark recognition ($\gamma < 1$), the apparent harvest rate can exceed 100%, especially if there are relatively large numbers of unmarked fish (U/M is large) that can mistakenly be harvested. When drop-off mortality ($\alpha\cdot\beta$) is high, the maximum apparent harvest rate (H_∞) may be less than 100%.

To understand better the influence of harvesting on survival of the unmarked fish, we would like to express the mortality rate for unmarked fish (μ) as a simple function of the apparent harvest rate (H) and to solve equation (8) for $\mu = f(H)$, but it seems impossible to do so. However, by solving equation (4) for t and substituting the result into equation (8), one can write H as the following function of μ:

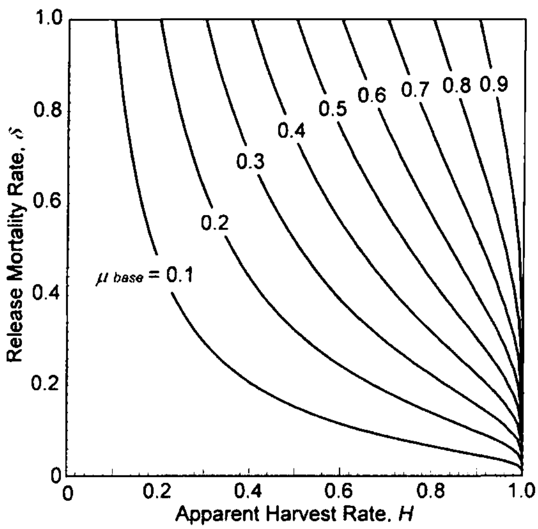

FIGURE 1.—The mortality rate of unmarked fish (μ) is an increasing function of the apparent harvest rate (H) and the release mortality rate (δ). In this base scenario (equation 14) there is perfect mark recognition ($\gamma = 1$), no drop-off mortality ($\alpha\cdot\beta = 0$), and no increase in release mortality rate (δ) with successive releases ($\Delta = 0$); as a consequence, μ is equal to zero whenever δ is equal to zero.

$$H = (1-\alpha)\cdot\gamma\cdot\frac{1-(1-\mu)^\theta}{(1-\alpha)\cdot[\gamma + (1-\gamma)\cdot\delta] + \alpha\cdot\beta} + \frac{(1-\alpha)\cdot(1-\gamma)\cdot\mu}{(1-\alpha)\cdot(\gamma\cdot\delta + 1 - \gamma) + \alpha\cdot\beta}\cdot(U/M); \quad (11)$$

$$\theta = \frac{\gamma + \delta - \gamma\cdot\delta - \alpha\cdot\gamma - \alpha\cdot\delta + \alpha\cdot\gamma\cdot\delta + \alpha\cdot\beta}{1 + \gamma\cdot\delta - \gamma - \alpha\cdot\gamma\cdot\delta - \alpha + \alpha\cdot\gamma + \alpha\cdot\beta}.$$

Alternatively, because both μ and H are relatively simple functions of t, it is easy to tabulate values of $\mu(t)$ and $H(t)$ to explore the relation between them.

If there is complete hook-and-release mortality ($\delta = 1$), as would occur in a nonselective or mixed-stock fishery in which all fish are retained, then equation (11) simplifies to

$$H = \left[\frac{(1-\alpha)\cdot\gamma}{1-\alpha+\alpha\cdot\beta} + \frac{(1-\alpha)\cdot(1-\gamma)\cdot U}{(1-\alpha+\alpha\cdot\beta)\cdot M}\right]\cdot\mu, \quad (12)$$

and μ and H are linearly related. If there is also perfect mark recognition ($\gamma = 1$) and no drop offs ($\alpha = 0$), equation (12) further simplifies to $H = \mu$.

As mentioned previously, because repeated handling could make fish more susceptible to mortal-

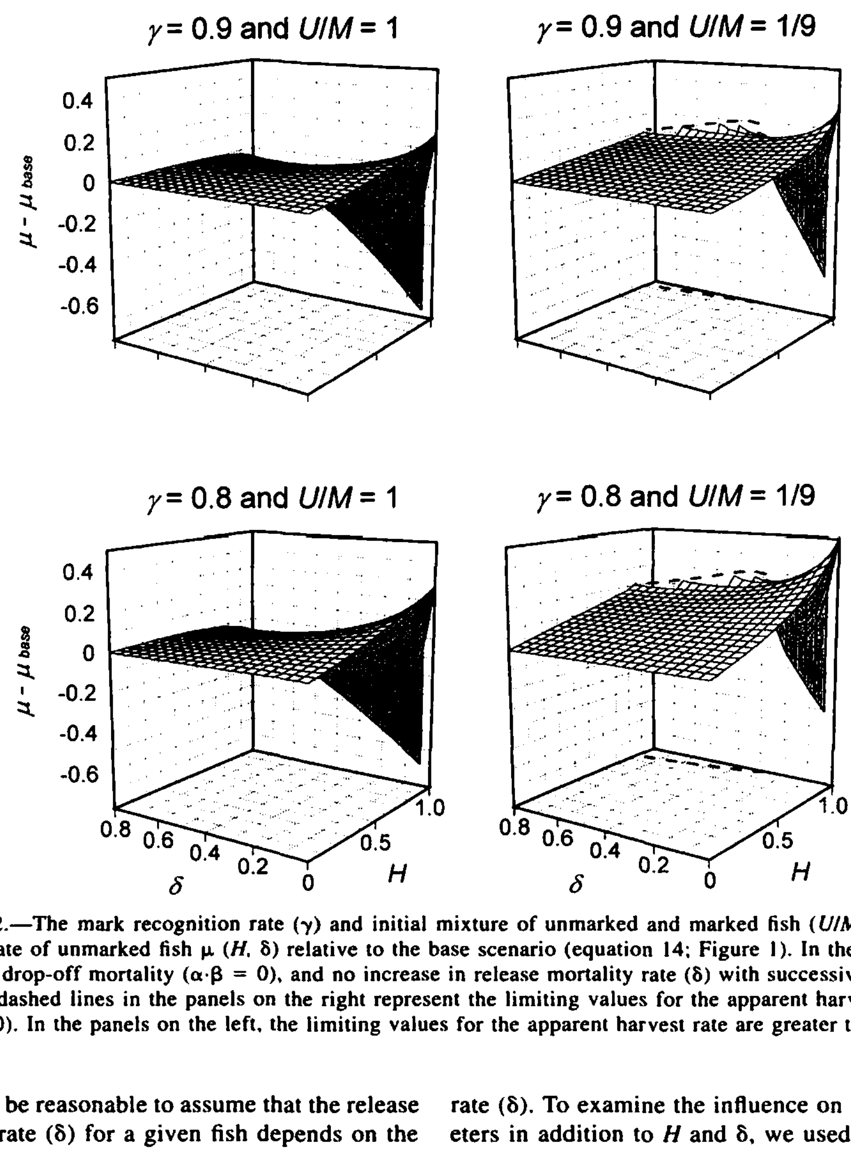

FIGURE 2.—The mark recognition rate (γ) and initial mixture of unmarked and marked fish (*U/M*) change the mortality rate of unmarked fish μ (H, δ) relative to the base scenario (equation 14; Figure 1). In these examples, there is no drop-off mortality ($\alpha \cdot \beta = 0$), and no increase in release mortality rate (δ) with successive releases ($\Delta = 0$). The dashed lines in the panels on the right represent the limiting values for the apparent harvest rate (H_x; equation 10). In the panels on the left, the limiting values for the apparent harvest rate are greater than one.

ity, it may be reasonable to assume that the release mortality rate (δ) for a given fish depends on the number of previous encounters with the gear, rather than to assume that it is constant as in the foregoing equations. To explore this case, we used a stochastic simulation model and calculated the mean of 1,000 simulation trials for each set of parameter values. For the *j*th encounter with the gear by a particular fish, we modeled the release mortality rate as

$$\delta \cdot (1 + \Delta)^{j-1}; \qquad (13)$$

Δ is the relative increase in the release mortality rate with each successive encounter.

In general, the mortality rate for unmarked fish (μ) is a nonlinear, increasing function of both the apparent harvest rate (H) and the release mortality rate (δ). To examine the influence on μ of parameters in addition to H and δ, we used the case of perfect mark recognition ($\gamma = 1$), no drop-off mortality ($\alpha \cdot \beta = 0$), and constant release mortality ($\Delta = 0$) as the base against which we compared other scenarios (Figure 1), such that

$$\mu_{\text{base}} = 1 - (1 - H)^{\delta}. \qquad (14)$$

To show changes in the mortality rate for unmarked fish relative to this base case, we generated series of surface plots (Figures 2–4) showing the differences in μ (H, δ) from the base surface:

$$\mu(H, \delta | \alpha, \beta, \Delta) - \mu_{\text{base}}. \qquad (15)$$

Results

We used the model to explore how the mortality rate for unmarked fish (μ) variés with the apparent

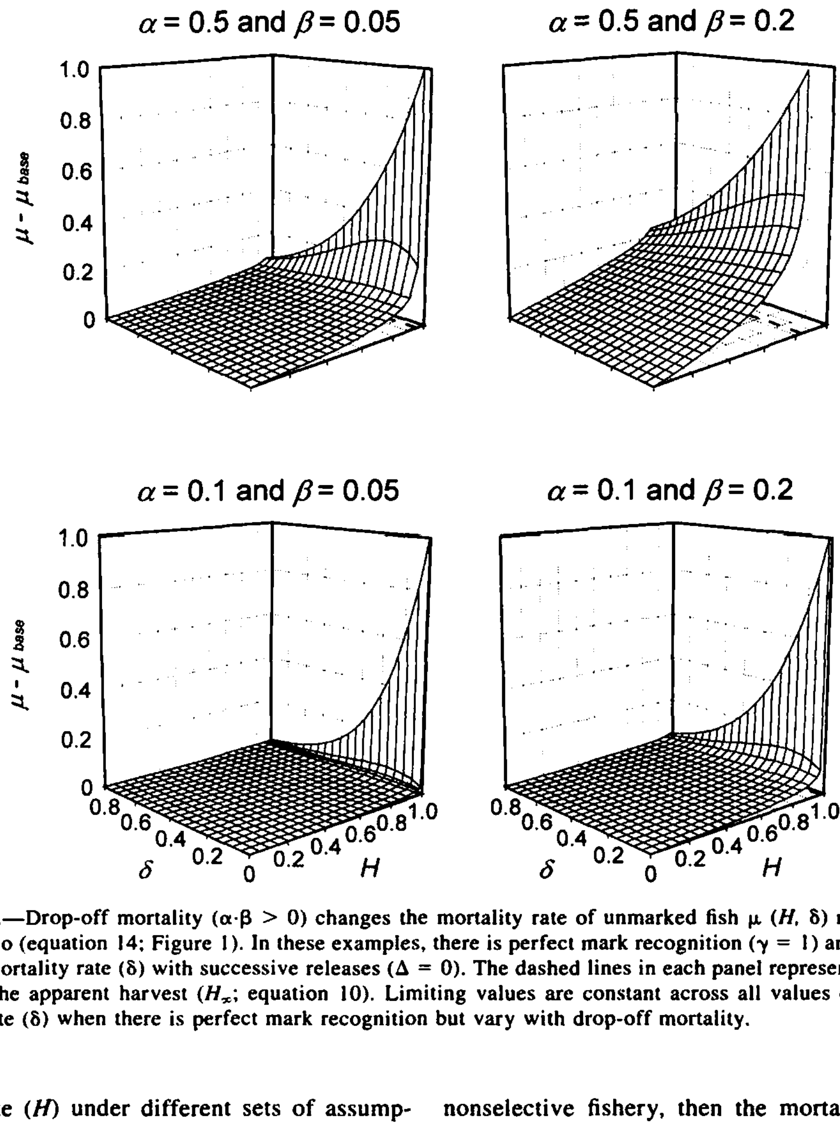

FIGURE 3.—Drop-off mortality ($\alpha \cdot \beta > 0$) changes the mortality rate of unmarked fish μ (H, δ) relative to the base scenario (equation 14; Figure 1). In these examples, there is perfect mark recognition ($\gamma = 1$) and no increase in release mortality rate (δ) with successive releases ($\Delta = 0$). The dashed lines in each panel represent the limiting values for the apparent harvest (H_∞; equation 10). Limiting values are constant across all values of the release mortality rate (δ) when there is perfect mark recognition but vary with drop-off mortality.

harvest rate (H) under different sets of assumptions. To facilitate comparisons between various plausible scenarios and to highlight influential parameters, we chose widely ranging values for the fundamental, but imprecisely known or unknown parameters (α, β, γ, δ, and Δ) and for the initial stock mixture. Although the harvest rate is the primary system variable the fishery management agencies can control, they can also manipulate the initial stock mixture by changing policy regarding release of marked hatchery fish. Furthermore, agencies might be able to influence mortality rates for unmarked fish by altering the fish marking techniques and hence the mark recognition rate, or by modifying the fishers' fish handling practices and hence release mortality.

If the release mortality rate is 100%, as in a nonselective fishery, then the mortality rate for unmarked fish as a function of apparent harvest rate, $\mu(H)$, is a simple straight line given by equation (12). This is reflected in the contour diagram for μ_{base} (H, δ) by equal spacing between contours along the line $\delta = 1$ (Figure 1). When the release mortality rate is less than 100%, the spacing between the contours of μ decreases as H increases. Because the curvature in $\mu(H)$ depends on δ, the contour lines (Figure 1) are not parallel.

If there is perfect mark recognition as in the base scenario (Figure 1), then the initial ratio of marked to unmarked fish has no influence on the relation between the mortality rate for unmarked fish and the apparent harvest rate, and the mortality rate for unmarked fish is zero whenever the release mortality rate is zero (the horizontal axis in Figure

1). If there is imperfect mark recognition ($\gamma < 1$, Figure 2), meaning that unmarked fish are mistakenly caught and marked fish are mistakenly released, then the mortality rate for unmarked fish is generally greater than that in the corresponding case of perfect mark recognition, except at very high apparent harvest rates. Furthermore, the mortality rate for unmarked fish is greater than zero for all positive values of the apparent harvest rate, even if the release mortality rate is zero. As the mark recognition rate diminishes (lower versus upper panels in Figure 2), the effect is accentuated. When the mark recognition rate is less than one and the release mortality rate or apparent harvest rate is small (say less than 0.2), the initial ratio of marked to unmarked fish has relatively little influence on the relation between the mortality rate of unmarked fish and the apparent harvest rate (left versus right panels in Figure 2), but its influence becomes more pronounced with increases in either the release mortality rate or apparent harvest rate.

If the drop-off probability (α) and drop-off mortality rate (β) are both greater than zero (Figure 3), then some fish suffer mortality but are not counted with either the harvested or released fish; thus, the mortality rate for unmarked fish is greater than zero for all positive values of the apparent harvest rate, even if the release mortality rate is zero. If drop-off probability is relatively small (lower panels in Figure 3), then the drop-off mortality rate has little influence on the relation between the mortality rate for unmarked fish and apparent harvest rate. Thus, the relation differs little from the corresponding base scenario in which there is no drop-off mortality (Figure 1). However, if the drop-off probability is relatively large (upper panels in Figure 3), then the relation between the mortality rate for unmarked fish and the apparent harvest rate is sensitive to the drop-off mortality rate when the drop-off mortality rate is also large (upper right panel in Figure 3), mortality of unmarked fish can be considerably larger than in the base case.

If the release mortality rate for a given fish increases after each successive encounter with the gear ($\Delta > 0$), then the mortality rate for unmarked fish differs little from the corresponding base scenario at harvest rates below 0.5 but increases as the apparent harvest rate approaches one (Figure 4). Because no fish survive their first encounter with the gear if the release mortality rate is equal to one, the deviations from the base are most pronounced at intermediate levels of the release mortality rate.

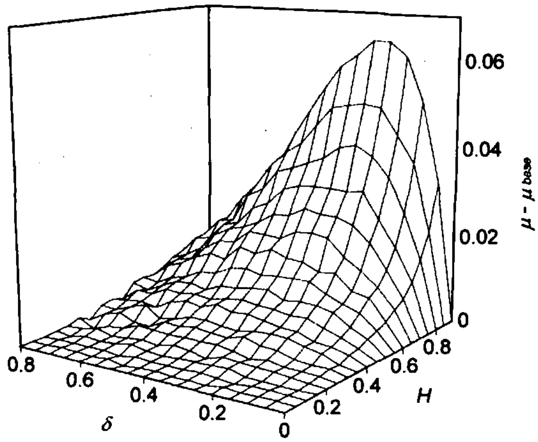

FIGURE 4.—Increases in the release mortality rate (δ) with successive releases (equation 13; $\Delta = 0.25$) change the mortality rate of unmarked fish μ (H, δ) relative to the base scenario (equation 14; Figure 1). In this example, there is perfect mark recognition ($\gamma = 1$) and no drop-off mortality ($\alpha \cdot \beta = 0$). Each point on the surface represents the average of 1,000 simulation trials.

Discussion

The mortality rates for unmarked fish in selective fisheries will be gear and stock dependent. Our modeling results suggest that within the range of parameter values we expect, the most important mortality source for unmarked fish will be hook-and-release mortality. Net fisheries generally have high release mortality rates (e.g., Baranski 1990), whereas recreational troll fisheries have low mortality rates and commercial troll fisheries are intermediate. In addition, hook-and-release mortality rates vary with bait type, hook type, salmon species, and size (Muoneke and Childress 1994). Hook-and-release mortality for salmon in the Pacific Northwest has been estimated recently for commercial marine fisheries and recreational marine and freshwater fisheries. Mortality rates estimated for commercial troll fisheries in Alaska were 17.4–24.5% (Wertheimer 1988; Wertheimer et al. 1989). The estimated hook-and-release mortality for recreational troll fisheries in Georgia Strait, British Columbia, was 7.2% for mature coho salmon and 10.0% for chinook salmon longer than 35 cm (T. Gjernes, Canada Department of Fisheries and Oceans, personal communication). First-ocean-year coho salmon had hook-and-release mortality rates of 13.5%, whereas first-ocean-year chinook salmon showed a 29.8% mortality rate (Gjernes et al. 1993). On the northern Washington coast, Natural Resources Consultants (1991) reported a 6.9% mortality rate for recreationally caught coho salmon longer than 34 cm and 9.0% for chinook salmon longer than 31 cm. A subsequent study (Natural Resources Consultants 1993) estimated mortality rates in the same range.

Drop-off probabilities and drop-off mortality rates are much more difficult to measure because the processes, by their nature, are unobserved. Effects of drop off are related almost exclusively to the apparent harvest rate (Figure 3) and hence to fishing effort. Drop-off probabilities for coho and chinook salmon in a recreational fishery in Puget Sound, Washington, were estimated by Lasater and Haw (1961) at 33% to 42%, depending on hook type. Conversations with fishers suggest that a likely range for drop-off probability is 10% to 70%, depending on the fishery. To our knowledge, drop-off mortality rates have never been estimated, but for a given fishery it is reasonable to expect the drop-off mortality rate to be lower than, but related to, the corresponding hook-and-release mortality rate. In fisheries with high drop-off probability or release mortality, especially in combination with a large harvest rate (e.g., $H > 50\%$), drop-off mortality may be a significant factor.

Because drop-off mortality occurs during all fishing activities, it may be possible to measure its effects indirectly from existing fishery data. For example, natural mortality rates can be estimated from cohort reconstruction analysis if maturation rates are assumed constant. If estimated natural mortality rates vary linearly with total fishing effort, then drop-off mortality may be a contributing factor. Alternatively, if selective fisheries are implemented, comparison of survival rates between mass-marked and unmarked hatchery releases can provide estimates of noncatch mortality for the unmarked group. Total mortality estimates exceeding those expected for hook-and-release mortality alone may indicate measurable drop-off mortality.

Selective fisheries have been considered for West Coast salmon. In a detailed study in 1985 (Pat Pattillo, Washington Department of Fisheries and Wildlife, personal communication), the harvest model of Hunter (1985) was used to explore the potential benefits of a selective fishery for coho salmon in the Oregon Production Index area south of Leadbetter Point, Washington. One conclusion from this study was that the cost of marking and the additional hook-and-release mortality (δ was assumed to be 30%) would negate most gains in catch from a selective fishery.

More recently, as naturally spawning salmon stocks have started to be listed under the U.S. Endangered Species Act, many have argued that without mass marking and selective fishing, there will be no salmon fishing allowed in large areas of the Pacific Northwest. Should selective fishing come to pass, it is important for managers to recognize the harvest rate constraints under which they will be operating. As harvest rates of marked stocks increase above 50%, incidental mortalities of unmarked stocks begin to rise rapidly.

Technical teams from the Pacific Salmon Commission have recently constructed a model with multiple time, area, and fish stock strata, which they have used to evaluate the possible effects of selective fisheries (Pacific Salmon Commission 1995). However, this model has proved difficult to use in the context of the complex West Coast salmon fisheries. Lawson and Comstock (1995) have taken the algorithms documented in our paper and produced a model useful for exploring possible effects of selective fisheries at a regional level. Their results suggest that selective fishing could reduce unmarked stock mortality rates in Pacific Northwest fisheries, but only if these stocks are not also caught heavily in mixed-stock fisheries. Catch may be substantially reduced in areas where unmarked stocks comprise a large proportion of the stock mix. Effort restrictions will be necessary to maintain harvest rates at acceptable levels.

Acknowledgments

R. Comstock aided in model development and reviewed an earlier version of this manuscript. S. Wright offered comments on appropriate mortality rates. The authors also benefited from discussions with the Modeling and Analysis Work Group of the Pacific Salmon Commission. G. Morishima contributed to early model development. R. Kope made several useful suggestions, and the paper also benefited from comments by two anonymous reviewers.

References

Baranski, C. 1990. Skagit River summer chinook brood stock collecting program, 1975–1979. Washington Department of Fisheries, Progress Report 104, Olympia.

Clark, R. D. 1983. Potential effects of voluntary catch and release of fish on recreational fisheries. North American Journal of Fisheries Management 3:306–314.

Clark, R. D., G. R. Alexander, and H. Gowing. 1980. Mathematical description of trout-stream fisheries. Transactions of the American Fisheries Society 109: 587–602.

Gjernes, T., A. R. Kronlund, and T. J. Mulligan. 1993. Mortality of chinook and coho salmon in their first year of ocean life following catch and release by anglers. North American Journal of Fisheries Management 13:524–539.

Horton, H. F., and R. Wilson-Jacobs. 1985. A review of hooking mortality of coho (*Oncorhynchus kisutch*) and chinook (*O. tshawytscha*) salmon and steelhead trout (*Salmo gairdneri*). Report to the Pacific Marine Fisheries Commission, Portland, Oregon.

Hunter, M. A. 1985. The 1976–78 brood coho model. Washington Department of Fisheries, Progress Report 222, Olympia.

Lasater, J. E., and F. Haw. 1961. Comparative hooking mortality between treble and single hooks on silver salmon. Pacific Marine Fisheries Commission Bulletin 5:73–76.

Lawson, P. W., and R. M. Comstock. 1995. Potential effects of selective fishing on stock composition estimates from the mixed-stock model: application of a high-dimension selective fisheries model. Oregon Department of Fish and Wildlife, Information Report 95-2, Portland.

Muoneke, M. I., and W. M. Childress. 1994. Hooking mortality: a review for recreational fisheries. Reviews in Fisheries Science 2:123–156.

Natural Resources Consultants. 1991. Hooking mortality study final project report—a report on a study to determine rates and causes of mortality in coho and chinook salmon caught and released with sport fishing tackle. Natural Resources Consultants, Seattle.

Natural Resources Consultants. 1993. Interim report to the steering committee on findings of September 1992 field study on hooking mortality in coho salmon. Natural Resources Consultants, Seattle.

Pacific Fishery Management Council. 1995. Review of 1994 ocean salmon fisheries. Pacific Fishery Management Council, Portland, Oregon.

Pacific Salmon Commission. 1995. Selective fishery evaluation. Report of the Ad-Hoc Selective Fishery Evaluation Committee. Pacific Salmon Commission, Vancouver.

Pacific States Marine Fisheries Commission. 1992. Mass marking anadromous salmonids: techniques, options, and compatibility with the coded wire tag system. Pacific States Marine Fisheries Commission, Portland, Oregon.

Parzen, E. 1962. Stochastic processes. Holden-Day, San Francisco.

Ricker, W. E. 1976. Review of the rate of growth and mortality of Pacific salmon in salt water, and noncatch mortality caused by fishing. Journal of the Fisheries Research Board of Canada 33:1483–1524.

Sampson, D. B. 1988. Fish capture as a stochastic process. Journal du Conseil, Conseil International pour l'Exploration de la Mer 45:39–60.

Washington Department of Fisheries and Northwest Indian Fisheries Commission. 1993. A review of recent studies of hooking mortality for chinook and coho salmon with recommendations for fishery management and future research. Washington Department of Fisheries, Olympia.

Wertheimer, A. 1988. Hooking mortality of chinook salmon released by commercial trollers. North American Journal of Fisheries Management 8:346–355.

Wertheimer, A., A. Celewycz, H. Jaenicke, D. Mortensen, and J. Orsi. 1989. Size-related hooking mortality of incidentally caught chinook salmon, *Oncorhynchus tshawytscha*. U.S. National Marine Fisheries Service Marine Fisheries Review 51(2):28–35.

Wright, S. 1970. A review of the subject of hooking mortalities in Pacific salmon. Pacific Marine Fisheries Commission Annual Report 23:47–65.