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A Life History Approach to Estimating Damage to Prince William Sound Pink Salmon From the *Exxon Valdez* Oil Spill

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Harold J. Geiger[1,2], Brian G. Bue[1], Sam Sharr[1],
Alex C. Wertheimer[3], and T. Mark Willette[1]

[1]Alaska Department of Fish and Game, Division of Commercial Fisheries Management and Development.

[2]The University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, Division of Fisheries.

[3]National Marine Fisheries Service, Auke Bay Laboratory

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ABSTRACT

The 1989 *Exxon Valdez* oil spill resulted in contamination of juvenile pink salmon (*Oncorhynchus gorbuscha*) habitat, including approximately 31% of the spawning streams, and much of the nearshore marine rearing habitat in the southwest portion of Prince William Sound. In this study we combined the results of other studies to evaluate the loss of returning wild adult pink salmon attributable to the *Exxon Valdez* oil spill. We estimated that approximately 1.9 million wild adult pink salmon failed to return to Prince William Sound in 1990, primarily because of a lack of growth in the critical near-shore life stage. This number of fish was approximately 28% of the potential wild-stock production from the southwestern part of Prince William Sound in 1990. We estimated that 60 and 70 thousand wild adult pink salmon failed to return in 1991 and 1992, respectively, because of direct poisoning of salmon in the embryo stage of development. In both 1991 and 1992 this was 6% or less of the potential wild-stock production in the southwestern part of the sound, and less than 2% of the potential wild production in the entire sound.

INTRODUCTION

In the confusion following the *Exxon Valdez* oil spill, anything from no effect to devastation of pink salmon (*Oncorhynchus gorbuscha*) populations in the southwestern part of Prince William Sound seemed plausible. In the weeks following the spill, the Alaska Department of Fish and Game and the National Marine Fisheries Service initiated several studies to 1) develop improved estimates of pink salmon escapement for pre- and post-spill years, 2) measure egg (embryo) survival, 3) measure fry survival, 4) observe the near-shore condition and distribution of fry in Prince William Sound, 5) measure hatchery and wild salmon survival in the saltwater environment, and 6) survey the pink salmon habitat affected by the oil spill.

These studies have now documented contamination of embryos in oiled streams (Wiedmer et al. 1995), and juvenile salmon in the nearshore environment (Carls et al. 1995). The contamination has been linked to reduced survival in embryos in oiled streams (Bue et al. 1995) and to reduced growth of pink salmon in the marine environment (Willette 1995; Wertheimer and Celewycz 1995). The reduced growth in the early marine environment has, in turn, been linked to reduced marine survival (Willette 1995). Here, we synthesize the results of these studies of individual life history stages and estimate the loss of returning wild adult Prince William Sound pink salmon in years following the oil spill.

Pink salmon populations in Prince William Sound are not static. Powerful forces that may have affected them in recent years include the Alaskan earthquake of 1964, an increasingly intense commercial fishery, tremendous increases in hatchery production, and the *Exxon Valdez* oil spill. The earthquake of 1964 severely damaged some stocks and eliminated some runs

entirely (Roys 1971). In the mid-1980's, large runs of hatchery-produced pink salmon began to equal and then far outnumber the wild salmon (Eggers et al. *in press*). Hatchery stocks are an important input to the commercial fishing industry, but from an ecological perspective, they are entirely different from the wild salmon. In this report we focus on the wild salmon which play an important role in the Prince William Sound ecosystem and an important economic role in the Prince William Sound fishing industry.

The size of pink salmon runs to Prince William Sound has fluctuated wildly (Figure 1) in response to unobserved phenomena in the freshwater and marine environments. With this much background variability, even extremely large damage would be entirely undetectable using before-and-after comparisons of any function of population size. To gain statistical power we focused on the affected life history stages, looking for differences in life history statistics between groups of fish classified as oiled and unoiled in the same year. We refer to the summary of the life stage comparisons as the life history model.

We followed the 1988 brood year by estimating parental escapement, survival to emergence, and survival to emigration in 1989, measuring growth and survival of coded-wire tag groups as they migrated through the oil in the near-shore environment in the spring of 1989, and by measuring their final return numbers in 1990. We then continued with the odd-year line: following the 1989 brood year as they incubated in the oiled and unoiled streams in Prince William Sound, migrated in the relatively unoiled near-shore areas in 1990, and returned in 1991. The 1990 through 1992 brood years were followed in a similar manner up to the summer of 1992. At each life stage for the 1988 through 1992 brood years we summarized the evidence that the presence of oil reduced survival, and the evidence that a survival reduction was translated to reduced survival at the adult life stage as well. Figure 2 illustrates the

life history pattern for pink salmon, showing the life stages, and points where oil detectably reduced survival in wild pink salmon.

The oil spill could have reduced survival at an early juvenile life stage, yet the final return of adult salmon have remained unaffected because of *compensatory mortality*: mortality that increases when density is high, and decreases when density is low. In her review of the pink salmon literature, Alexandersdottir (1987) cited Heard's (1978) work in Sashin Creek in Southeast Alaska in 1967 and Donnelly's (1983) work in Kodiak to conclude compensatory mortality was linked to an overabundance of spawners, and density dependent survival could be a factor from spawning to outmigration.

If compensatory mortality effects are negligible at a particular lifestage and all subsequent lifestages, then estimating the effects of the oil spill are straightforward: the estimated proportional loss of production can simply be the measured decrease in estimated survival at that lifestage. Alternatively, if compensatory mechanisms exist, the loss of production from the oil spill will be overestimated by assuming oil-induced mortality translates directly into reduced adult production. We examined the available evidence that compensatory mortality could be caused by oil-induced loss of production.

The effect of the *Exxon Valdez* oil spill on any important part of the biota will never be known exactly. Unfortunately, the failure to precisely measure injury from the oil spill is sometimes confused with justification for concluding the injury is nonexistent. Similarly, the ability to statistically detect some aspect of injury is sometimes confused with significance in a larger biological sense. Rather than perform a statistical test of the hypothesis that pink salmon populations were completely unchanged by the oil spill, we viewed our responsibility as to identify the *biologically* -- not *statistically* -- important sources of mortality, and provide the most

reasonable estimates of the magnitude of loss, in units of adult salmon, consistent with the information available to us.

METHODS

Prince William Sound Fishing Districts, Stocks and Stock Size Estimates

Prince William Sound is divided into nine fishing districts, which correspond to *stocks* for the purposes of fisheries management (Figure 3). In much of our discussion we will be restricting our focus to the Southwest Fishing District, where the greatest damage to freshwater spawning habitat occurred (Middleton et al. 1992). We used total production and revised estimates of district-specific escapement from a database maintained by the Alaska Department of Fish and Game in Cordova, Alaska. The data was the most current as of June of 1993.

Life History Parameters, Statistics, and Estimators

Let y_{t+2} represent the subsequent Prince William Sound wild pink salmon production in year t+2 from an escapement of x_t spawners in brood year t. Let s_t represent the random variable that summarizes survival and fecundity. This

is commonly called return-per-spawner, and is usually expressed as some function of previous escapement (e.g., Ricker 1975). We are interested in the life history steps underlying the return-per-spawner when escapement has been restricted to approximately what managers considered optimal. Formally, the process is described by

$$y_{t+2} = s_t x_t \ . \tag{1}$$

In year t+2, Prince William Sound salmon management attempts to harvest all of the return except a fixed escapement goal, x_{goal}. Due to management error, the actual escapement is x_{t+2}, and the process repeats.

In years when the oil spill reduced survival, let p_t be the fraction of the total number of eggs from brood year t that were potentially affected by oil sometime in their life. Let s'_t be the return-per-spawner reflecting the reduction due to the oil spill, including the effects of compensatory mortality.

In years when a fraction of the potential production is reduced by an oil-spill effect, we assume production is given by

$$y_{t+2} = [(1-p_t)s_t + p_t s_t']x_t \ . \tag{2}$$

Notice the quantity $(1-p_t)$ is the fraction of eggs unaffected by oil, s_t is the return-per-spawner, so that $(1-p_t)s_t x_t$ denotes the production from unoiled streams; similarly, $p_t s'_t x_t$ denotes the production from oiled streams, and production from both sources equals the total production.

In actual practice, managers observe $\hat{x}_t$, some function of x_t, where the function describes observational error. Similarly, $\hat{y}_{t+2}$ denotes the estimated total run, consisting of the catch, which is approximately known, and the estimated escapement.

To estimate parameters, we first assume no strong compensatory mortality mechanisms, or at least no compensatory mortality after the affected life stage. Without reference to stochastic models, we estimate parameters in equations (1) and (2) algebraically: assuming that s'_t is approximately equal to s_t multiplied by the estimated reduction in survival.

Letting r_t denote the product of reduction in survival at each affected life stage, estimates of s'_t and s_t are found as follows by replacing elements in equation (2) with their estimates and solving,

$$\hat{s}'_t = \hat{s}_t \hat{r}_t \,, \qquad \text{and, then from (2)}$$

$$\hat{s}_t = \frac{\hat{y}_{t+2}}{\hat{x}_t}((1-\hat{p}_t) + \hat{p}_t \hat{r}_t)^{-1} \,.$$

Production, expressed in units of adult salmon that would have returned had there been no oil spill, is then estimated by

$$\hat{y}_{no\ oil,t+2} = \hat{s}_t \hat{x}_t \,,$$

and the estimated loss in broodyear t, at the adult population level, is given by

$$\hat{L}_t = \hat{y}_{no\ oil,t+2} - \hat{y}_{t+2} \ .$$

To estimate typical values of s_t, for the purpose of projecting future production from the 1991 and 1992 escapements, we considered the median recruits-per-spawner from 1963 to 1987. Information on the steps that lead to s_t from the pink salmon literature was used to provide additional justification for this estimate. Five stochastic steps lead to the return-per-spawner value, s_t: 1) the fraction of the run consisting of females, denoted Fem_t, 2) the average fecundity per female, denoted, Fec_t 3) the fraction of the potential egg deposition that is actually deposited, denoted Dep_t, 4) the survival from eggs deposited to emergence, denoted Seg_t and 5) the marine survival, denoted Smr_t. The overall return-per-spawner, s_t, is simply the product of each of these stochastic outcomes:

$$s_t = Fem_t \times Fec_t \times Dep_t \times Seg_t \times Smr_t \ .$$

The Fraction of the Potential Egg Deposition in Oiled Streams

Estimates of the fraction of eggs in oiled streams were obtained by estimating the fraction of streams affected by oil and adjusting for the relative egg density in oiled streams. We assumed that only streams in the Southwest Fishing District were affected, ignoring some oiling on Montague Island and elsewhere.

To estimate the fraction of pink salmon spawning streams affected by oil, we needed a sample of streams with information on oiling level and information on egg density for each stream in the sample. In 1991 the aerial survey of spawning escapement was expanded to include a representative sample of oiled and control streams. To determine which streams in the 1991 aerial survey were affected by oil, we referred to Middleton et al. (1992), personal field observations, and conversations with other observers. In general, if a stream was classified as "*Heavy*" through "*Very Light*" in Middleton et al. we considered it an oiled stream. In cases where Middleton et al. disagreed with our field observation, we relied on our observations. The peak spawner density from this survey was used as a proxy for the egg density in each stream in this survey. To estimate the fraction of the potential egg deposition in the Southwest Fishing District that incubated in oiled streams, we calculated the weighted average of the proportion of streams classified as oiled in the 1991 survey, using the peak aerial escapement count in the 1991 aerial survey as the weights. Then, to estimate the fraction of the entire potential egg deposition in the whole sound affected by oil, we multiplied this weighted average by the fraction of the entire escapement that was in the Southwest Fishing District.

Oil-Induced Mortality in the Freshwater Stage

Let m_v be the underlying mortality rate of juveniles, at some life stage, with oiling level v. If this is the only affected lifestage, then the proportional reduction in survival at this life stage, defined as r above, is found by

$$r = \frac{(1-m_{oil})}{(1-m_{unoil})} .$$

To estimate r, we substituted the unweighted estimated average mortality in the embryos, using data described in Bue et al. (1995). Average mortality was not weighted by total eggs deposited at tide stage because estimates of total eggs deposited by tide stage were unavailable to us.

The Fraction Exposed in the Early Marine Stage

The fraction of eggs that could eventually be affected by exposure to oil in any life stage up through the early marine environment was the most difficult parameter to estimate. In the end, we simply used the estimated fraction of the 1988 escapement that was in the Southwestern Fishing District, knowing that fry that emerged anywhere in the Southwestern Fishing District in 1989 were a short distance from exposure once they emigrated into the marine environment. We know from Willette (1995) that some fish from unoiled areas emigrated into oiled marine areas and vice versa.

RESULTS

Willette (1995) estimated that fry from unoiled areas that reared in oiled near-shore environments in 1989 experienced a marine survival of 72% of their

unoiled potential based coded-wire tagging studies from the Wallace H. Noerenberg Hatchery.

We estimated that the survival from egg deposition to the fry stage was 92% of its potential in oiled areas for the 1989 brood year, and 88% of its potential for the 1990 brood year (Table 2). Bue et al. (1995) found statistically detectable excess mortalities in the eyed-embryo stage, which they attributed to oil-spill effects, but they failed to find statistically detectable effects in the preemergent fry stage of development. Our estimates of the proportional reduction in survival of oiled eggs, relative to control eggs, together with estimates of overall embryo-stage mortality for oiled and unoiled streams are provided in Table 1. Statistically detectable elevated mortalities were also noted by Bue et al. (1995) between oiled and unoiled sites for the 1991 and 1992 brood years.

We estimated the fraction of pink salmon spawning streams contaminated with oil to be 31% of all spawning streams in the Southwest Fishing District. Unoiled streams had larger average peak escapement counts than oiled streams, meaning that 31% is expected to overstate the proportion of eggs effected in the Southwest Fishing District. When we used peak spawner density from the 1991 areal escapement survey as a proxy for egg density, as described above, an estimated 20% of the potential egg deposition in the Southwest Fishing District was associated with streams classified as oiled. Using escapement information to estimate the fraction of the potential egg deposition in the entire sound potentially affected by oil in the freshwater stage, the estimate never exceeded 6% of the eggs (Table 2).

Estimated Adult Salmon that Failed to Return

In 1990, total production of wild pink salmon was estimated to be 18.40 million from an escapement of 4.99 million in the 1988 brood year. We assumed that 32% of the potential 1988 brood year was exposed to oil effects, using the proportional escapement in the Southwest Fishing District, as described above. Based on the observed reduction of marine survival of coded-wire tagged fish from Willette (1995), we estimated the proportional reduction in survival to be 72%, as described above. Substituting these estimates for the appropriate quantities in equation (2), yields

$$18.40 = ((1-0.32)\times s_{1988} + 0.32\times(s_{1988}\times 0.72))\times 4.99 \ .$$

Solving for s_{1988} produced an estimated return-per-spawner in the absence of oil of 4.06. Applying this return-per-spawner to the 1988 escapement produced an estimate of 20.26 million adults that would have returned in the absence of oil. By subtraction, the estimated loss of adult pink salmon in 1990 was approximately 1.86 million. Key statistics and results for the 1988 through 1991 brood years are provided in Table 2. Using the same reasoning, we estimate the loss of adult pink salmon to be approximately 60 thousand and 70 thousand for the 1989 and 1990 brood years, respectively.

Compensatory Mortality

We found no evidence that compensatory mortality mechanisms operate on the scale of variation induced by oil-spill effects. Figure 4 shows the new stock-recruitment history using the revised estimates of escapement. Although compensatory mortality mechanisms may control production in Prince William Sound at escapement extremes -- such as when escapement reaches 20 million -- for the important brood years of 1988, 1989, and 1990, the escapement remained very near what managers have traditionally thought of as optimum (the escapement goal in the old index-units can be found in Geiger and Savikko 1991; an escapement goal has not yet been formulated in the units of the revised escapement estimates).

To see if compensatory mortality was operating in the embryo stage, we examined estimated egg survival, up to the time the survey was conducted, as a function of observed egg density for 1989, 1990, and 1991. Although, some slight compensatory mortality might have occurred as densities exceed 2,500 eggs per unit of surface area (0.186 m^2) in the lower tide stages in 1989, overall no strong compensation was observed. We were unable to detect a relationship between egg density and the empirical logit (Agresti 1990) of the egg survival (Analysis of covariance, *P-val* = 0.3135) after adjusting for year, tide stage and oiling level.

If oil-induced mortality is strongly compensated for in the preemergent fry stage, then the proportion of live fry would be strongly related, with negative slope, to the proportion of live eggs. Figure 5 shows this relationship for the 1989 through 1991 fry dig studies. These graphs show considerable mortality and variation in mortality from site to site, yet the measured mortality is low in the fry stage, irrespective of the mortality

between egg deposition and the fry stage. Thus, no compensatory mortality was seen in this life stage.

To look for compensatory mortality in the marine life stages, we examined Prince William Sound pink salmon hatchery production as a function of fry released (from Eggers et al. *in press*, and recent estimates from Prince William Sound hatchery operators). This relationship is shown in Figure 6. The number of fry emigrating from freshwater systems shows a strong linear relationship to the number of returning adults, within the range of 0 to approximately 600 million hatchery fry. The slope of a smooth line through this data is approximately 5% -- a reasonable average survival for pink salmon (Heard 1991). These data indicate no compensatory survival mechanisms in the marine lifestages.

In summary, we found no evidence that oil-induced mortality in either the freshwater or the marine environment would be compensated for by density dependent mechanisms in Prince William Sound pink salmon populations.

Typical Life History Values and the 1991 and 1992 Brood years

The annual return-per-spawner is a random variable in equation (1). This random variable results from the realization of five previous stochastic steps, as described above. Table 3 shows our best estimate of approximate typical values for life history parameters at each of these steps from various sources in the pink salmon literature, and from post-spill unpublished coded-wire tagging studies of wild pink salmon (data available from the Alaska Department of Fish and Game, Cordova, Alaska). These estimates led to the

impression that typically, about 1.65 recruits-per-spawner are generated from an escapement near the optimum level.

Using the revised estimates of escapement the median return-per-spawner from the 1963 to 1987 brood year was 1.79. To ensure this statistic represents years with moderate to low escapement, brood years with an escapement in excess of 10 million spawners were excluded, yet the median return-per-spawner remained unchanged.

The life history parameters from Table 3 lead to a similar picture of the typical return-per-spawner values that have been observed recently in Prince William Sound. However, this image is quite different from the one based on previous escapement estimates (Heard 1991; Eggers et al. *in press*), where the typical return-per-spawner is thought to be closer to 4.0. We assumed 1.79 returns-per-spawner as a typical value, in the absence of oil-spill effects, for projection of future production at the time this report was originally prepared in June of 1993. The projected returns for the 1991 and 1992 brood years are 17.3 million and 4.9 million, in the absence of oil-spill effects. If the estimated egg-stage survival ratio between oiled and control areas represents persistent oil-spill effects, the projected return is reduced by approximately 240 thousand and 80 thousand for the 1991 and 1992 brood years, respectively.

DISCUSSION

The studies we examined indicate that the *Exxon Valdez* oil spill did result in a detectable loss of wild adult pink salmon. That conclusion by itself is not of much value without some measure of the magnitude of the loss, and a context

in which to view the magnitude. We estimated more that a million adult pink salmon failed to return in 1990 because of oil-induced mortality. This loss may have been over a quarter of the potential wild production in the Southwest Fishing District. Unless we have considerably underestimated the injuries in the 1989 and 1990 brood years, the loss of adult salmon was measurable, but small relative to other human-induced mortality, such as that caused by the commercial fishery. We concluded that the proportion of adult pink salmon missing from these brood years was less than 10% of the potential wild production in the Southwest Fishing District, and less than 2% of the potential wild production in the entire sound.

The 1990 pink salmon harvest was a record catch at approximately 44.2 million pink salmon (Geiger and Savikko 1991). The large harvest in 1990 legitimately helps makes the point that the *Exxon Valdez* oil spill did not devastate or cripple the commercial fishery following the year of the spill. However, the commercial harvest in 1990 is a poor indicator of effect of the oil spill on the wild pink salmon resource in the affected areas of Prince William Sound. The survival of the 1988 brood year was strengthened by favorable near-shore conditions for pink salmon fry -- a conclusion based on measured zooplankton abundance (Jeff Olsen, Prince William Sound Aquaculture Corporation, *personal communication*). The size of the harvest of wild salmon is masked by the harvest of hatchery salmon, which provide a wholly different ecological role in Prince William Sound. Well before the oil spill, the total catch of salmon in Prince William Sound was expected to increase throughout the 1980's because of increasing hatchery production. In 1989, fry from the 1988 brood year of wild salmon were joined by 507 million hatchery fry, the second largest release of pink salmon fry into Prince William Sound at that time.

Even though the salmon hatcheries largely masked the effect of oil on the wild salmon resource that returned in 1990, the oil had a detectable effect on the hatchery resource as well (Willette 1995). Of the total 507 million hatchery

pink salmon released in 1989, 160 million fry were from the Armin F. Koerning Hatchery, which sits just off the path of the oil in the southwestern portion of the Sound. Based on the observed growth reductions in Willette (1995), the potential loss of the hatchery resource in 1990 is in units of millions of adult salmon. The overall estimated survival for the 1988 brood year, which returned in 1990, was 4.24% for the Armin F. Koerning Hatchery. The survival at the Wallace H. Noerenberg Hatchery, a similar hatchery, but further from the path of the oil, had an estimated survival of 8.49% (unpublished data available from the Sam Sharr, Alaska Department of Fish and Game, Cordova, Alaska) -- approximately twice as large. The estimated survivals in years without an oil influence for the Armin F. Koerning and Wallace H. Noerenberg hatcheries were 6.8% and 8.8%, respectively, in 1987 (Peltz and Geiger 1990); 4.52% and 4.99%, respectively, in 1991; and 2.08% and 0.94%, respectively, in 1992 (unpublished data). Although not compelling in themselves, these data certainly are not in conflict with presumed large numbers of missing adult salmon that would have returned to the Armin F. Koerning Hatchery in 1990.

We also concluded some wild adult salmon that would have returned in 1991 and 1992 from the 1989 and 1990 brood years were lost due to the oil spill. The primary mechanism of the loss was decreased embryo-stage survivals. The presence of oil is known to elevate juvenile salmon mortality (Moles et al. 1987). This appears to have happened in the contaminated streams in Prince William Sound, yet relatively few streams were oiled -- approximately 31% of the streams, by our criteria, in that part of Prince William Sound most affected by oil. The oiled streams tended to face north, and were generally in the southwestern part of the Sound. The oiled streams had a lower density of spawners when the density was observed in 1991.

We compared our estimates of the spatial distribution of the oil contamination to those in presented in other studies, including those sponsored by the Exxon Corporation. Maki et al. (*in press*) estimated that 14% of the streams in the

affected area were oiled, but they considered a larger affected area than we did, including the Eshamy and Montague fishing districts. We found no classification disagreement in our sample with that of Bue et al. (1995). We did find two streams (16760 and 16610) out of 10 that were in both our sample and that of Brannon et al. (*in press*), which they considered *unoiled* yet we considered *lightly* or *very lightly oiled*. Moderate errors in the spawner density in these streams, moderate errors in number of streams oiled, or even moderate errors in the ratio of survival in oiled and unoiled streams would not have affected the larger conclusions about the result of egg-stage damage in the 1989 through 1992 brood years: the lost wild adult salmon probably was far less than 10% of the potential wild adult production in the Southwest Fishing District, and less than a few percent of the wild potential production in the entire sound.

The most serious criticism of these estimates is that our assumed fraction of fish exposed in the near-shore environment is little more than a guess. Most authors believe the most critical period for pink salmon survival is when the fish first enter the marine environment (e.g., Alexandersdottir 1987, Heard 1991). Carls et al. (1995) showed that juvenile salmon were contaminated, and Willette (1995) observed the reduced growth and survival that might have been predicted from an understanding of pink salmon biology. Even without an exact count of the number of fish exposed, because of the extent of the oiling of the marine environment, we surmised the greatest potential for damage to wild pink salmon resulting from the *Exxon Valdez* oil spill came from exposure in the critical near-shore environment.

The second most serious criticism of this study is that we may have missed large, delayed mortality in the marine life stage in brood years after 1988, and may have missed mortality in the fry stages in all brood years. Direct examination of pre-emergent fry in oiled streams by Wiedmer et al. (1995)

showed damage in individual pre-emergent fry from oiled streams. Unfortunately, Wiedmer et al. provided no quantitative assessment.

The most important question about pink salmon unanswered in this study is why the estimated egg-stage mortality did not converge to control levels -- but instead became more dissimilar in 1991 and 1992. The egg-stage effects we attributed to the oil spill could simply reflect natural differences in sites. Bue et al. (1995) explained why we feel this is unlikely, and speculate that the difference may be due to genetic damage. This hypothesis seems a reasonable, if untested explanation, but this explanation is far from certain. *Exxon Valdez* oil was shown to cause chromosome aberrations in larval herring that incubated in oiled areas in Prince William Sound, and these aberrations were reproduced in laboratory studies (Biggs et al. 1995; Hose et al. *in press*).

Taking all these uncertainties into consideration, we have attempted to gauge the order of magnitude of the wild pink salmon injury for each brood year, leaving the question of the larger significance of this loss for someone else. Even so, this study points to the large potential for loss of adult salmon resulting from contamination in the early marine life stage. It is this point, in particular, we hope is not lost when planning for and evaluating future oil spills in Alaska.

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Table 1. Estimated overall embryo mortalities from oiled and control sites in Prince William Sound, with estimated percentage reduction in survival in oiled areas, by brood year. The estimates are based on unweighted average mortalities by tide stage from data described in Bue et al. (1995).

Brood Year	Oiled Sites	Control Sites	Survival in Oiled Areas as Percent of Potential Survival
1989	0.174	0.104	92%
1990	0.295	0.195	88%
1991	0.433	0.221	73%
1992	0.450	0.250	73%

Table 2. Estimates of oil-spill induced losses of adult production with other important statistics for broodyears 1988, 1989, and 1990, and forecast future losses for broodyears 1991 and 1992 based on the assumption the genetic damage hypothesis is correct. Fish numbers are expressed in units of million adult salmon. Lost production is in the return two years following the broodyear. PED stands for the potential egg deposition; SW District denotes the Southwest Fishing District.

	Estimated			Projected	
Statistic \ Broodyear:	1988	1989	1990	1991	1992
Soundwide Escapement (Millions)	4.99	6.89	6.18	9.66	2.71
Escapement to SW District (Millions)	1.61	1.91	1.77	2.21	0.81
Subsequent soundwide production (Millions)	18.4	16.54	4.50	---	---
Estimated Return-per-spawner in the absence of oil	4.06	2.41	0.74	(1.79)	(1.79)
Percent of PED potentially affected by oil	32%	6%	6%	5%	6%
Estimated survival of oil affected fish relative to unoiled fish	72%	92%	88%	73%	73%
Estimated production without oil spill effects (Millions)	20.26	16.60	4.57	17.30	0.00
Estimated loss of adult fish (Millions)	1.86	0.06	0.07	0.24	0.08
Loss as a percent of potential production in the SW District	28%	1%	6%	6%	5%

Table 3. Life history survival and fecundity values from the pink salmon literature. Let *Fem* be the fraction of the run consisting of females, *Fec* the average fecundity per female, *Dep* the fraction of the potential egg deposition that is actually deposited, *Seg* is the survival from eggs to emergence, *Smr* is the marine survival, and $s_t = Fem_t\ Fec_t\ Dep_t\ Seg_t\ Smr_t$.

Life Stage	Conversion			Next Stage	Typical Value	Source
Escapement	times	*Fem*	=	Females;	*Fem*≈0.5	Assumed
Females	times	*Fec*	=	PED[1];	*Fec*≈1875	Heard(1991)
PED	times	*Dep*	=	AED[2];	*Dep*≈0.44	Heard(1991)
AED	times	*Seg*	=	Fry;	*Seg*≈0.20	Estimated by eye from data in Ignell (1988)
Fry	times	*Smr*	=	Adults;	*Smr*≈0.02	Unpublished coded-wire tag data from M. Willette, ADF&G, Cordova, Alaska
Escapement	times	*s*	=	Adults;	*s*≈1.65	By multiplication

[1]Potential Egg Deposition.

[2]Actual Egg Deposition.

LIST OF FIGURES

Figure 1. The estimated size of Prince William Sound wild pink salmon runs from 1963 to 1992.

Figure 2. Pink salmon life history stages, with stages affected by oil denoted.

Figure 3. Map of Prince William Sound showing the fishing districts.

Figure 4. Stock-recruitment history for Prince William Sound pink salmon. The numbers denote the brood year.

Figure 5. Proportion of live fry paired with the previous proportion of live eggs for years 1989 through 1991.

Figure 6. Production of pink salmon from Prince William Sound hatcheries as a function of fry released. Coded-wire tags were first introduced into the estimation process in 1987.

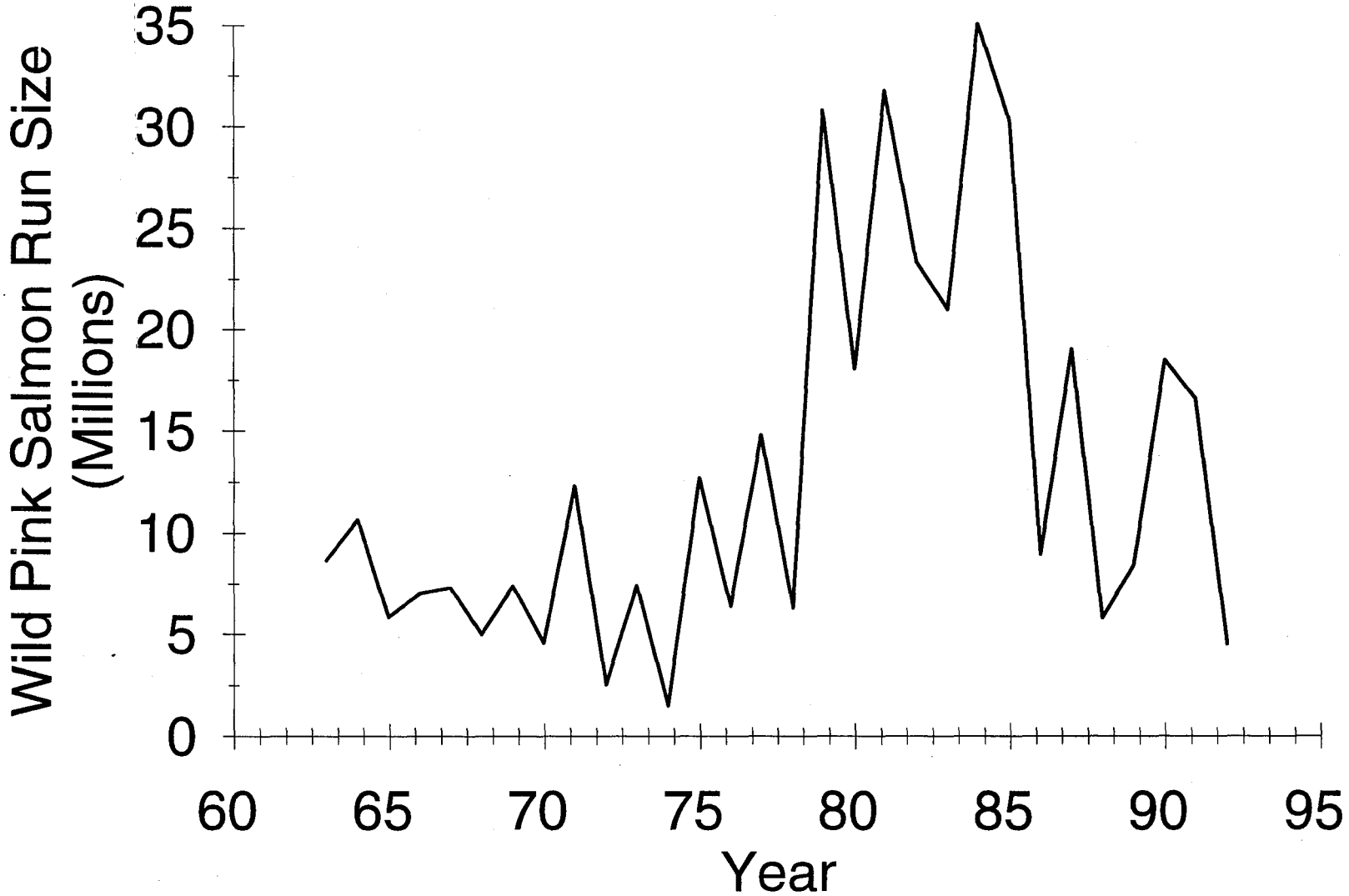


Figure 1

Fig 1

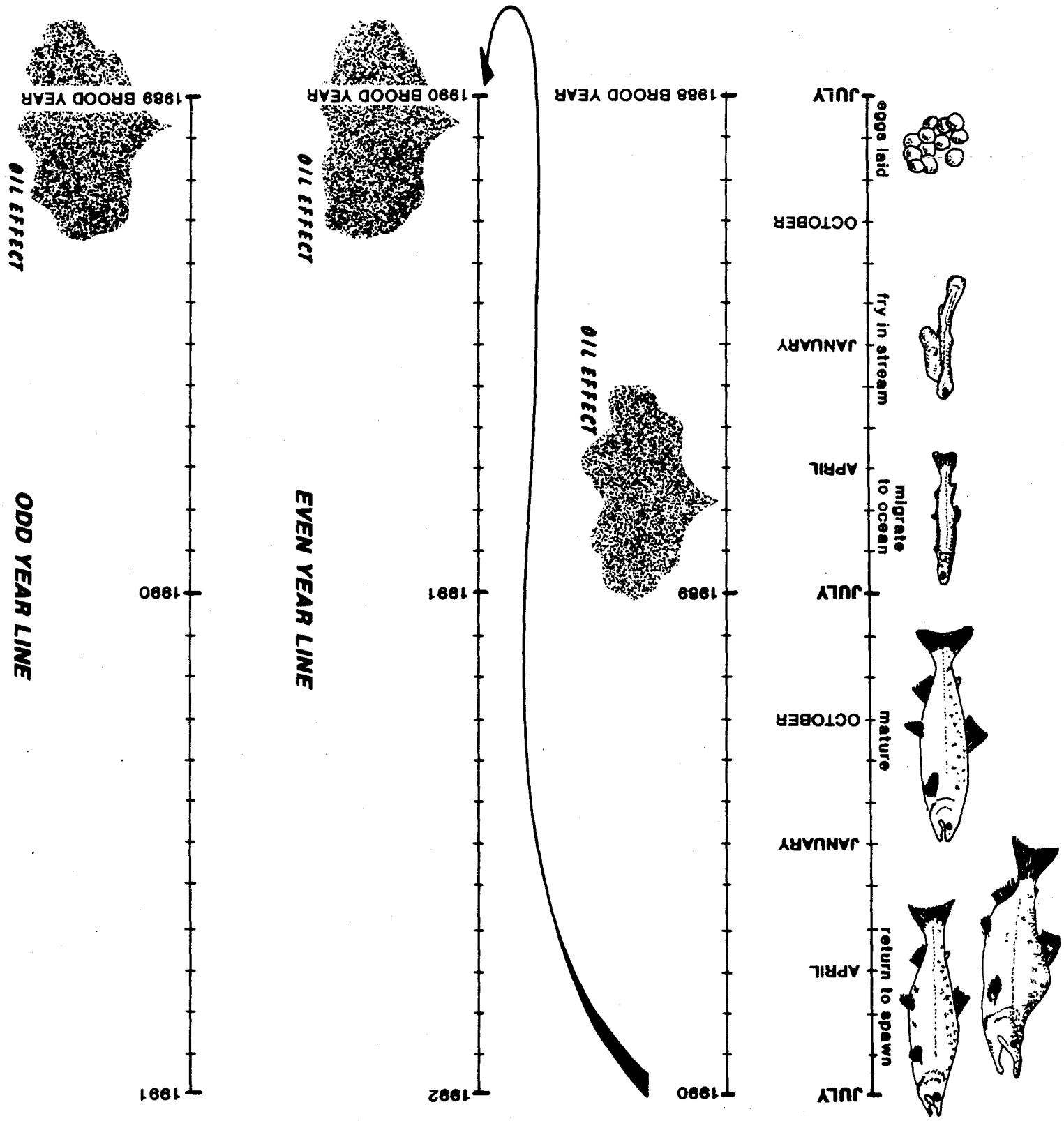

JULY
eggs laid
OCTOBER
JANUARY
fry in stream
APRIL
migrate to ocean
JULY
OCTOBER
mature
JANUARY
APRIL
return to spawn
JULY
1988 BROOD YEAR
1989
1990
OIL EFFECT
1990 BROOD YEAR
1991
1992
OIL EFFECT
EVEN YEAR LINE
1989 BROOD YEAR
1990
1991
OIL EFFECT
ODD YEAR LINE

Fig 2

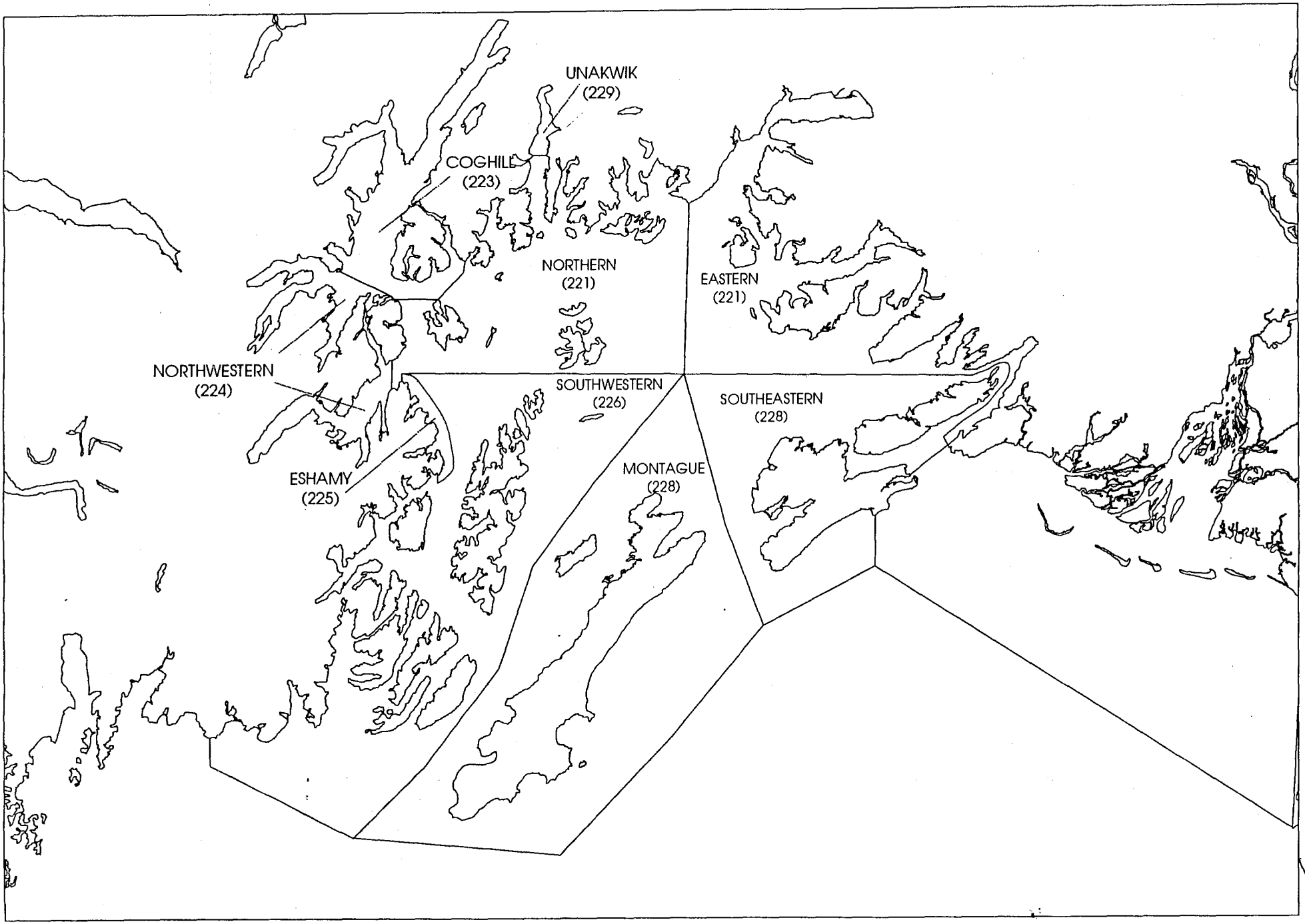


Figure 3

Fig 3

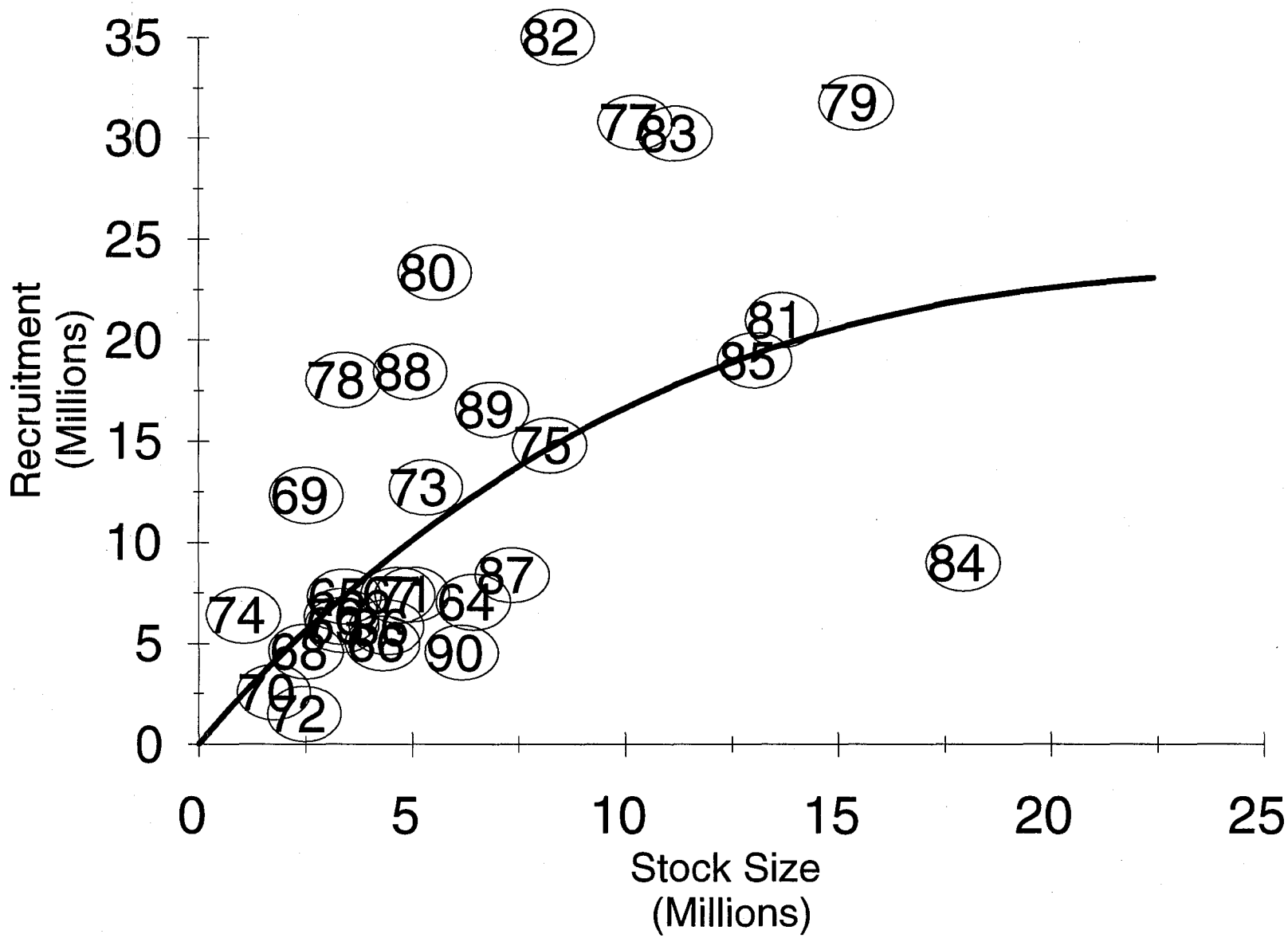
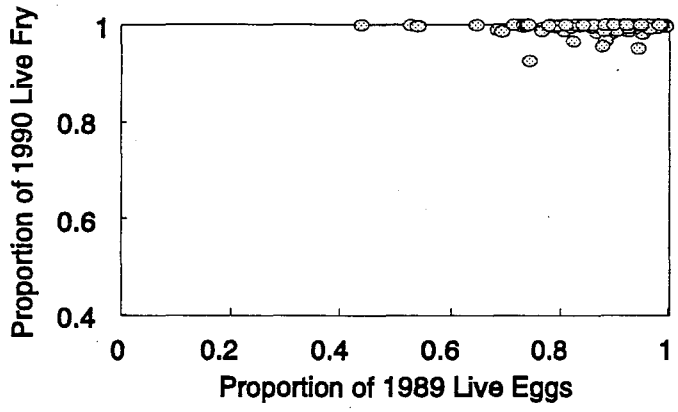
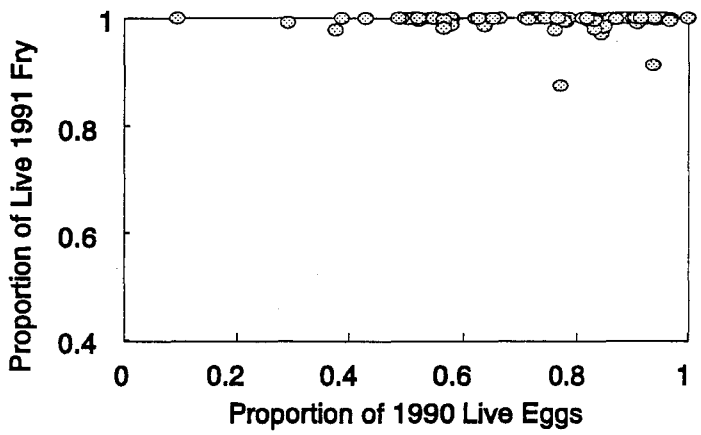


Figure 4

Fig 4


Proportion of 1990 Live Fry
1
0.8
0.6
0.4
0
0.2
0.4
0.6
0.8
1
Proportion of 1989 Live Eggs


Proportion of Live 1991 Fry
1
0.8
0.6
0.4
0
0.2
0.4
0.6
0.8
1
Proportion of 1990 Live Eggs

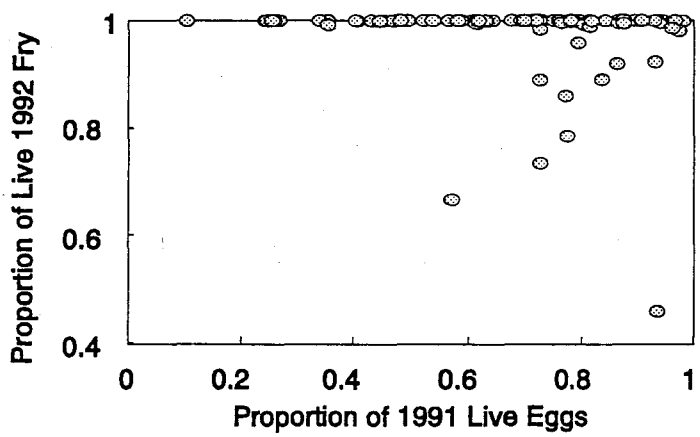
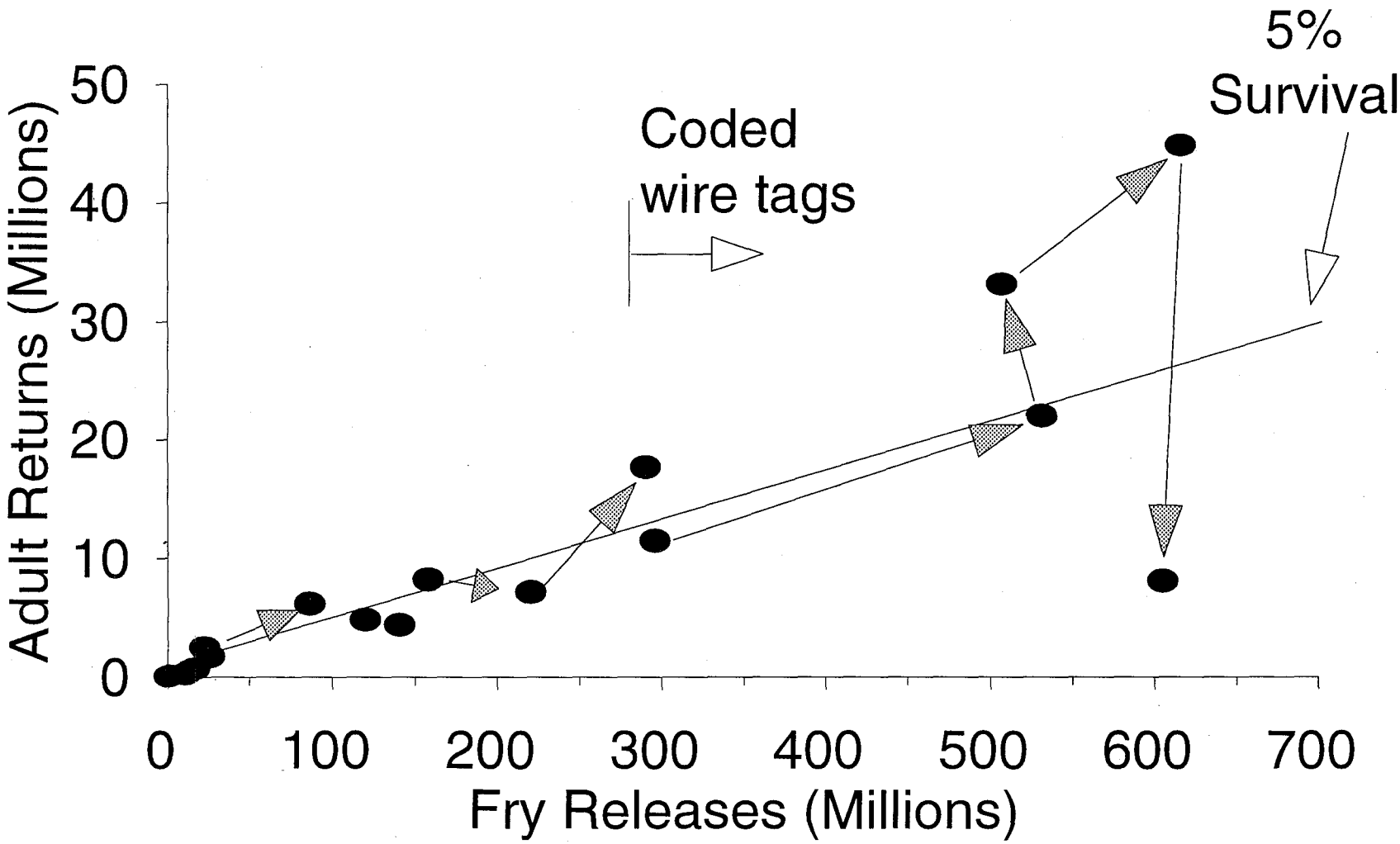

Proportion of Live 1992 Fry
1
0.8
0.6
0.4
0
0.2
0.4
0.6
0.8
1
Proportion of 1991 Live Eggs

Fig 5


5%
Survival
Coded
wire tags
Adult Returns (Millions)
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Fry Releases (Millions)