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Design and Analysis of Salmonid Tagging Studies in the Columbia Basin, Volume XX

Evaluation and Recommendations on Alternative Hydroacoustic Array Deployments for the Mouth of the Columbia River to Provide Estimates of Salmonid Smolt Survival and Movements

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THE DESIGN AND ANALYSIS OF SALMONID TAGGING STUDIES IN THE COLUMBIA BASIN

VOLUME XX

Evaluation and Recommendations on Alternative Hydroacoustic Array Deployments for the Mouth of the Columbia River to Provide Estimates of Salmonid Smolt Survival and Movements

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<u>The Design and Analysis of Salmonid Tagging Studies in the Columbia Basin</u>

Other Publications in this Series

Volume I: Skalski, J. R., J. A. Perez-Comas, R. L. Townsend, and J. Lady. 1998. Assessment of temporal trends in daily survival estimates of spring chinook, 1994-1996. Technical report submitted to BPA, Project 89-107-00, Contract DE-BI79-90BP02341. 24 pp. plus appendix.

Volume II: Newman, K. 1998. Estimating salmonid survival with combined PIT-CWT tagging. Technical report (DOE/BP-35885-11) to BPA, Project 91-051-00, Contract 87-BI-35885.

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Volume XI: Skalski, J. R., R. L. Townsend, A. E. Giorgi, and J. R. Stevenson. Submitted. Recommendations on the design and analysis of radiotelemetry studies of salmonid smolts to estimate survival and passage efficiencies. Technical report to BPA, Project 89-107-00, Contract DE-BI79-90BP02341. 33 pp.

Volume XII: Ryding, K. E., and J. R. Skalski. 1999. A multinomial model for estimating ocean survival from salmonid coded wire-tag data. Technical report (DOE/BP-91572-3) to BPA, Project 91-051-00, Contract 96-BI-91572.

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Volume XIV: Perez-Comas, J. A., and J. R. Skalski. 2000. Appraisal of the relationship between tag detection efficiency at Bonneville Dam and the precision in estuarine and marine survival estimates of returning pit-tagged chinook salmon. Technical report to BPA, Project No. 8910700, Contract DE-BI79-90BP02341.

Volume XV: Perez-Comas, J. A., and J. R. Skalski. 2000. Appraisal of the relationship between tag detection efficiency at Bonneville Dam and the precision in-river survival estimates of returning PIT-tagged chinook salmon. Technical report to BPA, Project No. 8910700, Contract DE-BI79-90BP02341.

Volume XVI: Skalski, J. R., and J. A. Perez-Comas. 2000. Alternative designs for future adult PIT-tag detection studies. Technical report to BPA, Project No. 8910700, Contract DEBI79-90BP02341.

Volume XVII: Burgess, C. A., and J. R. Skalski. 2001. Effects of ocean covariates and release timing on first ocean-year survival of fall Chinook salmon from Oregon and Washington coastal hatcheries. Technical report to BPA, Project No. 199105100, Contract 1996BI91572.

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Volume XIX: Buchanan, R. A., and J. R. Skalski. 2006. Analysis of fall Chinook salmon PIT-tag data: Estimating transportation effects. Technical report to BPA, Project No. 198910700, Contract 00012494.

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Preface

Project 1989-107-00 was initiated to develop the statistical theory, methods, and statistical software to design and analyze PIT-tag survival studies. This project developed the initial study designs for the NOAA Fisheries/University of Washington (UW) Snake River survival studies of 1993–present. This project continues to respond to the changing needs of the scientific community in the Pacific Northwest as they face new challenges to extract life-history data from an increasing variety of fish-tagging studies. The project's mission is to help assure tagging studies are designed and analyzed from the onset to extract the best available information using state-of-the-art statistical methods. In so doing, investigators can focus on the management implications of their findings without being distracted by concerns of whether the study's design and analyses are correct.

All studies in the current series, the Design and Analysis of Tagging Studies in the Columbia Basin, were conducted to help maximize the amount of information that can be obtained from fish tagging studies for the purposes of monitoring fish survival throughout its life cycle. Volume XX of this series investigates alternative hydroacoustic-array deployments for the Mouth of the Columbia River to provide estimates of salmonid smolt survival and movements. Eight alternative acoustic-array designs are examined, and paired-array designs were found to provide the same information as multiple-array designs but with fewer restrictive assumptions about smolt movement behavior. It is essential that the release-recapture model be evaluated to assure study objectives can be fulfilled and parameters of interest are estimable *before* studies are implemented.

Abstract

Estimation of movement parameters and survival of salmonid smolts through the estuary, the mouth of the Columbia River (MCR), and onto the continental shelf will require carefully designed release-recapture investigations. The advent of miniaturized acoustic tags makes such studies feasible. Our analysis found that simple triple-array designs with one array each at the MCR and on the north and south coasts confound survival and movement probabilities with detection rates. Multiple continental shelf arrays alleviate this problem—only if it can be correctly assumed smolts move unidirectionally along the coast, do not residualize nor move off the continental shelf. Replicated-array designs were found to be capable of estimating survival and movement probabilities with fewer assumptions concerning the nature of smolt movements. The cost of these more robust replicated-array designs is the need for paired arrays where otherwise one array my suffice.

Executive Summary

Eight alternative acoustic-array designs examined evaluated to provide information on salmon smolt survival and movements through the mouth of the Columbia River (MCR) and along the continental shelf. A simple three-array design with one transect each at the mouth, north shore, and south shore provides very limited information and is not recommended. A multiple-array design with two or more transects on the north and south shores could provide the requisite survival and movement parameters as long as smolts do not residualize, move off the continental shelf, or change migration direction between transects. Paired-array designs were found to provide the same information as multiple-array designs but with fewer restrictive assumptions concerning smolt movement behavior. Suggestions for testing model assumptions are provided. Regardless of deployment designs for an acoustic-tag study at the MCR, it is essential the release-recapture model be evaluated beforehand to assure study objectives can be fulfilled and the parameters of interest are estimable.

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Acknowledgements

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1.0 Introduction

The recent development of miniaturized acoustic tags permits the investigation of salmonid smolt survival and movements in the Columbia River estuary and onto the continental shelf. The success of such studies will be highly dependent on the release-recapture design used and the deployment scheme for the hydroacoustic arrays. This concern is particularly pertinent when release-recapture models are used to estimate not only survival but, in addition, movement parameters.

The purpose of this report is to evaluate alternative hydrophone array placements and their ability to estimate smolt survival and movement from the Columbia River estuary onto the continental shelf. For each deployment scheme, the estimable parameters will be identified, along with associated model assumptions. Robustness of the release-recapture models to model violations will be evaluated and discussed.

2.0 Comparison of Alternative Hydrophone Deployments

This preliminary report will evaluate three alternative deployment designs. In general, the more complex the deployment of hydrophone arrays, the more information that can be gathered. However, costs of the study increase as the number of arrays increases. Consequently, there is a need to balance costs versus information. As described below, however, in the case of the MCR, there are few acceptable alternatives.

2.1 Simple Triple-Array Design

2.1.1. No Movement Off the Continental Shelf

The simplest array design that has some hope of providing quantitative information on smolt movements and survival through the MCR is a triple-array design (Fig. 2.1). This design consists of an upriver release and a minimum of one array across the Columbia River before the mouth, and one array each, north and south of the Columbia River on the continental shelf, perpendicular to the coastline.

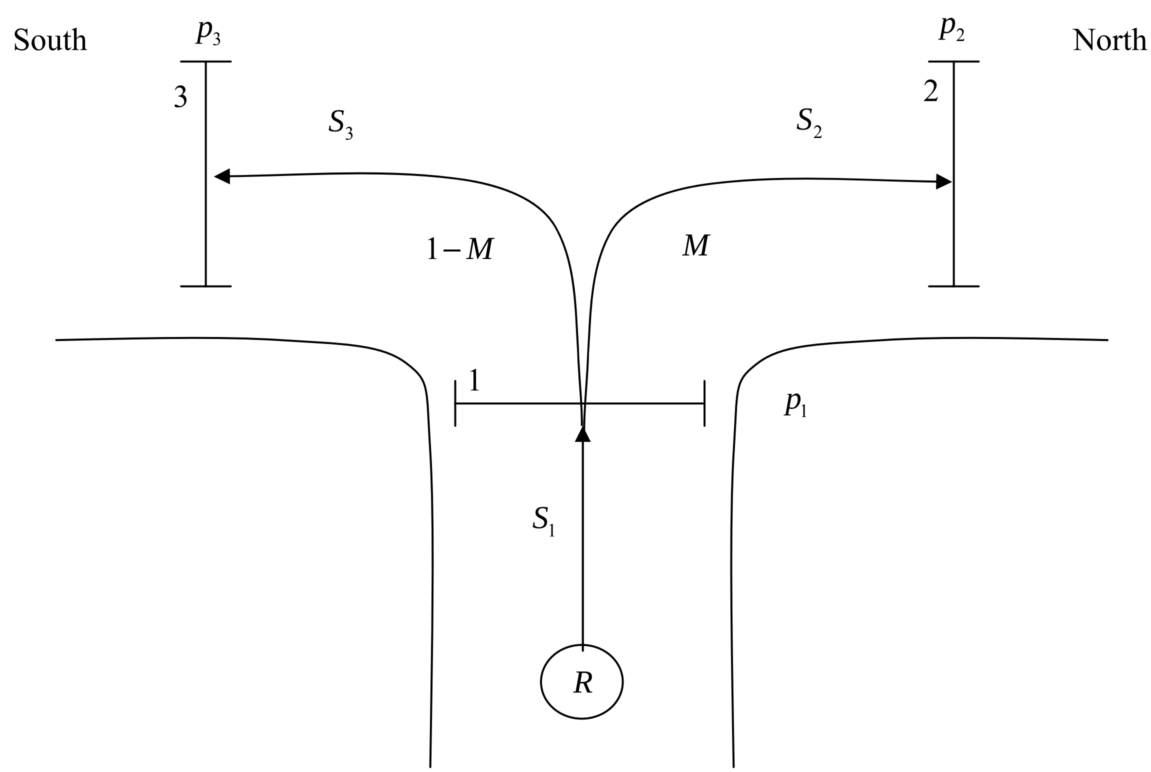

Figure 2.1. Triple-array design with only onshore movement of smolts used to estimate survivals (S_i), capture rates (p_i), and movement probabilities (M), based on a single release (R) upriver.

The array design will generate six unique capture histories (Table 2.1) which can be used to estimate model parameters. The release-recapture model is overparameterized based on unique survivals and capture rates at each array as depicted in Fig 2.1. The model has four minimum sufficient statistics, specifically,

$$
\begin{aligned}
&n_1 + n_2 + n_3 + n_4 + n_5 \\
&n_1 + n_2 + n_3 \\
&n_1 + n_4 \\
&n_1 + n_5,
\end{aligned}
$$

and four estimable parameters,

$$\begin{aligned}&S_1\\&p_1\\&\lambda_2 = MS_2p_2\\&\lambda_3 = (1-M)S_3p_3.\end{aligned}$$

Using the triple-array configuration, only survival from the initial release upriver to the array at the MCR (S_1) and associated capture probability (p_1) can be estimated distinctly. Once smolts are in the ocean, only the joint probability of a smolt moving northward, surviving, and being detected at the northern ocean array (i.e., MS_2p_2) or a smolt moving southward, surviving, and being detected at the southern ocean array (i.e., $(1-M)S_3p_3$) can be estimated. Separating movement probabilities from survival and detection probabilities in the ocean is *impossible* with this design configuration.

Table 2.1. Capture histories and associated probabilities of occurrence for the triple-array design based on Figure 2.1 and counts (n_i). Value 1 denotes detection; 0 denotes nondetection at an array.

	Arrays				Reparameterized probabilities
Count	1	2	3	Probabilities of occurrence	of occurrence
n_1	1	1	0	$S_1p_1MS_2p_2$	$S_1p_1\lambda_1$
n_2	1	0	1	$S_1p_1(1-M)S_3p_3$	$S_1p_1\lambda_2$
n_3	1	0	0	$S_1p_1\left[1-MS_2p_2-(1-M)S_3p_3\right]$	$S_1p_1(1-\lambda_1-\lambda_2)$
n_4	0	1	0	$S_1(1-p_1)MS_2p_2$	$S_1(1-p_1)\lambda_1$
n_5	0	0	1	$S_1(1-p_1)(1-M)S_3p_3$	$S_1(1-p_1)\lambda_2$
n_6	0	0	0	$(1-S_1)+S_1(1-p_1)\left[1-MS_2p_2-(1-M)S_3p_3\right]$	$(1-S_1)+S_1(1-p_1)(1-\lambda_1-\lambda_2)$

Model Assumptions

The assumptions of the triple-array design include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture history.
3. Fish reaching the ocean choose only one direction of movement.
4. Fish reaching the continental shelf move either northward or southward, but not off the shelf.

Should smolts move off the continental shelf, thereby violating assumption 4, the interpretation of the parameters λ_1 and λ_2 changes (see Section 2.1.2), but the number of estimable parameters (i.e., p_1, S_1) does not change.

With four minimum sufficient statistics and four parameters, closed-form estimators of the parameters are available. Using the expected values in Table 2.1, Program USER (http://www.cbr.washington.edu/paramest/user/#bspollination) can also be used to numerically solve for the estimates and associated variances.

Recommendations

The triple-array design depicted in Fig. 2.1 provides no information on ocean movements or survival through the MCR. The only quantitative value of the design is to provide an estimate of survival inriver to the MCR or wherever the last inriver array is located. Additional inriver arrays would contribute nothing to further estimating ocean survival or movement. Additional inriver arrays would allow partitioning inriver survival into smaller reach components only.

2.1.2. With Movements Off the Continental Shelf in the MCR

The release-recapture model for the triple array can be reparameterized to account for movement of smolts off the continental shelf as well as along shore movements (Fig. 2.2). The resultant model once again has the same four minimum sufficient statistics and four parameters (Table 2.2). This time, the estimable parameters are:

$$
\begin{aligned}
&S_1\\
&p_1\\
&\lambda_2 = M_2 S_2 p_2\\
&\lambda_3 = M_3 S_3 p_3.
\end{aligned}
$$

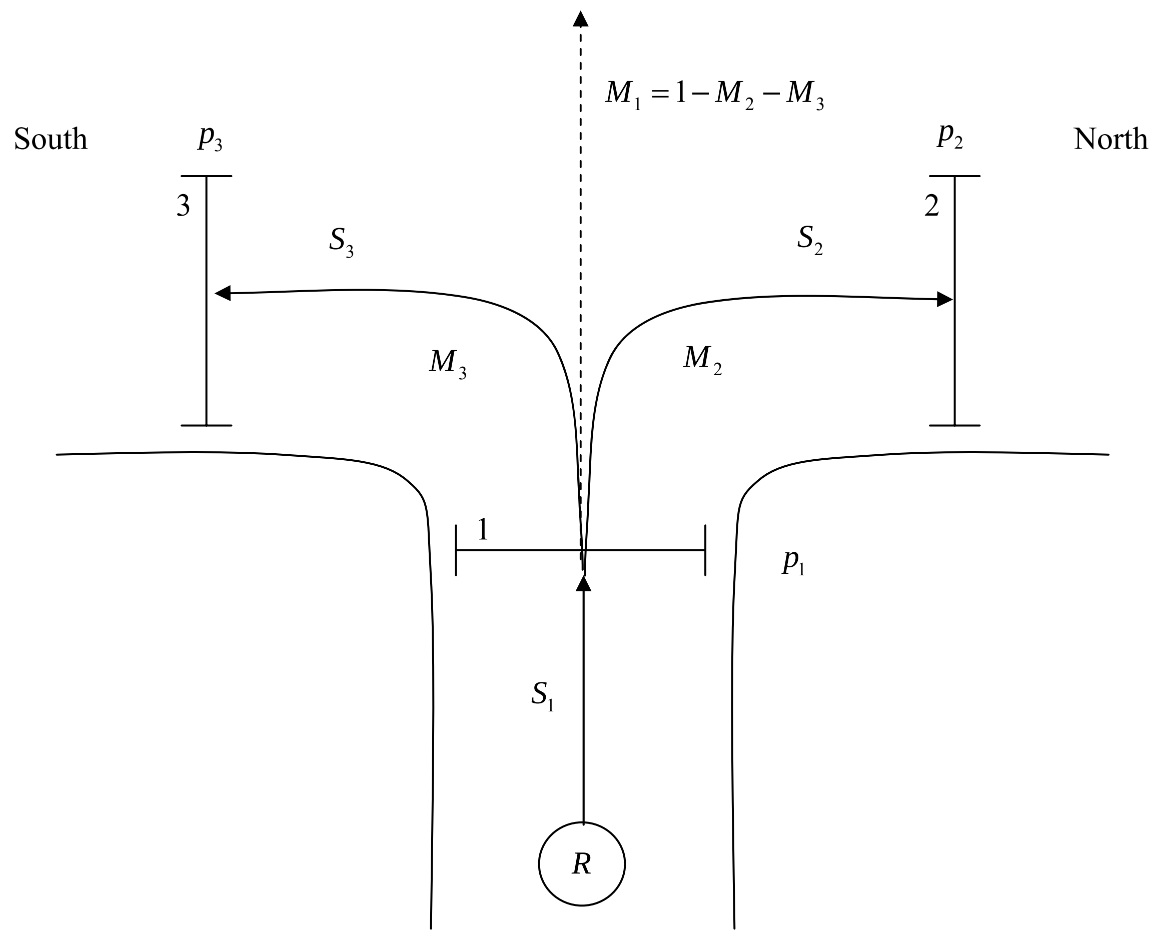

Figure 2.2. Triple-array design allowing movement of smolts off the continental shelf to estimate survivals (S_i), capture rates (p_i), and movement probabilities (M), based on a single release (R) upriver.

Table 2.2. Capture histories, associated probabilities of occurrence for the triple-array design with movements off the continental shelf based on Figure 2.2 and counts (n_i). Value 1 denotes detection; 0 denotes nondetection to an array.

	Arrays				Reparameterized probabilities of occurrence
Count	1	2	3	Probabilities of occurrence	
n_1	1	1	0	$S_1 p_1 M_2 S_2 p_2$	$S_1 p_1 \lambda_2$
n_2	1	0	1	$S_1 p_1 M_3 S_3 p_3$	$S_1 p_1 \lambda_3$
n_3	1	0	0	$S_1 p_1 (1 - M_2 S_2 p_2 - M_3 S_3 p_3)$	$S_1 p_1 (1 - \lambda_2 - \lambda_3)$
n_4	0	1	0	$S_1 (1 - p_1) M_2 S_2 p_2$	$S_1 (1 - p_1) \lambda_2$
n_5	0	0	1	$S_1 (1 - p_1) M_3 S_3 p_3$	$S_1 (1 - p_1) \lambda_3$
n_6	0	0	0	$(1 - S_1) + S_1 (1 - p_1)(1 - MS_2 p_2 - M_3 S_3 p_3)$	$(1 - S_1) + S_1 (1 - p_1)(1 - \lambda_2 - \lambda_3)$

This is similar to the previous model (Table 2.1) but, here, M_2 is not the complement of M_3 but, instead, $M_1 + M_2 + M_3 = 1$, where M_1 = movement off the continental shelf, M_2 = northerly movement, and M_3 = southerly movement.

Model Assumptions

The assumptions of the release-recapture model, as parameterized in Table 2.2, include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture history.
3. Fish reaching the ocean choose only one direction of movement.
4. Fish reaching the ocean have the choice of movement northerly, southerly, or off the continental shelf.

This model is a generalization of the previous model (see Section 2.1.1) without benefit of additional capture information. Hence, information from this model will be more general than that of the model described in Table 2.1.

The maximum likelihood estimators for the model parameters are the same for both models (i.e., Tables 2.1 and 2.2). However, the interpretations of λ_2 and λ_3 are slightly different between models.

Recommendations

The same recommendations for the previous triple-array design apply under this more generalized ocean movement scenario. No estimates of ocean survival or movement parameters are possible.

2.2 Multiple Continental Shelf Arrays

2.2.1. No Movement Off the Continental Shelf

The triple-array design can be augmented with additional coastal arrays to permit greater estimability of parameters (Fig. 2.3). Consider the case where there are two northern and two southern continental shelf arrays for the purposes of characterizing smolt survival and movements through the MCR. With the five arrays, there are 14 possible unique capture histories (Table 2.3).

Once again, not all the parameters are estimable because of nonseparability of some of the original parameters in Fig. 2.3 (i.e., M and S_{21}, $(1-M)$ and S_{31}, S_{22} and p_{22}, S_{32} and p_{32}). A total of eight distinct parameters can be estimated from the release-recapture model characterized in Table 2.3; these are:

$$
\begin{aligned}
&S_1 \\
&p_1 \\
&\psi_2 = MS_{21} \\
&p_{21} \\
&\psi_3 = (1-M)S_{31} \\
&p_{31} \\
&\lambda_2 = S_{22}p_{22} \\
&\lambda_3 = S_{33}p_{33}.
\end{aligned}
$$

The model has eight minimum sufficient statistics, permitting closed-form estimators of the eight parameters.

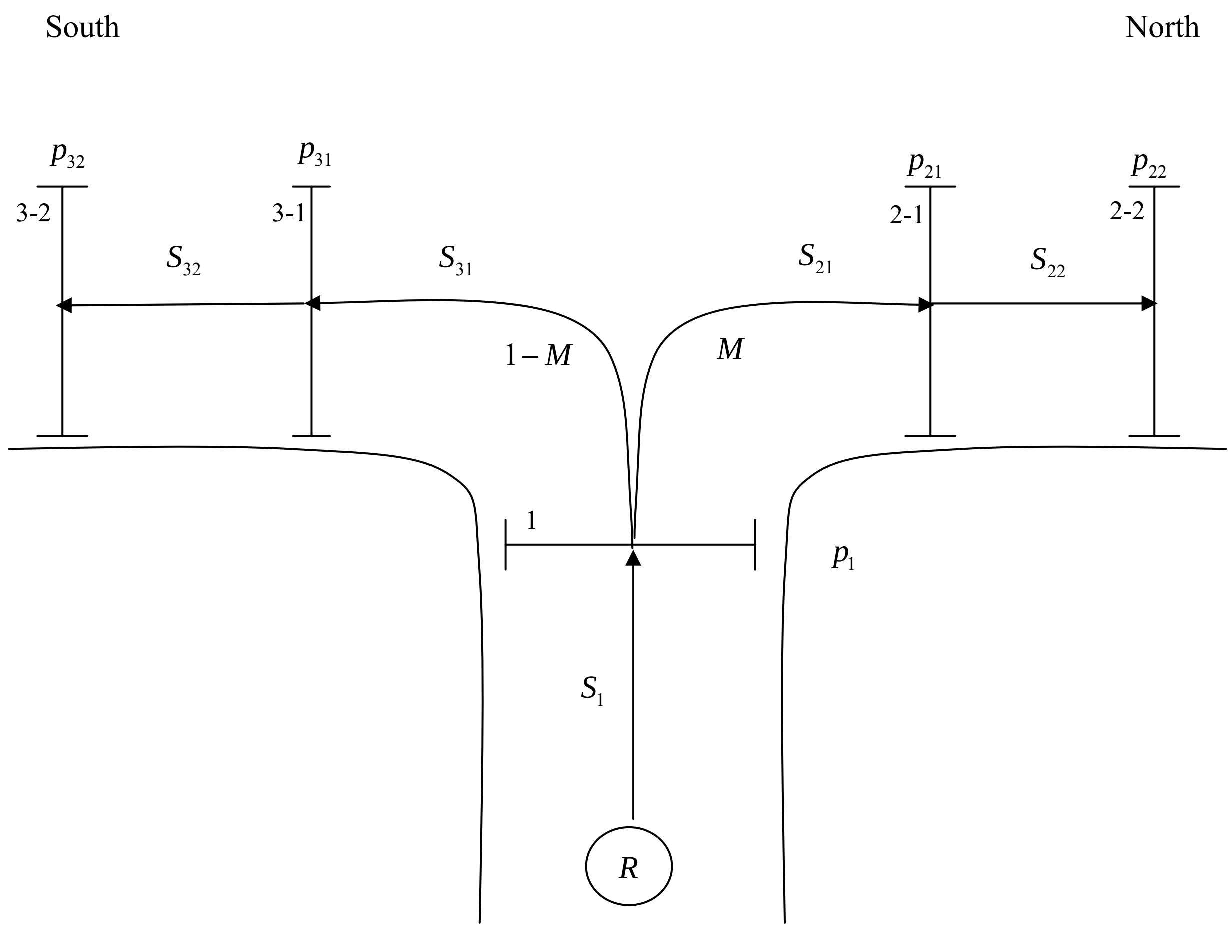

Figure 2.3. Multiple continental-shelf array design used to estimate survivals (S_i), capture rates (p_i), and movement probabilities (M), based on a single release (R) upriver.

Table 2.3. Capture histories, associated probabilities of occurrence, and counts (n_i) for the multiple continental-shelf array design (Figure 2.3). Value 1 denotes detection; 0 denotes nondetection at an array.

Count	Array 1	Array 2-1	Array 2-2	Array 3-1	Array 3-2	Probabilities of Occurrence	Reparameterized Probabilities of Occurrence
n_1	1	1	1	0	0	$S_1 p_1 M S_{21} p_{21} S_{22} p_{22}$	$S_1 p_1 \psi_2 p_{21} \lambda_2$
n_2	1	1	0	0	0	$S_1 p_1 M S_{21} p_{21} (1 - S_{22} p_{22})$	$S_1 p_1 \psi_2 p_{21} (1 - \lambda_2)$
n_3	1	0	1	0	0	$S_1 p_1 M S_{21} (1 - p_{21}) S_{22} p_{22}$	$S_1 p_1 \psi_2 (1 - p_{21}) \lambda_2$
n_4	1	0	0	1	1	$S_1 p_1 (1 - M) S_{31} p_{31} S_{32} p_{32}$	$S_1 p_1 \psi_3 p_{31} \lambda_3$
n_5	1	0	0	1	0	$S_1 p_1 (1 - M) S_{31} p_{31} (1 - S_{32} p_{32})$	$S_1 p_1 \psi_3 p_{31} (1 - \lambda_3)$
n_6	1	0	0	0	1	$S_1 p_1 (1 - M) S_{31} (1 - p_{31}) S_{32} p_{32}$	$S_1 p_1 \psi_3 (1 - p_{31}) \lambda_3$
n_7	1	0	0	0	0	$S_1 p_1 \big[1 - M S_{21} (\lambda_2 + p_{21} - \lambda_2 p_{21})$ $- (1 - M) S_{31} (\lambda_3 + p_3 - \lambda_3 p_3)\big]$	$S_1 p_1 \big[1 - \psi_2 (\lambda_2 + p_{21} - \lambda_2 p_{21})$ $- \psi_3 (\lambda_3 + p_{31} - \lambda_3 p_{31})\big]$
n_8	0	1	1	0	0	$S_1 (1 - p_1) M S_{21} p_{21} S_{22} p_{22}$	$S_1 (1 - p_1) \psi_2 p_{21} \lambda_2$
n_9	0	1	0	0	0	$S_1 (1 - p_1) M S_{21} p_{21} (1 - S_{22} p_{22})$	$S_1 (1 - p_1) \psi_2 p_{21} (1 - \lambda_2)$
n_{10}	0	0	1	0	0	$S_1 (1 - p_1) M S_{21} (1 - p_{21}) S_{22} p_{22}$	$S_1 (1 - p_1) \psi_2 (1 - p_{21}) \lambda_2$
n_{11}	0	0	0	1	1	$S_1 (1 - p_1)(1 - M) S_{31} p_{31} S_{32} p_{32}$	$S_1 (1 - p_1) \psi_3 p_{31} \lambda_3$
n_{12}	0	0	0	1	0	$S_1 (1 - p_1)(1 - M)$ $\cdot S_{31} p_{31} (1 - S_{32} p_{32})$	$S_1 (1 - p_1) \psi_3 p_{31} (1 - \lambda_3)$
n_{13}	0	0	0	0	1	$S_1 (1 - p_1)(1 - M)$ $\cdot S_{31} (1 - p_{31}) S_{32} p_{32}$	$S_1 (1 - p_1) \psi_3 (1 - p_{31}) \lambda_3$
n_{14}	0	0	0	0	0	$1 - \Sigma$[a]	$1 - \Sigma$[a]

a. Σ = sum of all the other probabilities of occurrence.

An estimate of mortality in the MCR from the last inriver array to the first continental-shelf arrays can be estimated by

$$1-\psi_2-\psi_3=1-MS_{21}-(1-M)S_{31}, \tag{1}$$

assuming no residualization in the MCR. Survival and capture parameters in the last reach, north and south, cannot be differentiated; only their joint probability is estimable (i.e., λ_2 and λ_3).

Assumptions

The assumptions of this release-recapture model, as parameterized in Table 2.3, include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture history.
3. Fish reaching the ocean chose only one direction of movement.
4. Fish reaching the continental shelf either move northward or southward but not out to sea.
5. Fish along the continental shelf continue to move forward, do not residualize between arrays, reverse course, or move off the shelf.

Violation of either assumptions 4 or 5 would seriously bias any estimates of ocean movement or survival (ψ_2,ψ_3). Currently, fish movements are poorly understood, so it is impossible to assess whether the model assumptions are realistic or not. Only by making the additional assumption $S_{21}=S_{31}$ can the movement parameter M be separately estimated to indicate the fraction of fish that move northward or southward.

Recommendations

The five-array design depicted in Fig. 2.3 permits estimation of the joint probabilities of movement and survival through the MCR (or their complement, mortality in the MCR) under a set of untested assumptions. Any movement offshore will violate model assumptions. Because such movement would go undetected in the current array configuration, the bias and its degree would go unobserved. Therefore, the design is not robust and should be treated cautiously until its assumptions can be verified.

Adding more continental shelf arrays to the design depicted in Fig. 2.3 permits estimation of survival along additional coastal reaches. However, in the last array, either north or south, only the joint probability of survival and detection (i.e., Sp) can be estimated. Additional inriver arrays or coastal arrays do not change what can be estimated in the MCR, nor does it relax the model assumptions, nor provide information on movements off the continental shelf.

2.2.2. With Movement Off the Continental Shelf in the MCR

Allowing movement off the continental shelf in the MCR relaxes some of the model assumptions of Section 2.2.1 (Fig 2.4), However, with the same array design, the interpretation of some model parameters is lost (Table 2.4). In this case, eight model parameters can be estimated (Table 2.4); these are:

$$
\begin{aligned}
&S_1 \\
&p_1 \\
&\psi_2 = M_2 S_{21} \\
&p_{21} \\
&\psi_3 = M_3 S_{31} \\
&p_{31} \\
&\lambda_2 = S_{22} p_{22} \\
&\lambda_3 = S_{32} p_{32}.
\end{aligned}
$$

This model has eight minimum sufficient statistics, permitting closed-form estimators of all the parameters. The quantity,

$$1 - \psi_2 - \psi_3 = 1 - M_2 S_{21} - M_3 S_{21}, \tag{2}$$

no longer estimates mortality in the MCR. Hence, relaxation of the model assumptions, permitting movement off the continental shelf, now precludes estimating survival from the last inriver array to the first continental-shelf arrays (Section 2.2.1). Instead, the quantity simply estimates the probability of a fish arriving to the arrays on the continental shelf, given it survived to the MCR.

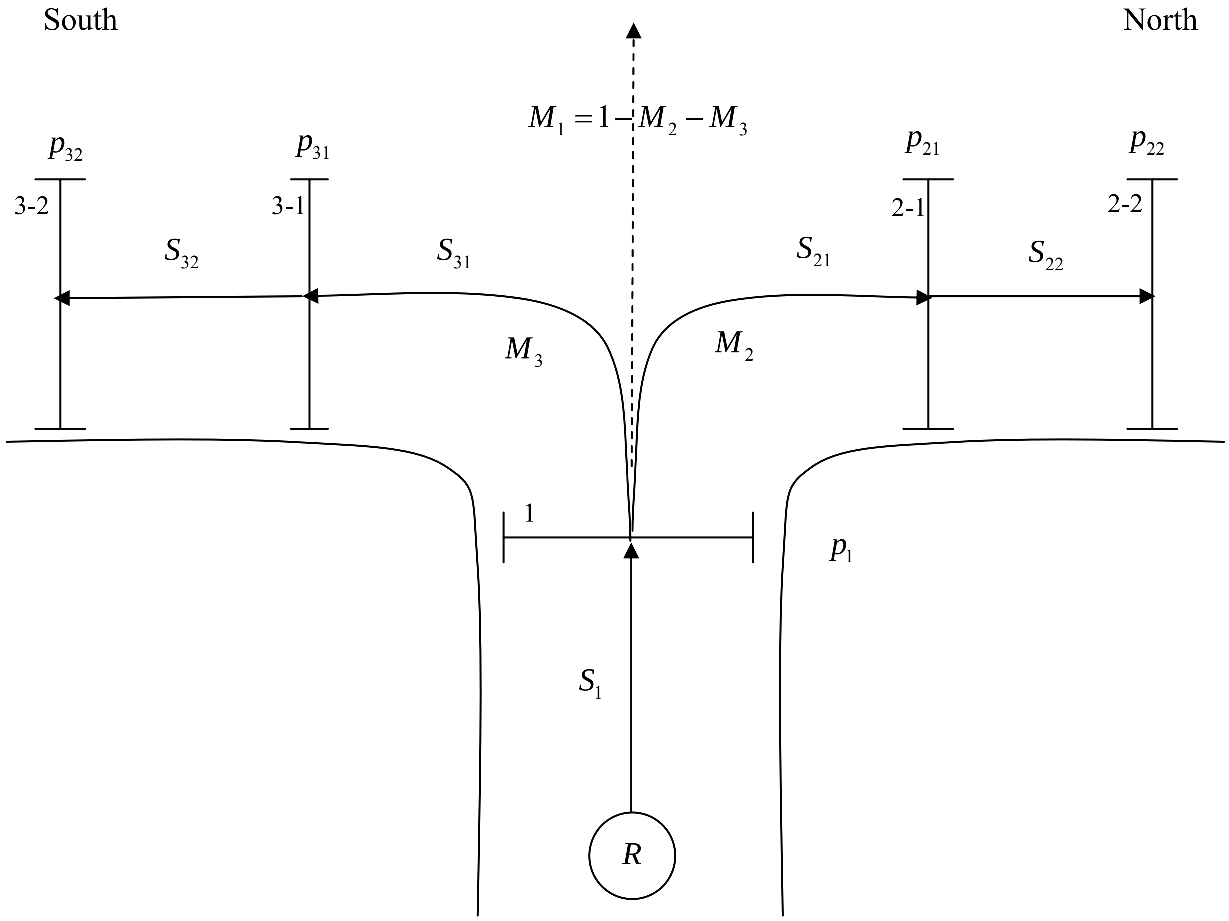

Figure 2.4. Multiple continental-shelf array design allowing movement of smolts off the shelf to estimate survivals (S_i), capture rates (p_i), and movement probabilities (M_i), based on a single release (R) upriver.

Table 2.4. Capture histories, associated probabilities of occurrence, and counts (n_i) for the multiple continental-shelf array design (Figure 2.4). Value 1 denotes detection; 0 denotes nondetection at an array.

Count	Array 1	2-1	2-2	3-1	3-2	Probabilities of Occurrence	Reparameterized Probabilities of Occurrence
n_1	1	1	1	0	0	$S_1 p_1 M_2 S_{21} p_{21} S_{22} p_{22}$	$S_1 p_1 \psi_2 p_{21} \lambda_2$
n_2	1	1	0	0	0	$S_1 p_1 M_2 S_{21} p_{21} (1 - S_{22} p_{22})$	$S_1 p_1 \psi_2 p_{21} (1 - \lambda_2)$
n_3	1	0	1	0	0	$S_1 p_1 M_2 S_{21} (1 - p_{21}) S_{22} p_{22}$	$S_1 p_1 \psi_2 (1 - p_{21}) \lambda_2$
n_4	1	0	0	1	1	$S_1 p_1 M_3 S_{31} p_{31} S_{32} p_{32}$	$S_1 p_1 \psi_3 p_{31} \lambda_3$
n_5	1	0	0	1	0	$S_1 p_1 M_3 S_{31} p_{31} (1 - S_{32} p_{32})$	$S_1 p_1 \psi_3 p_3 (1 - \lambda_3)$
n_6	1	0	0	0	1	$S_1 p_1 M_3 S_{31} (1 - p_{31}) S_{32} p_{32}$	$S_1 p_1 \psi_3 (1 - p_3) \lambda_3$
n_7	1	0	0	0	0	$S_1 p_1 \left[1 - M_2 S_{21} (\lambda_2 + p_{21} - \lambda_2 p_{21}) - M_3 S_{31} (\lambda_3 + p_3 - \lambda_3 p_3)\right]$	$S_1 p_1 \left[1 - \psi_2 (\lambda_2 + p_{21} - \lambda_2 p_{21}) - \psi_3 (\lambda_3 + p_{31} - \lambda_3 p_{31})\right]$
n_8	0	1	1	0	0	$S_1 (1 - p_1) M_2 S_{21} p_{21} S_{22} p_{22}$	$S_1 (1 - p_1) \psi_2 p_{21} \lambda_2$
n_9	0	1	0	0	0	$S_1 (1 - p_1) M_2 S_{21} p_{21} (1 - S_{22} p_{22})$	$S_1 (1 - p_1) \psi_2 p_{21} (1 - \lambda_2)$
n_{10}	0	0	1	0	0	$S_1 (1 - p_1) M_2 S_{21} (1 - p_{21}) S_{22} p_{22}$	$S_1 (1 - p_1) \psi_2 (1 - p_{21}) \lambda_2$
n_{11}	0	0	0	1	1	$S_1 (1 - p_1) M_3 S_{31} p_{31} S_{32} p_{32}$	$S_1 (1 - p_1) \psi_3 p_{31} \lambda_3$
n_{12}	0	0	0	1	0	$S_1 (1 - p_1) M_3 S_{31} p_{31} (1 - S_{32} p_{32})$	$S_1 (1 - p_1) \psi_3 p_{31} (1 - \lambda_3)$
n_{13}	0	0	0	0	1	$S_1 (1 - p_1) M_3 S_{31} (1 - p_{31}) S_{32} p_{32}$	$S_1 (1 - p_1) \psi_3 (1 - p_{31}) \lambda_3$
n_{14}	0	0	0	0	0	$1 - \Sigma^a$	$1 - \Sigma^a$

a. Σ = sum of all the other probabilities of occurrence.

Assumptions

The assumptions of the release-recapture model depicted in Fig. 2.4 include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture history.
3. Fish reaching the ocean chose only one direction of movement.
4. Fish reaching the ocean have the choice of movement northerly, southerly, or off the continental shelf.
5. Fish along the continental shelf continue to move forward, do not residualize between arrays, reverse course, or move off the shelf.

Recommendations

The greater flexibility of fish movement with the release-recapture design characterized in Table 2.4 provides a more realistic scenario. This model should be used until movements off the continental shelf in the MCR can be verified not to occur. However, this more realistic model implies that the information that can be extracted is less than might be expected. Survival through the MCR cannot be estimated nor can the proportions of fish that move seaward, north (M_2), or south (M_3) along the continental shelf.

2.3 Replicated-Array Design

2.3.1. No Movement Off the Continental Shelf

The multiple continental-shelf array designs are limited by the assumption that coastal fish move unidirectionally, do not residualize in a reach, and have no movement off the shelf between arrays. Unless these assumptions are true, the models in Section 2.2 will provide biased estimates of survival. The more spread out the coastal arrays, the more likely the restrictive movement assumptions may be violated.

One possible solution to the restrictive model assumptions of Section 2.2 is to locate replicate arrays in very close proximity (i.e., 1-2 km) (Fig. 2.5). Within that limited distance between the two arrays, the assumptions of closure (i.e., no mortality) and unidirectional movement along the continental shelf may be fulfilled. Under these circumstances, closed population estimation methods (i.e., Petersen-Lincoln Index) may be used to independently estimate detection probabilities.

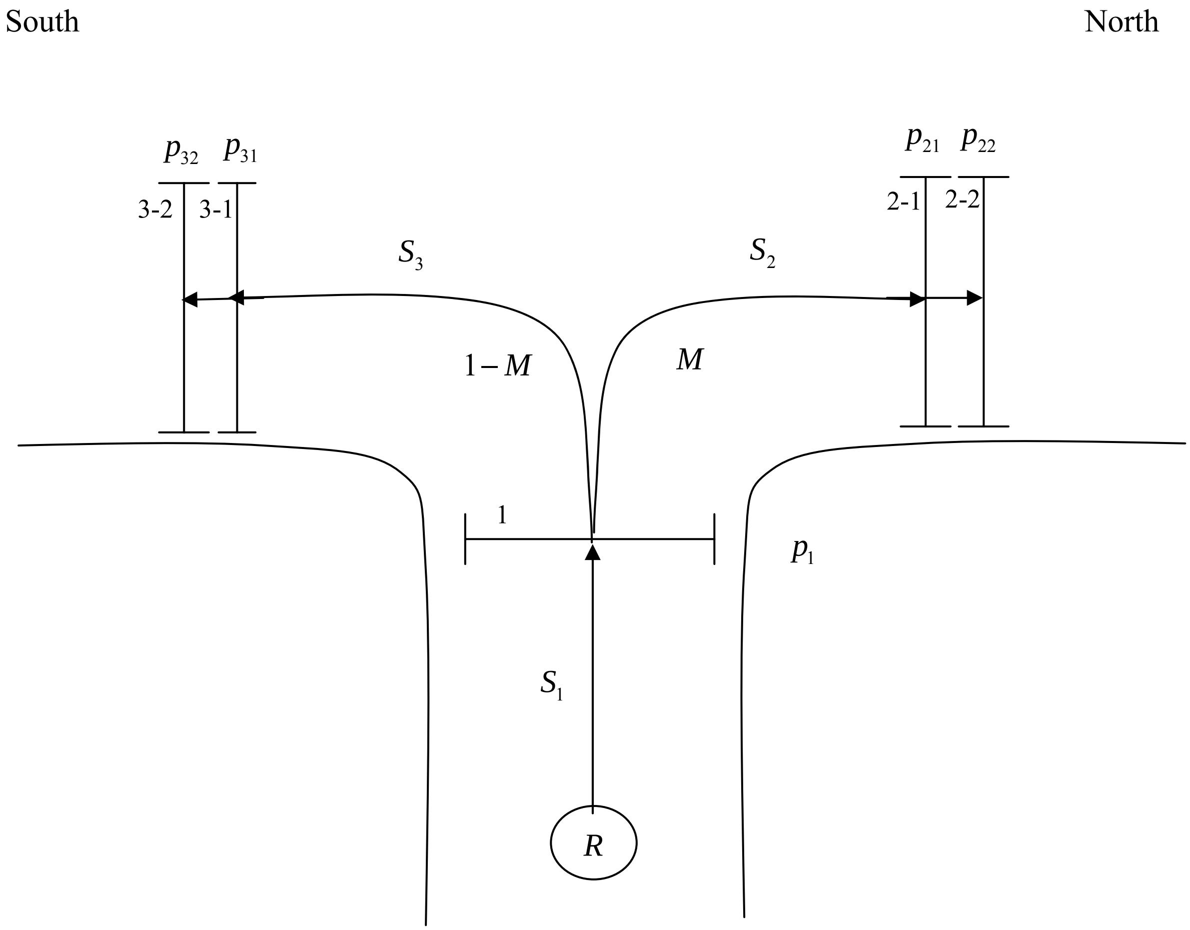

Figure 2.5. Replicated-array design used to estimate survivals (*S*), capture probabilities (*p*), and movement parameters (*M*), based on a single release (*R*) upriver.

A joint likelihood can be used to estimate the survival, movement, and capture probabilities. Table 2.5 lists the observable capture histories at the three major detection sites; inriver, north shore, and south shore on the continental shelf, and associated probabilities of occurrence. The likelihood model for the six observable capture histories in Table 2.3 is as follows:

$$L_1 = \binom{R}{\underset{\sim}{n}}\Big(\big(S_1 p_1 \psi_2 \left(1-(1-p_{21})(1-p_{22})\right)\big)^{n_1} \big(S_1 p_1 \psi_3 \left(1-(1-p_{31})(1-p_{32})\right)\big)^{n_2}\Big)$$
$$\cdot\Big(S_1 p_1 \big[1-\psi_2\left(1-(1-p_{21})(1-p_{22})\right)-\psi_3\left(1-(1-p_{31})(1-p_{32})\right)\big]\Big)^{n_3}$$
$$\cdot\Big(S_1(1-p_1)\psi_2\left(1-(1-p_{21})(1-p_{22})\right)\Big)^{n_4}\cdot\Big(S_1(1-p_1)\psi_3\left(1-(1-p_{31})(1-p_{32})\right)\Big)^{n_5}$$
$$\cdot\Big((1-S_1)+S_1(1-p_1)\big[1-\psi_2\left(1-(1-p_{21})(1-p_{22})\right)-\psi_3\left(1-(1-p_{31})(1-p_{32})\right)\big]\Big)^{n_6}. \quad (3)$$

Table 2.5. Capture histories and associated probabilities of occurrence for the replicated-array design (Figure 2.5) and counts (n_i). Value 1 denotes detection; 0 denotes nondetection at an array or any array pair.

	Arrays				
Count	1	2	3	Probabilities of occurrence	Reparameterized probabilities of occurrence
n_1	1	1	0	$S_1 p_1 M S_2 P_2$ [a]	$S_1 p_1 \psi_2 P_2$
n_2	1	0	1	$S_1 p_1 (1-M) S_3 P_3$ [b]	$S_1 p_1 \psi_3 P_3$
n_3	1	0	0	$S_1 p_1 \left[1-MS_2P_2-(1-M)S_3P_3\right]$	$S_1 p_1 (1-\psi_2 P_2-\psi_3 P_3)$
n_4	0	1	0	$S_1(1-p_1)MS_2P_2$	$S_1(1-p_1)\psi_2 P_2$
n_5	0	0	1	$S_1(1-p_1)(1-M)S_3P_3$	$S_1(1-p_1)\psi_3 P_3$
n_6	0	0	0	$(1-S_1)+S_1(1-p_1) \cdot\left[1-MS_2P_2-(1-M)S_3P_3\right]$	$(1-S_1)+S_1(1-p_1)(1-\psi_2P_2-\psi_3P_3)$

a. $P_2 = 1-(1-p_{21})(1-p_{22})$

b. $P_3 = 1-(1-p_{31})(1-p_{32})$

For instance, at the northern double array, there are three possible capture histories for a detected fish—11, 01, or 10, corresponding to whether a fish was detected at the first, second, or both arrays. The joint likelihood for the detection at the northern array can be written as

$$L_2 = \binom{m_{\bullet}}{\underset{\sim}{m}} \left(\frac{p_{21}(1-p_{22})}{1-(1-p_{21})(1-p_{22})} \right)^{m_{10}} \left(\frac{(1-p_{21})p_{22}}{1-(1-p_{21})(1-p_{22})} \right)^{m_{01}} \left(\frac{p_{21}p_{22}}{1-(1-p_{21})(1-p_{22})} \right)^{m_{11}}, \quad (4)$$

where

p_{21} = probability of detection at the first array of the northern pair,

p_{22} = probability of detection at the second array of the northern pair,

m_{10} = number of fish detected at the first array but not the second array,

m_{01} = number of fish detected at the second array but not the first array,

m_{11} = number of fish detected at both arrays,

$m_{\bullet} = m_{10} + m_{01} + m_{11}$.

An analogous likelihood (L_3) for the southern paired arrays would be formulated as a function of

p_{31} = probability of detection at the first array of the southern pair,

p_{32} = probability of detection at the second array of the southern pair.

The joint likelihood for the release-recapture analysis would be based on the product

$$L = L_1 \cdot L_2 \cdot L_3 . \quad (5)$$

The joint likelihood model would be able to estimate the following parameters:

$$S_1$$
$$p_1$$
$$\psi_2 = MS_2$$
$$\psi_3 = (1-M)S_3$$

$$p_{21}$$
$$p_{22}$$
$$p_{31}$$
$$p_{33}.$$

The complement,

$$1-\psi_2-\psi_3=1-MS_2-(1-M)S_3\,,$$

estimates the probability a smolt does not survive through the MCR from the last inriver array to either the northern or southern paired arrays, based on the assumptions of continued movement along the continental shelf, and no residualization between arrays. The overall probability of a fish being detected at the northern array is estimated by

$$\hat{P}_2=1-\left(1-\hat{p}_{21}\right)\left(1-\hat{p}_{22}\right),$$

while

$$\hat{P}_3=1-\left(1-\hat{p}_{31}\right)\left(1-\hat{p}_{32}\right)$$

estimates the overall probability of a fish being detected at the southern paired array.

Assumptions

The assumptions of the replicated array design and model depicted in Figure 2.5 include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture histories.
3. Fish entering the ocean choose only one direction of movement.
4. Fish reaching the ocean either move northerly or southerly but not out to sea.
5. Within the short distance between the arrays within a pair, fish move forward, do not residualize between arrays, and experience no mortality.

Assumption 5, requiring no residualization and only forward movement, is the same as assumption 5 for the multiple-array model (Section 2.2.1). However, the requirements are much easier to fulfill because the distance between arrays is substantially shorter (i.e., 2–3 km vs. 50–100's km). The additional requirement here in the paired-array design is that survival is 100% between arrays, which should be roughly true over short distances.

The relaxed assumptions concerning fish movements over short distances should make the replicated-array design more robust to model violations than the multiple-array design of Section 2.2. The trade-off is additional costs of paired arrays where previously a single array served.

Recommendations

Until smolt migration behavior along the continental shelf is better known, more conservative and robust designs such as Figure 2.5 are preferable to the designs in Section 2.2.

2.3.2. With Movement Off the Continental Shelf in the MCR

The assumptions of the replicated-array design can be relaxed to allow for movement out to sea (Figure 2.6). No longer can the probability of mortality between the last inriver array and the first shelf arrays be estimated. However, the interpretation of the estimable parameters (Table 2.6) degrades to a degree. Now the estimable parameters are

$$\begin{aligned} &S_1 \\ &p_1 \\ &\psi_2 = M_2 S_2 \\ &\psi_3 = M_3 S_3 \\ &p_{21} \\ &p_{22} \\ &p_{31} \\ &p_{33}. \end{aligned}$$

Under this model, however, the complement,

$$1 - \psi_2 - \psi_3 = 1 - M_2 S_2 - M_3 S_3,$$

no longer estimates mortality in the MCR between the last inriver array and the first northern and southern arrays. The quantity now estimates the joint probability of mortality or movement off the continental shelf. The parameters ψ_2 and ψ_3 in this model are the same values estimated by the model in Section 2.2.2.

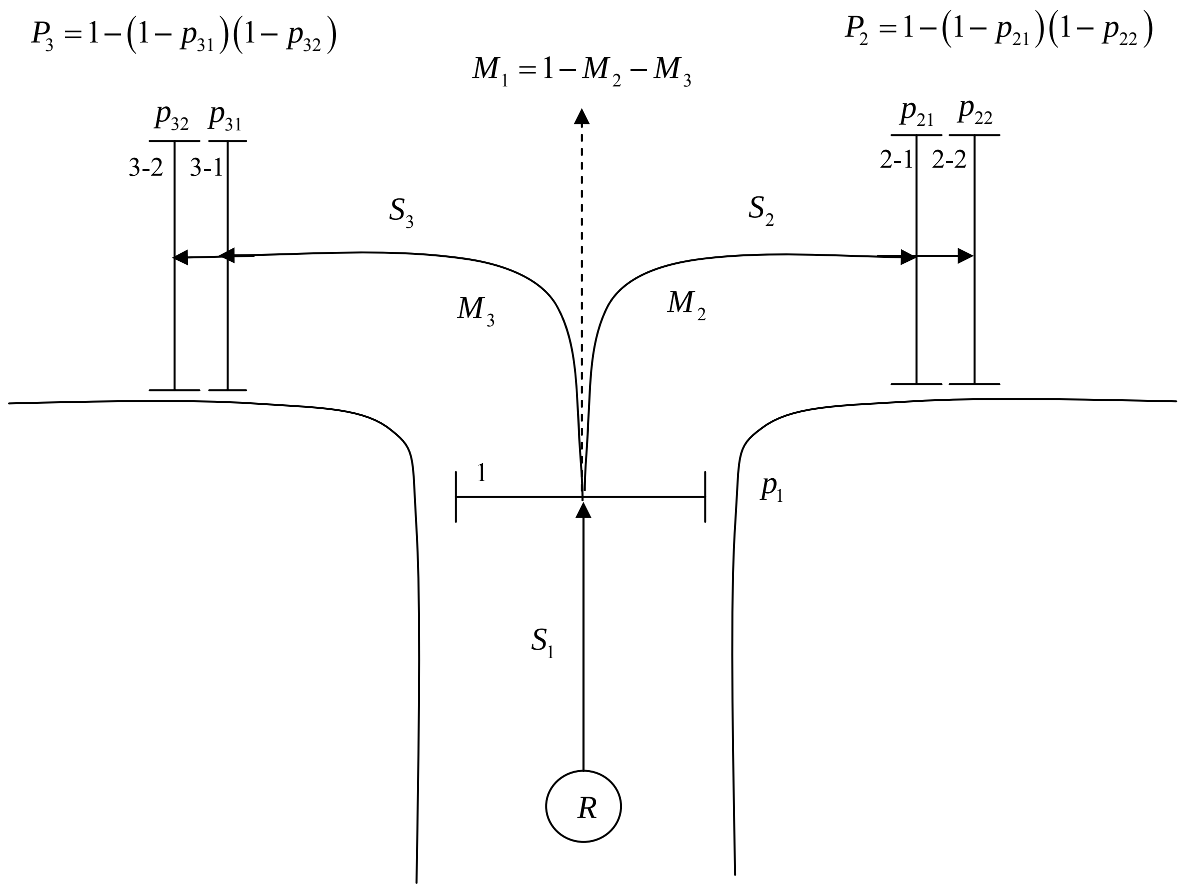

Figure 2.6. Replicated-array design allowing movement off the continental shelf in estimating survival (S_i), capture probabilities (p_i), and movement parameters (M_i), based on a single release (R) upriver.

Table 2.6. Capture histories, and associated probabilities of occurrence for the replicated-array design (Figure 2.5) and counts (n_i). Value 1 denotes detection; 0 denotes nondetection at an array or any array pair.

	Arrays				
Count	1	2	3	Probabilities of occurrence	Reparameterized probabilities of occurrence
n_1	1	1	0	$S_1 p_1 M_2 S_2 P_2$[a]	$S_1 p_1 \psi_2 P_2$
n_2	1	0	1	$S_1 p_1 M_3 S_3 P_3$[b]	$S_1 p_1 \psi_3 P_3$
n_3	1	0	0	$S_1 p_1 \left[1 - MS_2 P_2 - M_3 S_3 P_3\right]$	$S_1 p_1 \left[1 - \psi_2 P_2 - \psi_3 P_3\right]$
n_4	0	1	0	$S_1 (1 - p_1) M_2 S_2 P_2$	$S_1 (1 - p_1) \psi_2 P_2$
n_5	0	0	1	$S_1 (1 - p_1) M_3 S_3 P_3$	$S_2 (1 - p_2) \psi_3 P_3$
n_6	0	0	0	$(1 - S_1) + S_1 (1 - p_1) \cdot \left[1 - M_2 S_2 P_2 - M_3 S_3 P_3\right]$	$(1 - S_1) + S_1 (1 - p_1)(1 - \psi_2 P_2 - \psi_3 P_3)$

a. $P_2 = 1 - (1 - p_{21})(1 - p_{22})$

b. $P_3 = 1 - (1 - p_{31})(1 - p_{32})$

Parameter estimation is analogous to Section 2.3.1 with the reparameterization in Table 2.6. Parameterization in the auxiliary likelihoods (4) remains the same. Program USER can be readily programmed to compute the maximum likelihood estimate and their associated variances.

Assumptions

The assumptions of the replicated-array design depicted in Figure 2.6 include the following:

1. Each fish has an independent fate.
2. Capture, survival, and movement in the ocean are not affected by inriver capture histories.
3. Fish entering the ocean choose only one direction of movement.
4. Fish reaching the ocean have the choice of movement northerly, southerly, or off the continental shelf.

5. Within the short distance between the arrays within a pair, fish move forward, do not residualize between arrays, and experience no mortality.

Recommendations

Until smolt movements in the MCR are better understood, a more generic model permitting movements off the continental shelf is advisable. However, the consequence is that interpretation of the estimable parameters (i.e., ψ_2 and ψ_3) becomes less informative.

3.0 Discussion and Other Considerations

There is an almost unlimited combination of array designs that could be implemented to study salmonid movements through the MCR and along the continental shelf. The sampling schemes and models in Section 2.0 are representative of some of the more likely design options. Those designs can be readily extended to include more inriver arrays and/or more shelf arrays without loss of generality. The additional arrays inriver or along the coast, however, will not change the estimability of movement or survival parameters through the MCR and onto the shelf.

Because so little is known about smolt movements in the ocean, study designs should be developed to assess and test some of the model assumptions concerning behavior. For instance, additional arrays could be added to a design, say, Figure 2.3, to determine the existence of movement off the continental shelf (Figure 3.1). The horizontal arrays (i.e., parallel to the coast) could not be used to quantify the percent of fish that move off the continental shelf but could be used to detect its occurrence.

Another option in testing assumptions is to combine the estimation procedures of both the multiple-array and the replicated-array designs (Figure 3.2). This option permits estimation of detection probabilities at the double arrays by two methods. One approach is the closed Petersen/Lincoln Index approach of Eq. (4); the other approach is to estimate capture rates from the release-recapture model of Section 2.2.1. Only if the assumptions of unidirectional movement, no residualization, and no movement off the continental shelf are true will the two approaches provide comparable estimates of capture probabilities. Hence, this is another and perhaps simpler way of deploying arrays to test assumptions about smolt movement behavior along the continental shelf.

Regardless of deployment design used in smolt survival studies, it is *essential* the model development occur before implementation to assure study objectives can be fulfilled. Joint movement – survival studies are among the most complex and difficult release-recapture studies to design and implement. It is reckless to implement a study without first formally evaluating what can and cannot be statistically estimated. Beyond determining estimability is the need to perform sample size calculations to help assure studies can yield precise and useful information. Hopefully, this report will spur interest in the implementation of quantitatively defensible tag investigations in the estuary and along the continental shelf.

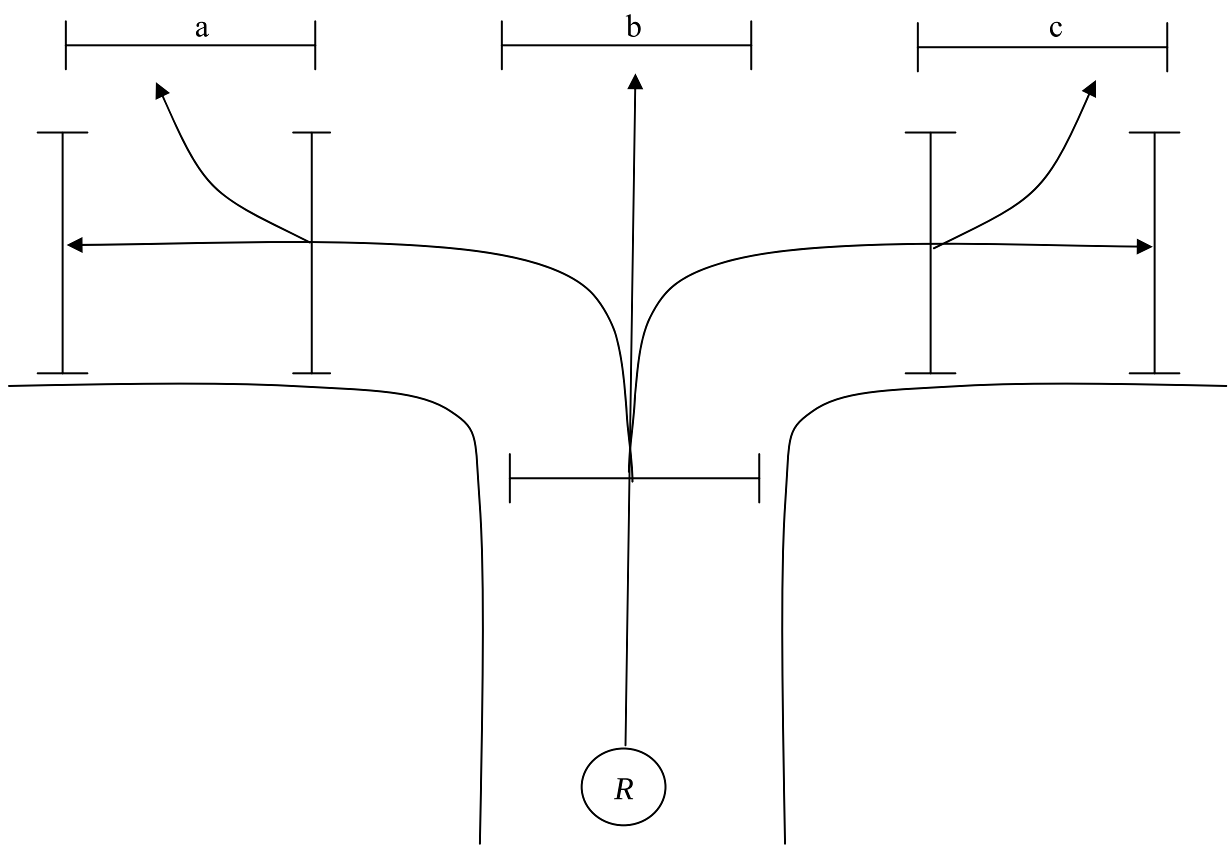

Figure 3.1. Acoustic-array design augmented with additional arrays parallel to the coast (i.e., a, b, c) used to detect movements off the continental shelf.

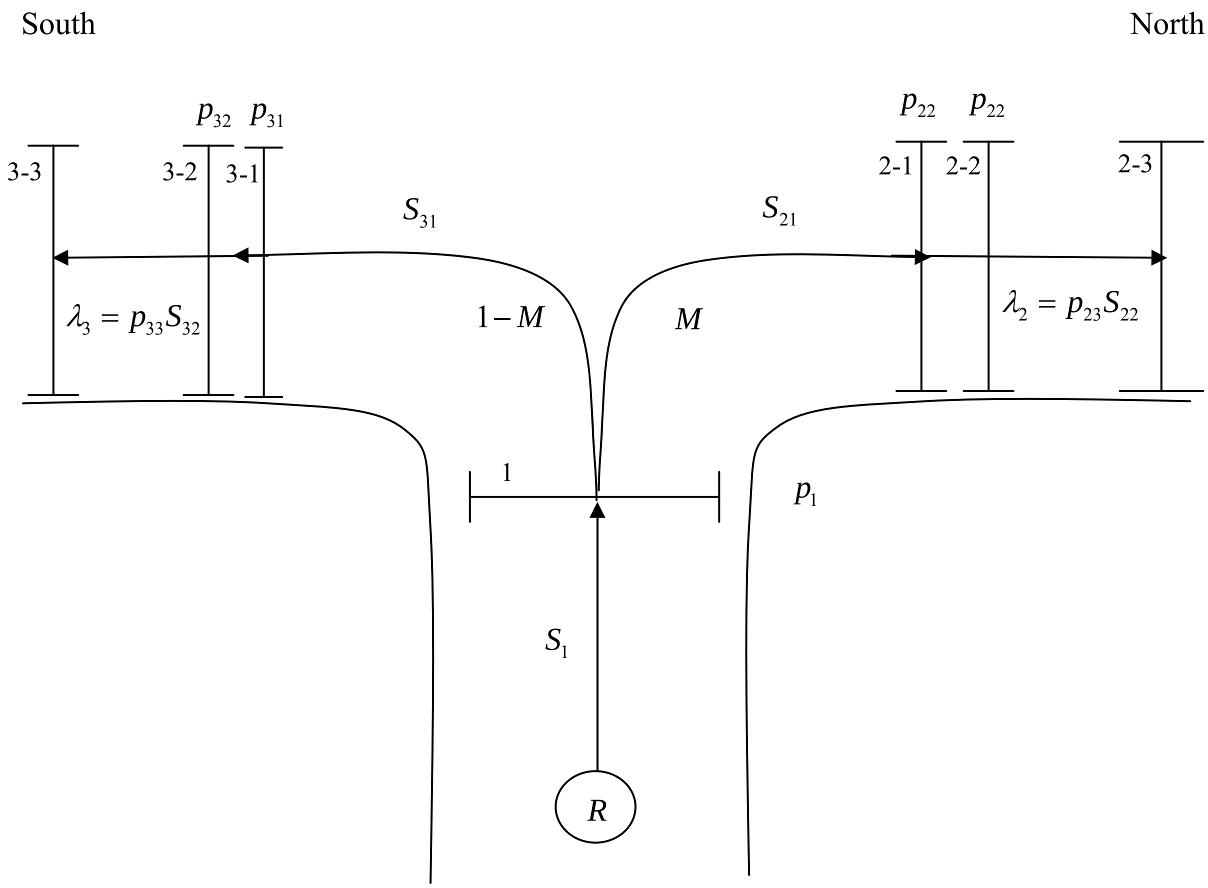

Figure 3.2. An acoustic-array design using the principle of both multiple-array and replicated-array designs useful in independently estimating detection rates of the first northern and southern arrays in two different ways.