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Evaluating alternative methods for monitoring and estimating responses of salmon productivity in the North Pacific to future climatic change and other processes: A simulation study

Brigitte Dorner[a,b,*], Kendra R. Holt[a,1], Randall M. Peterman[a], Chris Jordan[c], David P. Larsen[d], Anthony R. Olsen[e], Omar I. Abdul-Aziz[f,2]

[a] *School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[b] *General Delivery, Lasqueti Island, British Columbia V0R 2J0, Canada*
[c] *NOAA Fisheries, c/o U.S. Environmental Protection Agency, 200 SW 35th St., Corvallis, OR97333, USA*
[d] *Pacific States Marine Fisheries Commission, c/o U.S. Environmental Protection Agency, 200 SW 35th St., Corvallis, OR 97333, USA*
[e] *Western Ecology Division, National Health and Environmental Effects Laboratory, U. S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97333, USA*
[f] *School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195-5020, USA*

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ABSTRACT

We used empirically based simulation modelling of 48 sockeye salmon (*O. nerka*) populations to examine how reliably alternative monitoring designs and fish stock assessment methods can distinguish between changes in density-dependent versus density-independent components of productivity and identify the relative contribution of a climate-driven covariate. We explored a wide range of scenarios for ocean and freshwater conditions and the response of salmon productivity (adult recruits per spawner) to those conditions. Our results show that stock assessments based on historical relationships between salmon productivity and climate-driven oceanographic conditions will likely perform poorly when those relationships change, even when such changes are anticipated and incorporated into stock assessment models in a timely manner. Estimating the relative importance of climate-driven oceanographic influences as a driver of sockeye productivity will be difficult, especially if climatic changes occur rapidly and concurrently with other disturbances. Thus, better understanding of the mechanisms by which climatic changes and other drivers influence salmon productivity may be essential to avoid undesirable management outcomes. As well, an expansion of monitoring of juvenile salmon abundances on more salmon stocks is needed to help distinguish the effects of different drivers.

1. Introduction

Given the prospects for future climatic change and other pressures on salmon habitat, salmon (*Oncorhynchus* spp.) populations that inhabit the Northeastern Pacific Ocean face an uncertain future. Forecasts suggest that salmon from the west coast of North America will generally encounter warmer sea-surface temperatures (SSTs) and different marine conditions than in the past (IPCC, 2007). As well, previously documented decreasing trends in productivity for sockeye salmon (*O. nerka*) stocks ranging from Washington to Southeast Alaska (Peterman and Dorner, 2012) are consistent with, and may be linked to, unfavorable habitat conditions associated with climatic changes. However, the impacts of climatic change are likely complex and potentially confounded with other impacts on productivity caused by existing or future changes to spawning, rearing, and migration habitats, which have also predominantly affected stocks in the southern part of the species' distribution (Marmorek et al., 2011). A good understanding of the relative importance of different causal factors potentially affecting salmon productivity is a key step towards an appropriate management response to current and potential future declines in productivity.

Correlations between past indices of salmon productivity and coastal SST encountered by juveniles have been well documented (Mantua et al., 1997; Mueter et al., 2002a), and SST is therefore a likely candidate for an environmental covariate that can be

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* Corresponding author. Tel.: +1 250 333 8849; fax: +1 250 333 8849.
E-mail addresses: bdorner@driftwoodcove.ca (B. Dorner), kendra.holt@dfo-mpo.gc.ca (K.R. Holt), peterman@sfu.ca (R.M. Peterman), chris.jordan@noaa.gov (C. Jordan), larsen.phil@epa.gov (D.P. Larsen), olsen.tony@epa.gov (A.R. Olsen), oabdulaz@fiu.edu (O.I. Abdul-Aziz).

[1] Current address: Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Rd., Nanaimo, British Columbia, Canada V9T 6N7.

[2] Present address: Department of Civil and Environmental Engineering, Florida International University, 10555 W. Flagler Street, EC3602, Miami, FL 33174 USA.

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incorporated into stock assessment models to capture the effect of climatic changes on ocean conditions and hence salmon productivity. Unfortunately, the mechanisms driving the relationship between salmon productivity and SST are still poorly understood, and the likely effect of changes in SST on any individual stock's productivity is uncertain for several reasons. First, *increases* in early-summer SST (when juvenile sockeye enter the ocean) have historically been associated with *decreases* in productivity for central and southern British Columbia (B.C.) sockeye populations, but with *increases* in productivity of sockeye in the north (Alaska, plus Skeena and Nass populations in B.C.) (Mueter et al., 2002a). Furthermore, that boundary between positive and negative effects of SST on sockeye productivity may be moving northward as climatic change continues and alters ocean conditions (Peterman and Dorner, 2012). In addition, when climatic change drives a marine ecosystem into new conditions not observed in existing SST data sets, the resulting changes in oceanographic currents, timing of spring phytoplankton bloom, and other marine processes could alter the past observed relationships between early-summer SST and salmon productivity. Such a change is quite conceivable because at present, SSTs in marine waters are well below the upper thermal limit for salmon survival and distribution (Welch et al., 1995; Azumaya et al., 2007), so in the relationship between SST and salmon productivity noted above, SST is most likely just an indirect proxy for factors linked to ocean conditions, such as salmon food supply and/or abundance of major predators on salmon (Ware and McFarlane, 1995; Gargett et al., 2001). Thus, the magnitude and direction of effects of changes in SST on sockeye is likely location-dependent and may change in the future.

Making well-informed decisions in the presence of these uncertainties requires large-scale monitoring programs that can capture shifts in salmon response to climatic and other changes through space and time. Such data will help determine the relative importance of multiple, simultaneously operating causal factors on observed changes in salmon populations. For example, estimation of the relative importance of habitat loss and deteriorating oceanographic conditions requires comparison groups composed of several monitored salmon populations located across gradients in habitat loss, ocean conditions, and other potentially confounding factors (e.g., Peterman and Dorner, 2012). Such comparisons require data covering a large spatial extent, yet North American agencies face increasing budget pressures to reduce monitoring, not increase it. Thus, the more coordinated the design of these monitoring programs can be across agencies in different jurisdictions, the more cost-effective they will be at identifying the relative importance of various causes of future changes in salmon productivity and providing advice for appropriate management actions.

To explore large-scale monitoring designs, we draw upon that past experience, as well as the emerging principles and standards for such coordinated monitoring programs (Downes et al., 2002; Roni et al., 2005; the 2010 Salmon Monitoring Advisor web site (www.salmonmonitoringadvisor.org, accessed 6 December, 2011)). Specifically, in this paper, we use empirically based simulation modeling of various large-scale salmon monitoring designs for sockeye salmon populations of the Northeastern Pacific Ocean to examine how different designs affect our ability to estimate population parameters. We also answer questions about the relative influence of oceanographic changes represented by SST versus other factors driving sockeye productivity. We examine each design across a wide range of simulated scenarios about future changes in the factors driving productivity, as well as hypothesized salmon responses to these changes. We also address questions such as, (1) "Are there locations where a strategic increase in monitoring effort (i.e., establishment of new indicator stocks) would be most beneficial?", (2) "How much information could be gained by increasing monitoring effort, and conversely, how much might be lost if budget constraints lead to reduced monitoring?", and (3) "What are the trade-offs among different options for choosing monitoring designs and analysis of the resulting data?"

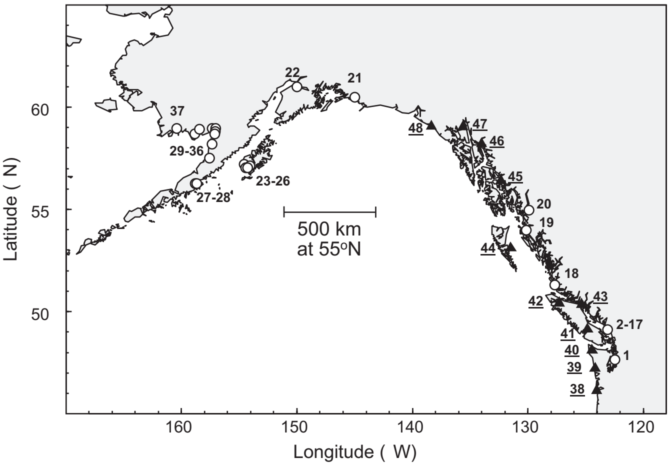

Fig. 1. Locations of the 37 current sampling sites (open circles) and 11 additional sites (solid triangles) that were the sources of time-series data on sockeye salmon spawner abundance and the resulting productivity (adult recruits per spawner). Current sites (1–37) are numbered from south to north. Additional sites (38–48) are underlined numbers. Table S.1 in the online Appendix E identifies all sites by name.

2. Methods

We evaluated the performance of various monitoring designs and their associated parameter estimation methods by first generating future "observed" data (containing noise in the form of observation error and natural variability) using computer simulations. We then used those data to estimate parameters describing salmon dynamics, and finally compared those estimates to the known "true" parameters that were used in the simulations to generate the "observed" data. Within our simulation framework, we considered a comprehensive range of hypothetical, but quite plausible, scenarios about (i) future changes in ocean conditions related to climatic changes, characterized here by summer sea surface temperature (SST), (ii) how salmon populations will respond to a given change in SST, and (iii) the simultaneous occurrence of stock- or watershed-specific declines in productivity through increases in density-dependent and/or density-independent mortality. For example, chemical spills or pathogens transmitted from aquaculture operations might increase density-independent mortality, whereas increased logging and road development could reduce spawning habitat and thus lead to increases in density-dependent mortality.

2.1. Historical salmon and SST data

To simulate projected future changes in salmon production dynamics, we built a model of salmon populations and initialized it based on historical productivity parameters and documented relationships between sockeye salmon productivity and SST. We used previously compiled data sets (Peterman et al., 1998; Mueter et al., 2002b) on annual abundances of spawners and their resulting adult recruits (spawners plus catch) for 37 sockeye salmon stocks from the period 1950 to 1999 (Table 1, Fig. 1). We refer to these 37 stocks as "current" monitoring sites for the purpose of this study. Age composition data identified the appropriate brood year for adult returns (i.e., when their parents spawned). Data series ranged in length from 15 to 47 years, with a median of 43 years. Some of the salmon monitoring designs that we explored involved adding new sockeye salmon indicator stocks in strategic locations. Because our