

## Forecasting Pacific Salmon Production in a Changing Climate: A Review of the 2011–2015 NPAFC Science Plan

\*Shigehiko Urawa<sup>1</sup>, James R. Irvine<sup>2</sup>, Ju Kyoung Kim<sup>3</sup>, Eric C. Volk<sup>4</sup>, Alexander V. Zavolokin<sup>5,6</sup>,  
Tomonori Azumaya<sup>7</sup>, Terry D. Beacham<sup>2</sup>, Alexander V. Bugaev<sup>8</sup>, Edward V. Farley, Jr.<sup>9</sup>, Jeffrey R. Guyon<sup>9</sup>,  
Sang Gyu Kim<sup>10</sup>, Michio J. Kishi<sup>11</sup>, Nataliya V. Klovach<sup>12</sup>, Maxim V. Koval<sup>8</sup>, Do Hyun Lee<sup>13</sup>, Svetlana V. Naydenko<sup>5</sup>,  
Dion S. Oxman<sup>14</sup>, Toshihiko Saito<sup>1</sup>, Shunpei Sato<sup>1</sup>, Mark W. Saunders<sup>2</sup>, Olga S. Temnykh<sup>5</sup>, Arlene M. Tompkins<sup>2</sup>,  
Marc Trudel<sup>2,15</sup>, Vladimir V. Volobuev<sup>16</sup>, Kenneth I. Warheit<sup>17</sup>, and Nancy D. Davis<sup>18</sup>

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**Abstract:** In recent decades, the marine production of Asian and North American Pacific salmon and steelhead populations has undergone significant variability linked to climate change. Improved forecasts of the abundance and distribution of salmon are needed that will benefit stock management in all salmon producing countries around the North Pacific Rim. The North Pacific Anadromous Fish Commission (NPAFC) Science Plan is a long-term comprehensive strategy for international cooperative research. The primary goal of the 2011–2015 Science Plan was to explain and forecast annual variations in Pacific salmon production. The plan was developed with an overarching research theme “Forecast of Pacific Salmon Production in the Ocean Ecosystems under Changing Climate” and five research topics. This paper describes progress made on each research topic and the overarching theme, much of which was assessed at an international symposium in Kobe, Japan, on May 17–19, 2015. In summary, the reliability of stock identification methods including genetic and otolith mark analyses has improved, enabling better monitoring of stock-specific ocean distribution and abundance. Salmon marine survival depends on early marine coastal environments but also on conditions later in life, including winter. Models incorporating fish mortality and various environmental factors improve our ability to forecast returns of specific salmon stocks. However, limitations on our ability to accurately explain and forecast annual variations in Pacific salmon production remain, in part because of uncertainty in the factors responsible for salmon mortality and from the effects of climate warming on the marine distribution and abundance of salmon. It is more important than ever to promote cooperative and innovative international research to identify and better understand the ecological mechanisms regulating the distribution and abundance of salmon populations for sustainable salmon and steelhead management.

**Keywords:** NPAFC Science Plan, review, Pacific salmon, distribution, marine production, survival, biological monitoring, stock identification, models, climate change, forecast

### INTRODUCTION

Over the past several decades, there have been significant variations in the marine production of Asian and North American anadromous salmon populations that are linked to climate change (Beamish et al. 2009). There is a strong need for international cooperative research that provides better scientific information on the ecological mechanisms regulating production of anadromous populations, climate impacts on Pacific salmon populations, and the utility of using salmon populations as indicators of conditions in North

\*Full author affiliation list given at the end of the article.  
All correspondence should be addressed to S. Urawa.  
e-mail: [urawa@afrc.go.jp](mailto:urawa@afrc.go.jp)

the biological characteristics and biomass of anadromous populations, winter open-ocean field research and monitoring programs have been too limited to test it directly. Better information on the status and trends in production and condition of Pacific salmon during the late fall to early spring period and knowledge of the variation in the characteristics of winter marine production in the Western Subarctic Gyre and Gulf of Alaska ecosystems is needed to conserve salmon populations.

Despite the potential importance of winter mortality in regulating the dynamics of salmon abundance, relatively little research has been conducted on the winter ecology of Pacific salmon in the marine environment, due largely to the challenges associated with conducting field work at this time of the year. The knowledge gained during the last five years on the winter ecology of Pacific salmon is based primarily on surveys conducted by Russia in central and western parts of Subarctic Frontal Zone in the winter and spring 2009–2011, a synthesis of surveys conducted by Russia in 1982–1992, and cruises by Canada on the continental shelf from west of Vancouver Island to Southeast Alaska in the fall and winter 2000–2014, much of mm m P

et al. 2016a, b; Shubin and Akinicheva 2016), coded-wire tags (Fisher et al. 2014; Tucker et al. 2015a), acoustic tags (Moore et al. 2012; Brosnan et al. 2014), and genetic stock identification methods (Tucker et al. 2011, 2012a, b; Sato et al. 2013; Shpigalskaya et al. 2013, 2016; Beacham et al. 2014a; Teel et al. 2015; Kondzela et al. 2016a, b). Overall, migration behavior of juvenile salmon has been shown to vary among species, stocks, and life histories (Tucker et al. 2011, 2012a, b; Beacham et al. 2014a; Fisher et al. 2014; Teel et al. 2015). Migration routes may also be genetically programmed (Sharma and Quinn 2012; Tucker et al. 2012a, b; Burke et al. 2013a, b), but the distribution of juvenile salmon along their migration trajectory may be affected by physiological condition such as body size (Hasegawa et al. 2013; Saito et al. 2013; Beacham et al. 2014b; Freshwater et al. 2016) and environmental cues such as water temperature (Kasugai et al. 2011; Urawa 2015; Nagata et al. 2016b), ocean currents (Burke et al. 2013a; Chistyakova and Bugaev 2016), phytoplankton biomass (Bi et al. 2008; Peterson et al. 2010), location of river mouths (Burke et al. 2014), and magnetic cues (Putman et al. 2014). Furthermore, migration behavior of hatchery and wild fish appears to be different at small scales during early marine life (Moore et al. 2012), but similar over larger scales (Tucker et al. 2011). The distribution and inshore-offshore movements of juvenile salmon may also be linked to food availability, zooplankton community succession, and the geomorphology of juvenile salmon habitat (Frenkel et al. 2013; Koval and Morozova 2013; Morozova 2013).

#### *Hydrological Characteristics, Primary Production and Prey Resources in Juvenile Salmon Habitats*

Our understanding of the dynamics of zooplankton communities in Russia's far-eastern seas and adjacent waters has been enhanced by the creation of the TINRO-Center zooplankton database. Data analyses revealed that important juvenile salmon prey items such as euphausiids, amphipods, pteropods, and appendicularians have generally larger biomass in the western North Pacific Ocean compared to the eastern North Pacific Ocean and exhibit different trends between basins (Shuntov and Temnykh 2011a). Zooplankton biomass appeared to have varied inversely between the Bering Sea and Okhotsk Sea from 1980 to the early 2000s (Shuntov and Temnykh 2011a). Changes in zooplankton community composition and abundance have been linked to

et al. 2015; Plumb and Moffitt 2015). This research has shown that the optimal temperature for growth was much higher than previously thought. It is important, however, to note that these parameters were also derived for freshwater environments. Consequently, further effort is needed to parameterize these models for juvenile salmon in the marine environment.

#### *Ecological Interactions of Juvenile Salmon*

Juvenile salmon may interact with other salmon species or populations through competition or predation (Hasegawa et al. 2014). Competition is expected to be more intense among species that share similar prey, such as juvenile pink, chum, and sockeye salmon, and may be modulated by the presence of parasites (Godwin et al. 2015). Competition between wild and hatchery fish may be asymmetrical (Beamish et al. 2008, 2010) and is likely more intense in offshore waters as recent studies also indicate that hatchery and wild salmon often feed on different prey in the nearshore environment but feed on similar prey offshore (Sweeting and Beamish 2009; Daly et al. 2012; Sturdevant et al. 2012b). Stable isotope analyses have recently shown that the diet overlap between juvenile pink and chum salmon increased as their abundance increased, suggesting that competitive interactions were stronger at higher densities (Jenkins et al. 2013). Although an increase in the biomass of juveniles

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juvenile chum salmon when they migrate into the coastal ocean because the heavy parasite infection disturbs the osmoregulation of juveniles (Urawa 1993, 1996, 2013).

It is generally thought that large and fast-growing fish have higher survival, either because large fish are less vulnerable to gape-limited predators or can sustain starvation (i.e., in winter) for longer periods of time (Beamish and Mahnken 2001). However, while larger and fast-growing salmon have frequently been found to have a survival advantage over small and slow-growing juvenile salmon (Duffy and Beauchamp 2011; Farley et al. 2011; Tomaro et al. 2012; Irvine et al. 2013; Woodson et al. 2013; Zavolokin and Strezhneva 2013; Miller et al. 2014b), size-selective mortality has not always been apparent during either summer or winter in juvenile salmon (Welch et al. 2011; Trudel et al. 2012). Furthermore, a negative relationship between adult returns and juvenile salmon growth has also been observed (Miller et al. 2013), indicating that other factors may override the effects of large size and fast growth on the marine survival of juvenile salmon.

Survival mechanisms have also been inferred indirectly through correlational studies of smolt survival with climatic and oceanographic conditions. These analyses have been performed using simple tools such as linear regression models (Tanasichuk and Routledge 2011; Tucker et al. 2015b) as well as more sophisticated approaches such as the maximum covariance analysis (Burke et al. 2013b), Bayesian Belief Network (Araujo et al. 2013; Malick et al. 2015a; Hertz et al. 2016a), and state-space models (Ye et al. 2015). It should be remembered though, that no matter how sophisticated the analysis, correlation does not mean causation (Peters 1991), and correlations often break down over time (Skud 1983; Walters and Collie 1988). Nevertheless, correlation analyses have helped to generate and test a number of hypotheses relating salmon survival to ocean conditions, including changes in prey availability (Tanasichuk and Routledge 2011; Wells et al. 2012; Doubleday and Hopcroft 2015; but see Shuntov and Temnykh 2011a, b; Radchenko et al. 2013), the timing of prey availability (Malick et al. 2015b; Satterthwaite et al. 2015), prey quality (Peterson et al. 2014; Tucker et al. 2015b), and climate (Killduff et al. 2015; Hertz et al. 2016a). If correlations break down over time, it may simply indicate that other factors not initially considered may contribute to the dynamics of salmon populations, and thereby lead to the generation of new hypotheses and theories of salmon production. A more holistic approach that simultaneously accounts for the interactions of multiple factors may be necessary to understand the complex interactions between climate, marine ecosystems, and salmon.

#### *Population Size and Carrying Capacity of Juvenile Salmon*

The number of salmon that can be sustained in the North Pacific Ocean has long been a component of NPAFC-related research. Estimation of this number requires knowledge of the abundance of juvenile salmon in the marine environment, their feeding rates, the availability and production of their

prey, and the abundance and feeding rates of other species that may be eating the same prey. Research conducted by Russian scientists suggest that the size of juvenile salmon is large when their abundance is high and small when their abundance is low, which is contrary to expectations from density-dependent interactions when food is limiting (Shuntov and Temnykh 2011a; Zavolokin 2013). Bioenergetic model calculations indicate that juvenile salmon consume only a small proportion of the available zooplankton biomass, suggesting that salmon abundance and size may not be limited by competition (Orsi et al. 2004). In contrast to these findings, the size of juvenile pink and chum salmon was inversely related to their abundance on the west coast of North America (Jenkins et al. 2013). The intensity of competitive interactions may also vary among regions of the North Pacific Ocean. Notably, the western North Pacific Ocean is thought to be more productive than the eastern North Pacific Ocean (Saito et al. 2011) and may therefore support higher salmon biomass (PICES 2005; Shuntov and Temnykh 2011a).

#### **Winter Period**

##### *Winter Distribution of Salmon*

Myers et al. (2016) reviewed winter salmon research on the high seas of the North Pacific Ocean and Bering Sea. Early high-seas research (1950s–1970s) established that salmon exhibit broad seasonal (north–south) movements, that there are stock-specific marine distributions, and identified dominant oceanographic features of the winter habitat. In succeeding decades (1980–2015), new fisheries-oceanographic survey methods, stock-identification techniques, remote-sensing technologies, and analytical approaches enabled researchers to expand their knowledge of the winter distribution and ecology of salmon, although empirical data remain limited.

The winter distribution of salmon is “complex and variable, depending on spatiotemporal scale and synergies among genetics, environment, population dynamics, and phenotypic plasticity” (Myers et al. 2016). For instance, the winter distribution of Pacific salmon in the open ocean depends on the general state of the Western Subarctic Cyclonic Gyre and on the position of the frontal zone of the East Kamchatka current ocean branch sector (Figurkin and Naydenko 2013, 2014). New data on the vertical distribution of Pacific salmon during winter and spring indicate that they are more dispersed in the water column compared to summer and fall (Starovoytov et al. 2010a, b; Glebov et al. 2011). Pink salmon are distributed across a wide range of temperatures during winter (0.5–11.5°C), whereas sockeye and coho salmon tend to occupy cooler (1.5–6.5°C) and warmer (4.0–11.5°C) waters, respectively. Most small chum salmon (< 30 cm FL) are distributed in the Subarctic Front Zone between 3°C and 8°C, while larger chum salmon shift to cooler water with a peak at 4.5°C (Naydenko et al. 2016). Urawa et al. (2016) summarized that the SST of pink and chum salmon winter

the western subarctic water during the winters of 1996, 1998 and 2006, while the SST of the winter habitat in each area was stable across the three years. These observations suggest that salmon select similar temperature regimes each winter, despite variable SST in the western subarctic waters.

Few salmon species remain on the continental shelf during winter. On the west coast of North America, winter catches of salmon are dominated by immature Chinook and coho salmon (Trudel et al. 2007; Tucker et al. 2011, 2012a, b), although one population of sockeye salmon remains on the continental shelf during winter (Tucker et al. 2009; Beacham et al. 2014a, b). Stock composition appears relatively stable among years despite highly variable ocean conditions, even at a small geographic scales, suggesting that their coastal distribution is genetically programmed (Tucker et al. 2012a, 2015a). Unlike in the open ocean, juvenile/immature salmon tend to be caught deeper in the water column during wintertime (Orsi and Wertheimer 1995; Trudel and Tucker

Lipid dynamics during winter has been rarely examined in juvenile salmon. The total muscle lipid content of age-0.1 chum salmon in the Gulf of Alaska was extremely low, suggesting fish malnutrition during winter (Kaga et al.

## CLIMATE CHANGE IMPACTS ON SALMONID PRODUCTION AND THE MARINE ECOSYSTEM

Climate change and its impact on salmon carrying capacity in the Bering Sea have been investigated through the Bering-Aleutian Salmon International Survey (BASIS) program initiated by NPAFC in 2001. Evidence has linked increased levels of atmospheric carbon dioxide to warming air and sea temperatures, reduced sea ice extent during winter, and melting of the polar cap in the Arctic region (Bond et al. 2008); and it has been suggested that climate change will alter the current geographic distributions and behaviors of humans, marine mammals, seabirds, and fish by restructuring their habitats within the Bering Sea ecosystem (NPRB 2007). However, there are mixed opinions regarding the effects of climate change on Bering Sea ecosystems, with some studies indicating no direct effect on the ecosystem (e.g., Shuntov and Temnykh 2009), and others suggesting reduced ecosystem productivity with increasing sea surface temperatures (Coyle et al. 2008, 2011).

### Climate-ocean and Biological Factors Related to Salmon and Ecologically Related Species

The extent and duration of winter and spring sea ice along the eastern Bering Sea shelf plays a key role in structuring the ecosystem. Interannual variability in spring sea ice extent over the shelf has recently given way to “stanzas” of warm and cold events (Overland 2011). These stanzas have had profound effects on the ecosystem by restructuring the types and abundances of zooplankton and fish communities, and fitness of fishes along the shelf (Stabeno et al. 2012a, b). For example, Pacific salmon research under BASIS covered two periods: warm (2003–2006) and cold (2007–2012). During the warm period, small- and medium-sized zooplankton dominated in the eastern Bering Sea (Stabeno et al. 2012b). During the cold period, the portion of large-sized zooplankton (euphausiids, hyperiids, copepods, and chaetognaths) significantly increased. These changes in zooplankton communities were reflected in Pacific salmon diets (Farley et al. 2007). During the warm period, most of the diet of pink, chum, and sockeye salmon juveniles comprised



**Influence of Climate-ocean Conditions on Biological Parameters of Salmon**

The body size of most Russian chum salmon stocks, particularly Anadyr chum salmon, decreased significantly from 1960 to the 2000s (Zavolokin et al. 2011; Temnykh et al. 2012). As estimated from scale measurements, first-year growth increased, but third and fourth year growth

unusual mortality event of large whales in the western Gulf of Alaska (NOAA 2016), and population losses of gulls, puf-

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less abundant than their historical levels, while inter-annual patterns of sockeye salmon abundance vary greatly among regions.

Over the long term (1926–2010), odd-year pink salmon have become increasingly dominant over even-year returning fish, particularly in the southeastern portion of their range (Irvine et al. 2014). In Asia, Russian pink salmon catches increased since the 1990s in Chukotka (Khokhlov 2012), west and east Kamchatka (Karpenko and Koval 2012), Sakhalin-Kuril region (Kaev 2012; Kaev and Irvine 2016), and the northwestern coast of the Okhotsk Sea, including the Amur River basin (Klovach et al. 2014, 2015). In contrast, there are relatively few pink salmon in Japan, which is near the southern extent of their distribution in the western North Pacific Ocean. Their adult returns have declined dramatically since 2011, which may be associ-

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northern Honshu (Saito and Nagasawa 2009). To clarify regional differences in biological characteristics of chum salmon in Japan, Saito et al. (2015) reviewed adult returns (coastal and river catches), peak timing of upriver migration (PUM), coastal sea surface temperature at the PUM, fork length of age-4 adults, age at maturity, egg diameter, and fecundity of age-4 females for seven regional populations monitored between 1994 and 2008. All biological characteristics showed clear differences among the regions or between some pairs of regions, and some characteristics appeared to change along latitudinal gradients. In particular, the values for PUM, fork length, age at maturity, and egg diameter in river stocks along the Sea of Japan coast exhibited an abrupt change at the boundary of the Tsugaru Strait. In Hokkaido, the PUM was earlier than before the 1960s, probably resulting from artificial alterations of the run timing in many stocks. Consequently, the advanced PUM resulted in fish experiencing higher sea temperatures during their spawning migration. Standardized egg diameters decreased over the study period, although a problem in the dataset might have influenced the apparent trend. Takahashi (2015) also reviewed trends in artificial enhancement activities (timing of spawning operations, effective population size, timing of fry releases, and body size of released fry) among seven regional populations of chum salmon. Monitoring programs such as these have proved indispensable to identify future directions to maintain Japanese chum salmon populations: (1) better understand the features of each regional population, (2) conserve the diversity of each population, and (3) identify optimal timing of fry releases and body sizes to maximize their survival in the changing ocean environments.

Commercial chum salmon catches increased after 1990 in Prince William Sound and Southeast Alaska, following the start of modern hatcheries in Alaska in the late 1970s (Heard and Wertheimer 2012). In Kodiak, chum salmon catches varied widely before hatcheries were built, but subsequently increased (Heard and Wertheimer 2012). In Southeast Alaska, commercial catches of chum salmon have comprised primarily hatchery fish, and estimated catches of wild chum salmon have recently declined to levels similar to those of the 1970s (Piston and Heintz 2012). Population abundance of chum salmon originating in the Columbia River and southward to Newport, Oregon, is highly variable and has fallen more than 80% from historic levels (Johnson et al. 2012).

During 1971–2010, sockeye salmon catches increased in west and east Kamchatka (Karpenko and Koval 2012). In 2013, Russian sockeye catches exceeded 50 thousand metric tonnes, which was almost a historic high (NPAFC 2016a). In Bristol Bay, Alaska, commercial fishing has reduced sockeye salmon population diversity (Schindler et al. 2010). Decreasing trends in productivity for sockeye salmon have occurred since 1950 across a large geographic area ranging from Washington, British Columbia, Southeast Alaska, and up through the Yakutat peninsula, Alaska, but not in central and western Alaska (Peterman and Dorner 2012). In the Fra-

ser River, the total returns of sockeye salmon in 2009 were the lowest recorded since quantitative records began in the late 1940s (Beamish et al. 2012), but one of the strongest sockeye returns was recorded in 2010 (Irvine and Akenhead 2013; McKinnell et al. 2014).

Contrary to the upward trends in pink, chum, and sockeye salmon abundance, many populations of coho, Chinook, and cherry (masu) salmon have been declining. Although reasons for the high production of pink and chum salmon are not fully understood, these species appear to have benefited more than other species from favorable conditions: (1) changing environmental factors; (2) biological and life-history characteristics of pink and chum salmon allowing these species to benefit from changing conditions; and (3) human activities including stock enhancement and responsible fisheries management (Davis and Beamish 2012).

### Annual Regional Production of Hatchery and Wild Salmon

Total North Pacific salmon hatchery releases have been fairly stable during the last 28 years at approximately 5 billion fish (Fig. 2). Asian hatchery production has generally been > 2.5 billion releases since 1981, with the exception of reduced chum salmon releases that was linked to the Great East Japan earthquake in 2011. Asian hatchery releases are predominately chum salmon.

North American hatchery production has exceeded 2 billion releases since 1988. Pink and chum salmon are the primary species released from North American hatcheries, mainly from Alaska. The relatively large numbers of enhanced Canadian sockeye salmon are produced in spawning channels, not hatcheries. Hatcheries in Washington, Oregon, California, and Idaho produce mostly Chinook salmon.

Provisional abundance of pink, chum, and sockeye salmon in major regions of the North Pacific from 1952 through 2015 were recently estimated (Irvine and Ruggerone 2016). Estimates included numbers and biomass of natural-origin and hatchery-origin salmon returns (i.e., catch plus escapement) by species, as well as total biomass that included immature salmon. Temporal abundance patterns generally followed commercial catch patterns. The proportion of hatchery-origin chum salmon abundance peaked in the late 1990s at ~70%, and is currently ~45%. Hatchery-origin pink and sockeye salmon currently constitute ~19% and ~4% of the total returns for these species, respectively (Irvine and Ruggerone 2016). These values are similar to ones provided in earlier estimates by Kaeriyama et al. (2012) who estimated hatcheries contributed 50% of the biomass of chum salmon, more than 10% for pink salmon, and less than 10% for sockeye salmon. Total abundance and biomass of adult pink, chum, and sockeye salmon peaked in 2009 (910 million fish; 1.7 million metric tonnes), while the total biomass including immature fish exceeded 5 million metric tonnes in 2009 and again in 2013 (Irvine and Ruggerone 2016).



## DEVELOPMENT AND APPLICATIONS OF STOCK IDENTIFICATION FOR SALMONID POPULATION MANAGEMENT

Genetic baselines for salmon are needed to monitor stock-specific ocean distributions and abundance as well as to produce more accurate estimates of the timing and abundance of adults returning to coastal rivers. High-seas tagging and otolith-mark programs, in addition to those provided by genetic analysis, are also important to examine migration behavior of specific populations.

### Development of Genetic Baselines

Genetic baselines for salmon throughout the Pacific Rim have been developed for chum salmon using microsatellites (Beacham et al. 2009a) and single nucleotide polymorphisms (SNPs; Seeb et al. 2011) to assess population structure. Beacham et al. (2009a, b) reported that the most genetically diverse chum salmon were observed from Asia, particularly Japan, whereas chum salmon from the Skeena River and Queen Charlotte Islands in northern British Columbia and those from Washington State displayed the least genetic variation compared with chum salmon in other regions. Seeb et al. (2011) reported that variable linkage relationships between SNPs were associated with ancestral groupings and that outlier loci displayed alleles associated with latitude. The population structure of chum salmon has been investigated in Japan using allozyme (Sato and Urawa 2015), mitochondrial DNA (Tsukagoshi et al. 2016), and SNPs (Sato et al. 2014), and in Washington using SNPs (Small et al. 2015). Sato et al. (2014) reported the presence of eight regional groups of chum salmon in Japan, with six groups in Hokkaido and two groups in Honshu. Using 10 microsatellite loci, Chen et al. (2005) detected two groups of chum salmon in northwest China. Small et al. (2015) reported that similar to the genetic patterns detected with microsatellites and allozymes, genetic variation with SNPs followed a regional structure along geographic distance, with genetic diversity being highest in the north and decreasing southward, then increasing in and near the Columbia River. Within Puget Sound, Washington, genetic variation was structured further according to run timing (fall, summer, and winter) and shared ancestry.

Asian and North American chum salmon stocks mix frequently in offshore waters especially after the first year of ocean life. Pacific Rim genetic baselines have been used to estimate the stock composition of chum salmon caught in the Bering Sea and North Pacific during summer and fall (Kondzela et al. 2009, 2016a, b; Moriya et al. 2009; Sato et al. 2009a; Urawa et al. 2009), and in subarctic waters and the Gulf of Alaska during winter (Sato et al. 2006, 2007; Beacham et al. 2009b; McCraney et al. 2012; Urawa et al. 2016). These genetic analyses have contributed to estimating the stock-specific distribution and abundance of chum salmon in

Chinook salmon by microsatellite analysis (Van Doornik et al. 2011; Moran et al. 2013; Teel et al. 2015). Teel et al. (2015) developed a coast-wide microsatellite baseline to investigate stock-specific distributions of juveniles occupying coastal habitats extending from coastal Oregon to northern

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reported that the southern population, including Sakhalin stock, was dominant (58%), followed by the northern population (24%; west Kamchatka and north Okhotsk Sea stocks) and the Amur/Primorye population (17%).

### **Disk Tag and Data Storage Tag Recoveries**

The NPAFC database of disk tag recoveries has been summarized (NPAFC Secretariat 2012) and will be publically available at the NPAFC web site. These data on known ocean distributions of juvenile, immature, and maturing salmon and steelhead are a valuable resource to examine changes in ocean distributions.

Data storage tag (DST) tagging experiments on high seas salmon and steelhead trout from the late 1990s to the late 2000s were conducted by the High Seas Salmon Research Program of the University of Washington. Various electronic tags recorded information such as water temperature, depth, and conductivity experienced by the salmon during its movements and migrations at sea. The High Seas Research Program provided the DST data files to NPAFC, and these files are available for download (NPAFC Secretariat 2014). Although some tags did not successfully complete their data mission, a total of 92 DSTs was recovered from 38



ment of genetic baselines encompassing the species range of Chinook, coho, chum, sockeye, pink salmon (odd- and even-year), and steelhead trout. High-quality marker development will continue to be important for accurate delineation of stocks. Such baselines are critical to inform our understanding of stock composition collected on the high seas and to improve migration models. Refinements in models will come from future studies that include development of the following: (1) higher throughput genotyping methods for stock composition analysis, potentially taking advantage of next generation DNA sequencing methodologies; (2) parental-based tagging methods for identifying hatchery stocks; and (3) additional statistical protocols for the analysis of fisheries stock composition data.

## **FORECASTING SALMONID PRODUCTION AND LINKED ECOSYSTEMS IN A CHANGING CLI**

Annual timing of adult Yukon River Chinook salmon exiting the marine environment and entering the Yukon River was related to modelled sea surface temperature, air temperature, and sea-ice cover within the north-eastern Bering Sea where the best linear model explained 59% of the annual variability in migratory timing (Mundy and Evenson 2011). The model suggests that changes in phenology of high-latitude Chinook salmon could occur in response to global warming. The 13-year time series of late summer integrated ecosystem surveys in the northern Bering Sea (BASIS) have also provided a wealth of information on juvenile Yukon River Chinook salmon ecology (Murphy et al. in press). Foremost, the surface trawl catch data, mixed layer depth adjustments, and genetic stock mixtures have been used to estimate juvenile abundance of Canadian-origin Yukon River Chinook salmon in the northern Bering Sea. This combination of information

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## REFERENCES

Abdul-Aziz, O.I., N.J. Mantua, and K.W. Myers. 2011. Potential climate change impacts on thermal habitats of

Beamish, R.J. 2012b. A proposal to establish an International Year of the Salmon. N. Pac. Anadr. Fish Comm. Doc. 1425. 16 pp. (Available at [www.npafc.org](http://www.npafc.org)).

Beamish, R.J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural reg # - r

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- years on the Eastern Bering Sea shelf. *J. Mar. Biol.* doi:10.1155/2009/640215.
- Farley, E.V., Jr., J.M. Murphy, M. Adkison, and L. Eisner. 2007. Juvenile sockeye salmon distribution, size, condition and diet during years with warm and cool spring sea temperatures along the eastern Bering Sea shelf. *J. Fish Biol.* 71: 1145–1158.
- Farley, E.V., Jr., J.M. Murphy, J. Moss, A. Feldmann, and L. Eisner. 2009. Marine ecology of western Alaska juvenile salmon. *Am. Fish. Soc. Symp.* 70: 307–330.
- Farley, E.V., Jr., A. Starovoytov, S. Naydenko, R. Heintz, M. Trudel, C. Guthrie, L. Eisner, and J. Guyon. 2011. Implications of a warming eastern Bering Sea for Bristol Bay sockeye salmon. *ICES J. Mar. Sci.* 68: 1138–1146.
- Farley, E.V. Jr., A. Starovoytov, S. Naydenko, R. Heintz, M. Trudel, C. Guthrie, L. Eisner, and J.R. Guyon. 2013. Implications of a warming Bering Sea for Bristol Bay sockeye salmon. *N. Pac. Anadr. Fish Comm. Tech. Rep.* 9: 255–258. (Available at [www.npafc.org](http://www.npafc.org)).
- Ferriss, B.E., M. Trudel, and B.R. Beckman. 2014. Assessing marine pelagic ecosystems: regional and inter-annual trends in marine growth rates of juvenile salmon of the British Columbia Coast. *Mar. Ecol. Prog. Ser.* 503: 247–261.
- Figurkin, A.L., and S.V. Naydenko. 2013. Spatial distribution of pink salmon in the Subarctic Front Zone in winter-spring. *Izv. TINRO* 174: 69–84. (In Russian with English abstract).
- Figurkin, A.L., and S.V. Naydenko. 2014. Spatial distribution of pink salmon in the Subarctic Front Zone in winter and spring. *N. Pac. Anadr. Fish Comm. Doc.* 1507. 21 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Fisher, J.P., L. Weitkamp, D.J. Teel, S.A. Hinton, J.A. Orsi, E.V. Farley, Jr., J.F.T. Morris, M.E. Thiess, R.M. Sweeting, and M. Trudel. 2014. Early ocean dispersal patterns of Columbia River Chinook and coho salmon. *Trans. Am. Fish. Soc.* 143: 252–272.
- Frenkel, S.E., B.P. Smirnov, and A.V. Presnyakov. 2013. Characteristics of zooplankton at the coast of Iturup Island in the time of salmon juveniles of f-shore migration. *Izv. TINRO* 172: 89–195. (In Russian with En
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- Pac. Anadr. Fish Comm. Tech. Rep. 9: 54–58. (Available at [www.npafc.org](http://www.npafc.org)).
- Kishi, M.J., K. Awa, T. Miwa, H. Ueno, and T. Nagasawa. 2012. Ecosystem approach for management of artificial release of chum salmon from Japan based on a bioenergetic model coupled with NEMURO. N. Pac. Anadr. Fish Comm. Tech Rep. 8: 117–120. (Available at [www.npafc.org](http://www.npafc.org)).
- Klimov, A.V., P. Lozovoy, and I.V. Zhiganova. 2013. Behavioral and biochemical adaptations of juvenile Pacific salmon in the Okhotsk Sea and northwestern Pacific Ocean. N. Pac. Anadr. Fish Comm. Tech. Rep. 9: 131–135. (Available at [www.npafc.org](http://www.npafc.org)).
- Kline, T.C., Jr. 2010. Stable carbon and nitrogen isotope variation in the northern lampfish and *Neocalanus*, marine survival rates of pink salmon, and meso-scale eddies in the Gulf of Alaska. Prog. Oceanogr. 87: 49–60.
- Kline, T.C., Jr., J.L. Boldt, E.V. Farley, Jr., L.J. Haldorson, and J.H. Helle. 2008. Pink salmon (*Oncorhynchus gorbuscha*) marine survival rates reflect early marine carbon source dependency. Prog. Oceanogr. 77: 194–202.
- Klovach, N.V., O.S. Temnykh, V.A. Shevlyakov, A.V. Bugaev, A.M. Kaev, and V.V. Volobuev. 2014. Biostatistical information on salmon catches, escapement and enhancement production in Russia in 2013. N. Pac. Anadr. Fish Comm. Doc. 1502. 4 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Klovach, N.V., O.S. Temnykh, V.A. Shevlyakov, E.V. Golub, A.N. Kanzeparova, E.A. Shevlyakov, A.M. Kaev, and V.V. Bbodrod (

- Krkošek, M., B.M. Connors, A. Morton, M.A. Lewis, L.M. Dill, and R. Hilborn. 2011b. Effects of parasites from salmon farms on productivity of wild salmon. *Proc. Natl. Acad. Sci.* 108(35): 14700–14704.
- Larson, W.A., F.M. Utter, K.W. Myers, W.D. Templin, L.E. Seeb, C.M. Guthrie III, A.V. Bugaev, and L.W. Seeb. 2013. Single-nucleotide polymorphisms reveal distribution and migration of Chinook salmon (*Oncorhynchus tshawytscha*) in the Bering Sea and North Pacific Ocean. *Can. J. Fish. Aquat. Sci.* 70: 128–141.
- Larson, W.A., J.E. Seeb, C.E. Pascal, W.D. Templin, and L.W. Seeb. 2014. Single-nucleotide polymorphisms (SNPs) identified through genotyping-by-sequencing improve genetic stock identification of Chinook salmon (*Oncorhynchus tshawytscha*) from western Alaska. *Can. J. Fish. Aquat. Sci.* 71: 698–708.
- Malick, M.J., S.P. Cox, R.M. Peterman, T.C. Wainwright, and W.T. Peterson. 2015a. Accounting for multiple pathways in the connections among climate variability, ocean processes, and coho salmon recruitment in the Northern California Current. *Can. J. Fish. Aquat. Sci.* 72: 1–13.
- Malick, M.J., S.P. Cox, F.J. Mueter, and R.M. Peterman. 2015b. Linking phytoplankton phenology to salmon productivity along a north–south gradient in the Northeast Pacific Ocean. *Can. J. Fish. Aquat. Sci.* 72: 697–708.
- Marty, G.D., S.M. Saksida, and T.J. Quinn II. 2010. Relationship of farm salmon, sea lice, and wild salmon populations. *Proc. Natl. Acad. Sci.* 107: 22599–22604.
- McClelland, E.K., T.J. Ming, A. Tabata, T.D. Beacham, R.E. Withler, and K.M. Miller. 2013. Patterns of selection and allele diversity of class I and class II major histocompatibility loci across the species range of sockeye salmon (*Oncorhynchus nerka*
-

potential of juvenile pink salmon (*Oncorhynchus gorbuscha*) in the Gulf of Alaska. Deep Sea Res. II 56: 2553–2559.

Moss, J.H., E.V. Farley, Jr., A.M. Feldmann, and J.N. Ianelli.  
2009b. Spatial distribution,  $q_{r\_}$   $q_{r\_}$

- NPAFC (North Pacific Anadromous Fish Commission) Secretariat. 2014. Data files from data storage tags placed on Pacific salmon and steelhead trout by the High Seas Salmon Research Program, University of Washington. N. Pac. Anadr. Fish Comm. Doc. 1512. 19 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- NPAFC (North Pacific Anadromous Fish Commission). 2016a. N. Pac. Anadr. Fish Comm. Pacific salmonid catch statistics (updated 20 July 2016). (Available at [www.npafc.org](http://www.npafc.org)).
- NPAFC (North Pacific Anadromous Fish Commission). 2016b. N. Pac. Anadr. Fish Comm. Pacific salmonid hatchery release statistics (updated 20 July 2016). (Available at [www.npafc.org](http://www.npafc.org)).
- NPRB (North Pacific Research Board). 2007. The Bering Sea Integrated Ecosystem Research Plan (BSIERP). North Pacific Research Board. Anchorage, Alaska. 2 pp.
- Orsi, J.A., and N.D. Davis. 2013. Migration and survival mechanisms of juvenile salmon and steelhead in ocean ecosystems: the workshop synopsis. N. Pac. Anadr. Fish Comm. Tech. Rep. 9: 274–279. (Available at [www.npafc.org](http://www.npafc.org)).
- Orsi, J.A., and E.A. Fergusson. 2015. Annual survey of juvenile salmon, ecologically-related species, and biophysical factors in the marine waters of southeastern Alaska, May–August 2014. N. Pac. Anadr. Fish Comm. Doc. 1617. 64 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Orsi, J.A., and A.C. Wertheimer. 1995. Marine vertical distribution of juvenile Chinook salmon and coho salmon in southeastern Alaska. *Trans. Am. Fish. Soc.* 124: 159–169.
- Orsi, J.A., A.C. Wertheimer, M.V. Sturdevant, E.A. Fergusson, D.G. Mortensen, and B.L. Wing. 2004. Juvenile chum salmon consumption in marine waters of southeastern Alaska: a bioenergetics approach to implications of hatchery stock interactions. *Rev. Fish Biol. Fish.* 14: 335–359.
- Orsi, J., A. Piston, E. Fergusson, and J. Joyce. 2014. Biological monitoring of key salmon populations: Southeast Alaska pink salmon. N. Pac. Anadr. Fish Comm. Newsletter 36: 13–19. (Available at [www.npafc.org](http://www.npafc.org)).
- Orsi, J.A., E.A. Fergusson, A.C. Wertheimer, E.V. Farley, Jr., and P.R. Mundy. 2016. Forecasting pink salmon production in Southeast Alaska using ecosystem indicators in times of climate change. N. Pac. Anadr. Fish Comm. Bull. 6: xxx–yyy. (Available at [www.npafc.org](http://www.npafc.org)).
- Osterback, A.-M.K., D.M. Frechette, S.A. Hayes, M.H. Bond, S.A. Shafer, and J.W. Moore. 2014. Linking individual size and wild and hatchery ancestry to survival and predation risk of threatened steelhead (*Oncorhynchus mykiss*). *Can. J. Fish. Aquat. Sci.* 71: 1877–1887.
- Overland, J.E. 2011. Potential Arctic change through climate amplification processes. *Oceanography* 24: 176–185.
- Park, Y., and K.E. Hong. 2013. A brief on Korean chum salmon: past and future. N. Pac. Anadr. Fish Comm. Newsletter 33: 14–16. (Available at [www.npafc.org](http://www.npafc.org)).
- Parker, R.R. 1968. Marine mortality schedules of pink salmon of the Bella Coola River, central British Columbia. *J. Fish. Res. Board Can.* 25: 757–794.
- Peacock, S.J., B.M. Connors, M. Krkošek, J.R. Irvine, and M.A. Lewis. 2013. Can reduced predation offset negative effects of sea louse parasites on chum salmon? *Proc. Roy. Soc. B.* 281: 20132913. doi:10.1098/rspb.2013.2913.
- Pearcy, W.G. 1992. Ocean ecology of North Pacific salmonids. Univ. Washington Press, Seattle. 179 pp.
- Perry, R.W., J.M. Plumb, and C.W. Huntington. 2015. Using a laboratory-based growth model to estimate mass- and temperature-dependent growth parameters across populations of juvenile Chinook salmon. *Trans. Am. Fish. Soc.* 144: 331–336.
- Peterman, R.M. 1982. Model of salmon age structure and

- Strait of Georgia from 1960 to 2010. *Prog. Oceanogr.* 115: 28–40.
- Putman, N.F., K.J. Lohmann, E.M. Putman, T.P. Quinn, A.P. Klimley, and D.L.G. Noakes. 2013. Evidence for geomagnetic imprinting as a homing mechanism in Pacific salmon. *Curr. Biol.* 23: 1–5.
- Putman, N.F., M.M. Scanlan, E.J. Billman, J.P. O’Neil, R.B. Couture, T.P. Quinn, K.J. Lohmann, and D.L.G. Noakes. 2014. An inherited magnetic map guides ocean navigation in juvenile Pacific salmon. *Curr. Biol.* 24: 446–450.
- Radchenko, V.I., O.S. Temnykh, and A.V. Zavolokin. 2013. Review of studies on Asian juvenile Pacific salmon stocks, 2006–2012. *N. Pac. Anadr. Fish Comm. Tech. Rep.* 9: 1–10. (Available at [www.npafc.org](http://www.npafc.org)).
- Riddell, B.E., R.J. Beamish, L.J. Richards, and J.R. Candy. 2008. Comment on “Declining wild salmon populations in relation to parasites from farm salmon”. *Science* 322: 1790. (Available at [www.sciencemag.org/cgi/content/full/322/5909/1790b](http://www.sciencemag.org/cgi/content/full/322/5909/1790b)).
- Ruzicka, J.J., T.C. Wainwright, and W.T. Peterson. 2011. A



Sweeting, R.M., and R.J. Beamish. 2009. A comparison of the diets of hatchery and wild coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia from 1997–2007. N. Pac. Anadr. Fish Comm. Bull. 5: 255–264. (Available at [www.npafc.org](http://www.npafc.org)).

Takahashi, M. 2015. Status of hatchery production of chum salmon populations in Japan. Bull. Fish. Res. Agency 39: 49–84. (In Japanese with English abstract) (Available at [www.fra.affrc.go.jp/bulletin/bull/bull39/39-05.pdf](http://www.fra.affrc.go.jp/bulletin/bull/bull39/39-05.pdf)).

Tanasichuk, R., and R. Routledge. 2011. An investigation of the biological basis of return variability for sockeye salmon (*Oncorhynchus nerka*) from Great Central and Sproat lakes, Vancouver Island. Fish. Oceanogr. 20: 462–478.

Teel, D.J., B.J. Burke, D.R. Kuligowski, C.A. Morgan, and D.M. Van Doornik. 2015. Genetic identification of Chinook salmon: stock-specific distributions x

stocg

w

Sprq

hyn

- static stock-specific patterns in a dynamic ocean. *Mar. Ecol. Prog. Ser.* 449: 245–262.
- Tucker, S., M.E. Thiess, J.F.T. Morris, A. Mazumder, and M. Trudel. 2012b. Concordant distribution, abundance, growth of juvenile pink, chum and sockeye salmon in eastern Pacific coastal waters. *N. Pac. Anadr. Fish Comm. Doc.* 1404. 13 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Tucker, S., T. Beacham, and M. Trudel. 2015a. Seasonal distribution of juvenile Vancouver Island Chinook salmon. *N. Pac. Anadr. Fish Comm. Doc.* 1603. 15 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Tucker, S., M.E. Thiess, J.F.T. Morris, D. Mackas, W.T. Peterson, J.R. Candy, T.D. Beacham, E.M. Iwamoto, D.J. Teel, M. Peterson, and M. Trudel. 2015b. Coastal distribution and consequent factors influencing production of endangered Snake River sockeye salmon. *Trans. Am. Fish. Soc.* 144: 107–123.
- Tucker, S., J.M. Hipfner, and M. Trudel. 2016. Size- and condition-dependent predation in a marine pelagic system: a seabird disproportionately targets substandard individual juvenile salmon. *Ecology* 97: 461–471.
- Ueno, Y., Y. Ishida, K. Nagasawa, and T. Watanabe. 1997. Winter distribution and migration of Pacific salmon. *N. Pac. Anadr. Fish Comm. Doc.* 271. 22 pp. (Available at [www.npafc.org](http://www.npafc.org)).
- Urawa, S. 1993. Effects of *Ichthyobodo necator* infections on seawater survival of juvenile chum salmon (*Oncorhynchus keta*). *Aquaculture* 110: 101–110.
- Urawa, S. 1996. The pathobiology of ectoparasitic protozoans on hatchery-reared Pacific salmon. *Sci. Rep. Hokkaido Salmon Hatchery* 50: 1–99. (Available at <http://salmon.fra.affrc.go.jp/kankobutu/srhsh/data/srhsh370.pdf>).
- Urawa, S. 2013. Control of the parasitic flagellate *Ichthyobodo salmonis*, a causative agent of marine mortalities of juvenile chum salmon. *N. Pac. Anadr. Fish Comm. Tech. Rep.* 9: 214–215. (Available at [www.npafc.org](http://www.npafc.org)).
- Urawa, S. 2015. Ocean distribution and migration of Japanese chum salmon. *Bull. Fisheries Research Agency* 39: 9–19. (In Japanese with English abstract). (Available at [www.fra.affrc.go.jp/bulletin/bull/bull39/39-03.pdf](http://www.fra.affrc.go.jp/bulletin/bull/bull39/39-03.pdf)).
- Urawa, S., S. Sato, P.A. Crane, B. Agler, R. Josephson, and T. Azumaya. 2009. Stock-specific ocean distribution and migration of chum salmon in the Bering Sea and North Pacific Ocean. *N. Pac. Anadr. Fish Comm. Bull.* 5: 131–146. (Available at [www.npafc.org](http://www.npafc.org)).
- Urawa, S., S. Sato, M. Takahashi, and T. Saito. 2012. Status of hatchery-origin chum salmon in the Bering Sea





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Shigehiko Urawa<sup>1</sup>, James R. Irvine<sup>2</sup>, Ju Kyoung Kim<sup>3</sup>, Eric C. Volk<sup>4</sup>, Alexander V. Zavolokin<sup>5,6</sup>, Tomonori Azumaya<sup>7</sup>, Terry D. Beacham<sup>2</sup>, Alexander V. Bugaev<sup>8</sup>, Edward V. Farley, Jr.<sup>9</sup>, Jeffrey R. Guyon<sup>9</sup>, Sang Gyu Kim<sup>10</sup>, Michio J. Kishi<sup>11</sup>, Nataliya V. Klovach<sup>12</sup>, Maxim V. Koval<sup>8</sup>, Do Hyun Lee<sup>13</sup>, Svetlana V. Naydenko<sup>5</sup>, Dion S. Oxman<sup>14</sup>, Toshihiko Saito<sup>1</sup>, Shunpei Sato<sup>1</sup>, Mark W. Saunders<sup>2</sup>, Olga S. Temnykh<sup>5</sup>

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