Migration and Survival Mechanisms of Juvenile Salmon and Steelhead in Ocean Ecosystems: The Workshop Synopsis

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The North Pacific Anadromous Fish Commission (NPAFC) hosted the 3rd International Workshop on juvenile salmon in Honolulu, Hawaii, on 25-26 April 2013. The purpose of this workshop was to share, review, and summarize new research results pertaining to the "Migration and Survival Mechanisms of Juvenile Salmon and Steelhead in Ocean Ecosystems." The Workshop included two full days of oral and poster presentations and was attended by over 95 participants from Canada, China, Japan, Korea, Russia, and the United States.

Since the 2nd International Workshop on juvenile salmon convened in 2006, numerous ocean surveys and subsequent studies have occurred along the North Pacific Rim of Asia and North America. Much of this research focused on the initial period of salmon migration and subsequent overwinter period because of the prevailing paradigm that early ocean periods are highly influential to the survival and production of salmon. Consequently, to gain a better understanding of mechanisms or processes influencing the production of anadromous populations, additional information was needed on inter-annual variations in abundance, growth, and survival rates of juvenile salmon migrating in ocean ecosystems over both regional and basin scales. To accomplish this end, the NPAFC organized the 3rd International Workshop in 2013.

To condense results from the workshop, this synopsis is presented in several sections: (1) the two North Pacific Rim salmon reviews, (2) five themes summarizing most workshop presentations, (3) a Workshop "Wrap Up" overview, and (4) some implications of juvenile salmon marine research for salmon management.

The references cited in this synopsis refer to abstracts compiled in this volume (NPAFC Technical Report 9).

Review of studies from Asia and North America, 2006-2013

Radchenko et al. and Trudel and Hertz summarized advances in marine research on juvenile Pacific salmon made since the previous NPAFC Workshop. Both contributions provided excellent summaries of the extensive research by NPAFC member countries in Asia and North America.

Radchenko et al. reported on studies conducted on the Asian coast (Korea, Japan, and Russia) showing the effects of climate and oceanography on the feeding and migration of juvenile salmon. A high degree of annual variability in salmon diet occurred in ocean regions such as the Bering Sea. It was also reported that in comparison with other nekton, estimates of large zooplankton consumption by Pacific salmon is modest, even in years of high salmon abundance. As for top-down control mechanisms, an example study of con-specific pink salmon predation was noted for controlling brood-line dominance, but concluded it was unlikely because intraspecific interaction is minimal due to the narrow window of spatial overlap between juveniles and adults, and the rapid growth of juveniles quickly puts them beyond the optimum prey size of adults. Low ocean sea surface temperatures were cited as delaying migration and reducing growth and thus contributing to high mortality, which was validated by studies on early marine chum salmon scale growth.

Trudel and Hertz reviewed extensive research conducted by investigators working along the North American coast (Canada and the United States). They reported that the actual causes of juvenile salmon ocean mortality are still poorly known. Furthermore, evidence remains inconsistent regarding effects of hatchery releases on wild salmon production in the marine environment, regardless of the similarity in their diets. Inter-specific interactions of highly abundant pink salmon with other salmon may be context dependent: juvenile pink salmon may be competitors in one region (Strait of Georgia) and a buffer to predation in another (Southeast Alaska). Much work on pathogens off British Columbia have linked sea lice transfers from adult wild salmon to farmed pen-reared salmon and back to wild juvenile salmon with negative consequences. Impacts of predators on juvenile salmon may be modulated by the availability of alternate prey, such as forage fish, but predation events on juvenile salmon are seldom reported. Changes in salmon prey availability and quality have been linked to changes in ocean currents, winds, and climate.

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Theme 1. Critical periods or size of juvenile salmon related to production

Many studies support the hypotheses that increased survival for juvenile salmonids in ocean ecosystems is predicated on two critical ocean mortality periods: early marine (high growth minimizing vulnerability to size-selective predation) and winter (high overwinter energy and size needed for survival/growth and predation avoidance). In a study on the Sea of Japan side of Hokkaido, the early marine critical period was validated by sampling otolith-marked chum salmon and comparing the catch per effort in surface trawls to subsequent adult returns (Sasaki et al.). Off the coast of British Columbia in summer, size-selective and stock-specific predation of juvenile salmon by rhinoceros auklets (*Cerorhinca monocerata*) was documented by Tucker et al., thus validating the concept of a critical early marine period of mortality and the importance of the link between fish condition and susceptibility to predation. In the northern California Current, high krill and chlorophyll-*a* abundance was related to the spatial distribution of Chinook salmon, which may aid ecosystem-based assessments by identifying critical marine habitat for juveniles during their early marine residence (Hassrick et al.).

Presentations on modeling and hatchery releases reinforced the importance of growth and size for positively influencing survival. Results from a 4-parameter model relating ocean survival of juvenile salmon to their size, based on susceptibility to predation, supported a critical-size hypothesis (Passolt and Anderson). Rutter and Anderson presented information on a model estimating the growth rate of salmonids by accounting for the effects of size-dependant culling in the frequency distribution of populations. From experimental release times and sizes of age-0 sockeye salmon smolts in Auke Bay, Alaska, Heard et al. demonstrated that release of larger fish produced shorter residence times and higher subsequent marine survivals than release of smaller fish, thus supporting the critical early marine period hypothesis and size-dependant offshore migration. Abundance of juvenile and immature Chinook salmon caught in rope trawls in Southeast Alaska were significantly correlated with brood year survival of wild and hatchery stocks when linked to ocean entry year, thus suggesting critical marine periods both in spring and during the over-wintering period (Orsi et al. Chinook salmon abstract). Farley et al. presented information on Bristol Bay sockeye salmon energetic condition related to marine survival in 2002-2008 and demonstrated size-selective mortality of fish between fall and their first winter at sea was due to inadequate lipid stores to avoid predation. Leon and McPhee did not find a significant relationship between freshwater growth and recruitment of two western Alaskan Chinook salmon populations, but they did report growth in a given year was correlated to growth in the previous year. Ruggerone et al. examined a long-term data set to determine the role of size-selective mortality on sockeye salmon smolts based on scales from adults originating from five watersheds in Bristol Bay. Stormer and Juanes proposed a study on ocean-type Chinook salmon in the laboratory to measure growth and lipids after periods of fasting for subsequent modeling of the conditions during their early marine critical period.

Theme 2. Inter-annual variation in abundance, growth, and survival of salmon

Several studies highlighted the importance of maintaining long-term time series of ocean metrics to enable researchers to detect interannual factors influencing salmon production. By sampling nearshore conditions in the Strait of Georgia, Downey et al. found high annual differences in the timing, abundance, and composition of plankton prey for outmigrating juvenile salmon. They suggested the policy of a standard time of release for hatchery-reared juvenile coho salmon may contribute to low marine survival because juvenile releases may not coincide with the timing of abundant prey. From a 35-yr data set of hatchery releases of Chinook salmon from Little Port Walter, Southeast Alaska, Guyon et al. found a decreasing trend in survival and age at maturity possibly linked to environmental variation. Models that explained marine survival of 14 coho salmon stocks in Southeast Alaska varied by locality, but only the North Pacific Index had a consistent (positive) effect (Adkison et al.). Coastal ocean metrics associated with juvenile salmon were identified as important leading indicators of pink and coho salmon production in Southeast Alaska (Orsi et al. Connecting the "Dots" abstract). Sampling off the coast of British Columbia, Friedland et al. found that initial marine growth of Keogh River steelhead was not as important as sustained growth conditions in the summer and fall of the post-smolt year.

Annual variation in survival of salmon may also be related to hatchery practices. Liu et al. described adverse impacts of low salinity on liver cells of juvenile chum, and Urawa indicated a parasitic flagellate (*Ichthyobodo salmonis*) may cause marine mortality in juvenile chum salmon and described a treatment study using corn vinegar to control the parasite in hatcheries.

Theme 3. Ecological interactions of juvenile salmon in the context of marine survival

Examining the marine ecology of juvenile salmon migrating in the ocean provided insight to possible mechanisms influencing salmon distribution and production due to interactions with prey, competitors, or predators. Primary prey organisms and migration pathways were identified for juvenile chum salmon during their early ocean critical period in coastal waters off northern Japan (T. Sato et al.) and Korea (Kim et al.). In the northern and southern Bering Sea, Gann et al. noted differences in the abundance and taxonomic composition of zooplankton that may have implications for the distribution of juvenile salmon and other forage fishes. Of four major prey types consumed by juvenile Chinook, coho, chum salmon, and steelhead in the California Current, Brodeur et al. found euphausiids and fish were positively selected relative to their abundance in the neuston, and the opposite was true for decapods and amphipods.

There were many presentations discussing the role of competition as a potential influence on juvenile salmon marine survival. In examining feeding rates and growth of juvenile Pacific salmon in the North Pacific, Zavolokin concluded that salmon abundance in the past 30 years had increased, but adaptive changes in feeding habitats compensated for competition and there were no negative consequences of increased salmon abundance on juvenile salmon in the Okhotsk Sea and western Bering Sea. By examining the diets of five species of Pacific salmon in the Bering Sea in fall, Auburn and Sturdevant found that feeding behavior was related to diel period and sampling localities, thus giving insight to migration strategies for juveniles confronted with a short growing season. Jenkins et al. examined diet overlap of juvenile pink and chum salmon in warm and cold years off British Columbia and Southeast Alaska and concluded that niche overlap increased with high salmon abundance and was not related to fish size. Naydenko and Kuznetsova reported on food supply of pink salmon and other fish and squid in the subarctic frontal zone of the North Pacific Ocean in winter and spring of 2009-2011. She concluded that a decrease in stomach fullness of salmon in winter was not evidence of unfavorable winter feeding conditions, but it was related to the fish's physiological cycle in the winter due to cooler environmental conditions. Regional shifts in annual Chinook feeding ecology were found by Hertz et al. and may be related to declining stocks in North America because years with higher growth and survival indicated fish were feeding at a higher trophic level.

Several researchers reported on competitive interactions between juvenile pink salmon and Pacific herring. Morozova indicated juvenile Pacific salmon interactions occur in the coastal epipelagic zone of Kamchatka. She noted that spatial variability was found among the salmon species, and Pacific herring migrated into salmon habitat in late August and overlapped juvenile salmon diet, which may have displaced them seaward. Spatial overlap was found between Pacific herring and juvenile Chinook and coho salmon in Puget Sound, Washington, by Kemp et al. They suggested the greater biomass of herring impacted zooplankton more than juvenile salmon, but competition for prey could negatively influence growth and survival of juvenile Chinook salmon during their early critical marine period. In Prince William Sound, zooplankton predation by pink salmon was shown to likely influence herring production (Studevant et al.).

Scales collected from adult salmon were used to estimate growth of juvenile stages. Martinson used the early marine growth on scales of adult chum from Southeast Alaska to show that adult pink salmon did not influence chum growth and that early marine growth was a positive predictor of chum salmon production three years later.

Several authors reviewed the role of predation on juvenile salmon marine survival. From data sets of adult pink salmon diets off Southeast and Prince William Sound, Alaska, Sturdevant et al. reported that pink salmon cannibalism by adult fish on juveniles was not a large contributor to alternate brood-year oscillations in pink salmon. Tucker et al. identified the stock-specific consumption of juvenile sockeye, pink, and chum salmon migrating past colonies of chick-provisioning rhinoceros auklets in areas of coastal British Columbia. In samples collected from the coastal zone near the Anadyr River, Baranov identified predation on juvenile chum salmon by char and toothed smelt. Koval and Gorin suggested the strong hydrographic features and tidal influences in western Kamchatka estuaries negatively affected seaward migrating juvenile salmon and they identified negative ecological interactions of marine mammal predators on adult salmon in summer.

Theme 4. Climate or ecosystem change at several scales related to salmon production

The influences of local, regional, and basin scale factors in marine ecosystems on salmon production were identified in many studies. At the local scale, juvenile pink, chum, and sockeye salmon exhibited higher levels of growth, as measured by insulin-like growth factor in the blood, and plankton density was similarly high along the perimeter of the Sitka Eddy in the Gulf of Alaska (Moss et al.). Kline found mesoscale eddies forming in May in the Alaska Coastal Current were influenced by the hydrological cycle and that climate was a critical factor for driving ocean survival for pink salmon because it "set the stage" for the arrival of salmon migrating into the area. Beamish et al. indicated that recently improved productivity of selected stocks of sockeye salmon from the Fraser River appear related to later ocean entry time of sea-type stocks matching long-term changes in the timing of prey populations. Short-term exposure to increased temperatures during early development (from fertilization to swim up) was found to influence the sexual development of steelhead (Cole et al.).

At the regional scale, influences of climate or ecosystem change on salmon production were presented from studies in the Northeast Pacific. J. Miller et al. suggested both local and regional processes positively affect survival of Snake River Chinook salmon. Such conditions include a negative Pacific Decadal Oscillation (PDO), a large size of fish at marine entry, a copepod community dominated by northern boreal species, and increased river discharge (Columbia River plume). Using survival data from hatchery and wild coho salmon releases from coastal and inshore marine waters of Washington State, Zimmerman et al. found that the marine survival of stocks in distinct geographic regions responded differently to ocean conditions. For example, ocean indicators like the PDO and surface temperatures were better predictors of marine survival for coastal populations than for interior stocks in Puget Sound. Fergusson et al. examined trophic relationships among pink, chum, sockeye, and coho salmon with climate over a 16-yr time series in Southeast Alaska and reported that during relatively warm years fish were larger, diets were more diverse, but energetic conditions of the fish were similar to those in cold years. From 2010 to 2012 off the coast of Southeast Alaska, marine spatial variation in the abundance and condition of juvenile chum salmon was highly influenced by changes in temperatures (Kohan et al.). Juvenile Chinook salmon from the Yukon River were found to disperse northward in warm years, southward in cold years, and average catch latitude was negatively correlated with marine survival, suggesting the northern Bering Sea is not good overwintering habitat for juveniles (Murphy et al.)

At the basin scale, the influences of climate or ecosystem change on juvenile salmon metrics or adult production was identified. Mazumder et al. examined carbon isotope signatures of juvenile Chinook salmon from the west coast of North America and suggested that in most regions there is an ontogenetic shift in diet of fish after growing to a body length of 200 mm. Peterman and Dorner reported that declining trends in sockeye salmon productivity have been synchronous among stocks from Washington to Southeast Alaska, while opposite trends were seen in western Alaska, thus implicating a large-scale influence of climate on salmon productivity. Long term monitoring of ocean indicators off the northern California Current suggest linkages of basin-scale forcing (PDO) and circulation patterns, which in turn affect transport of a lipid-rich food chain (copepods) favorable to juvenile coho and Chinook salmon survival, and this can be used to develop forecast models for adult production (Peterson et al.). By using Bayesian networks, Malick et al. found large-scale climate influences on biophysical components of the ecosystem, but uncertainties increased down the causal chain in the network, thus dampening the effect of large-scale climate patterns on coho salmon survival. In samples collected in 2010 and 2011 as the El Niño Southern Oscillation (ENSO) conditions shifted from positive to negative, Fournier observed reduced size and weight of the fish in the Gulf of Alaska, which suggested poorer conditions in a negative ENSO year. Irvine and Akenhead reported that sustained releases of hatchery salmon after 1990 corresponded with the hypothesis that the North Pacific Ocean entered into a period of low productivity for salmonids and contributed to reduced survival of sockeye salmon.

The question of "What do we really know about the cumulative effect of environmental stressors on the health of salmon?" was posed by K. Miller et al. They suggested a broad range of infectious agents carried by smolts in the ocean and biological stressors may be less tolerated and associated with higher levels of mortality in years of poor ocean productivity.

Theme 5. Migration and distribution of salmon stock groups

It is important to know the spatial and temporal distribution of stock groups to adequately understand ecological interactions or to model habitat utilization patterns. Several studies based on genetics and phenotypic differences indicated the migration and distribution of salmon stock groups. Juvenile sockeye salmon from 35 stocks were identified from ocean sampling off North America and larger body-sized individuals within populations were distributed further northwards in the ocean than smaller fish (Beacham et al.). Extreme annual shifts in abundance of juvenile sockeye salmon in the Strait of Georgia in 2011 (low) and 2012 (high) were documented by Neville et al. S. Sato et al. used single nucleotide polymorphism (SNP) markers to determine migrations of Japanese chum salmon stocks to the Okhotsk Sea from mid-June to early July and reported the Great 2011 Earthquake and Tsunami in Tohoku adversely affected chum salmon releases from Honshu hatcheries along the Pacific coast. T. Saito et al. reported thermal marks were used to determine new unrecognized migration patterns for Hokkaido chum salmon migrating to sea. Guthrie et al. used genetic markers to validate the presence of juvenile Yukon Chinook salmon stocks collected off the river mouth. Yoon et al. described genetic structure of contemporary populations of Far East Asian chum salmon from microsatellite and mitochondrial DNA analysis. Genetic analysis of mixed-stock aggregations of juvenile pink salmon collected in autumn in the Okhotsk Sea showed that stocks could be separated to northern and southern regional stocks and that accuracy of the odd-year brood-line is relatively lower than the even-year line (Shpigalskaya et al.) As a potential method to access fitness decline, a graphical method was presented to help understand correlated gene expression that provides the basis of complicated traits, and thus making it possible to estimate direct genetic effects in determining phenotype (Nakamichi et al.). Chistyakova et al. observed otolith microstructure and identified mixed stocks of pink and chum salmon in the Okhotsk Sea and regional origins of major Asian stock groups. Izergin et al. reported on pink salmon migrations from Taui Bay to the Sea of Okhotsk from May to July.

Other techniques for examining juvenile salmon migration and distribution employed modeling, observational, and telemetry. Burke et al. described simulation modeling of the initial ocean migration of juvenile stream-type Chinook salmon and suggested that directed swimming by fish aided by a sense of space and time was the most likely model scenario to describe observed movement. Watanabe et al. examined the increasing age at maturity through immature ratios of chum salmon in the Bering Sea and central North Pacific Ocean to see if poorly understood ocean mortality could be attributed to these changes. A modeling study of Fraser River sockeye salmon concluded that the fish use magnetic cues to navigate across the open ocean (Putman et al.). Bracis and Anderson found that spring-summer Chinook salmon display age-specific differences when they arrive at the river mouth as older fish arrive earlier. Chinook salmon in the southern part of their range partitioned habitat use by season and age of fish (Ammann et al.). Kilmov et al. reported that juvenile pink, chum, and sockeye salmon migrating in the Okhotsk Sea had different foraging strategies. Pink and chum salmon widely explored marine areas, foraged instensively, and then migrated seaward, whereas sockeye salmon foraged for extensive periods within coastal waters and moved offshore later. Another study suggested that the complexity of life history, diet, and size-dependant rearing strategies of Chinook salmon in the Strait of Georgia may be related to marine survival trends (Sweeting). Brosnan et al. used acoustic telemetry data of yearling Chinook salmon in the Columbia River estuary to estimate survival as influenced by predation, ocean productivity, plume dynamics, and prior river experience.

The Workshop "Wrap Up"

Heard presented a Workshop "Wrap Up" to highlight important findings and insights with respect to migration and survival of juvenile salmonids in ocean ecosystems. He summarized the major new information on stock-specific migration gathered using multiple technologies and homing migration behavior based on empirical evidence and validated geomagnetic imprinting. He mentioned that the concept of rapid early marine growth to avoid size-selective mortality was reinforced by many studies and is a cornerstone of the critical-size hypothesis of "getting bigger quicker is better." He pointed to new information presented on the potential deleterious impacts of marine debris on the ecology and survival of salmon that provided insights to anthropogenic effects on salmon production. Heard reviewed evidence that phenology of salmon migration mis-matched to suitable marine prey resources may be linked to climate. He emphasized the importance of maintaining long-term time series and ocean surveys during the recent periods of climate change and said these metrics are critical tools to help determine what is really happening in salmon habitats.

Implications of juvenile salmon marine research for salmon management

Marine research on juvenile salmon has expanded in many respects with advances in our knowledge of migration and survival mechanisms of salmonids in ocean ecosystems and towards improved understanding of the processes required for sustainable conservation and management. Here are some new (or reinforced) insights on juvenile salmon marine migrations, and how these insights might inform salmon management.

<u>Survival and production estimates</u>. The paradigm of two marine critical periods for juvenile salmon rang true as a central message of many workshop contributors: an early marine nearshore coastal period predicated on size-selective mortality, and a second period over the first marine winter related to both size and energy. This information, coupled with ocean survey data and large-scale ecosystem indicators associated with juvenile salmon, can be used to assess abundance of salmon "survivors" to develop pre-season salmon forecast models to benefit fishery managers and resource stakeholders.

<u>Autumn estuarine migrations of salmon</u>. New insights on salmon life history strategies and migration of several species were discussed, namely age-0 sockeye and coho salmon juveniles in fall. For these two species in the fall, sea-type sockeye reared extensively inshore (Beamish et al.) and coho fry migrated inshore along the coast and reinvaded distant freshwater habitats to overwinter (Shaul et al.). Thus, the later and protracted estuarine migrations of these species emphasize the importance of maintaining intact networks of continuous anadromous habitats. As estuaries serve as conduits to adjacent habitats and neighboring stream systems, applying this knowledge to land use practices concerning estuaries will enable managers to better sustain healthy salmon populations.

<u>Maintaining a diversity of out-migration times</u>. For migrating juvenile salmon, stock-specific migration information indicated that the largest fish within a cohort were located furthest north, suggesting one survival strategy of migrating fast and early. In contrast, late-fall migrating sockeye (sea-type) actually have fared better in recent years than the earlier spring-migrating fish of adjacent stocks, suggesting salmon have a wide spectrum of outmigration timing to ensure an optimal survival window is available each year for a particular stock group. This has implications for the release strategies of hatchery projects because enhancement programs often constrain release periods that may mis-match timing with estuarine productivity during some years. Thus, salmon production may prove more sustainable if a wide spectrum of salmon outmigration times of wild and hatchery stock groups are maintained.

<u>Influences of marine debris in the open ocean</u>. The potential bioaccumulation of chemicals from marine debris ingested by juvenile and immature salmon and steelhead was proposed by Myers et al. as a possible cause of ocean mortality. Evidence was presented that ingestion of marine debris was most prevalent in steelhead and was observed in other salmon species. Moreover, the highest incidence of plastic ingestion occurred closest to the Subarctic Current. Thus, reducing our "garbage footprint" in the ocean will contribute to healthier salmon stocks and help maintain sustainable fisheries.

<u>Validation of salmon migration routes and "critical" periods</u>. Welch et al. suggested that multiple periods may be critical to survival throughout the marine life history of Pacific salmon, rather than only during early marine and overwintering periods. Tucker et al. observed seabird predation on specific salmon stocks and showed the later coastal migration period was a cause of marine mortality by avian predators. K. Miller et al. suggested that there were a broad range of infectious agents carried by smolts during ocean migration and in years of poor ocean productivity these agents may be less tolerated and could be associated with higher mortality. A better understanding of the cumulative interactions of migrating salmonids in ocean ecosystems will better inform mangers as to the most appropriate pre-season indicators of salmon productivity.

Future collaboration, coordination, and compilation of coastal ocean time series. Additional data sharing among national researchers is needed—both on regional and Pacific Rim scales—to better inform managers with suitable ecosystem metrics to anticipate future salmonid production. This could be accomplished by developing a standard suite of ecosystem metrics shared and applied over a large spatial scale during critical periods of the salmon life history. Thus it is important for researchers to identify key metrics and time periods for particular species that are related to salmon production (i.e., abundance, growth, size-at-time, energy density, prey fields, diet, temperature, etc.). Such information is vitally important if we are to successfully develop forecasts for salmon stocks that are at historically high levels of abundance as well as stocks that have shown large-scale declines.