North Pacific Anadromous Fish Commission
Technical Report No. 8: 113-116, 2012

Recent Production Trends of Chum Salmon *Oncorhynchus keta* Under Conditions of Warming Climate

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Keywords: chum salmon, production trend, global warming, hatchery-program effect

Pacific salmon (*Oncorhynchus* spp.) play an important role as a keystone species and in ecosystem services in the subarctic North Pacific. Planktivorous pink (*O. gorbuscha*) and chum salmon (*O. keta*) abundance has increased since the 1975/76 regime-shift until the present, but their abundances have shown stable or declining trends in Canada, Japan, and USA since the 1990s, even though Russian chum and pink salmon abundance have been increasing (Fig. 1). Run size of Japanese chum salmon showed a decreasing trend in Honshu Island since the late 1990s and in Hokkaido Island since the early 2000s (Fig. 2). The carrying capacity of sockeye (*O. nerka*), chum, and pink salmon has changed to a downward trend since the early 2000s (Kaeriyama et al. 2011).

Abundance of wild chum salmon in the 1990s decreased to 50% below that of the 1930s, while there have been significant increases in hatchery populations (Kaeriyama et al. 2009). Hatchery-derived salmon genetically disturb native-wild Pacific salmon. Araki and Schmid (2010) examined 266 peer-reviewed papers on effects of hatchery fish stocking on wild stocks and the consequences for stock enhancement. They concluded that negative effects of hatchery rearing on a variety of fish species are common and there are few indications of successful stocking. Hatchery-derived chum salmon have lower genetic diversity than wild salmon (Okazaki 1982). Yokotani et al. (2009) surveyed the population structure in the Yurappu River using mitochondrial DNA (mtDNA) analysis. Yurappu River chum salmon showed eight haplotypes (Ht1-Ht8) in the 481 bp 5' variable portion of the mtDNA control region (Fig. 3). Pairwise population F_{ST} estimates showed that the December-run population (YPD) differed significantly from the October-run population (YPO) in the Yurappu River. The YPO population was closely related to others, such as the Chitose, Tokachi, and Nishibetsu river-populations (Table 1). These results suggest that Yurappu River chum salmon are genetically different and perhaps reproductively isolated by run-timing. It is thought that the native population persists as the late-run timing component, and that the early-run

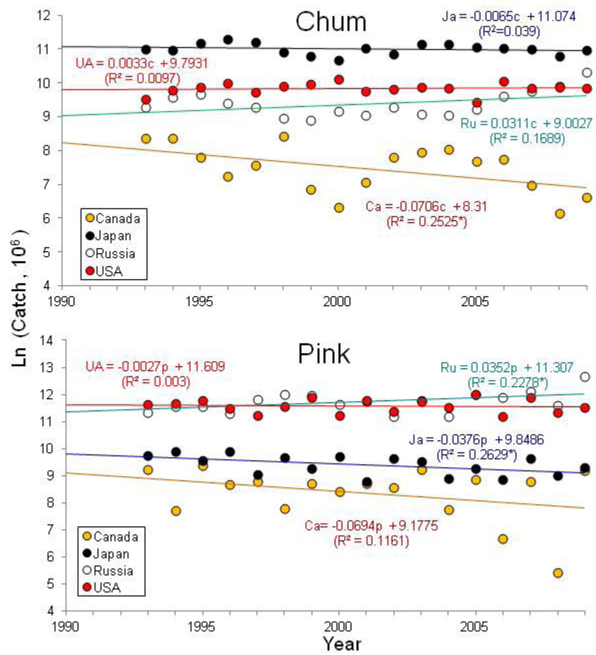

Fig. 1. Annual changes in catch of chum and pink salmon in the North Pacific Ocean since 1990. Catch data are based on NPAFC Statistical Yearbooks (www.npafc.org/new/pub_statistics.html). Ca: Canada, Ja: Japan, Ru: Russia, UA: USA.

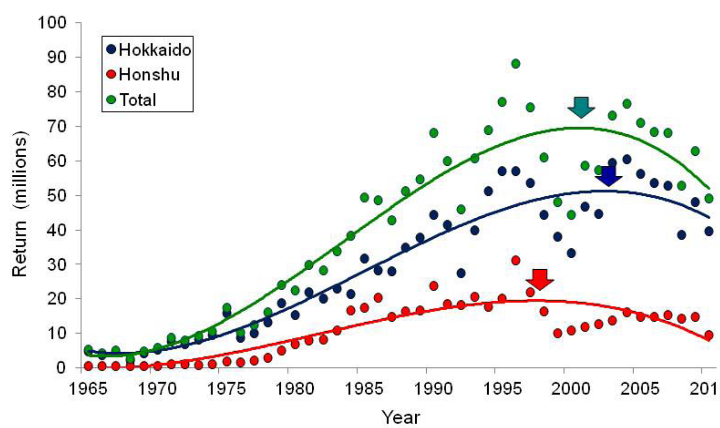

Fig. 2. Annual change in return of chum salmon to Japan during 1965-2010. Arrows indicate estimated time when the number of returning chum salmon started to decrease.

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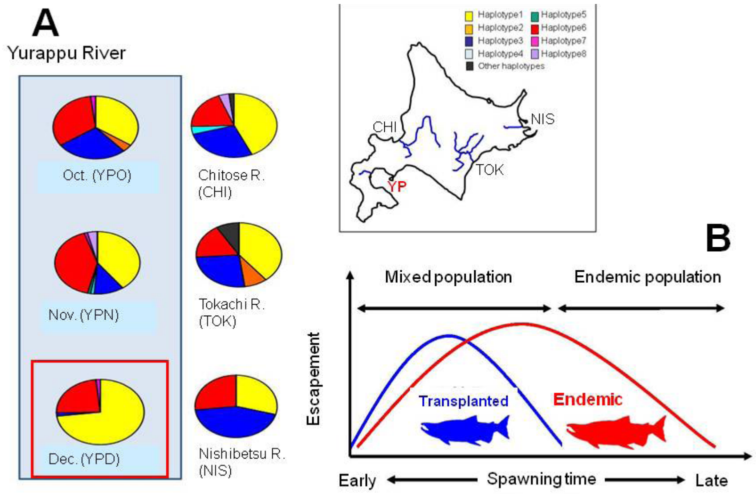

Fig. 3. Genetic population structure of chum salmon in the Yurappu (October; YPO, November: YPN, December: YPD), Chitose (CHI), Tokachi (TOK), and Nishibetsu (NIS) Rivers using mitochondrial DNA (mtDNA) analysis based on variable nucleotide sites in the 481 bp 5' portion of mtDNA control region. A: haplotype distribution of populations. B: genetic population structure of Yurappu River chum salmon. (Modified from Yokotani et al. 2009.)

timing component represents an introgressed population consisting of the native strain and out-of-basin transplants. This phenomenon could be observed in almost all populations of Hokkaido chum salmon because of the strong hatchery program. Hatchery programs lead to drastic declines in the genetic variability of wild Pacific salmon populations (Edpalina et al. 2004; Araki et al. 2007). This information suggests that ecological and genetic interactions between wild- and hatchery-derived salmon populations should be elucidated because wild salmon have greater ability to adapt to new environmental conditions (Kaeriyama et al. 2011).

Table 1. Pairwise population F_{ST} estimated between chum salmon populations in Hokkaido. Chum salmon populations include October-run (YPO), November-run (YPN), December-run (YPD) from the Yurappu, Chitose (CHI), Tokachi (TOK), and Nishibetsu (NIS) Rivers (from Yokotani et al. 2009).

	CHI	TOK	NIS	YPO	YPN	YPD
CHI	0.000					
TOK	0.000	0.000				
NIS	0.013	0.034	0.000			
YPO	0.000	0.000	0.030	0.000		
YPN	0.039	0.027	0.145*	0.013	0.000	
YPD	0.211**	0.160**	0.486**	0.168**	0.059**	0.000

Kaeriyama et al. (2011) advised that since the late 1980s global warming is positively affecting Hokkaido chum salmon by providing environmental conditions supporting increased growth for age-1 fish and survival. They predicted that global warming will affect all populations of chum salmon through mechanisms that will (1) decrease carrying capacity by reducing the area of distribution in the Bering Sea, (2) move fish to northern areas (e.g., the Chukchi Sea), (3) induce a strong density-dependent effect, (4) change the fish's wintering area from the Gulf of Alaska to the western Subarctic Gyre, (5) cause the loss of migration routes of juvenile Hokkaido chum salmon to the Okhotsk Sea, and (6) cause a crash in population abundance in the future.

In the Japan Sea, the Tsushima Warm Current flows northwards. Since the early 1990s, the current has been influenced by the warming climate (Fig. 4A). Abundance of early-run chum salmon returning to Hokkaido's Japan Sea coast in years when the current was strong was significantly lower than when the current was weak (ANOVA $p < 0.05$; Fig. 4B). In turn, the escapement pattern of Hokkaido chum salmon has changed dramatically. Where there were two populations of Hokkaido chum salmon in the 1980s, the late-run populations disappeared during the 1990s-early 2000s due to selection in the hatchery program favoring the salmon fisheries industry. Since 2006 early-run populations have decreased slightly from global warming effects (Fig. 5). The early-run population has a low adaptability because it has been mixed and artificially-disturbed by unregulated transplantation of hatchery stocks. On the other hand, the late-run population may have had higher adaptability because it is a wild population that spawned naturally. Therefore, the remnant wild late-run population of Hokkaido chum salmon is an important genetic resource that should be preserved for the future.

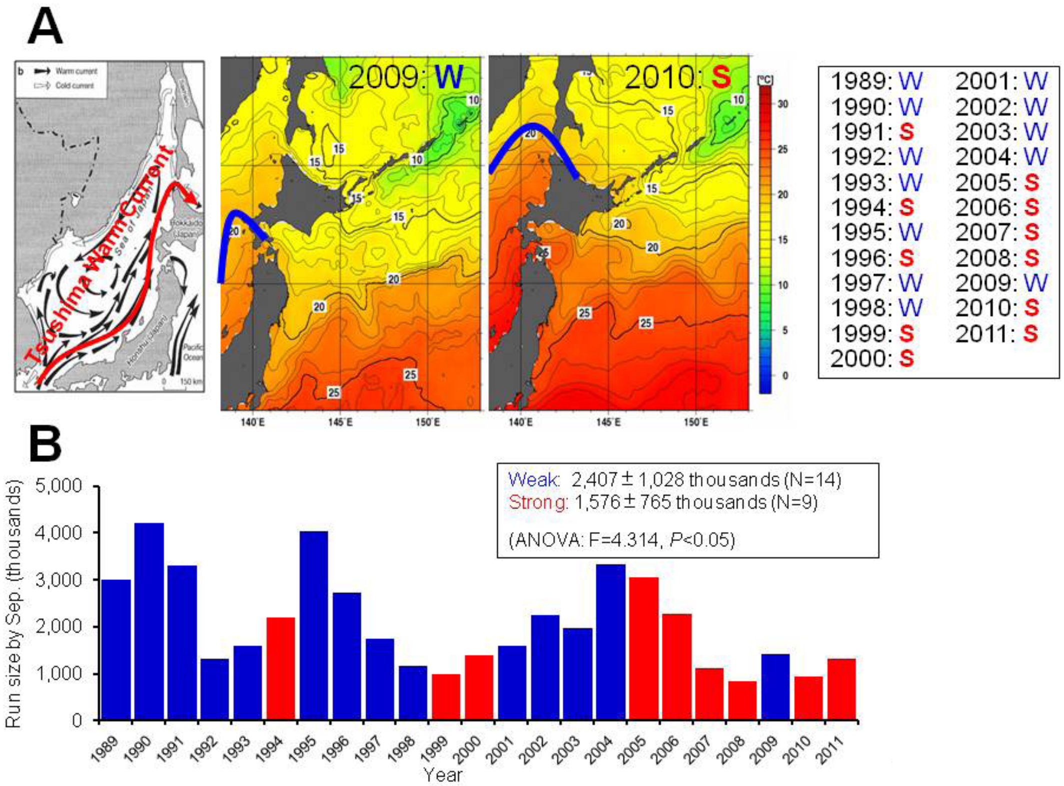

Fig. 4. Fluctuation in the strength of Tsushima Warm Current compared to the run size of early-population chum salmon returning to the Japan Sea coast of Hokkaido. A: mean SST isothermal diagrams around Japan in September of 2009 (typical of a weak Tsushima Warm Current) and 2010 (typical of a strong Tsushima Warm Current). B: annual change in the run size of early-population chum salmon returning to the Japan Sea coast in Hokkaido. W and S: weak and strong years of the Tsushima Warm Current, respectively. Mean SST isothermal diagrams from the Japan Meteorological Agency (www.data.kishou.go.jp/kaiyou/db/hakodate/monthly/sst_h.html).

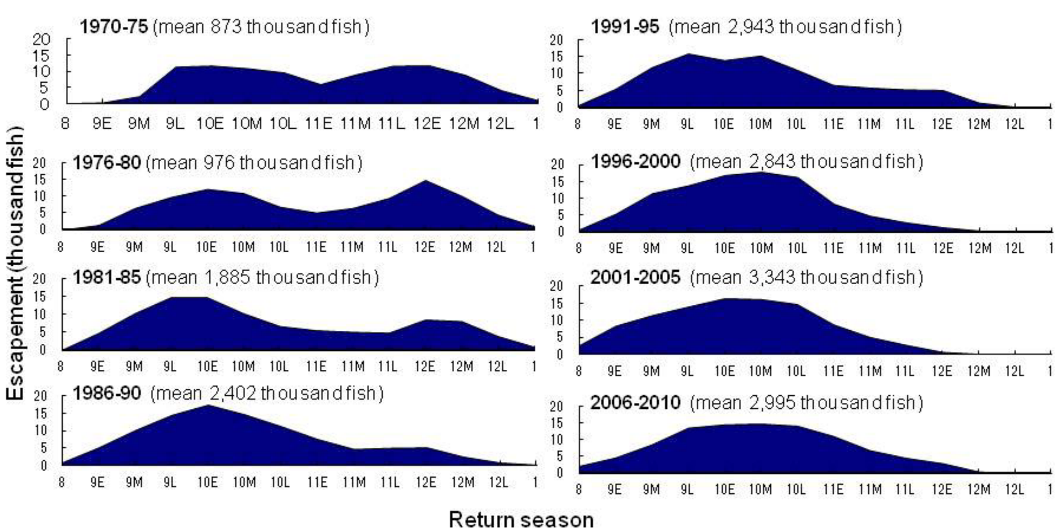

Fig. 5. Long-term change in the escapement data of Hokkaido chum salmon (data from Y. Miyakoshi, miyakoshi-yasuyuki@hro.or.jp, personal communication). E: early, M: middle, L: late portion of the populartion.

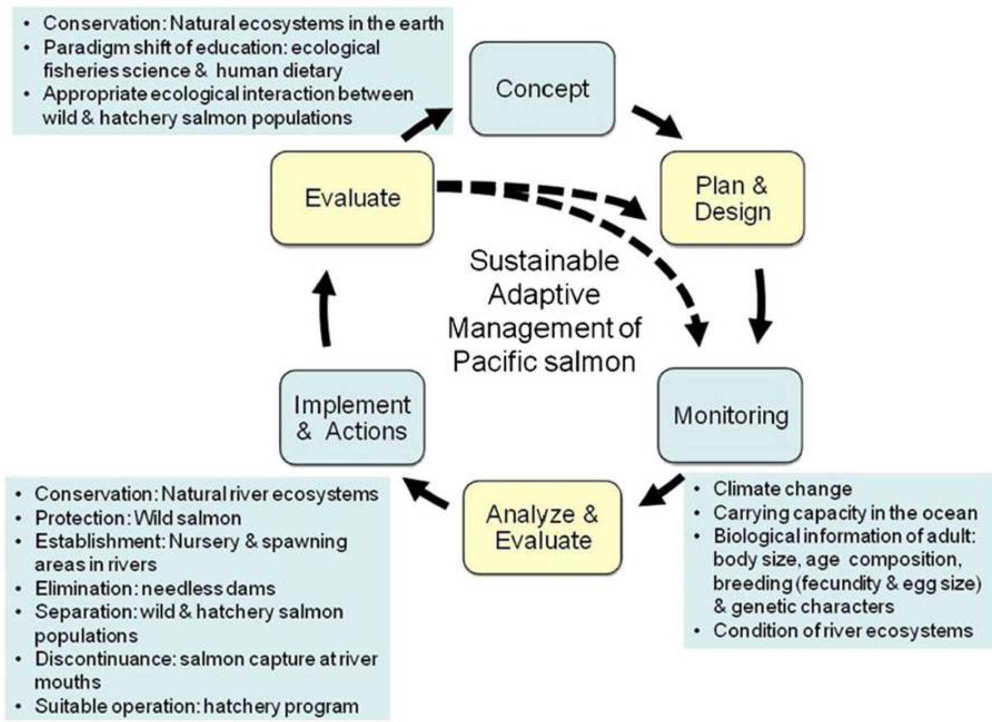

Fig. 6. Conceptual diagram showing components of a plan for sustainable adaptive management of Pacific salmon (from Kaeriyama et al. 2011).

We should recognize *ex dono* ecosystem services and understand the threats to these services. In the North Pacific Ocean, the carrying capacity of Pacific salmon is limited and fluctuates in synchrony with long-term climate change. As issues on sustainability and conservation of Pacific salmon in North Pacific develop, it is imperative that we establish sustainable adaptive management of the fisheries and hatchery programs (Fig. 6). Feedback control based on monitoring and modeling is critically important for adaptive management. The NPAFC should move quickly to establish a framework and methodology for conservation of Pacific salmon.

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