

Evaluation of Carrying Capacity of Pacific Salmon in the North Pacific Ocean for Ecosystem-Based Sustainable Conservation Management

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The change in biomass of Pacific salmon (*Oncorhynchus* spp.) indicates a 30- or 40-year periodicity in the North Pacific Ocean coinciding with long-term climate conditions. I estimated the carrying capacity (K) of sockeye (*O. nerka*), chum (*O. keta*), and pink salmon (*O. gorbuscha*) in the North Pacific Ocean using the replacement level of the Ricker's recruitment curve, and defined residual carrying capacity (RCC):

$$\text{RCC} = (\text{Carrying capacity} - \text{Biomass}) / (\text{Carrying capacity}) \times 100$$

A significant positive correlation between the Aleutian low pressure index (ALPI) and the carrying capacity was observed at the species level. Factors affecting carrying capacity at the population level, such as reproductive regimes (e.g. survival rate and sea surface temperature (SST) in the early marine life period and hatchery technology), differed by population in Hokkaido chum salmon. The RCC was significantly positively correlated with body size and negatively related to age at maturity in Hokkaido chum salmon populations. The biomass of chum salmon wild populations in the 1990s decreased 50% below that of the 1930s, despite the significant increases in the biomass of hatchery populations. Biological interaction between wild and hatchery populations should be an important consideration in the sustainable management of Pacific salmon production based at the ecosystem level.

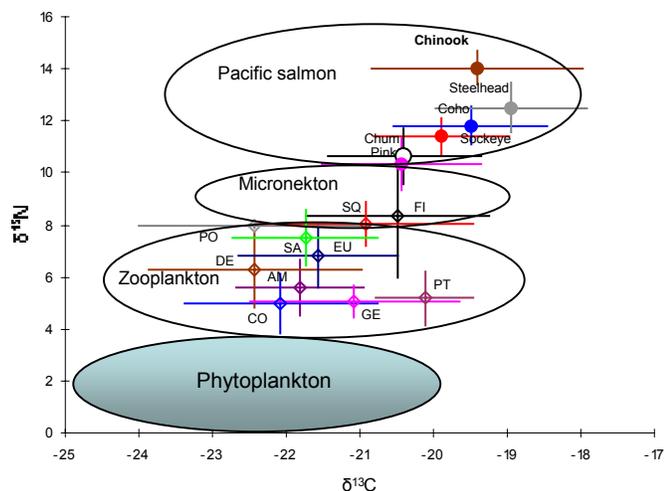
In the North Pacific Ocean, the annual catch of Pacific salmon increased from the late 1970s to the early 1990s due to favorable oceanic conditions associated with long-term climate change and successful hatchery programs (e.g. Beamish and Bouillion 1993; Kaeriyama 1998; Klyashtorin 1998). The period of the change in catch also coincided with the climatic regime-shift year. According to the prediction of Minobe (2000), the new climatic regime shift occurred in 1998–1999. This suggests that there may be a change in biomass of Pacific salmon in the near future resulting from the changes in oceanic conditions.

Pacific salmon occupy higher trophic levels in food webs of the Western and Eastern Subarctic Pacific Gyres. Chum, sockeye, and pink salmon obtained higher biomass in the Subarctic Pacific Gyres (Aydin et al. 2003). Relationship between carbon and nitrogen stable isotope of animals in the Gulf of Alaska shows that the Pacific salmon occupy the fourth trophic level, and that trophic levels of chinook salmon (*O. tshawytscha*) and steelhead trout (*O. mykiss*) are higher than those of sockeye, chum, pink, and coho (*O. kisutch*) salmon (Fig. 1). Thus, Pacific salmon are important key species not only as human food resources, but also to the ecosystem in the Subarctic Pacific Ocean.

The purpose of this paper is to evaluate carrying capacity of Pacific salmon in order to develop sustainable conservation management based on the ecosystem.

Pacific salmon catch data from the INPFC statistical yearbooks, the NPAFC statistical yearbooks, FAO yearbooks, and Fredin

Fig. 1. Relationship between carbon and nitrogen stable isotope of animals in the Gulf of Alaska, 1999–2000. EU: Euphausiids, CO: Copepods, AM: Amphipods, DE: Decapods, PT: Pteropods, PO: Polychaetes, GE: Gelatinous zooplankton, SA: Sagiita, SQ: Squids, FI: Fishes.



(1980), and the Aleutian low pressure index (ALPI) from Beamish et al. (1997) and URL: <http://www.pac.dfo-po.gc.ca/sci/sa-mfpd/downloads/alpi.txt> were used to evaluate biomass and carrying capacity of Pacific salmon and long-term climate change. The estimation of biomass from catch data was based on the method of expansion of terminal run to total biomass by D. Eggers (Alaska Department of Fish and Game, unpublished data). From the Ricker's recruitment curve ($R = \alpha Pe^{-\beta t}$), calculated by the Levenberg-Marquardt method, the replacement level ($\ln(\alpha)/\beta$, Ricker 1975) was defined as the index of carrying capacity (K). In the data set of Ricker's curve, pink salmon included 10 generations divided by odd- and even-year groups, while sockeye and chum salmon included 20 brood years. Residual carrying capacity (RCC) was defined as above.

SST in the coasts around Hokkaido was provided by the Metrological Agency of Japan as a monthly mean of one degree latitude and longitude blocks. SST of each block was further averaged for spring (April–June).

Data on mean fork length of age-4 female adults returning to 11 rivers and mean age at maturity in Hokkaido chum salmon population (Kaeriyama 1998) were used to estimate the relationship between the RCC and the somatic growth reduction.

In three species of Pacific salmon (i.e. sockeye, chum, and pink salmon), the carrying capacity since the 1976 regime-shift year has increased to approximately double that of 1947–1975. The carrying capacity of chum salmon since 1976 was the same as it was in 1924–1946. However, carrying capacities of sockeye and pink salmon since 1976 were 1.2 and 1.4 times more than those in 1924–1946, respectively. Significant positive correlations between ALPI and total carrying capacity of sockeye, chum, and pink salmon were observed without a time lag. At minus values in the ALPI, carrying capacity tended to preserve the minimum level (Fig. 2). At the species level, therefore, carrying capacity was significantly synchronized with the long-term climate change.

In chum salmon, carrying capacities of Russia ($r = 0.56$, $F = 32.1$, $P < 0.001$) and southeastern Alaska populations ($r = 0.58$, $F = 35.8$, $P < 0.001$) were significantly linked with the ALPI. Carrying capacity of populations at the edge of distribution such as Hokkaido, Western Alaska, and British Columbia and Washington did not synchronize with the long-term climate change. The results of stepwise multiple regression analysis on carrying capacity of Hokkaido chum salmon showed that (1) the multiple regression identified body size of juvenile at the release, return rate, and the SST in spring, and that (2) relationship between ALPI or number of juvenile released and the carrying capacity did not indicate significant trends over time (Table 1). Kaeriyama (1999) reported that the relationship between return rate, which is the survival rate from the release to the return, and body size of juveniles at release showed significant-positive correlation in Hokkaido chum salmon population. Despite a positive correlation between SST in the coast and the return rate of Hokkaido chum salmon ($r = 0.711$, $F = 30.75$, $P < 0.001$), the relationship between the ALPI and the SST was not significantly positively correlated in all coasts around northern Japan, and showed a negative correlation in Okhotsk Sea and a part of Japan Sea near Hokkaido (A. Yatsu, National Research Institute of Fisheries Science, Japan. unpublished data)

Fig. 2. Changes in mean Aleutian low pressure index (ALPI) and total carrying capacity (K ; million individuals) of sockeye, chum, and pink salmon in the North Pacific Ocean.

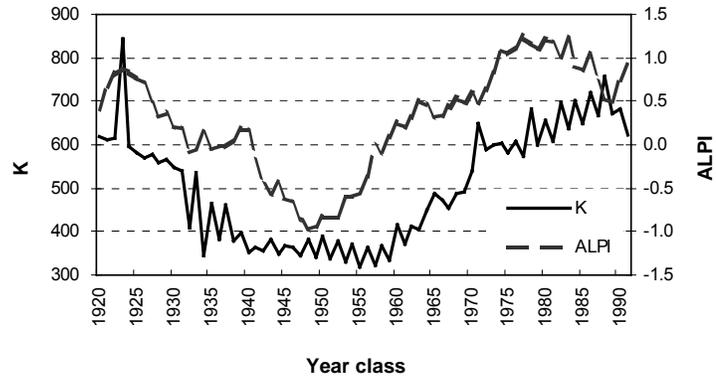


Table 1. Summary of stepwise multiple regression on carrying capacity of Hokkaido chum salmon population.

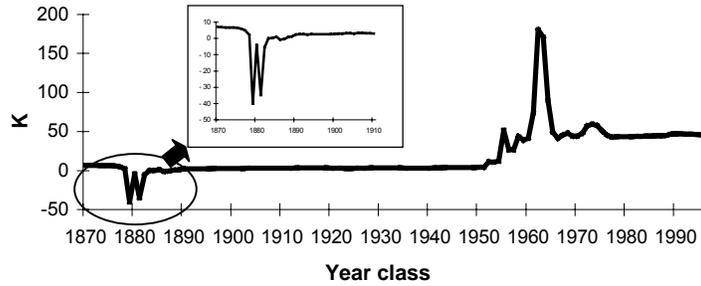
Dependent variable: Carrying capacity (K)			
Predictor variable	Partial regression coefficient	Partial correlation coefficient	P-value
ALPI	0.409	0.159	0.586
SST	-9.763	-0.678	0.008
N_j	0.003	0.072	0.806
RR	2.107	0.696	0.006
BW	8.893	0.798	0.001

$r^2 = 0.952$, $AIC = 23.927$, $Constant = 82.869$

*ALPI: Aleutian low pressure index, SST: Sea surface temperature along the coast around Hokkaido, N_j : number of released juvenile, BW: mean body weight (g) of juvenile released.

In Hokkaido chum salmon, wild population decreased since the late 1880s due to the negative impact of the poor hatchery technology, while hatchery populations increased exponentially since the late 1970s as a result of the development of progressive hatchery technology (Kaeriyama and Edpalina in press). As a result, the carrying capacity of Hokkaido chum salmon decreased abruptly at a negative critical point in the 1880s year-classes and dramatically increased at positive critical point since the 1960s year-classes (Fig. 3).

Fig. 3. Change in carrying capacity (K; million individuals) of Hokkaido chum salmon population.



These results suggest that the carrying capacity of Hokkaido chum salmon does not relate to the ALPI and is affected by reproductive regimes such as hatchery technology, survival, and environmental factors (e.g. SST) in the early marine life period. Although the carrying capacity at the species level synchronizes with change in ecosystem linked with long-term climate change, the factors affecting carrying capacity at the population level will differ by population.

Relationship between the RCC and the fork length in Hokkaido chum salmon populations indicated a significant-positive correlation. On the other hand, relationship between the RCC and the age at maturity in Hokkaido chum salmon populations showed a significant-negative correlation (Fig. 4). The reduction in somatic growth with increase in population size is caused by the population density-dependent effect (Kaeriyama 1998). Therefore, these results suggest that carrying capacity of chum salmon may be closely related with both the long-term climate change and population dynamics.

In annual change in biomass of wild and hatchery chum salmon (Fig. 5), mean biomass of both wild and hatchery salmon in the 1990s (132 million individuals) is roughly the same as it in the 1930s (140 million individuals). However, wild salmon in the 1990s decreased 50% from that in the 1930s, despite the significant increase in the biomass of hatchery salmon. This phenomenon in chum salmon suggests that:

- (1) Despite the high carrying capacity, the biomass of wild salmon did not increase due to low survival rate (e.g. Russian, West-, and Central-Alaska populations).
- (2) Wild salmon were replaced with hatchery salmon such as pink salmon in Prince William Sounds (Hilborn and Eggers 2000). The primary reason is that, hatchery salmon have higher survival rate than wild salmon especially during their early marine life period.

Fig. 4. Relationships between residual carrying capacity (RCC, %) and A. mean fork length (FL, mm) of age-4 female adult returning to 11 rivers, and B. mean age (Age) at maturity in Hokkaido chum salmon.

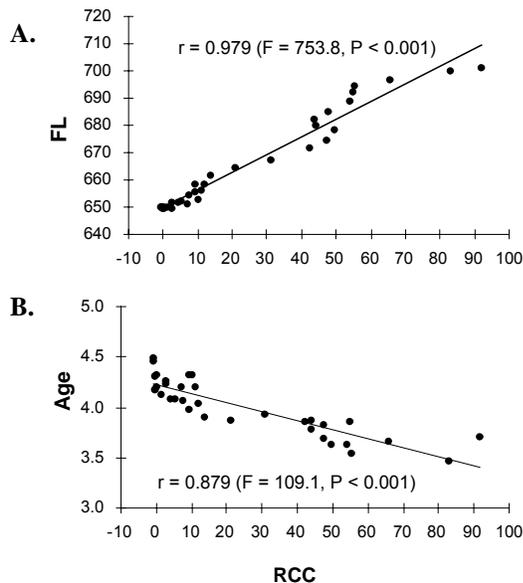
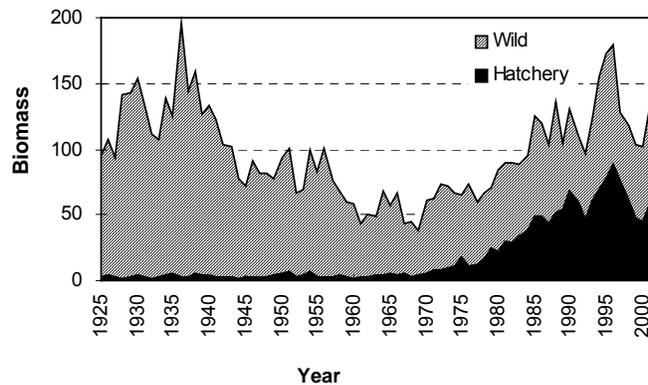


Fig. 5. Annual change in biomass (millions of individuals) of wild and hatchery populations of chum salmon in the North Pacific Ocean.



Therefore, biological interaction between wild and hatchery population should be an important consideration in the sustainable management of Pacific salmon production based on the ecosystem level.

While it is true that salmon hatchery programs play an important role in meeting the demands of an expanding human population in the twenty-first century, we also would like to stress the negative impact of these hatchery programs to the wild salmon population such as the population density-dependent effect and the replacement between wild and hatchery populations. The following issues are extremely important:

- (1) harmonization with the ecosystem and
- (2) coexistence of wild and hatchery populations in the North Pacific.

To address these issues, the ecosystem-based sustainable conservation management should be adopted and implemented. A management plan should incorporate the following activities: (1) climatic and oceanic monitoring (e.g. long-term climate change, ecosystem structure), (2) biological monitoring (e.g. carrying capacity, individual somatic growth and age composition of a population, genetic and reproductive characters), and (3) sustainable management of Pacific salmon production (e.g. biological interaction between hatchery and wild populations, rehabilitation and conservation of wild salmon and riparian ecosystem) should be very important considerations.

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