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Ecosystem-Based Sustainable Conservation and Management of Pacific Salmon

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Pacific salmon (*Oncorhynchus* spp.) play an important role as a keystone species in North Pacific ecosystems, where their populations are influenced by natural factors and human impacts. Carrying capacity for Pacific salmon is related to the long-term climate change, and also to density-dependent effects. For example, the residual carrying capacity of chum salmon (*O. keta*) was positively correlated with body size of adult salmon but negatively correlated with age at maturity. The abundance of wild chum salmon in the North Pacific in the 1990s declined to about 50% of what it was in the 1930s, despite significant increases in introduction of hatchery-produced salmon. This indicates that fisheries management has limitations at the population level, and that biological interactions between wild and hatchery-produced populations of Pacific salmon should be considered. Global warming has affected growth and survival of Asian chum salmon since the 1990s, and has had a positive effect on Hokkaido populations but negative effects for more southern populations in Iwate Prefecture and in Korea. Predictions about global warming effects on chum salmon suggest that their area of distribution will change resulting in a displacement to the northern area such as the Arctic Ocean, and the loss of migration routes such as the Okhotsk Sea. This paper presents a framework for ecosystem-based sustainable conservation and management of Pacific salmon, which takes account of climate change and interactions between wild and hatchery fish.

KEYWORDS ecosystem-based sustainable conservation and management; Pacific Ocean; carrying capacity; climate change effects

1. Introduction

Marine food should be reproducible resources for human beings. However, world fish catches have peaked since the 1990s despite increase in aquaculture production (Fig. 1). Tuna (*Thunnus* spp.) abundance extremely decreased by overfishing since the 1980s (Myers and Worm 2003). Bluefin tuna (*T. thynnus*) is already “critical species” in the IUCN. Although production from aquaculture is increasing world-wide, many aquaculture programs also cause the destruction of aquatic ecosystem such as vanishing mangrove forests caused by the shrimp aquaculture over the last 20 years in the Eastern Asia (Primavera *et al*. 2005), marine pollution, and threats to marine food security (e.g., contaminants in farmed Atlantic salmon; Hites *et al*. 2004).

Traditional fisheries science consider only fisheries, some consequences of which include fishing down marine food webs (Pauly *et al*. 1998), the over fishing by the tuna laundering, the tragedy of commons, the food mileage, ecosystem crashes, and food pollution. A paradigm shift is needed from the traditional fisheries science to a new fisheries science and oceanography for the protection of marine ecosystems and human food resources.

Analyses of the nitrogen stable isotope concentration in animals in the Gulf of Alaska have demonstrated that Pacific salmon occupy the fourth and fifth trophic levels in this ocean ecosystem (Kaeriyama 2003). Pacific salmon play an important role as a keystone species in the Subarctic Ocean and the freshwater ecosystems. Pacific salmon are also a key species for sustaining the biodiversity and productivity in the riparian ecosystem because they supply marine-derived material into river systems and the adjacent watersheds (Kline *et al*. 1990; Hilderbrand *et al*. 1999; Helfield and Naiman 2001). Therefore, Pacific salmon are important not only as fisheries resources but also as keystone species in the Subarctic aquatic ecosystem.

The objectives of this paper are to consider the following issues in relation to Pacific salmon: 1) carrying capacity, 2) global warming effects, and 3) sustainable conservation and management.

2. Carrying Capacity

Changes in the catches of Pacific salmon have a 30- or 40-year periodicity that coincides with long-term climate indices such as the Pacific Decadal Oscillation (PDO; Mantua *et al*. 1997) and climate regime shifts

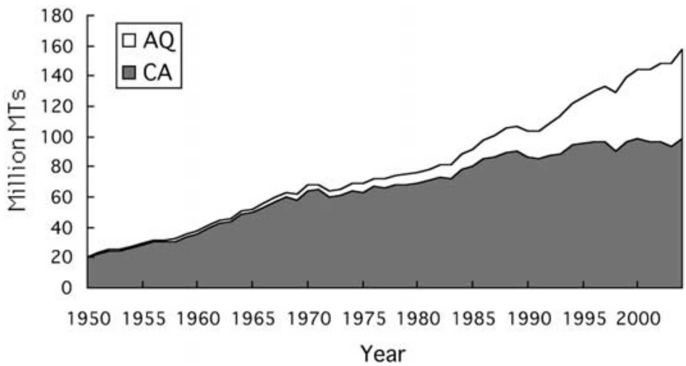

Fig. 1. Time trend of capture fisheries (CA) and aquaculture production (AQ) in the world during 1950–2001 (from FAO Fisheries Statistics).

(Fig. 2; Kaeriyama and Edpalina 2004). Kaeriyama (2003) defined the carrying capacity (*K*) of Pacific salmon as the replacement level of the Ricker recruitment curve. The carrying capacity of sockeye (*O. nerka*), chum (*O. keta*), and pink salmon (*O. gorbuscha*) since the 1976 regime-shift year has increased approximately by 100% compared with that in the 1947–1975 year classes. Statistically significant correlations were consistently detected between the mean Aleutian Low Pressure Index (ALPI; Beamish and Bouillion 1993) and the carrying capacity (*K*) of these three salmon species, but were not always significant for the α and β parameters of the Ricker curve. Thus, it appears that the carrying capacity of Pacific salmon is significantly synchronized with long-term changes in climate variation (Kaeriyama 2003).

Annual changes in biomass, which include catch and escapement, of wild and hatchery chum salmon indicate that the mean population biomass of both wild and hatchery chum salmon in the 1990s (132 million individuals) was roughly the same as that in the 1930s (140 million individuals). However, the abundance of wild chum salmon in the 1990s (67 million individuals) was only 50% of that in the 1930s (136 million individuals) despite the significant increase in the biomass of hatchery populations (Fig. 3; Kaeriyama and Edpalina 2004). This phenomenon in chum salmon suggests that the hatchery chum salmon recruited into the vacant ecological niche in the North Pacific Ocean left empty through recruitment failures in wild salmon stocks, that were linked to mass poaching (Korolev 2001). Wild populations were replaced with hatchery derived individuals such as occurred for pink salmon in Prince William Sound (Hilborn and Eggers 2000). The residual carrying capacity (RCC) was defined as RCC = $(K - \text{biomass})K^{-1}$ (Kaeriyama 2003). Relationships between the RCC and the fork length of adult Hokkaido chum salmon indicated a positive correlation. In contrast, the mean age at maturity of adult Hokkaido chum salmon negatively correlated with the RCC (Fig. 4). This indicates a density-dependent population effect reduces the individual growth in Hokkaido chum salmon population with a resulting decrease in the residual carrying capacity (Kaeriyama and Edpalina 2004). The same result was observed in the relationship between the RCC of total chum salmon in the North Pacific and the individual growth reduction of Hokkaido chum salmon (Kaeriyama and Edpalina 2004). These results suggest that the carrying capacity of chum salmon in the North Pacific would be closely related to changes in climate change, but also with density-dependent population effects. Therefore, biological interactions between wild and hatchery populations should be an important consideration in sustainable fisheries management that operates at the ecosystem level.

3. Global Warming Effect

After spending their early marine life in coastal waters, Hokkaido chum salmon migrate to the Okhotsk Sea and then move to the Western Subarctic Gyre for their first-wintering. Thereafter, they migrate between the summer feeding grounds in the Bering Sea and the overwintering grounds in the Alaska Gyre. After about four years, they return to their natal rivers for spawning (Urawa 2000; Yatsu and Kaeriyama 2005). There are two hypotheses concerning the periods of critical mortality in Pacific salmon: (1) size-selective (predation) mortality in the early marine life period (the first few months after seaward migration; Healey 1982) and (2) size-related mortality over the first marine fall and winter which is dependent upon the salmon achieving sufficient growth by the end of first marine summer (Beamish *et al.* 2004). As the survival rate of Hokkaido chum salmon is significant—positively correlated with the mean

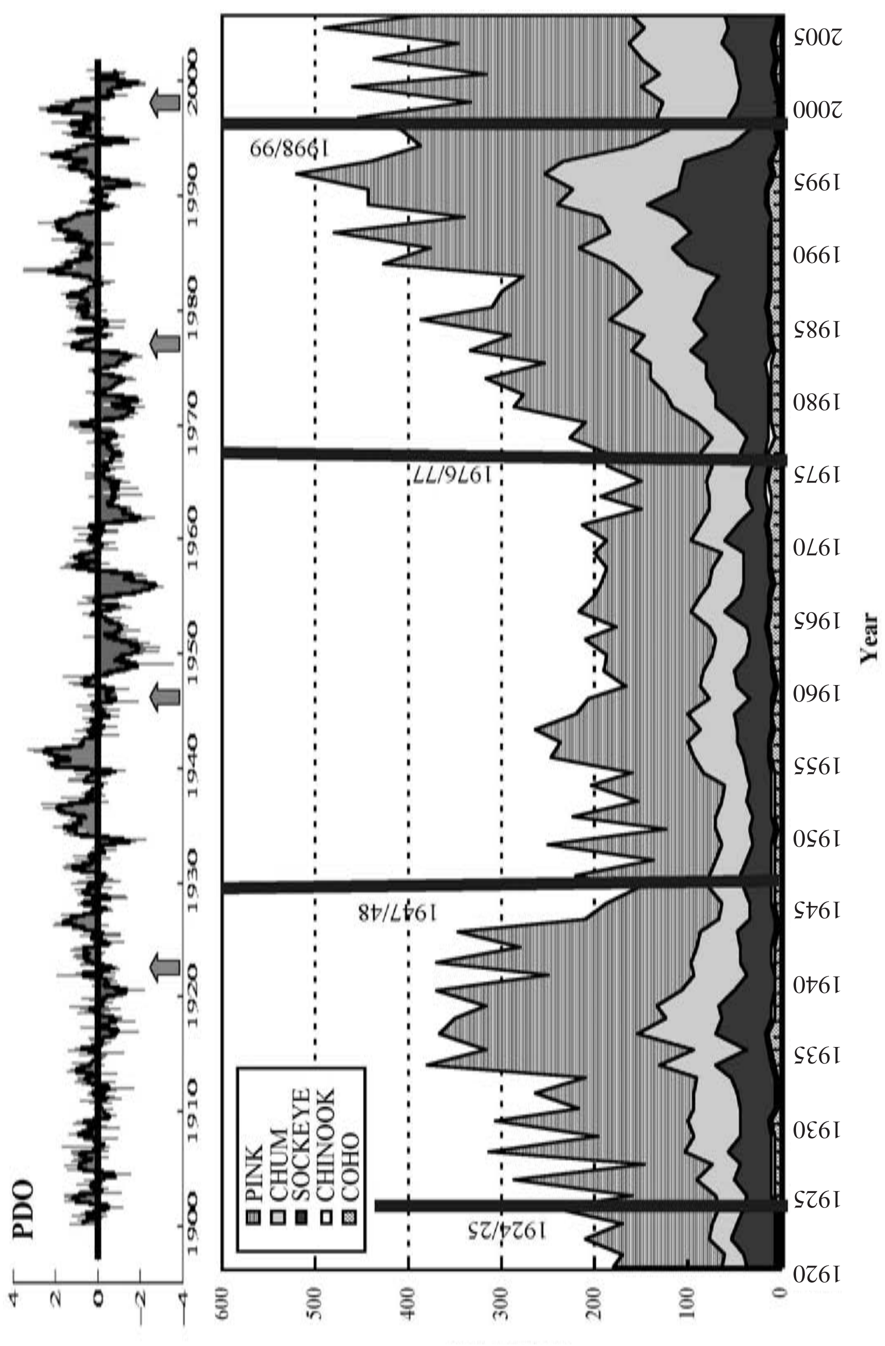

Fig. 2. Annual changes in the catch of Pacific salmon and the Pacific Decadal Oscillation (PDO) in the North Pacific Ocean in 1920–2006. Bars and arrows indicate the regime-shift year. The PDO is based on Mantua *et al.* (1997).

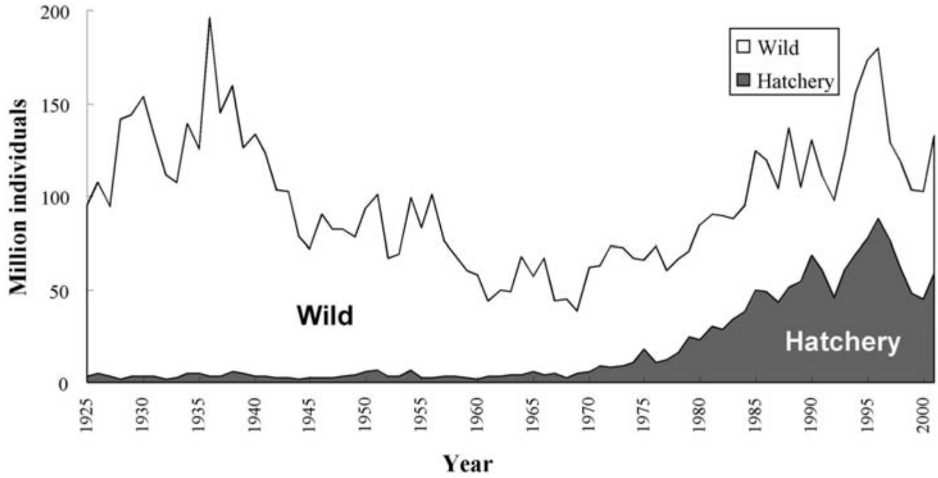

Fig. 3. Temporal change in biomass of wild and hatchery populations of chum salmon in the North Pacific during 1925–2001 (Kariyama and Edpalina 2004).

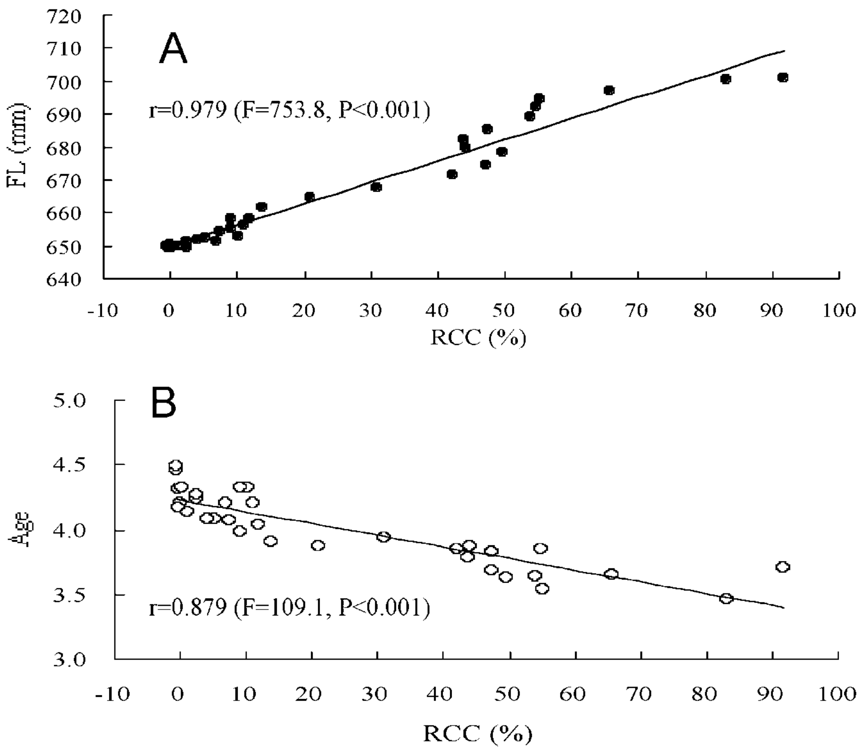

Fig. 4. Relationship between residual carrying capacity (RCC) and mean fork length (FL, **A**) of age-4 female adult-returning to 11 rivers or mean age at maturity (**B**) of Hokkaido chum salmon.

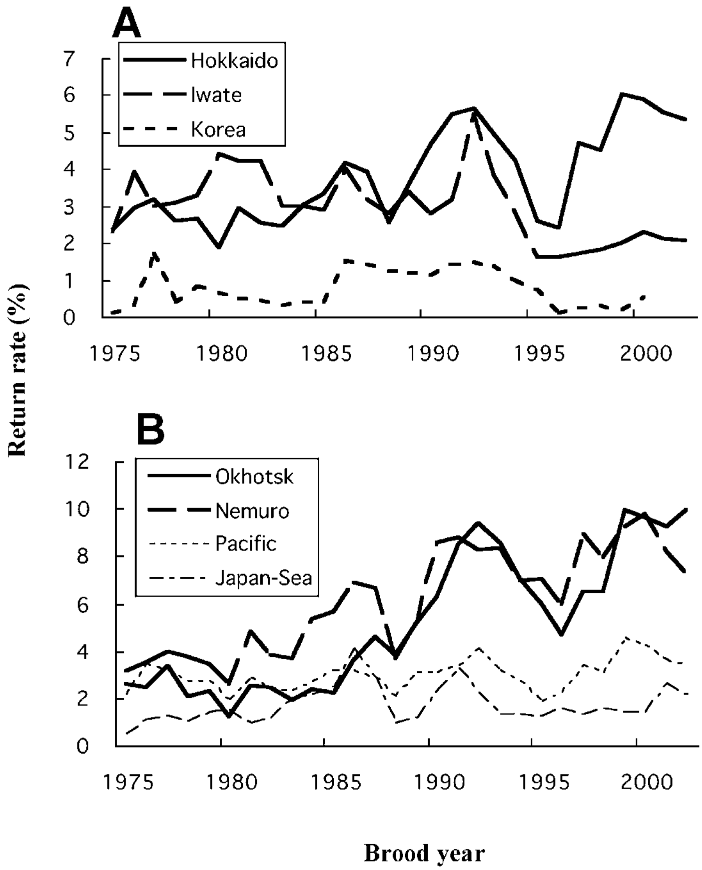

Fig. 5. Temporal changes in return rate of Hokkaido, Iwate, and Korean chum salmon populations (**A**), and of local populations in Hokkaido (**B**).

body-size of juveniles released and the growth anomaly of juvenile in the Okhotsk Sea, they would be affected by size-related mortality in the first marine winter after their growth period in the Okhotsk Sea, although mortality rates in the early marine period would be higher than those during their first marine winter (Kaeriyama *et al*. 2007).

Using scale analyses, back-calculated growth rates from Hokkaido chum salmon show that their growth anomaly is strongly and positively correlated with sea surface temperature (SST) during summer and fall, but is negatively correlated with the rate of sea-ice-covered area during winter in the Okhotsk Sea (Kaeriyama *et al*. 2007). Zooplankton biomass in the Okhotsk Sea has also been decreasing since the 1980s (Shuntov and Dulepova 1996). Therefore, the increase in growth of Hokkaido chum salmon during the 1990s appears to have been affected by the increase in SST and not by a decrease in zooplankton productivity, relating to the sea ice concentration in the Okhotsk Sea (Kaeriyama *et al*. 2007). The extent of sea ice concentrations have been decreasing during the last 100 years as air temperatures on the Okhotsk Sea coast of Hokkaido have increased. Aota (1999) suggested that this phenomenon would be one

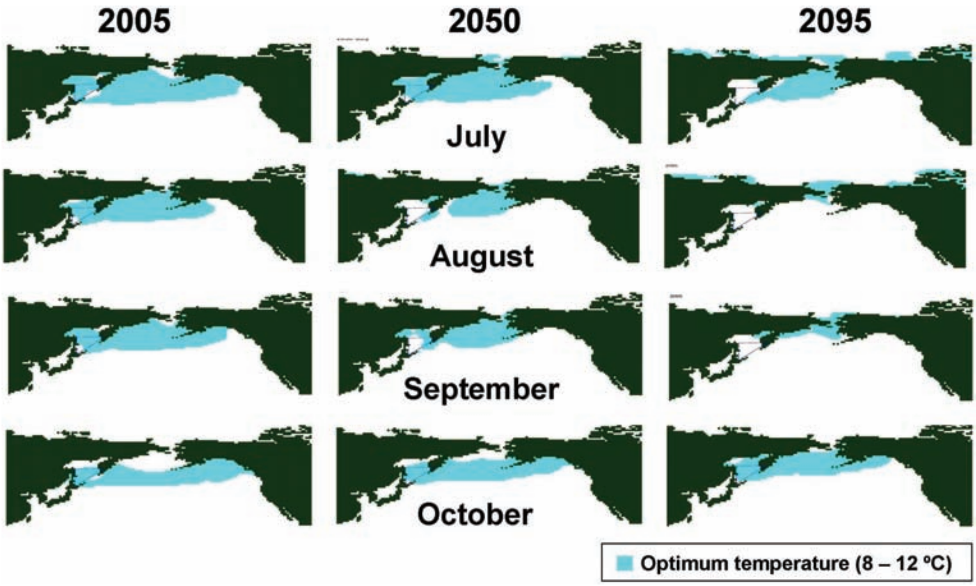

Fig. 6. Prediction of the global warming effect on chum salmon in the North Pacific Ocean based on the SRES-A1B scenario of the IPCC.

of the symptoms of global warming. Therefore, increases in the growth of Hokkaido chum salmon in the Okhotsk Sea since the 1990s may be related to the effects of global warming on sea ice cover.

Return rates of Korean and Iwate chum salmon have decreased since the 1990s, although that of Hokkaido chum salmon has increased since the 1976 regime-shift year (Fig. 5a). In Hokkaido, the chum salmon populations of Nemuro and Okhotsk Sea coasts, located near the Okhotsk Sea, have had return rates markedly higher than other populations (Fig. 5b). Korean and Iwate chum salmon are distributed in southern water and are affected by the Tsushima Warm Current during their spring offshore-migration period. Declines in their return rates did not coincided with the years of the climate regime shifts (1976, 1988, and 1998). These results suggest that global warming can be expected to have positive effects on Hokkaido chum salmon populations in the Okhotsk Sea, but negative effects on Korean and Iwate populations because of inproving force of the Tsushima Warm Current.

In the near future, what and how will Pacific salmon be affected by the global warming? Using the SRES-A1B scenario of the IPCC, it is possible to infer the global warming effect on chum salmon based on their optimal temperature for growth (8–12°C; Kaeriyama 1986; Ueno and Ishida 1998). This leads to the suggestion that chum salmon would be brought into direct competition with other salmon populations leading to a decrease in survival rate and population density-dependent effects because of the reduction of distribution area, displacement to the north (e.g., the Arctic Ocean), and the loss of migration routes (e.g., the Okhotsk Sea; Fig. 6).

4. Ecosystem-Based Sustainable Conservation and Management

The population dynamics of Pacific salmon is directly affected by a number of stresses (climatic and human impacts) that need to

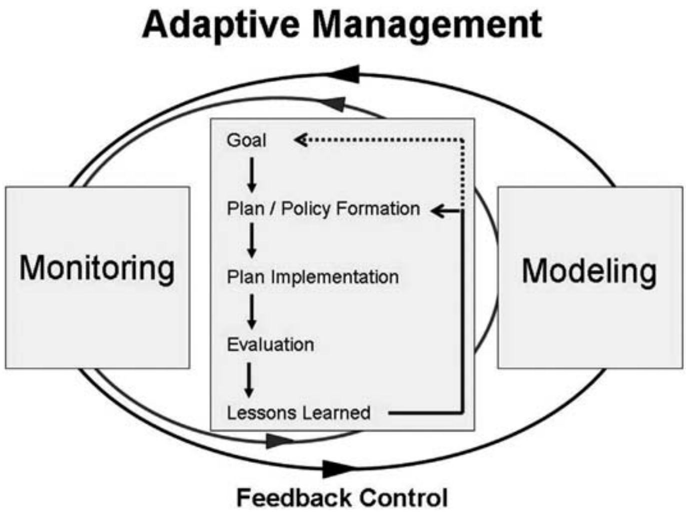

Fig. 7. Conception of the adaptive management for the sustainable fisheries management of Pacific salmon based on the ecosystem approach.

be considered within an ecosystem context. The structure and function of the ecosystem includes the interaction between the abiotic environment and the organism, and biodiversity, respectively. The aquatic ecosystem is subject to disturbance by natural factors and human impacts. Recently, human impacts have strongly affected the aquatic ecosystem (e.g., global warming, overfishing, habitat loss, artificial river channelization, dam construction, and negative effects of aquaculture and hatchery programs; Kaeriyama and Edpalina 2004). We need to recognize the limitations of fisheries management that is focused at the population level, and establish sustainable conservation and management based on the integration of population level approaches within a wider ecosystem-based approach.

Definitions of an ecosystem-based approach to fisheries management have been proposed by several authors (NRC 1999; Witherell *et al*. 2000; FAO 2003; McLeod *et al*. 2005; Murawski and Matlock 2006; Marasco *et al*. 2007). In this paper, I have used the definition of McLeod *et al*. (2005): "Ecosystem-based management is an integrated approach to management that considers the entire ecosystem, including humans. The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive, and resilient condition so that it can provide the services human want and need. Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern. It considers cumulative impacts of different sectors." In this century, the ecosystem conservation and the stable production of food from marine sources are the most important issues for human beings in the global earth system, taking into account increases in human population and impacts such as global warming. Sustainable conservation management based on the ecosystem approach (SCMEA) for Pacific salmon should be part of the sustainability science of fisheries and oceans. Three aspects of the structure and function of the ocean ecosystem should be monitored, in particular for Pacific salmon;

1) spatial and temporal changes: carrying capacity, food web and trophic level,

2) climatic oceanic conditions: global warming, regime shifts,
3) biological interactions: between wild and hatchery populations, density-dependent effects, and inter- and intra-specific competition.

For the SCMEA of Pacific salmon, adaptive management and the precautionary principle are important. In particular, adaptive management should be conducted based on the feedbacks between monitoring, modeling, and adaptive learning, which includes learning by undertaking risk analyses and consensus building (Fig. 7).

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