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Perspectives on wild and hatchery salmon interactions at sea, potential climate effects on Japanese chum salmon, and the need for sustainable salmon fishery management reform in Japan

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Abstract

Pacific salmon (*Oncorhynchus* spp.) play an important role as a keystone species and provider of ecosystem services in the North Pacific ecosystem. We review our studies on recent production trends, marine carrying capacity, climate effects and biological interactions between wild and hatchery origin populations of Pacific salmon in the open sea, with a particular focus on Japanese chum salmon (*O. keta*). Salmon catch data indicates that the abundance of Pacific salmon increased since the 1976/77 ocean regime shift. Chum and pink salmon (*O. gorbuscha*) maintained high abundances with a sharp increase in hatchery-released populations since the late 1980s. Since the 1990s, the biomass contribution of hatchery returns to the total catch amounts to 50% for chum salmon, more than 10% for pink salmon, and less than 10% for sockeye salmon (*O. nerka*). We show evidence of density-dependence of growth and survival at sea and how it might vary across spatial scales, and we provide some new information on foraging plasticity that may offer new insight into competitive interactions. The marine carrying capacity of these three species is synchronized with long-term patterns in climate change. At the present time, global warming has positively affected growth and survival of Hokkaido populations of chum salmon. In the future, however, global warming may decrease the marine carrying capacity and the area of suitable habitat for chum salmon in the North Pacific Ocean. We outline future challenges for salmon sustainable conservation management in Japan, and recommend fishery management reform to sustain the hatchery-supported salmon fishery while conserving natural spawning populations.

Keywords: Pacific salmon, ecological interaction, wild and hatchery-derived populations, carrying capacity, density-dependent effect, global warming, sustainable conservation management

Introduction

The structure and function of ecosystems are influenced and disturbed not only by natural factors such as climate regimes, but also by anthropogenic impacts such as the global warming and overfishing. Pacific salmon (*Oncorhynchus* spp.) play an important role as a keystone species in the North Pacific ecosystems, and are useful for evaluation of ecosystem status given their high trophic level position in the ecosystem. According to results of carbon and nitrogen stable isotope analyses, they occupy the fourth and fifth trophic levels (Welch and Parsons 1993; Staterfield and Finney 2002; Kaeriyama et al. 2004; Johnson and Schindler 2008). Pacific salmon are also important for sustaining the biodiversity and productivity in the riparian freshwater ecosystem by supplying marine-derived material to the terrestrial ecosystem (Bilby et al. 1996; Hilderbrand et al. 1999; Kaeriyama & Minagawa 2008). However, in Japan Pacific salmon tend to be valued only as seafood and not for their important ecological role in the North Pacific (Kaeriyama 2008).

The biomass of Pacific salmon in the North Pacific Ocean increased from the late 1970s to the present owing to the favorable oceanic environment and increasing hatchery production (Beamish and Bouillon 1993; Mantua et al. 1997; Kaeriyama 1999a; Ruggerone et al. 2005). However, wild chum salmon (*O. keta*) populations since 1970s have decreased since the 1950s despite significant increases in hatchery stocking of this species in the North Pacific (Kaeriyama and Edpalina 2004; Ruggerone et al. 2010). One possible explanation for this is that hatchery fish have directly competed with and displaced wild salmon. Hilborn and Eggers (2000) reported that wild pink salmon (*O. gorbuscha*) were replaced with hatchery salmon in Prince William Sound due to higher survival rates and greater overall abundance than the wild fish, especially during their early marine life stages. Wertheimer et al (2001) later questioned the conclusions of Hilborn and Eggers (2000). In their rebuttal, Wertheimer et al. (2001) challenged their conclusion that hatchery pink salmon have replaced rather than enhanced pink salmon returns to Prince William Sound. They emphasized that there are a number of ways to interpret the data, and other equally plausible hypotheses to explain the observed trends, including hypotheses that address density-independent factors (e.g. zooplankton production) in the marine environment. They conclude that the situation is more complex than that implied by the analytical approach used by Hilborn and Eggers (2000). This debate underscores the need to develop better monitoring and assessment programs that would allow for a more direct assessment of effects hatchery salmon are having on wild salmon. This is becoming a more urgent need as hatchery salmon biomass in the North Pacific has grown along with interest in conservation of wild salmon populations (Kaeriyama and Edpalina 2004; Ruggerone et al. 2010).

While the focus of the 2010 State of the Salmon Conference focused primarily on ecological interactions between wild and hatchery salmon, it is important to acknowledge the genetic risks to wild salmon posed by hatchery programs. Hatchery-origin salmon can introgress with wild salmon and ultimately influence the fitness of wild Pacific salmon. Araki and Schmid (2010) reviewed 266 peer-reviewed papers on effects of hatchery fish stocking on wild stocks and consequences for stock enhancement, and concluded that negative effects of hatchery rearing on a variety of fish species are common. Population and genetic structure of hatchery populations of Hokkaido chum salmon has been studied in recent years (Okazaki 1982; Kaeriyama 1999a, Edpalina et al. 2004; Yokotani et al. 2009). The hatchery-derived chum salmon have been determined to exhibit lower genetic diversity than wild salmon. Okazaki (1982) noted that the average heterozygosities of Japanese hatchery chum salmon were significantly lower than those of North American populations based on allozyme analyses of populations. Heterozygosities estimated on the basis of 22 loci ranged between 3% and 5%, which is relatively low compared with those of North American chum salmon. Yokotani et al. (2009) surveyed population structure in the Yurappu River using mitochondrial DNA (mtDNA) analysis. The Yurappu River chum salmon showed 8 haplotypes (Ht1-Ht8) in the 481bp 5’ variable portion of the mtDNA control region. 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 the other-river populations such as Chitose, Tokachi, and Nishibetsu river-populations on the neighbor-joining tree. These results suggest that the 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 timing component represents an introgressed population consisting of the native strain and out-of-basin transplants (Yokotani et al. 2009). Furthermore, hatchery programs can drastically lead to declines in the genetic variability of wild Pacific salmon populations (Edpalina et al. 2004, Araki et al. 2007). Based on a review of 18 case studies, Berejikian and Ford (2004) concluded that steelhead (*O. mykiss*), coho (*O. kisutch*), and Atlantic salmon (*Salmo salar*) populations have low lifetime relative fitness in the wild compared to native, natural populations. Araki et al. (2007) indicate that hatchery salmonids have lower fitness in natural environments than wild fish. This fitness decline can occur very quickly, sometimes following only one or two generations of captive rearing. Outbreeding is a potential genetic risk in Pacific salmon when aquaculture practices introduce nonnative domesticated fish to the wild environments, making interbreeding with wild populations possible (McClelland et al. 2005). This information suggests that we need to elucidate both ecological and genetic interactions between wild and hatchery-derived salmon populations to help assure that both populations persist. Our rationale to conserve wild and naturally reproducing salmon populations in Japan is based on their ability to adapt readily to new environmental conditions.

We have reported on the population density-dependent effect of Hokkaido chum salmon with increasing population size since the 1980s (Kaeriyama 1989, 1998). This density-dependent effect was also observed in North American populations of chum salmon in the same period (Helle and Hoffman 1998), in wild sockeye salmon populations in Bristol Bay (Rogers and Ruggerone 1993), and in wild chum (Volobuev 2000) and pink salmon (Shuntov and Temnykh 2005) in the Okhotsk Sea and in the Anadyr River (Zavolokin et al. 2009). While these studies have focused on large scale ocean dynamics, we contend we can learn from experiences in small freshwater systems. In the case of a sockeye salmon population in the oligotrophic Lake Shikotsu, Hokkaido, large number of juveniles released from a hatchery increased the species density in this system and caused density-dependent responses in growth and survival, leading to a crash of the population, a decline in the effective population size, skewing of the sex ratio in the population, abnormal gonad development, and an epidemic of fungal disease (Kaeriyama 1991). This system may serve as a microcosm of the larger North Pacific ecosystem. While the scale and complexity of the North Pacific ecosystem is considerably greater, there is an urgent need to accurately clarify mechanisms, and describe the extent and intensity of density-dependent effects operating on salmon populations in order to conserve Pacific salmon.

Global demand for wild and sea-ranched Pacific salmon has grown unabated, and this has lead to growing economic interest in increasing hatchery production and improving survival rate of released juveniles. This trend underscores the need to fully investigate potential negative effects of hatchery fish on wild Pacific salmon. These biological interactions between wild and hatchery-derived salmon populations should be given urgent attention in relation to their ecology, behavior, genetics, and physiology. Additionally, chum salmon have been mass-produced by hatchery programs in Japan, while numerous wild chum and masu salmon (*O. masou*) populations have been put at risk from negative effects of hatchery programs operating in concert with a host of other threats, including habitat loss and degradation, artificial river channelization, increases in recreational fishing, and transplantation of exotic fishes into the river ecosystems in Japan (Kaeriyama and Edpalina 2004).

In this paper, we review our studies on recent production trends, the relationship between long-term climate change and carrying capacity, and biological interactions between wild and hatchery-derived populations of Pacific salmon in the open sea. We add some new information relating to marine salmon feeding ecology and we provide some new insights into how global warming might affect Hokkaido chum salmon through the use of a path model. We offer our perspective on these issues with a genuine interest in conserving wild salmon.

Current situation of Pacific salmon biomass dynamics

Based on records of catch of wild and hatchery-origin Pacific salmon in the North Pacific (Fig. 1), the catches of pink, chum, and sockeye salmon (*O. nerka)* constituted more than 90% of the total catch. The annual change in catch has roughly a 30- or 40-year periodicity, corresponding to the long-term climate changes such as the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and ocean regime shifts. It should be noted, however, that we did not see a marked shift in the North Pacific salmon abundance (as reflected in catch) during the 1988/89 regime shift (Fig. 1, Kaeriyama 2008).

We have been investigating trends in ocean salmon abundance and are developing quantitative approaches to assess marine carrying capacity of sockeye, chum, and pink salmon (Kaeriyama et al. 2009). North Pacific salmon abundance was estimated from catch data using an expansion rate based on the fisheries exploitation rate (Eggers 2004; Kaeriyama et al. 2009). Traditionally, the Ricker stock-recruitment function is assumed to account for density-dependence operating on the spawning grounds or at some point during early life history in freshwater. Alternatively, we think it is a useful exercise to explore the use of this model to explain potential density-dependent processes operating during their marine life history (Yatsu and Kaeriyama 2005; Yatsu et al. 2008). Kaeriyama et al. (2009) estimated the Ricker stock-recruitment equilibrium level (the stock biomass at which recruits per spawner (R/S) = 1, i.e. the point at which the population is at replacement) from brood tables based on expanded catch data. This equilibrium point is a measure of production capacity of the species at the gross scale of the North Pacific, and provides an index of carrying capacity (*K*) for each salmon species (Kaeriyama et al. 2009). We used a moving temporal window of twenty years (projecting forward 10 generations of odd- and even-year of pink salmon and 4-5 generations of chum and sockeye salmon) to resolve the potential influence of low frequency ocean climate cycles (Fig. 2, Kaeriyama et al. 2009). While the causal mechanism and the critical life history where recruitment success is determined are uncertain, Kaeriyama et al. (2009) documented strong coherence between a large scale ocean climate signal (Aleutian Low Pressure Index; Beamish and Bouillion 1993) and this Ricker stock equilibrium level (Fig. 2A). The carrying capacity of three species (sockeye, chum, and pink salmon) decreased since the 1925 year-class, was minimal during 1945-1955 year classes, increased during 1956-1975 year classes, and remained constant during 1976-1997 year classes (Fig. 2B). These results suggest that there may be some broad, density-dependent controls over salmon recruitment and productivity in the marine environment.

Intra-specific interactions of chum salmon

Trends in abundance, which include catch and escapement, of wild and hatchery chum salmon through the North Pacific region indicate that the mean population abundance 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, Kaeriyama et al. 2009). However, the abundance of wild chum salmon in the 1990s (67 million individuals) was only 50% of that in the 1930s despite a significant increase in the abundance of hatchery populations across the North Pacific region (Fig. 3). The 1990s hatchery populations have contributed up to 50% to the total returns of chum salmon. Contributions of hatchery fish to returns of pink and sockeye salmon have been more modest (10%, Fig. 3B, Kaeriyama et al. 2009). It is important here to recognize that the production potential of wild salmon has been reduced during this period. In Japan, this is related to substantial habitat loss, artificial river-channelization, and negative effects of hatchery programs (specifically river migration impediments in the form of weirs and broodstock take by hatcheries). Although more difficult to quantify, illegal take of salmon in Russia is also thought to be a significant threat to wild salmon (Dronova and Spiridonov 2008). As previously noted, there is some evidence that wild populations have been replaced with hatchery salmon due to competitive interactions during their early marine life stages, such as pink salmon in the Prince William Sound (Hilborn and Eggers 2000). Ruggerone et al. (2010) alleged that large and increasing abundance of hatchery salmon have affected density-dependent processes of wild salmon.

Determining the nature and magnitude of density-dependence and ecological interactions of salmon during their ocean life history is a very challenging area of research. We contend that examining feeding habits of salmon in the ocean can provide novel insight into ecological processes that may be regulating growth and survival during this important life stage. As a demonstration of this, we surveyed the feeding habits of chum salmon collected by surface trawl nets in the Bering Sea in the summer 2009, using the method of Kaeriyama et al. (2004). Chum salmon fed on diverse prey-animals in the wider area, and predominantly consumed nekton in the coastal waters of the Aleutian Islands, pteropods in the middle Bering Sea region, and a mixture of pteropods and copepods in the northern part of the Bering Sea (Fig. 4). We found a positive correlation between an index representing consumed food diversity (Shannon-Wiener Index) and CPUE (number of fish captured per unit trawling effort) (Fig. 5). These results suggest that chum salmon show plasticity in their feeding, shifting their diets from dominant, preferred prey species to more diverse prey with increased salmon population density in order to minimize intra-specific competition. This phenomenon has been observed in other studies. Tadokoro et al. (1996) found the diet of chum salmon was correlated with the abundance of pink salmon owing to inter-specific competition. In this study, the authors documented a shift in diets of chum salmon in the central Subarctic Pacific related to the abundance of a resource competitor, pink salmon. In years with low pink salmon abundance, chum salmon consumed a diet consisting mostly of nutritious assemblage of crustaceans. In years of high pink salmon abundance, chum salmon consumed gelatinous zooplankton, a prey of significantly lower quality. Thus, the increase of ocean salmon abundance caused by the increase in hatchery populations could lead to elevated intra-specific interactions (e.g., ecological interactions between hatchery and wild salmon leading to a population density-dependent effect). On the other hand, there is an opinion that Pacific salmon do not overpopulate under the high abundance because of changing prey animals and expanding their distribution area (Shuntov and Temnykh 2005).

Insights can be gained by exploring relationships between size at age and age at maturity of returning chum salmon to a simple index representing ocean production potential for chum salmon. Here, we introduce a term, residual carrying capacity (RCC), which is meant to represent the gap between potential ocean capacity to produce chum salmon (defined as carrying capacity above) and that observed (total returns, summing catches and escapement). We present the following simple equation here:

$$RCC = (\text{carrying capacity} - \text{abundance}) / (\text{carrying capacity}) \times 100,$$

where carrying capacity is derived from the Ricker stock equilibrium abundance (in return number as defined above), and abundance is total returns (sum of catch and escapement) (Kaeriyama 2003). We demonstrate the use of this by estimating RCC for a particular sex and age class of chum salmon (age-4 females). We found a significant positive relationship between the RCC of Hokkaido chum salmon and mean fork length (FL) of age-4 female adult chum salmon returning to 11 rivers in Hokkaido ($r=0.979$, $F=753.8$, $P<0.001$). On the other hand, the mean age at maturity determined for these 11 Hokkaido rivers showed a negative correlation ($r=-0.879$, $F=109.1$, $P<0.001$) with the RCC (Fig. 6; Kaeriyama 2008). These results suggest that growth rates of these 11 Hokkaido chum salmon populations respond to a population density-dependent effect, and growth reductions may occur under conditions when RCC is low.

In an earlier paper we further explored how these chum salmon growth dynamics can be scale-dependent. Seo et al. (2009) evaluated this by determining if variability in growth rates of chum salmon observed in two separate river systems (Ishikari River in Japan and Namdae River in Korea) could be explained by changes in abundance by evaluating dynamics at three different spatial scales. These scales were: 1) Population level (sum of catches of chum salmon bound for Ishikari and Namdae Rivers), 2) Asian population aggregate level (sum of catches of chum salmon bound for Korea, Japan and Russia) and 3) North Pacific level (sum of all chum salmon captured across the North Pacific). Growth rate (represented by FL at maturity of fish returning to the Ishikari and Namdae Rivers) was found to vary only as a function of population abundance, and was not significantly related to more aggregated abundance levels in the North Pacific. These results suggest that growth of these two study populations (as reflected by changes in FL at maturity) responds significantly to variability in their own abundance, but their dynamics do not appear to be strongly influenced by competitive interactions occurring with other chum salmon stocks in the North Pacific. This may be indicative of population-specific migration paths that lead to discrete partitioning of ocean habitat occupied during their marine life history (e.g., Bugaev et al. 2009; Myers et al. 2009; Urawa et al. 2009).

At present, hatchery-derived chum salmon may not significantly affect wild salmon in areas in the open sea such as the Bering Sea. The density-dependent effect seems to be limited to body growth at the population level for chum salmon in the open sea. Ruggerone et al. (this volume), however, provides some new, compelling evidence that productivity of western Alaska chum salmon has been reduced as a result of increases in Hokkaido hatchery chum salmon in the Bering Sea over the past several decades, leading to elevated intraspecific competitive interactions. In addition, Ruggerone et al (2005) found a growth interaction between multiple populations of Bristol Bay sockeye and an aggregate measure of Asian pink salmon. The density-dependent effects on Pacific salmon may increase in the open sea in the near future, because global warming will likely decrease their distribution areas and carrying capacity in the North Pacific Ocean.

Global warming effect on chum salmon

There is growing concern over potential impacts of climate change on Pacific salmon (Rand et al. 2006; Battin et al. 2007; Crozier et al. 2008, Schindler et al. 2008). Rand et al. (2006) simulated the spawning migration of sockeye salmon in the Fraser River by accounting for energetic demands, and results indicated that a long-term decline in the mean mass of adult sockeye salmon completing their marine residency could erode their migratory fitness during the river migration and hence jeopardize the sustainability of sockeye salmon and the fishery that targets them. Crozier et al. (2008) predicted that global warming poses a direct threat to freshwater stages in Snake River Chinook salmon, increasing their risk of extinction based on projections from several General Circulation Models. Here we review some recent investigations on how climate variables, particularly sea surface temperature, has influenced dynamics in Hokkaido chum salmon and how climate change may effect this population and the North Pacific ecosystem in the future.

We have investigated how SST explains significant variation in the annual changes in survival rate and growth to age 1 (G1) of chum salmon returning to the Ishikari River from 1943 to 2005 (Kaeriyama et al. 2007; Seo et al. 2009). Ishikari River chum salmon live in the coastal waters of Hokkaido and the Okhotsk Sea at age 1 (Urawa 2000), and they have responded positively (increased survival and growth rate) to a trend in warming temperature observed in this region (Fig. 7). In a more recent paper (Seo et al. 2011) we extended these results by examining how past trends in climate have directly and indirectly affected Hokkaido chum salmon. A path analysis was conducted to assess both direct and indirect effects using a host of climate variables. The authors found evidence of a direct negative effect between air temperature and sea ice cover in the Okhotsk Sea region. The model also revealed a direct effect of SST on both growth and survival of chum salmon (Fig. 8). Chum salmon growth, in particular was correlated both with surface air and sea surface temperature. This study points to the importance of understanding the complexity of interactions leading to effects of climate dynamics on Pacific salmon.

By examining projected temperature isotherms and applying a optimum (8-12 °C; optimum growth rate and feeding habit), adaptable (5-13 °C; available habitat for swimming and feeding), and wintering temperature range (4-6 °C) of chum salmon (Kaeriyama 1986; Fukuwaka et al. 2007; Kaeriyama 2008), Kaeriyama (2008) projected a northward shift in the distribution of this species in the North Pacific into the Chukchi Sea by 2050, and a loss of a critical link in the migration route of chum salmon connecting Hokkaido with the Okhotsk Sea due to a thermal impediment (Fig. 9). A similar decrease in preferred habitat has also been projected for sockeye salmon in the North Pacific as a result of global warming (Welch et al. 1998). This projected loss of habitat would likely result in more intense ecological interactions occurring within and between salmon species occupying these habitats, and this could have important implications on growth, survival, production, fish condition and disease transmission. These effects may be exacerbated by growing contributions of hatchery releases to the salmon biomass in the North Pacific.

Under a global warming scenario, therefore, interactions between wild and hatchery populations, including genetic, ecological, behavioral, and physiological dynamics, will likely become more intense in the near future. Japan, in particular, faces mounting challenges with sustaining wild and hatchery salmon populations. We outline some of these challenges and potential management responses in a companion paper in this special issue (Nagata et al., this issue). Efforts in Japan are now planned or underway to rehabilitate and restore freshwater salmon habitat, develop and implement a new management framework so wild salmon can be managed separately from hatchery populations, initiate new monitoring efforts to quantify natural escapement, and evaluate the effectiveness of different hatchery release strategies. Salmon are highly adaptable, and we believe these efforts will help Japanese chum salmon and other Japanese salmon populations and species cope with the broad impacts of global warming we expect in the future (Kaeriyama 1999b).

Concluding remarks

We outlined above some of our key research results relating to salmon abundance dynamics, intra-specific interactions operating in the marine environment, and how climate dynamics can affect Japanese chum salmon. The theme of this issue is focused on ecological interactions between wild and hatchery salmon. Understanding these interactions, and developing a management framework that can address this issue, is critical for the future of conservation and sustainable use of Japanese salmon. Therefore, these ecological interactions between hatchery and wild populations should be an important consideration in the sustainable conservation of Pacific salmon.

To fully address this issue, we promote the use of adaptive management approaches and application of the precautionary principle to conserve salmon. Kaeriyama and Edpalina (2004) defined some of the important principles that need to guide future management of Japanese salmon. Their action plan included: (1) the separation of wild and hatchery salmon populations in order to protect the genetic diversity and endemism of populations, (2) establishment of appropriate management zones (i.e., recreational fishing and hatchery program zones for commercial salmon fisheries) in rivers, (3) shifting the location of hatchery brood stock from river mouths to the outlet of the hatchery facilities (thus allowing greater natural escapement into rivers where hatcheries operate), and (4) regular biological monitoring of salmon body size, age composition, reproductive indices (fecundity and egg size), and dynamics of salmonid populations (Kaeriyama and Edpalina 2004). Based on more recent research, we suggest two additional issues that must be addressed to ensure salmon are conserved and sustainably used. The first is recognition of limitations and fluctuations of carrying capacity for Pacific salmon in the North Pacific. There is a growing body of scientific literature focusing on this issue, some of which we have referenced in the present paper. This issue cannot be ignored, and it is logical to conclude these interactions will likely become more intense in the future as demand for wild capture seafood continues to increase and ocean habitat for salmon will likely diminish. Finally, and perhaps most importantly, we need to focus on educating and training the next generation of fishery scientists, guided by a paradigm shift from the traditional fisheries science tailored to meet the needs of the fisheries industry to a new fisheries science based on ecological principles emphasizing aquatic ecosystem protection and sustainable fishing practices to provide seafood to future generations. In Figure 10, we provide an overview of the important characteristics of an adaptive management system that could be implemented to improve conservation management of Pacific salmon in Japan. New information on the status of natural reproduction of chum salmon is already being generated in Japan (see Miyakoshi et al., this issue). It will be important to develop mechanisms to allow our management system to adapt to this new information. Key questions will soon present themselves. For example, how can fishing pressure and effort be managed to allow increases in natural escapement in this region? How do we prioritize salmon river restoration and dam modification or removal to increase the contribution of natural spawners to overall juvenile salmon recruitment in this region? How can we ensure fishery management adaptively responds to emerging new information on trends and status of naturally-reproduced salmon? While these issues are complex and challenging, we are committed to working on salmon management reform to address these questions and work at sustaining our productive hatchery-based salmon fishery while minimizing the future risks to wild salmon in Japan and throughout the North Pacific region.

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Figure Captions

Fig. 1. Annual changes in catch of Pacific salmon and PDO in the North Pacific Ocean. Catch data includes both wild and hatchery-derived salmon (Kaeriyama 2008)

Fig. 2. Temporal changes in ALPI and carrying capacity (K) of total (A) and each 3 species (B), which are sockeye, chum, and pink salmon (Kaeriyama et al. 2009).

Fig. 3. Annual changes in abundance of wild and hatchery-derived populations of sockeye, chum, and pink salmon in the North Pacific (modified Kaeriyama 2009).

Fig. 4. Cluster analysis result of feeding habits of chum salmon in the Bering Sea in the summer 2009. Chum salmon fed on (1) diverse prey animals (red area), and predominantly consumed (2) pteropods, (3) pteropods and copepods, and (4) nekton.

Fig. 5. Relationship between the CPUE and food diversity of chum salmon collected by surface trawl nets in the Bering Sea in the summer of 2009. The CPUE indicates number of fish per troll per hour. The food diversity is calculated by the Shannon-Wiener’s Index (H’).

Fig. 6. Relationships between the residual carrying capacity (RCC) and the fork length (A) or the age at maturity (B) of chum salmon returning to 11 rivers in Hokkaido. The residual carrying capacity is defined as “(carrying capacity – abundance) / carrying capacity” (Kaeriyama 2008).

Fig. 7. Temporal changes in growth at age 1 (G1) and survival rate (SR) of Hokkaido chum salmon. Growth anomaly was calculated for adult chum salmon returning to the Ishikari River using scale analysis and back-calculation (modified Seo et al. 2011).

Fig. 8. Path models of climate and oceanic environmental indexes, and growth at age 1(G1) and survival rate (SR), and population size (PS) of Hokkaido chum salmon. The growth at age 1 was calculated for adult chum salmon returning to the Ishikari River using scale analysis and back-calculation. Climate and oceanic environmental indexes are defined as follows. SAT: annual change in global anomalies of Surface Air Temperature, PDO: Pacific Decadal Oscillation, ALPI: Aleutian Low Pressure Index, SI: Siberian High, OH: Okhotsk High, AO: Arctic Oscillation, SST_O: SST from June to October in the southern Okhotsk Sea, and ICE: Sea ice cover area (%) in the Okhotsk Sea (Seo et al. 2011).

Fig. 9. Prediction of the global warming effect for chum salmon in the North Pacific based on the SRES-A1B scenario of IPCC (modified Kaeriyama 2008).

Fig. 10. Conceptual diagram on the sustainable adaptive management of Pacific salmon.

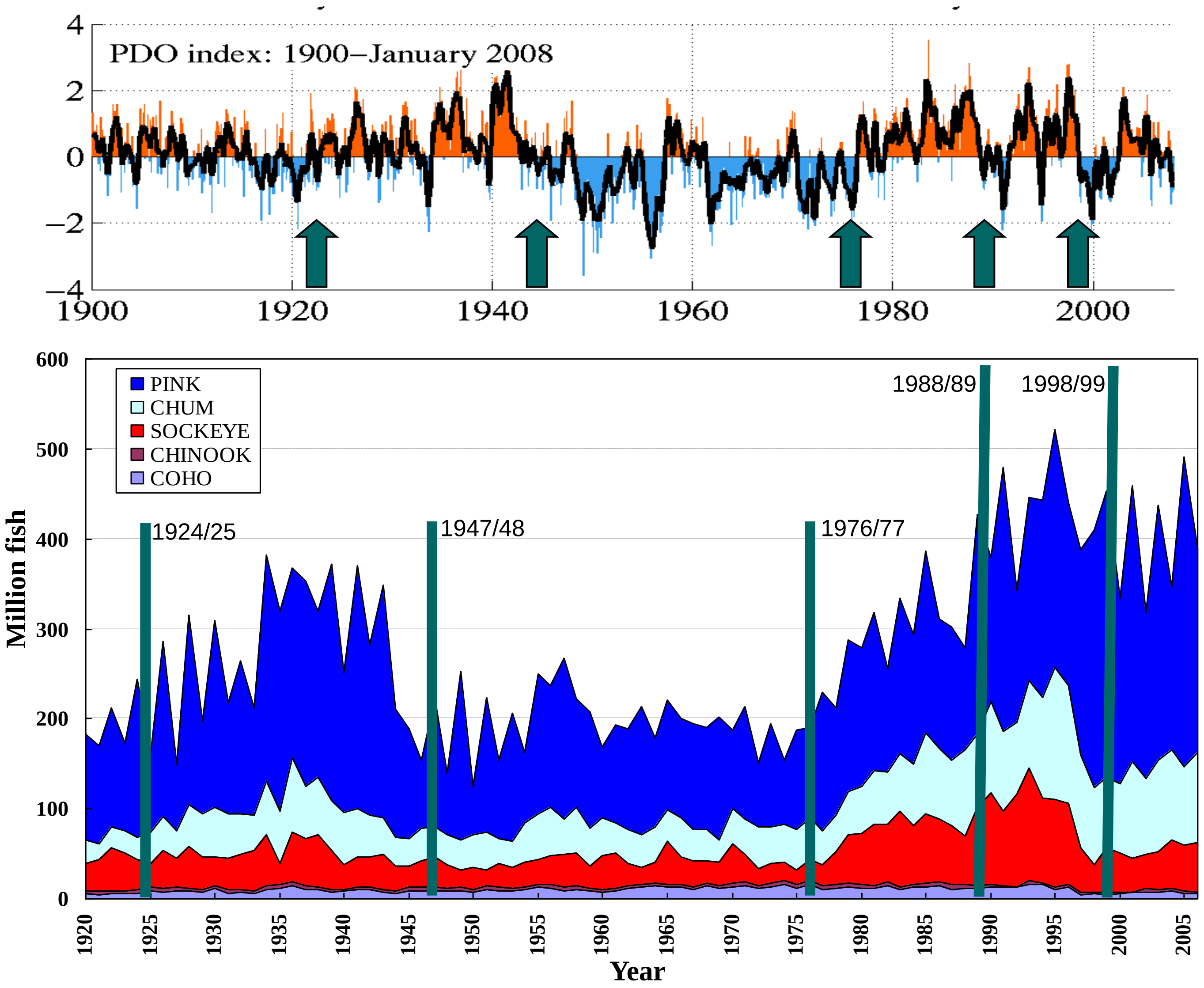
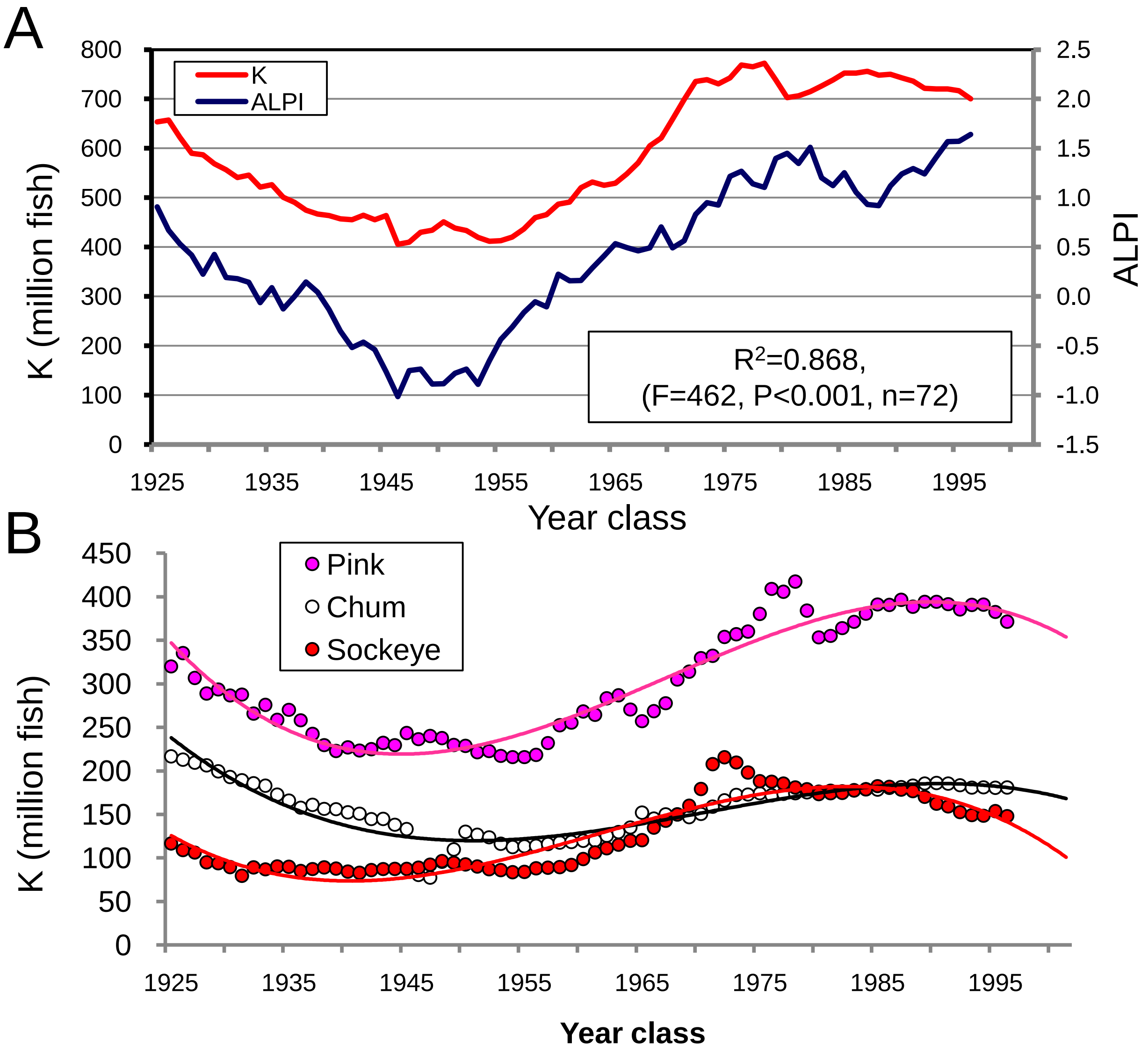


Fig. 1. （Kaeriyama et al. ）



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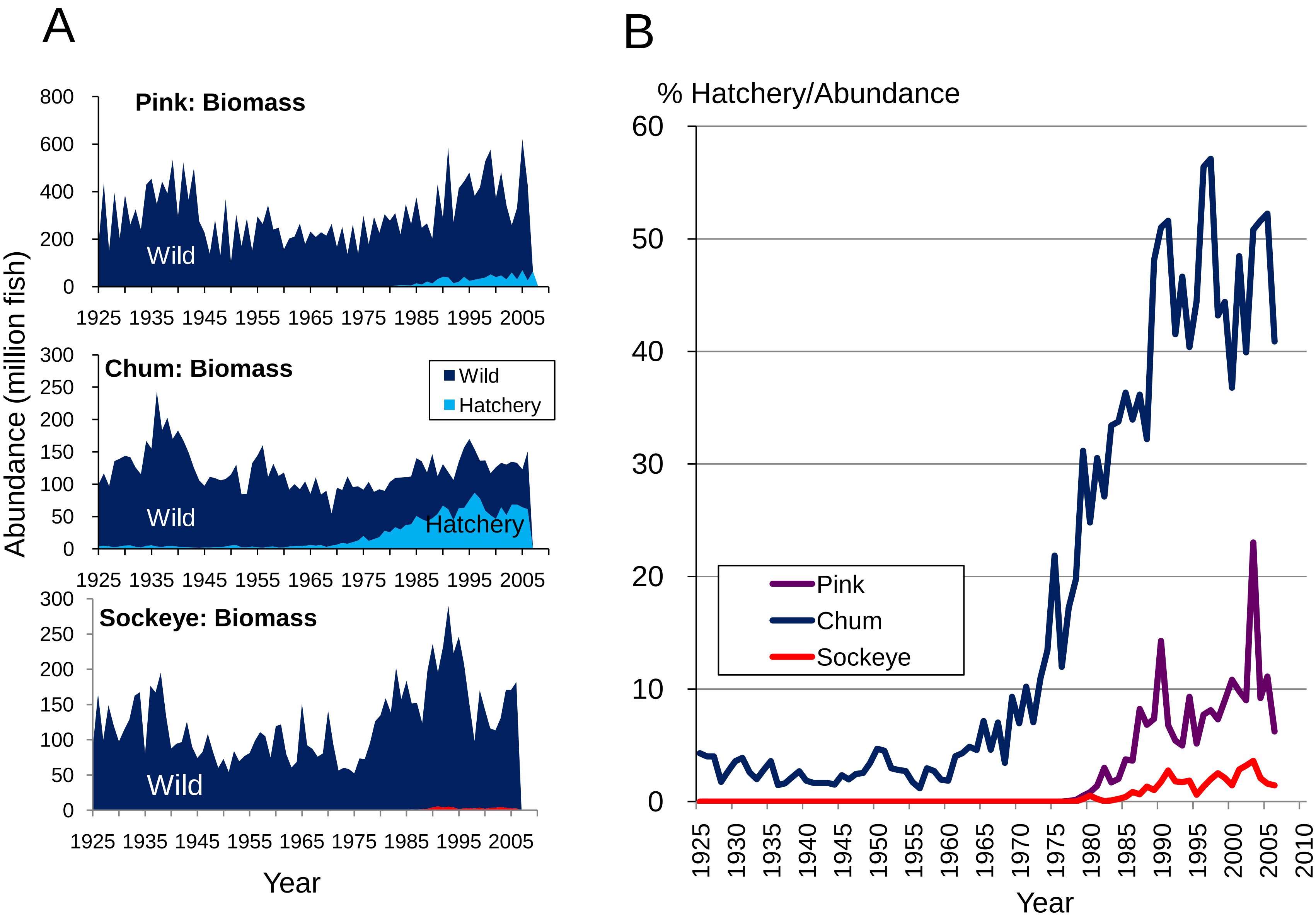

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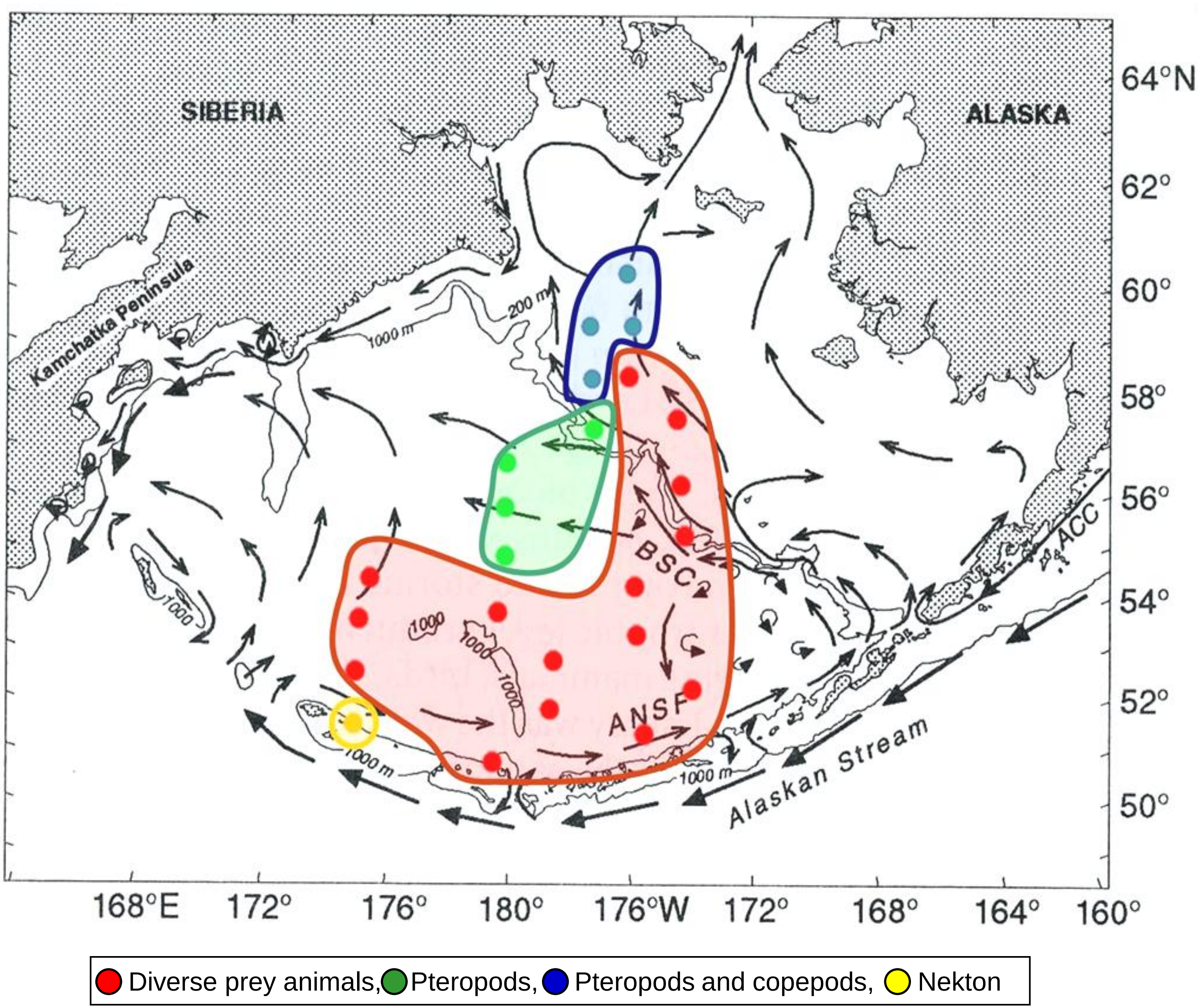


Fig. 4. （Kaeriyama et al. ）

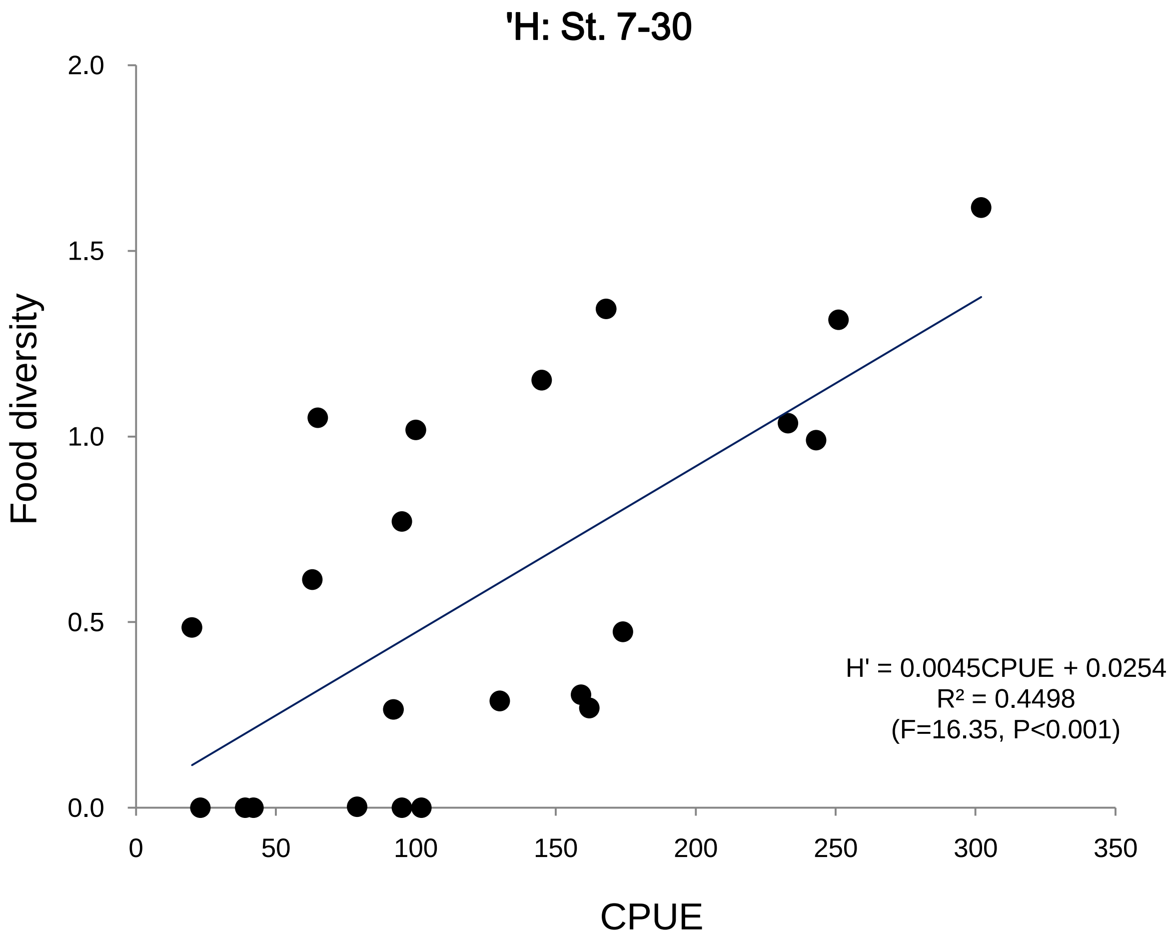


Fig. 5. （Kaeriyama et al. ）

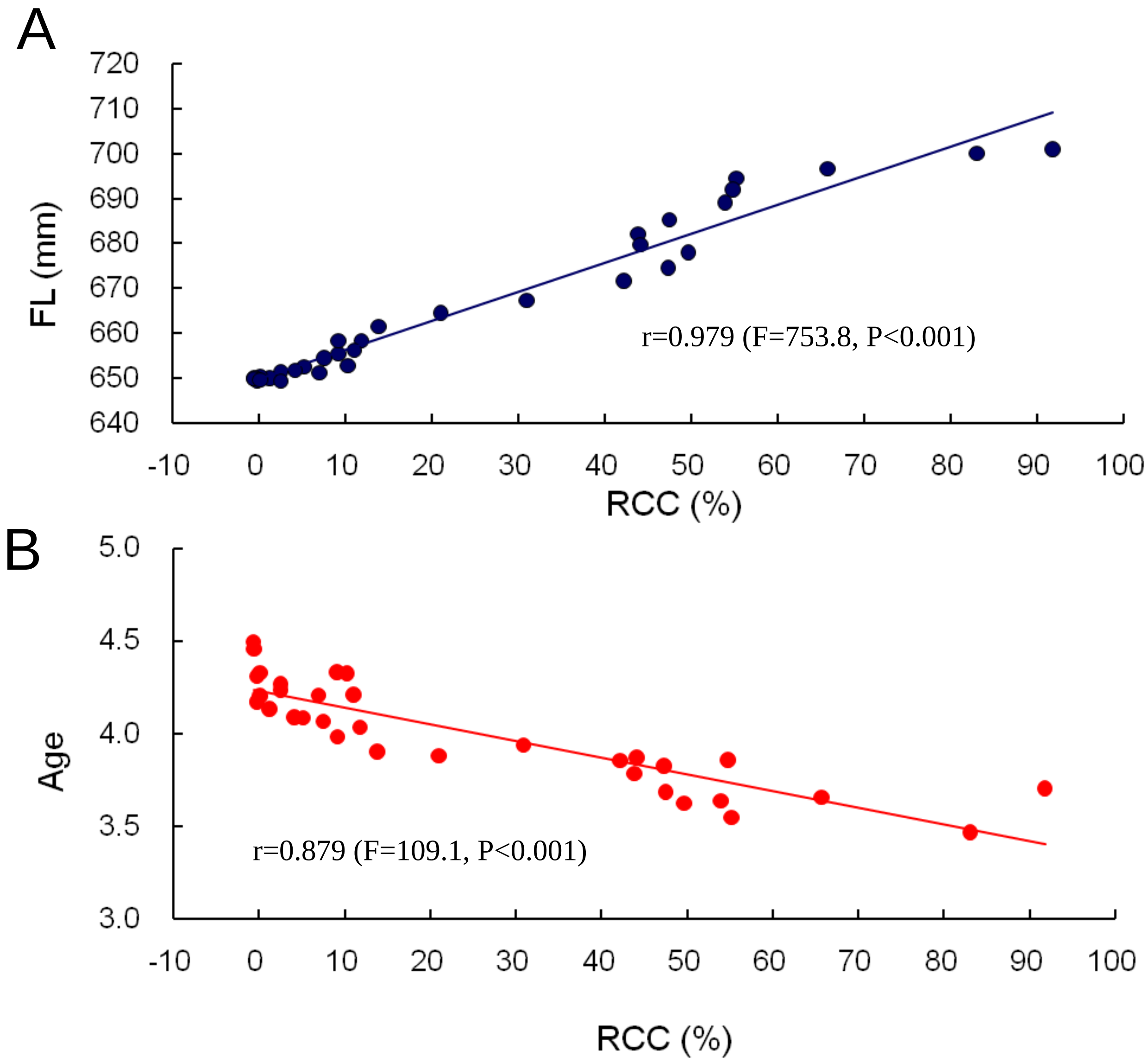


Fig. 6. （Kaeriyama et al. ）

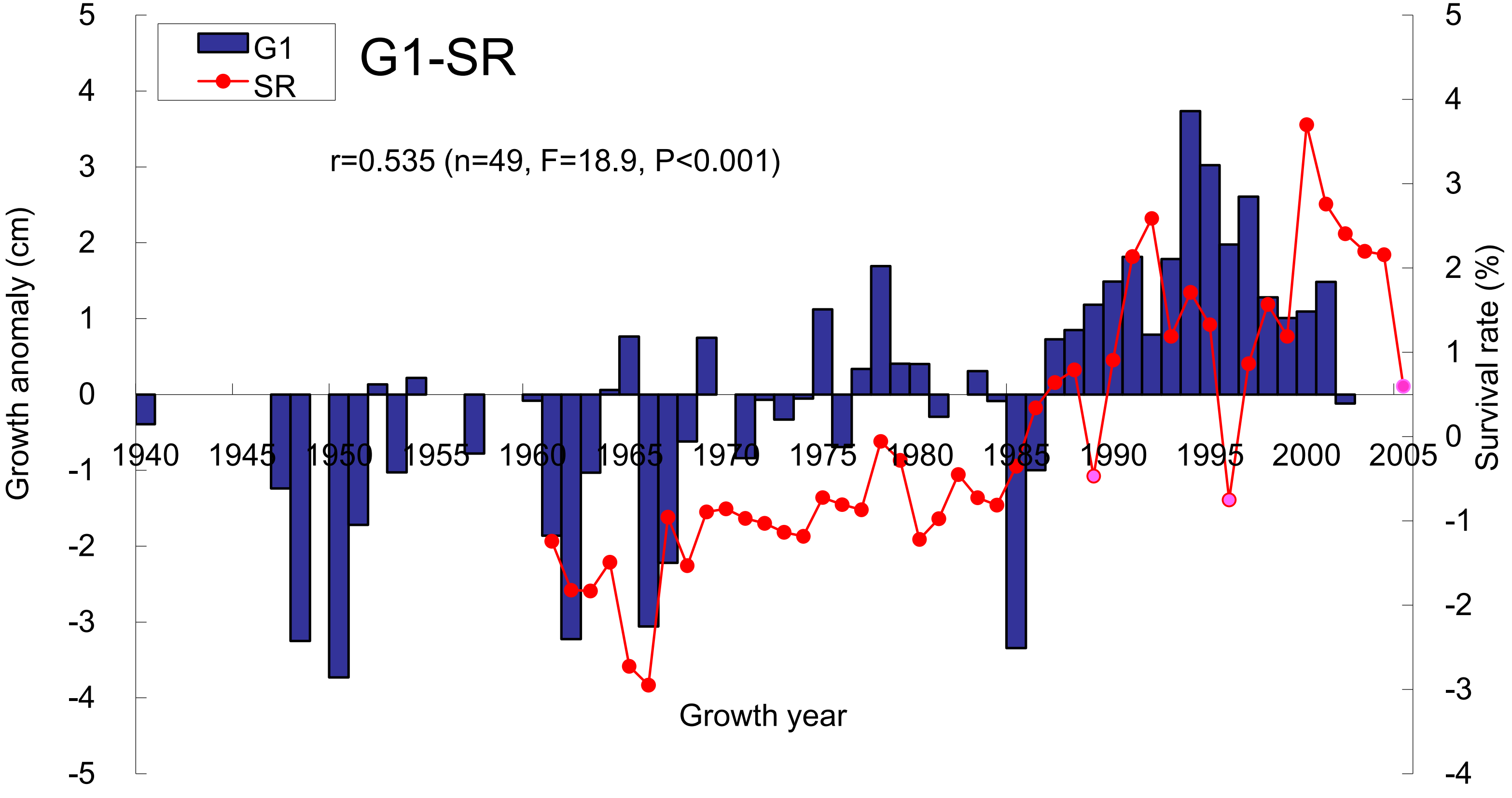


Fig. 7. （Kaeriyama et al. ）

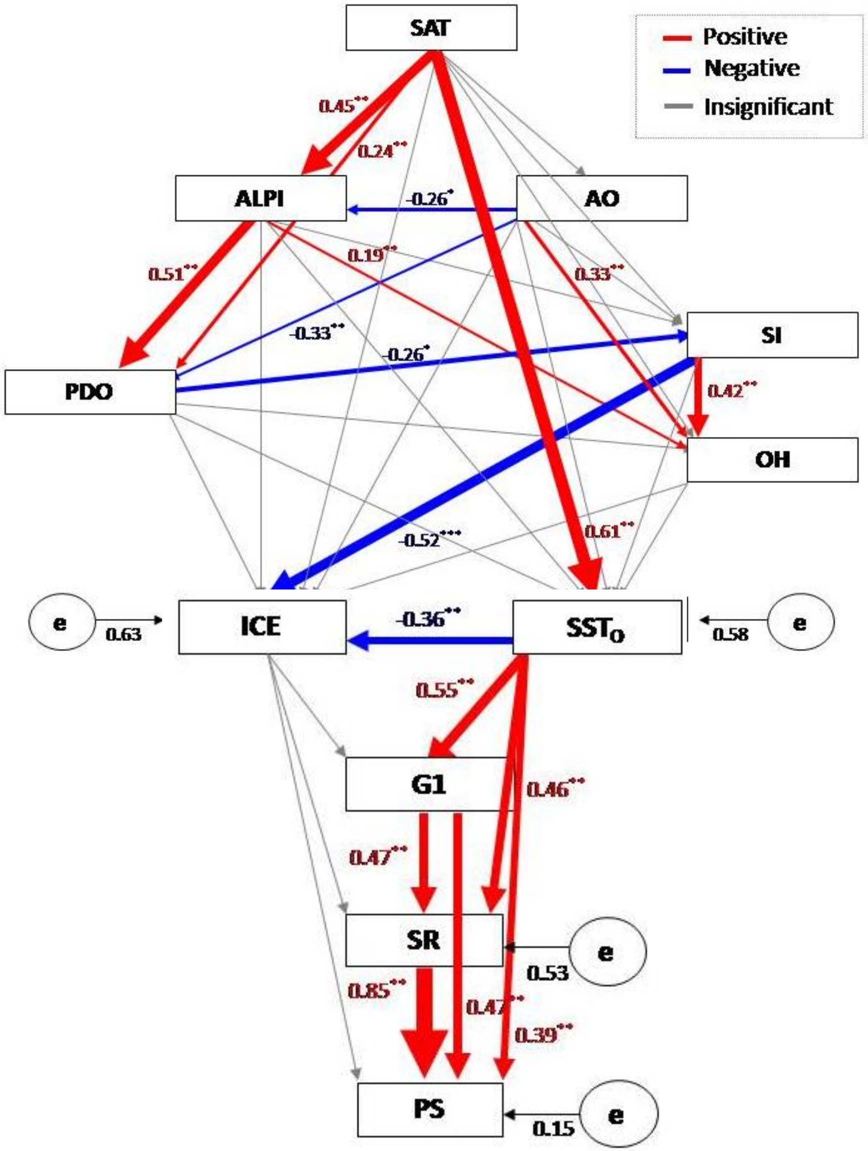


Fig.8. （Kaeriyama et al. ）

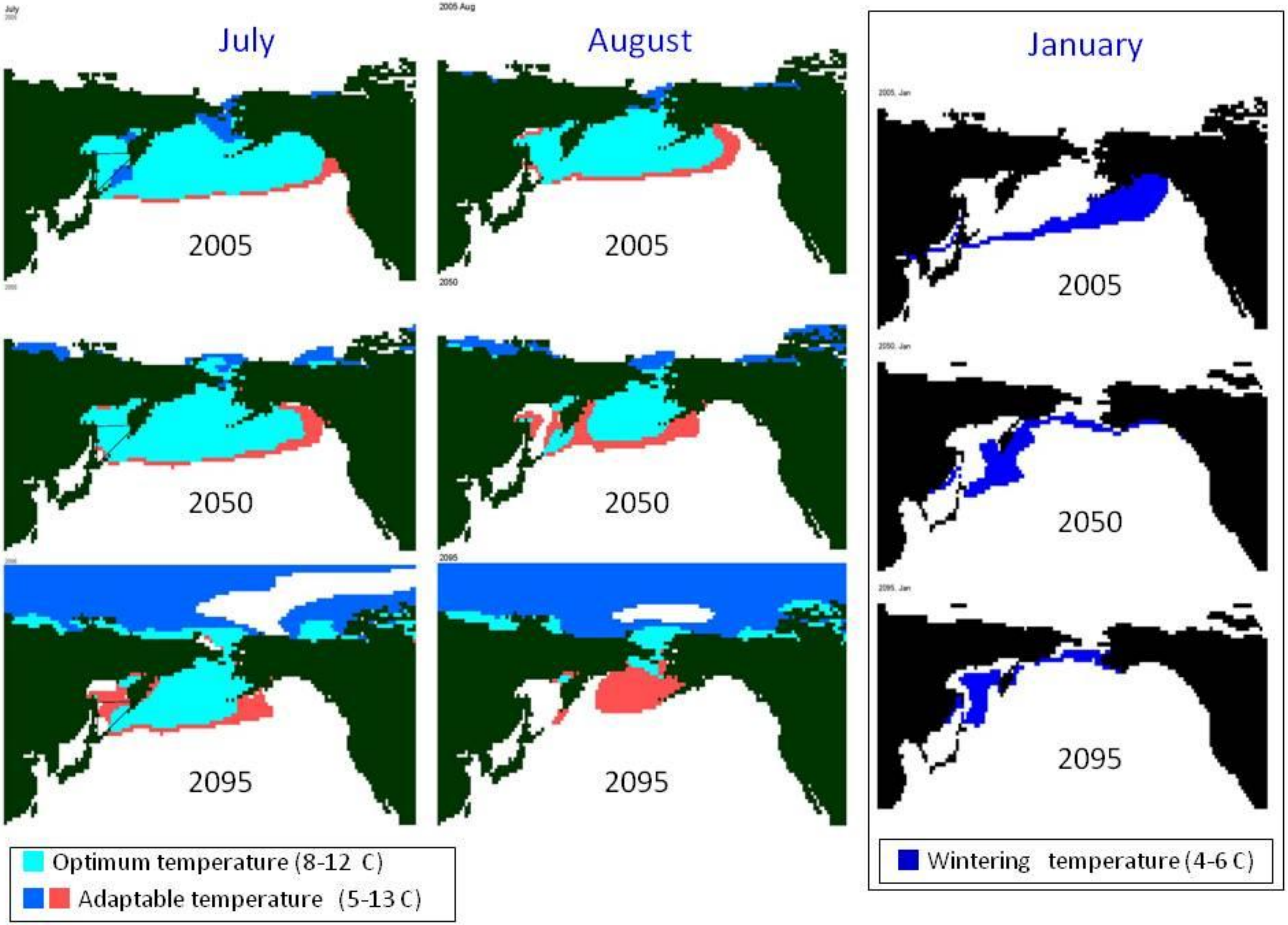
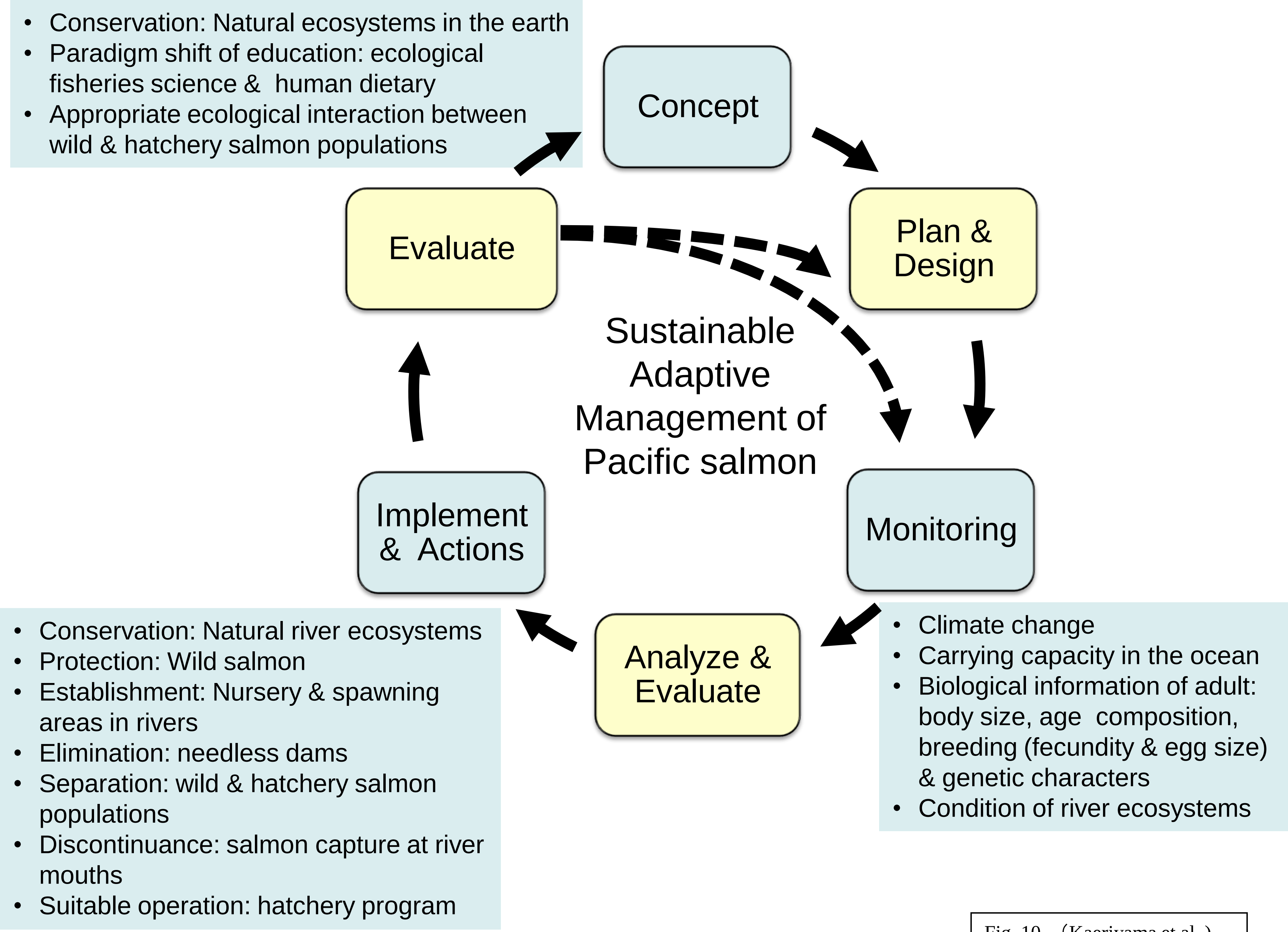


Fig. 9. （Kaeriyama et al. ）



- Conservation: Natural ecosystems in the earth
- Paradigm shift of education: ecological fisheries science & human dietary
- Appropriate ecological interaction between wild & hatchery salmon populations

Concept

Plan & Design

Monitoring

- Climate change
- Carrying capacity in the ocean
- Biological information of adult: body size, age composition, breeding (fecundity & egg size) & genetic characters
- Condition of river ecosystems

Analyze & Evaluate

Implement & Actions

- Conservation: Natural river ecosystems
- Protection: Wild salmon
- Establishment: Nursery & spawning areas in rivers
- Elimination: needless dams
- Separation: wild & hatchery salmon populations
- Discontinuance: salmon capture at river mouths
- Suitable operation: hatchery program

Evaluate

Sustainable Adaptive Management of Pacific salmon

Fig. 10. （Kaeriyama et al. ）