The Science of Pacific Salmon Conservation: Foundations, Myths, and Emerging insights
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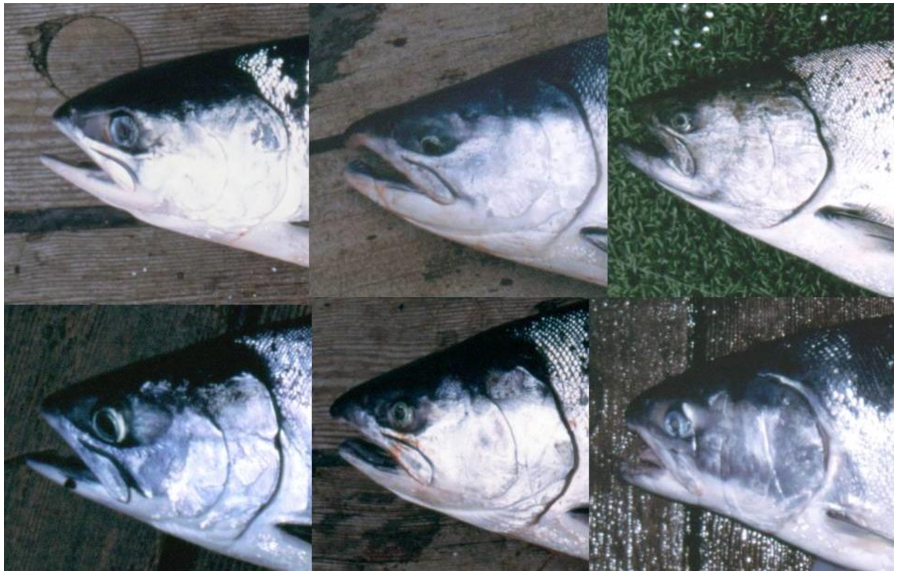
Ocean carrying capacity and biological interaction among Pacific salmon on the high seas under the changing climate



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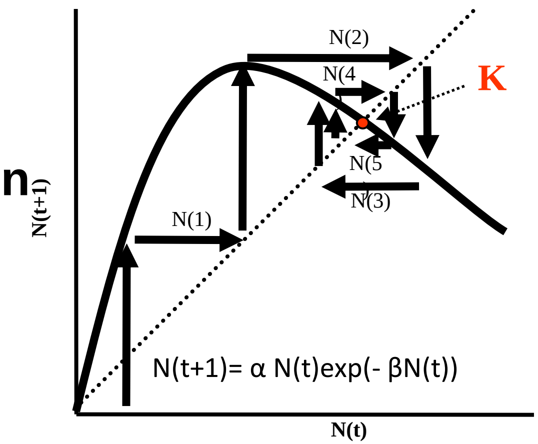
Objects

- To evaluate carrying capacity and inter- and intra-specific interaction of Pacific salmon under the warming climate, for establishing their sustainable conservation management

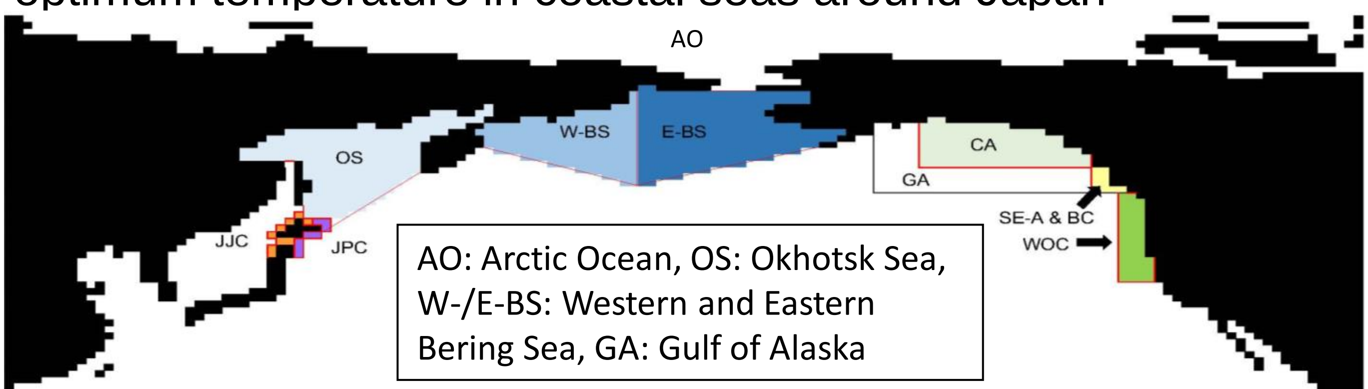
Material & Method

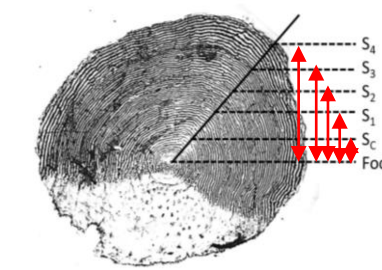
- Sea surface temperature (SST): **COBE-SST database** of Japan Meteorological Agency ($1^{o} \times 1^{o}$, 1920-2018)
- Catch data of Pacific salmon in 1925-2018: **NPAFC Salmonid Catch Statistics**
- Carrying capacity (K): the **replacement point on the Ricker's reproduction curve** (1 year-class = 20 brood-year populations)
- Growth: the **scale back-calculation**
- Trophic level: the **stable isotope analysis**
- Inter- & intra-specific interaction: **the Lotka-Volterra equation**



Definition for chum salmon

- **Adaptable temperature (AT):** 5-7 ^{o}C
- **Optimum temperature (OT):** 8-12 ^{o}C
- **Resident duration**: period at the adaptable and optimum temperature in coastal seas around Japan

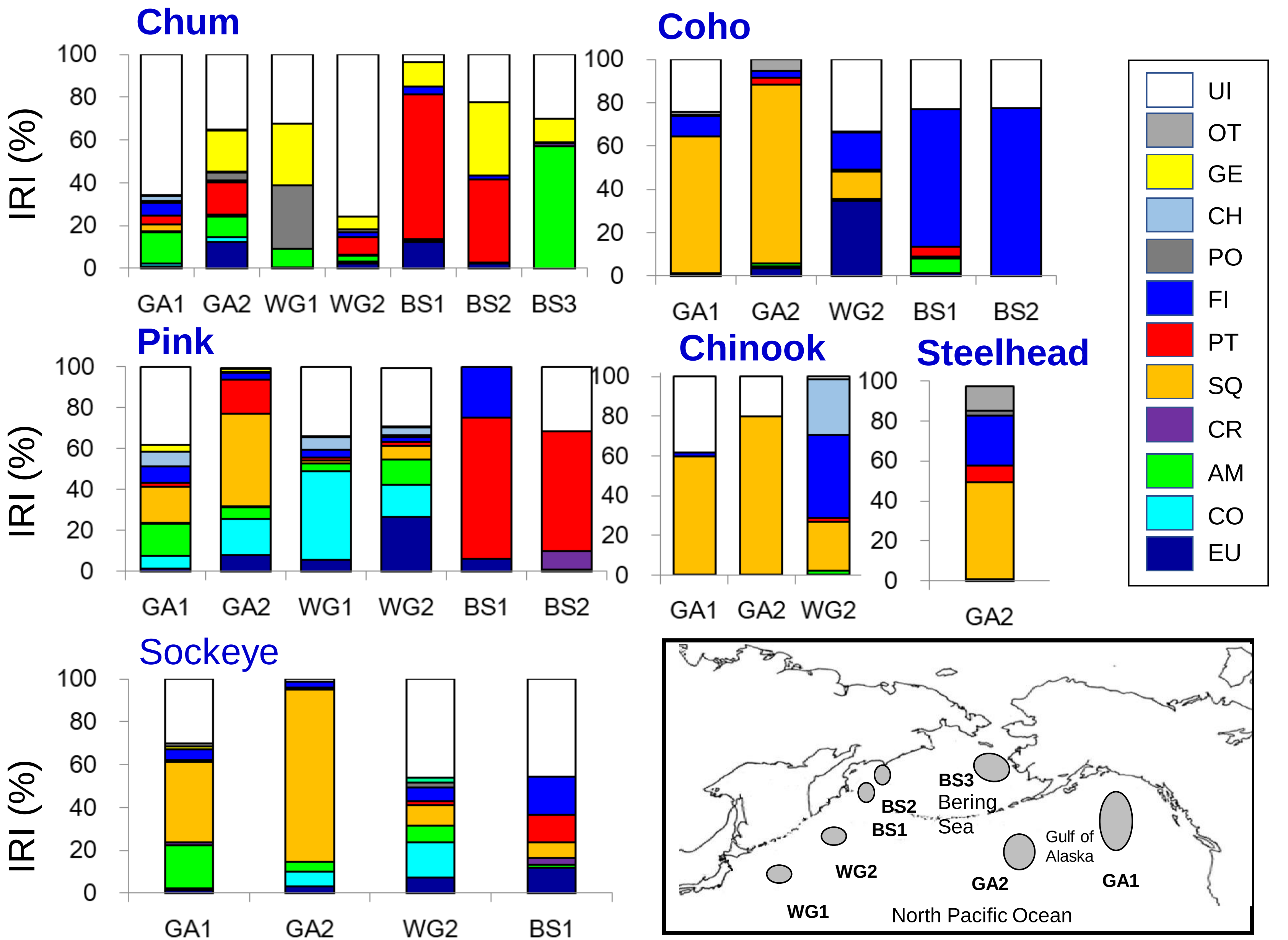




L_i = FL – (TS-S_i)/(TS-114) × (FL-4)
FL: fork length, TS: ΣS_i, (Seo et al. 2011)

Kaeriyama (2019)

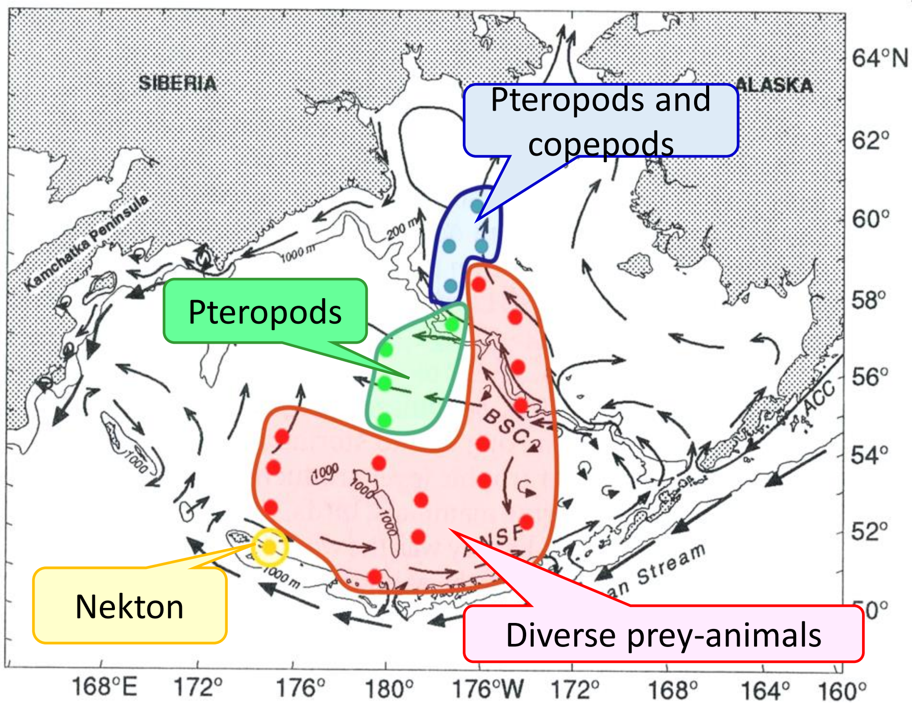
● Feeding pattern of Pacific salmon in the North Pacific Ocean ecosystems during summers of 1994-2008 (Qin and Kaeriyama 2016)

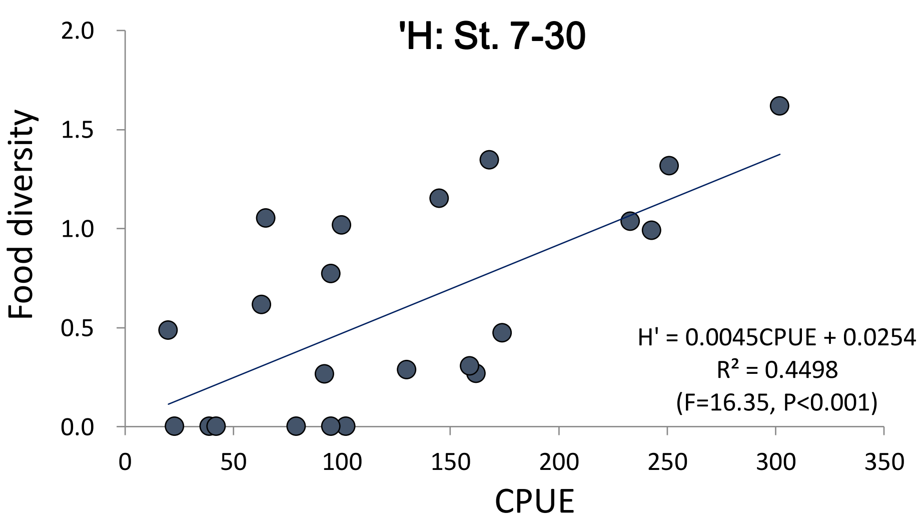


Kaeriyama (2019)

● Feeding behavior of chum salmon (Bering Sea, 2009)

(Kaeriyama et al. 2012)





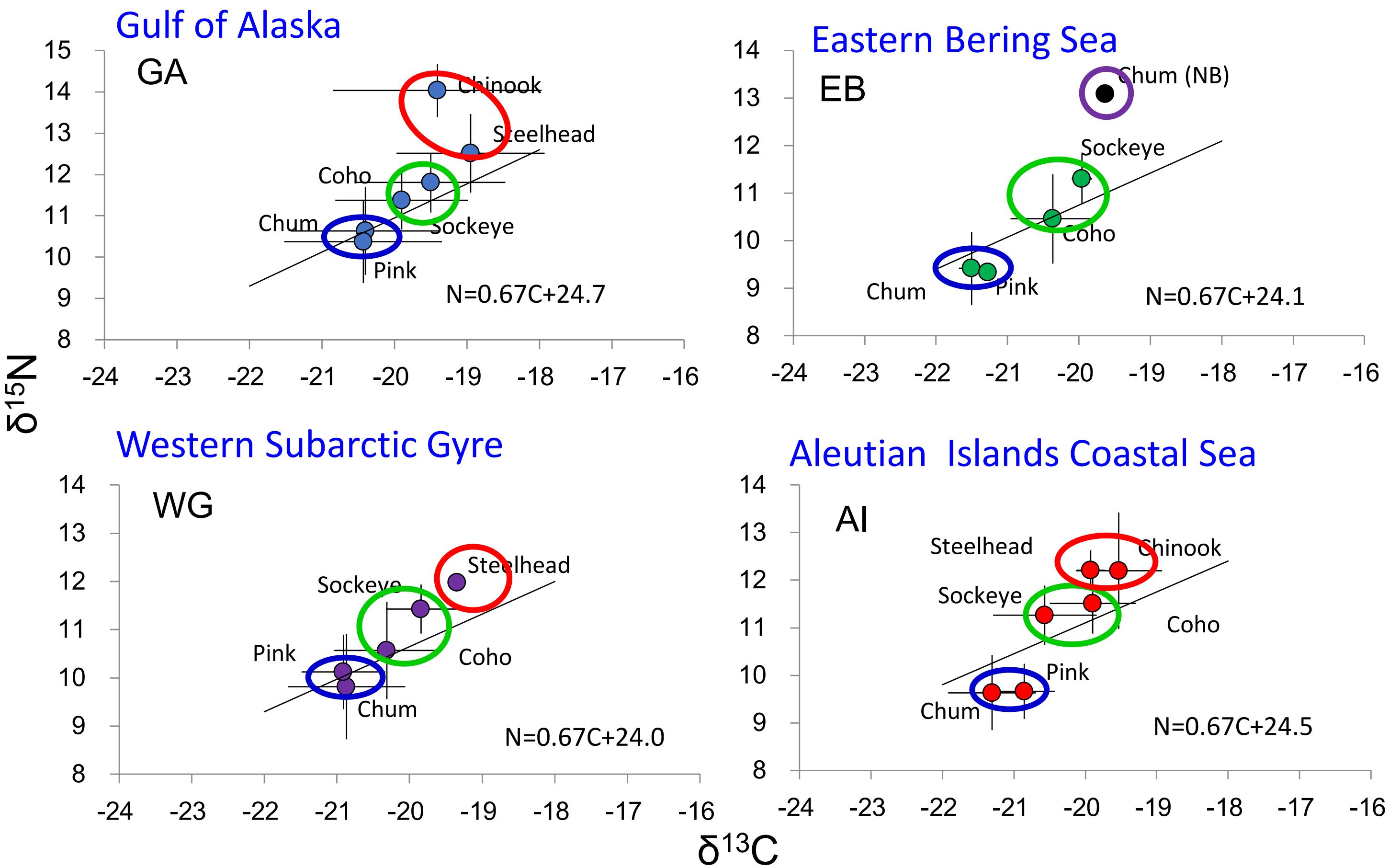
- Only chum salmon adapted to feed on gelatinous zooplankton because of wider esophagus (Welch 1997), strong gastric acid (Azuma 1992), and more pyloric caeca (Kaeriyama & Urawa 1990)
- Their food diversity increased with population density (CPUE)
- Chum salmon shifted their diet in response to competition with pink salmon (Tadokoro et al. 1996)

Inter- & Intra-specific interaction:

Chum salmon will avoid the competition among Pacific salmon without the competitive exclusion principle.

Kaeriyama (2019)

- Mean and SD in δ^{13}C and δ^{15}N of Pacific salmon in the North Pacific Ocean and the Bering Sea (Qin and Kaeriyama 2016)



ANCOVA (GLM)
δ^{13}C×Area
F=2.283, P=0.079
No interaction
Slope 0.67
t=15.733, P<0.001
Intercept 24.0±0.28

- Pacific salmon δ^{15}N: 1. Chinook & Steelhead, 2. Sockeye & Coho, 3. Chum & Pink salmon
- Exception: chum salmon had higher stable isotope off St. Lawrence island, where will has higher enrichment because of strong upwelling and hih nutrient

Kaeriyama (2019)

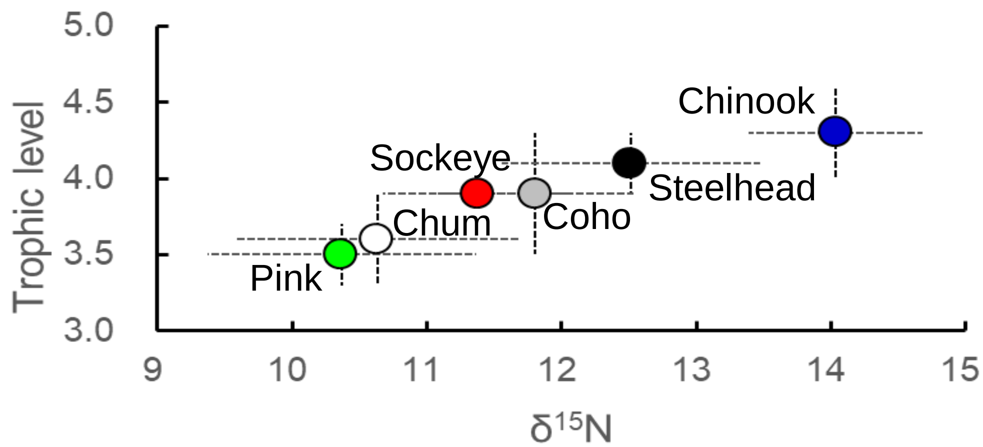
- Temporal-spatial change in feeding pattern of Pacific salmon in the North Pacific Ocean ecosystems

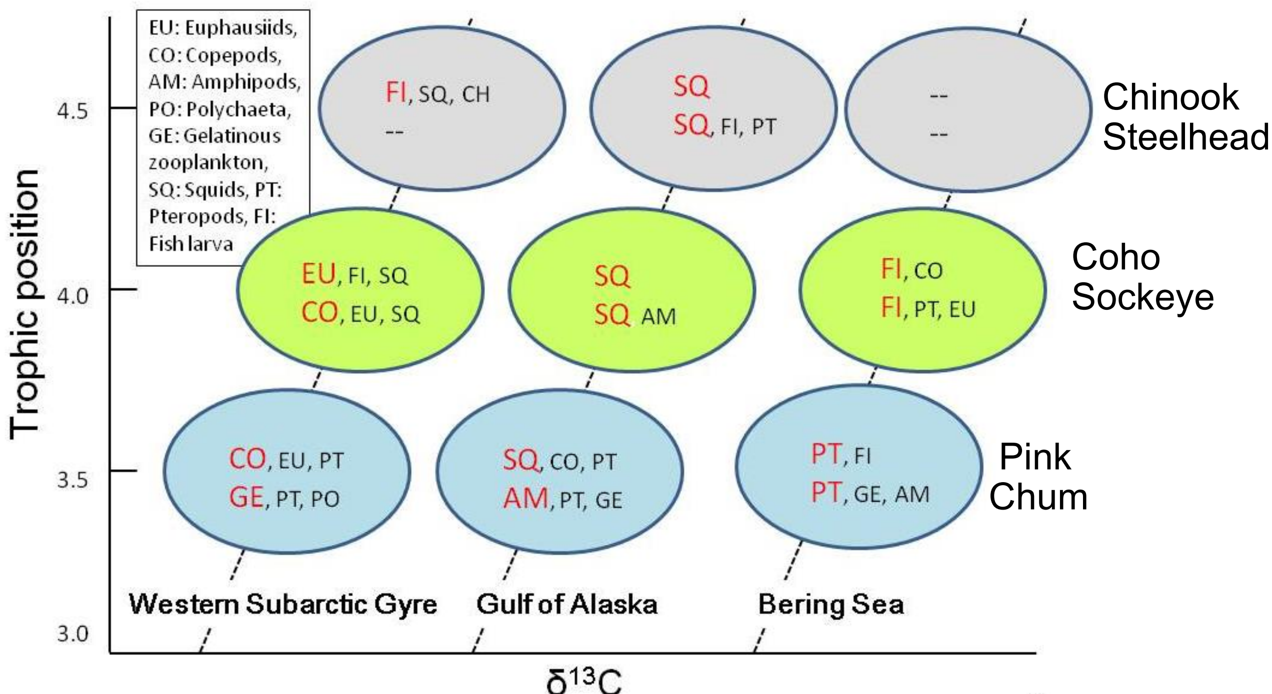
(Qin and Kaeriyama 2016)

Framework & function of feeding pattern in Pacific salmon

Trophic position & ecosystem structure in the North Pacific Ocean

Species specificity & Plasticity





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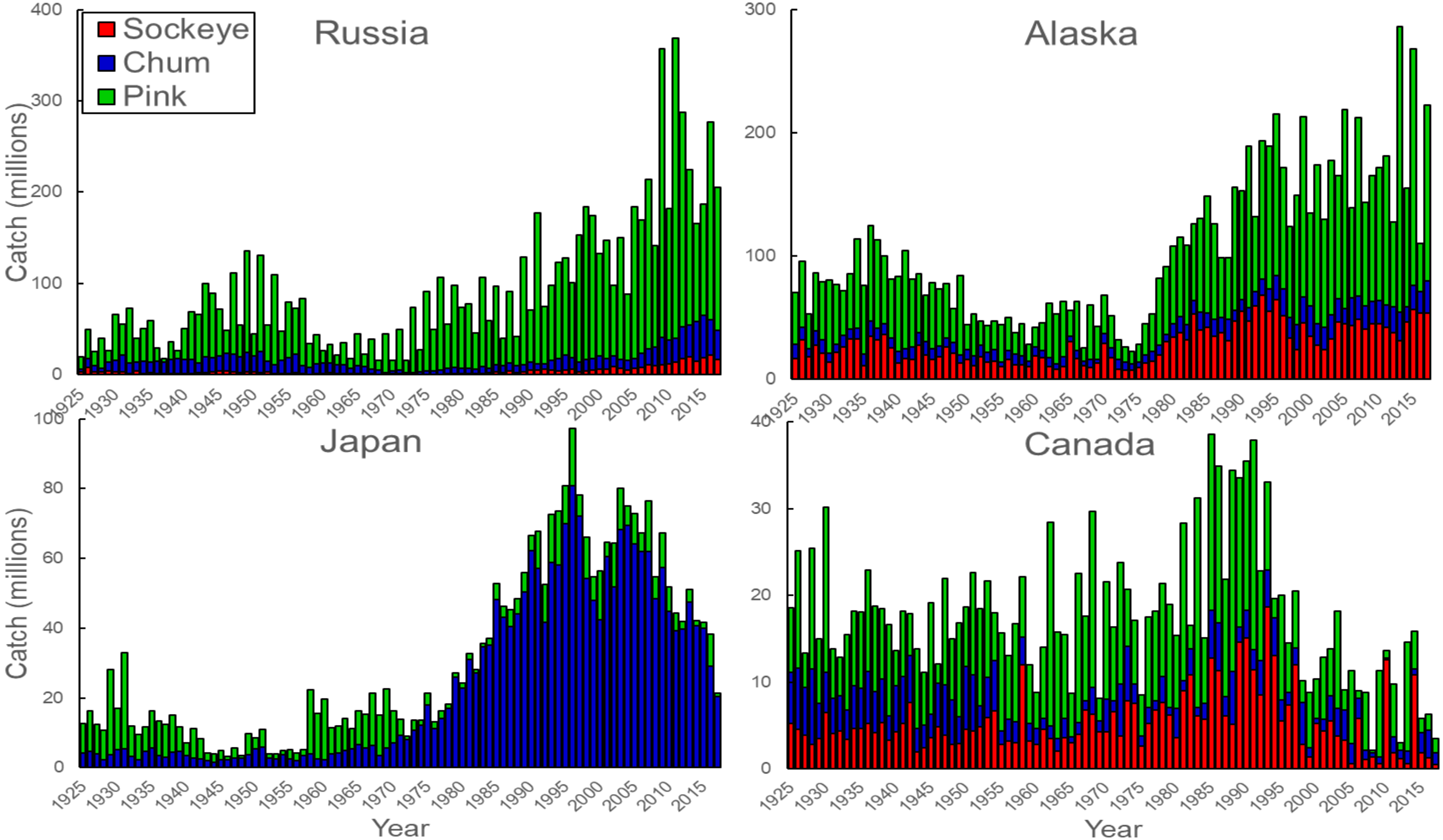
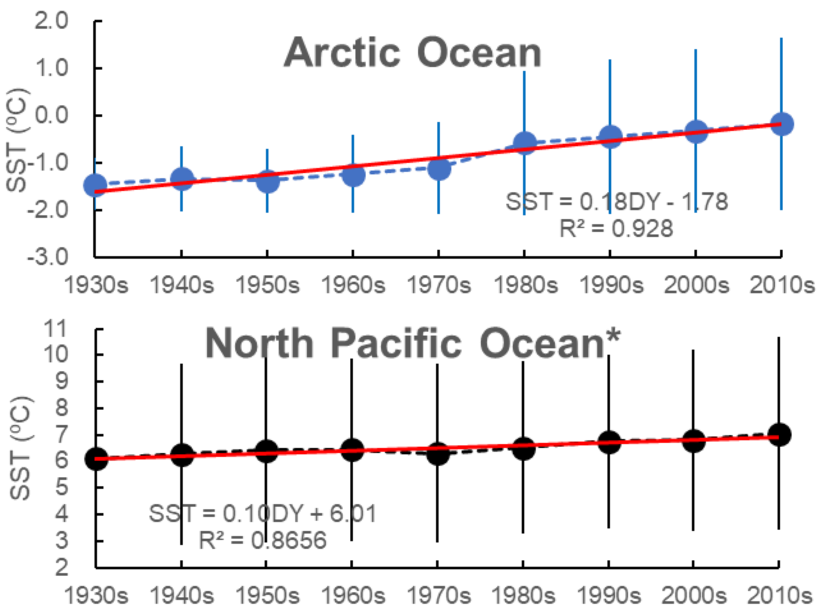
- Annual change in catch of pink, chum and sockeye salmon in 1925-2017

- Southern populations: Decreasing
- Northern populations: Increasing or high stable



Kaeriyama (2019)

● Temporal changes in the decadal mean of SST (dSST) in the North Pacific Ocean and the Arctic Ocean



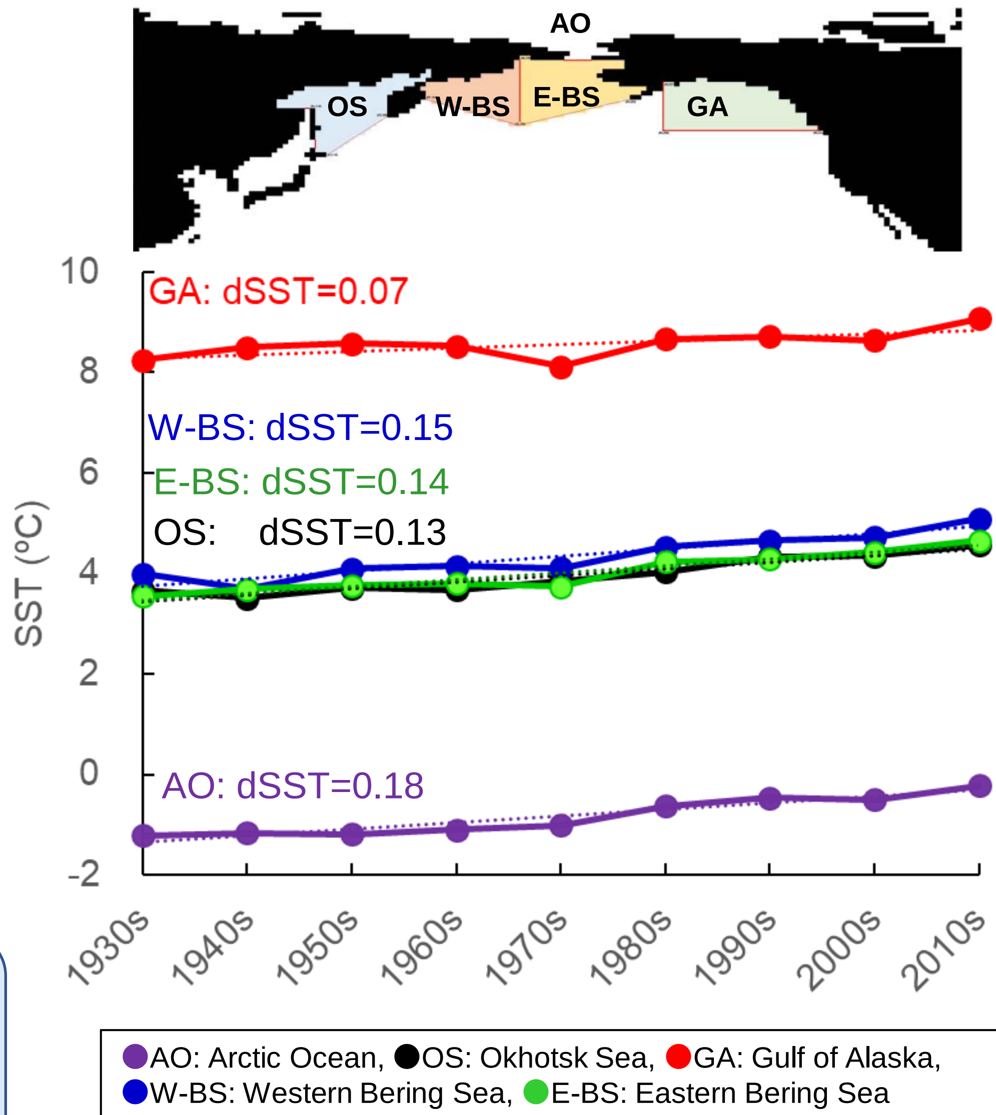
* Northward of 40 º N

■ **Increase in the dSST (℃)**

Arctic Ocean: 0.18

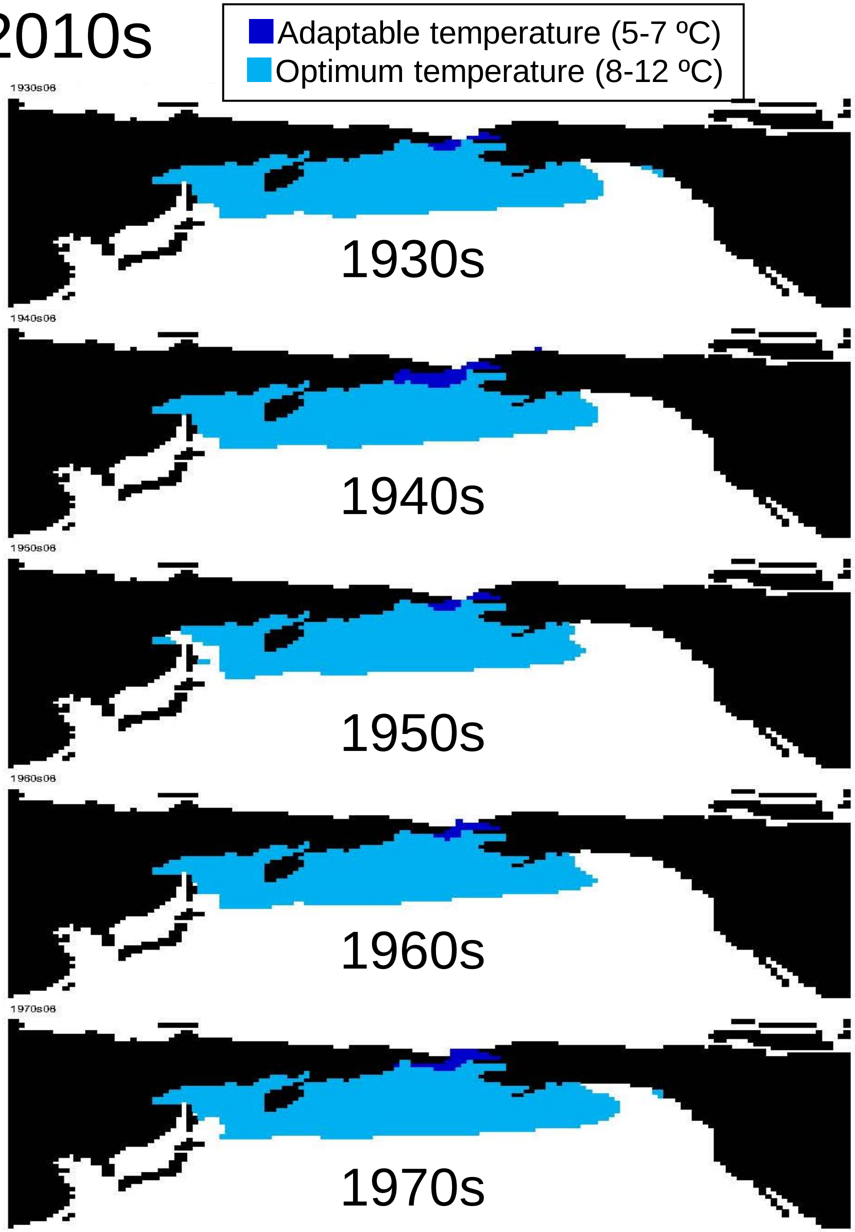
North Pacific Ocean: 0.10

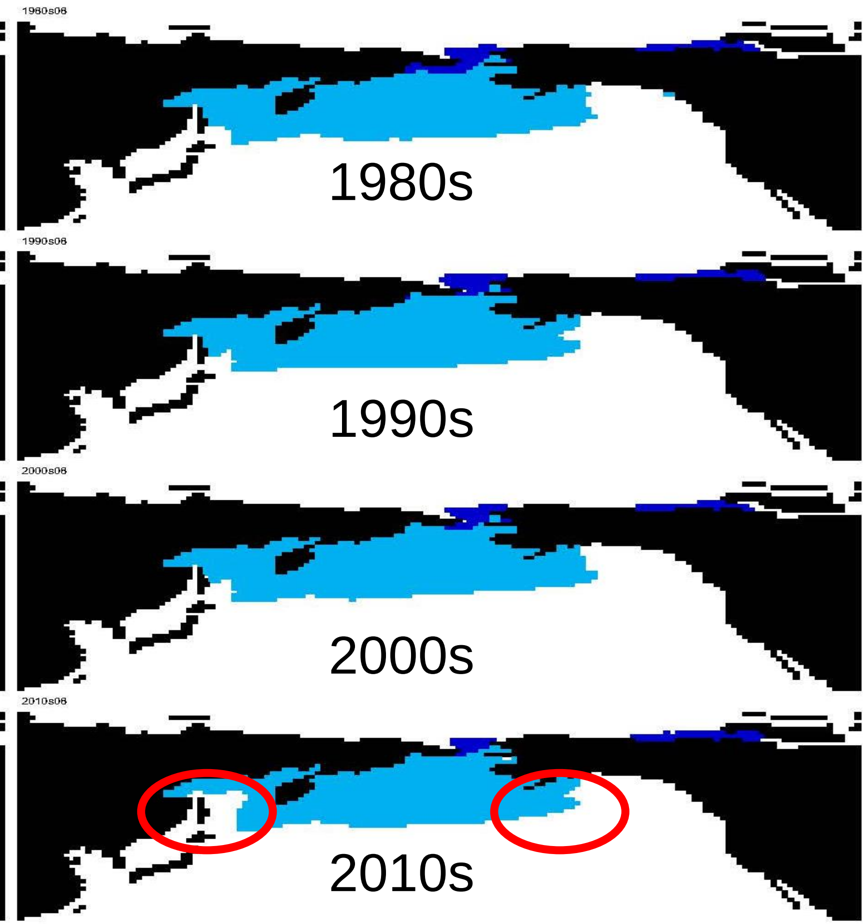
- ●The SST increased 1.0 ºC in a century in the North Pacific Ocean.
- ●The dSST is higher in northern than in southern ecosystems



Kaeriyama (2019)

- Temporal change in areas of adaptable and optimum temperatures for chum salmon in August from the 1930s to the 2010s

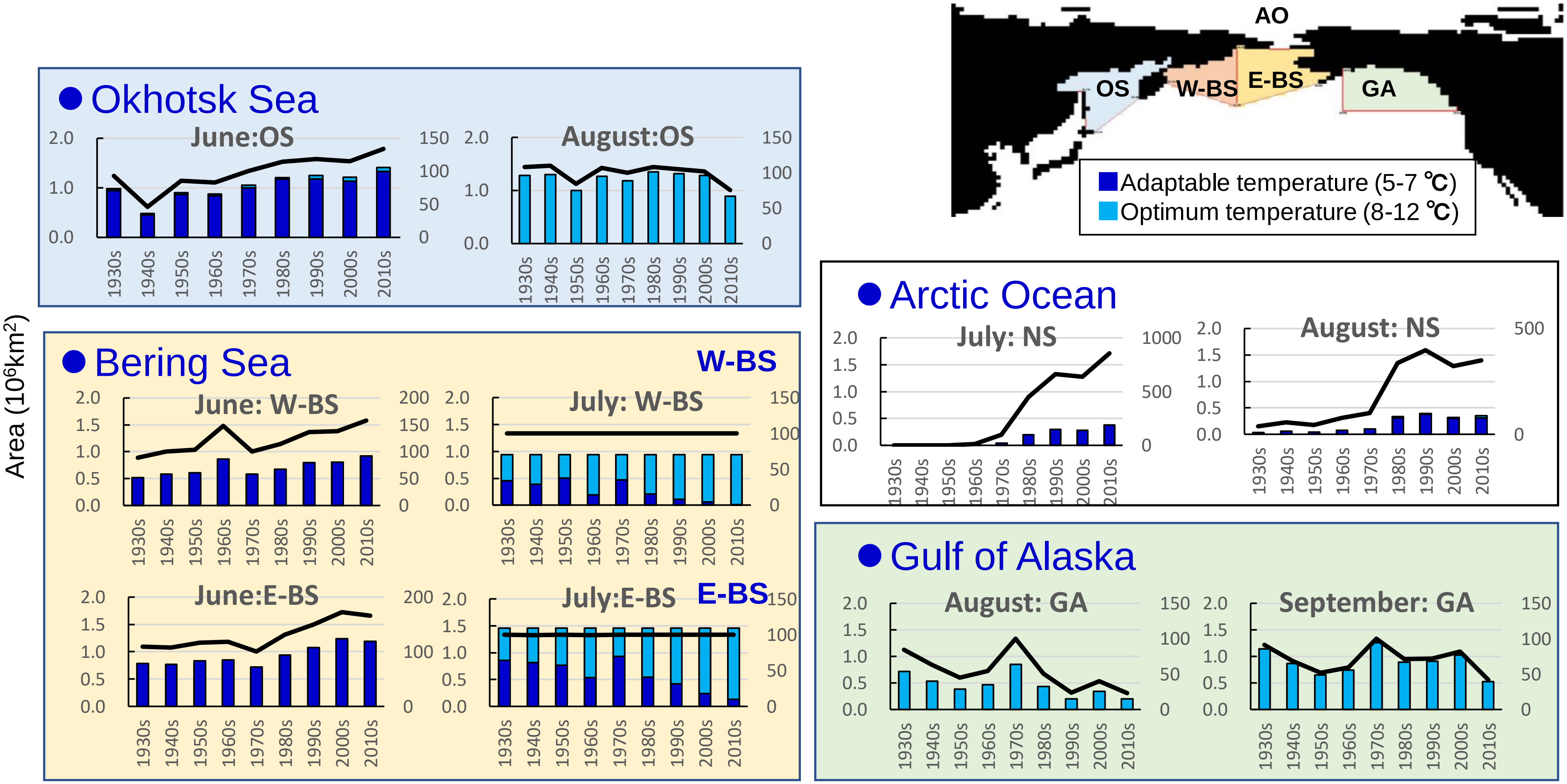




The area of optimum temperature is decreasing for the last several decades, especially in the Okhotsk Sea and the Gulf of Alaska

Kaeriyama (2019)

● Temporal changes in areas of adaptable and optimum temperatures for chum salmon from the 1930s to the 2010s



Since the 2000s, Okhotsk and Bering seas are favorable ecosystems for survival and carrying capacity of chum salmon

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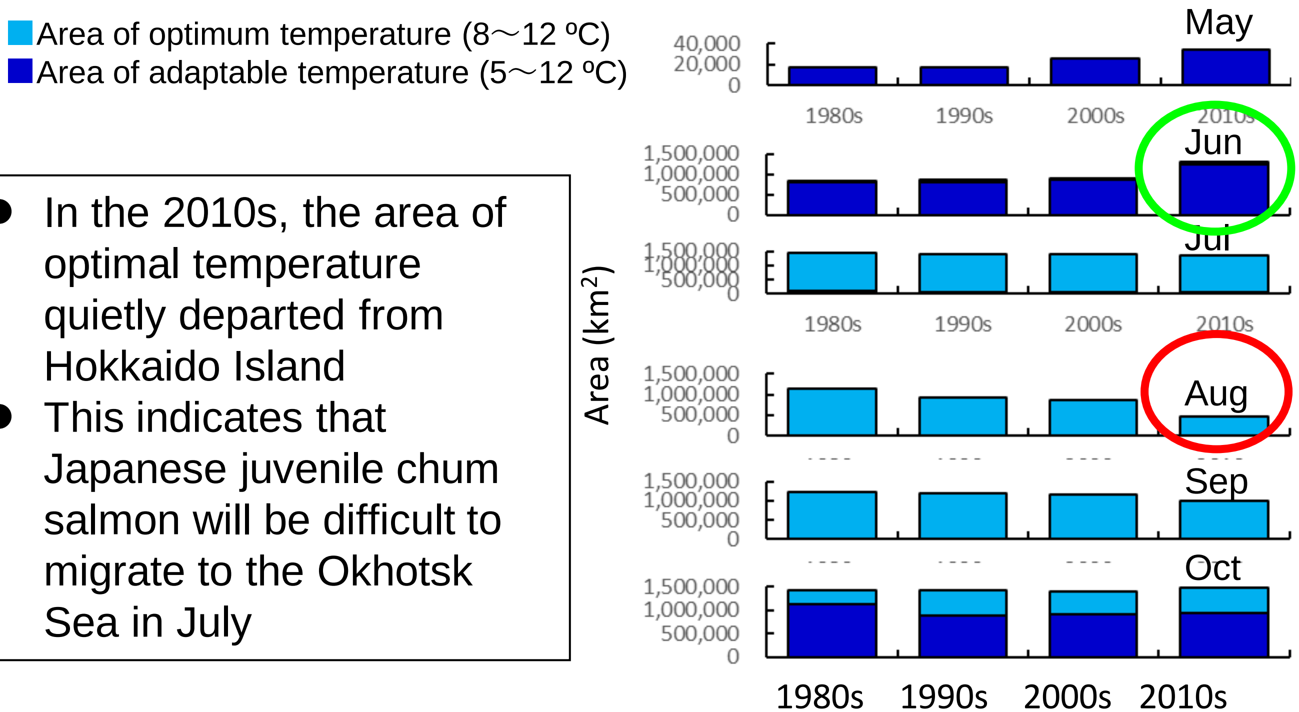
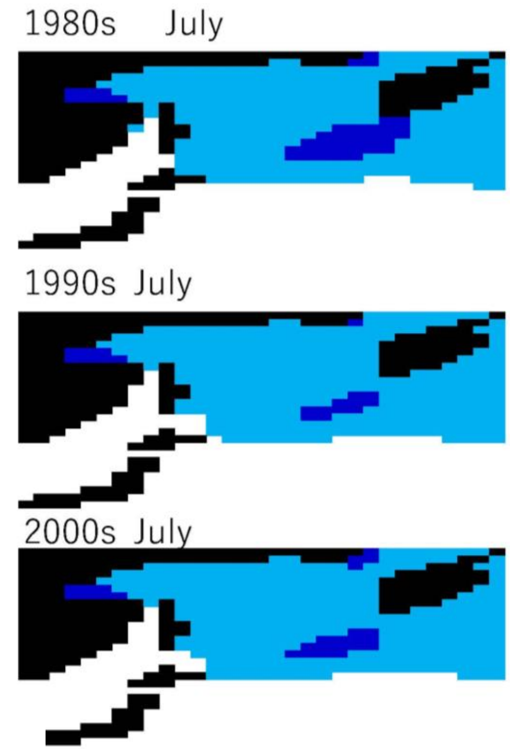
● Temporal change in areas of adaptable (AA) and optimum (AO) temperatures in July in the Okhotsk Sea



- In the 2010s, the area of optimal temperature quietly departed from Hokkaido Island
- This indicates that Japanese juvenile chum salmon will be difficult to migrate to the Okhotsk Sea in July

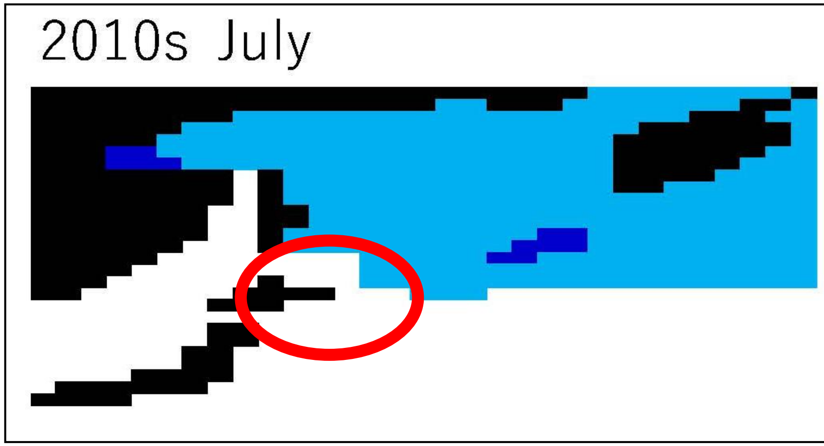


- The June AA: increase since the 2000s

→ **contribute for Russian juvenile chum and pink salmon to rise survival rate**

- The AO became less than half in August of the2010s

→ **introduce the decline in carrying capacity of Pacific salmon in the Okhotsk Sea**



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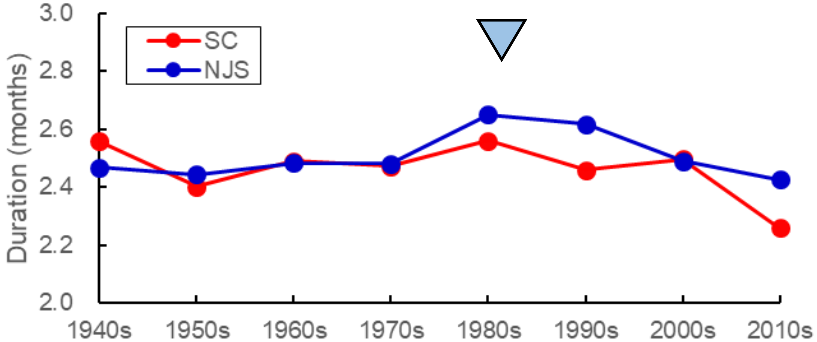
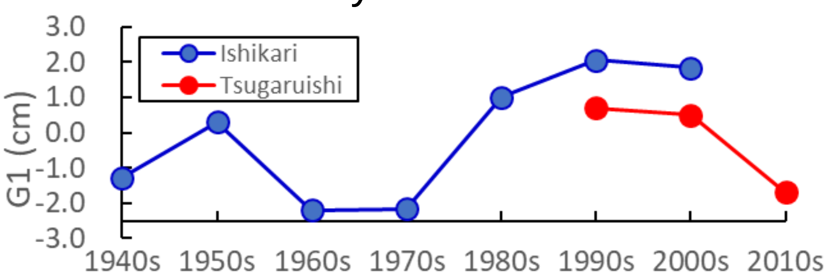
● Relationship between growth at the age-1 (G1) and survival rate of chum salmon returning to Ishikari and Tsugaruishi Rivers

●Hokkaido, ●Sanriku

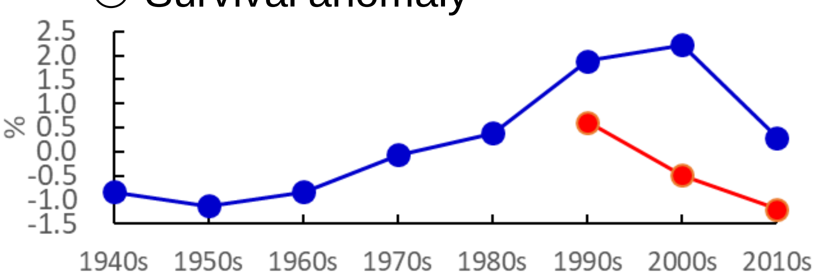
○ Resident duration



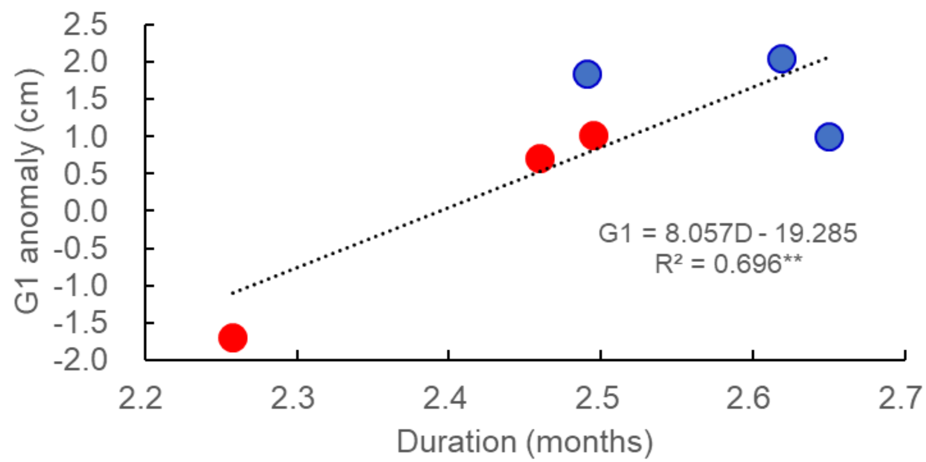
○ G1 anomaly



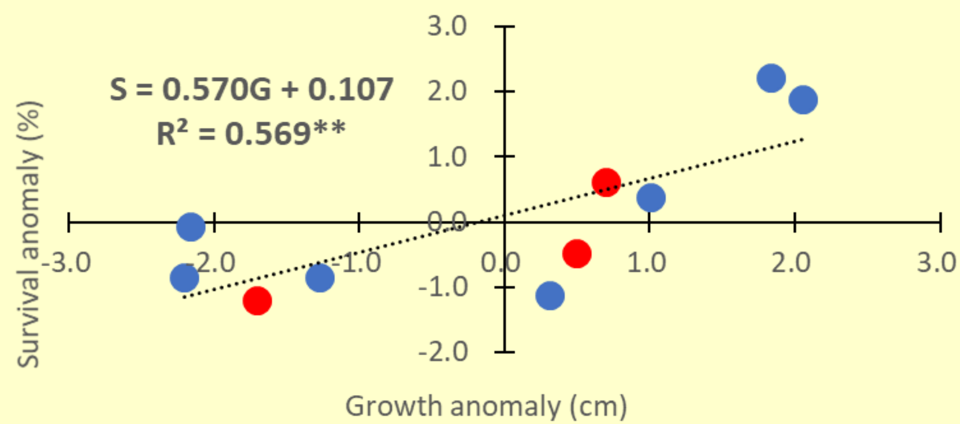
○ Survival anomaly



■ Relationship between resident duration and G1 anomaly since the 1980s



■ Relationship between Growth and Survival



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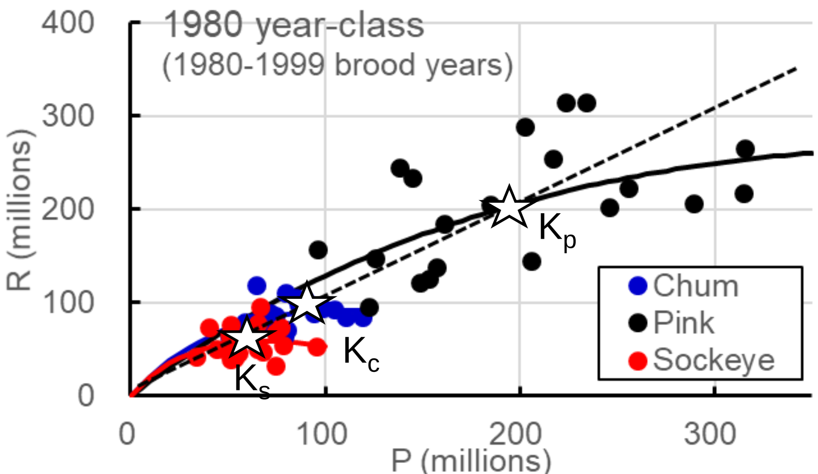
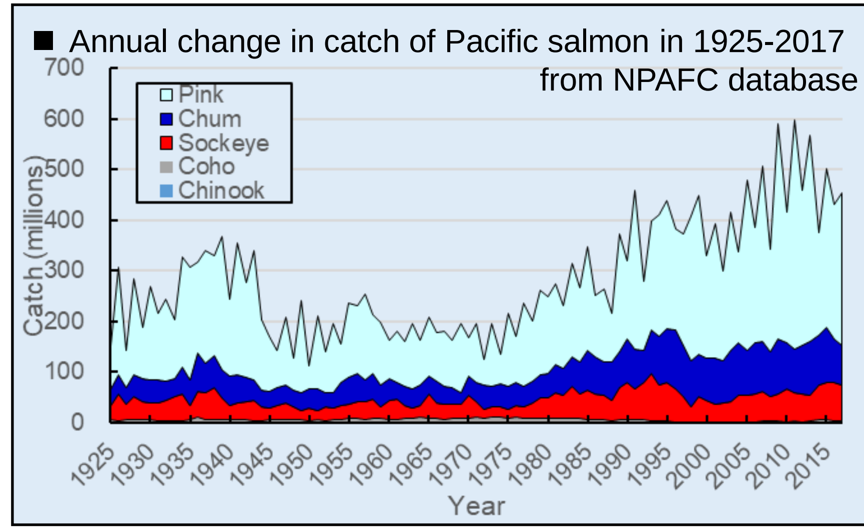
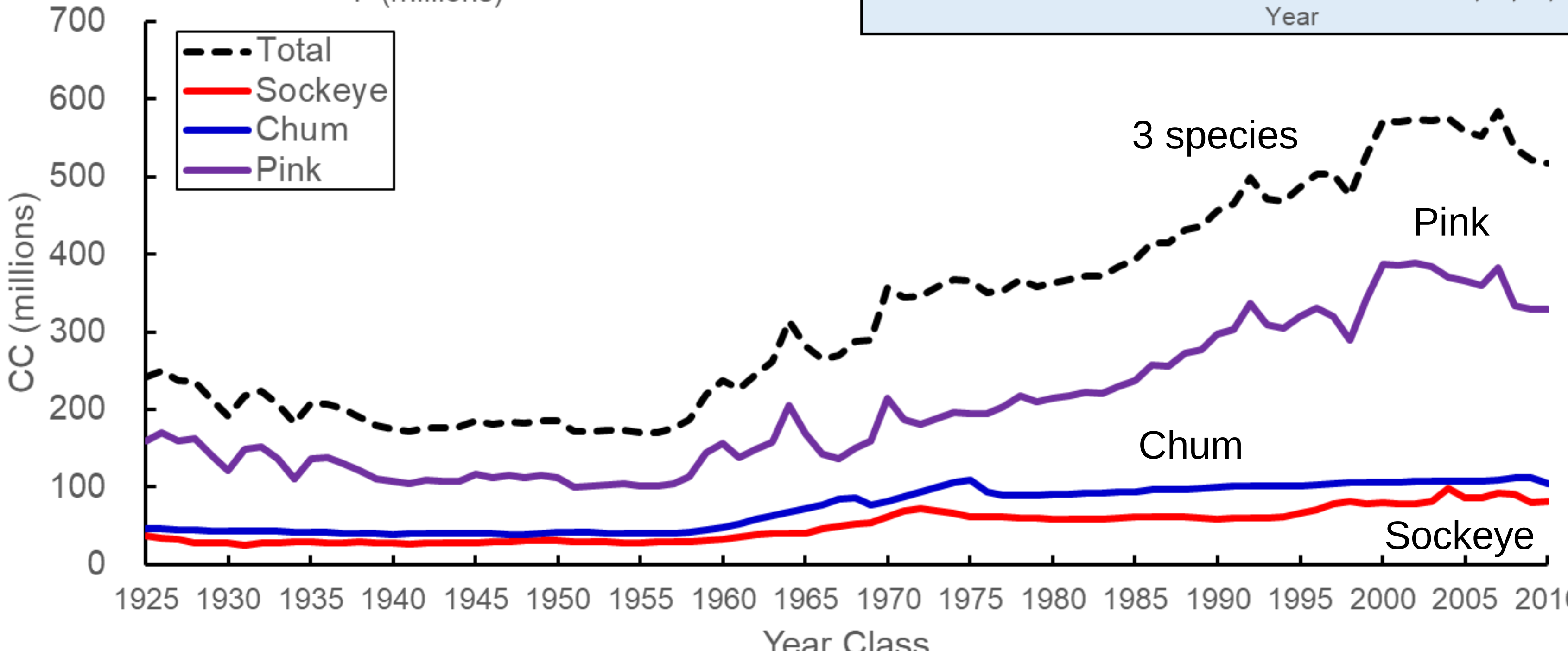
- Temporal change in carrying capacity of Pacific salmon (sockeye, chum, and pink salmon)



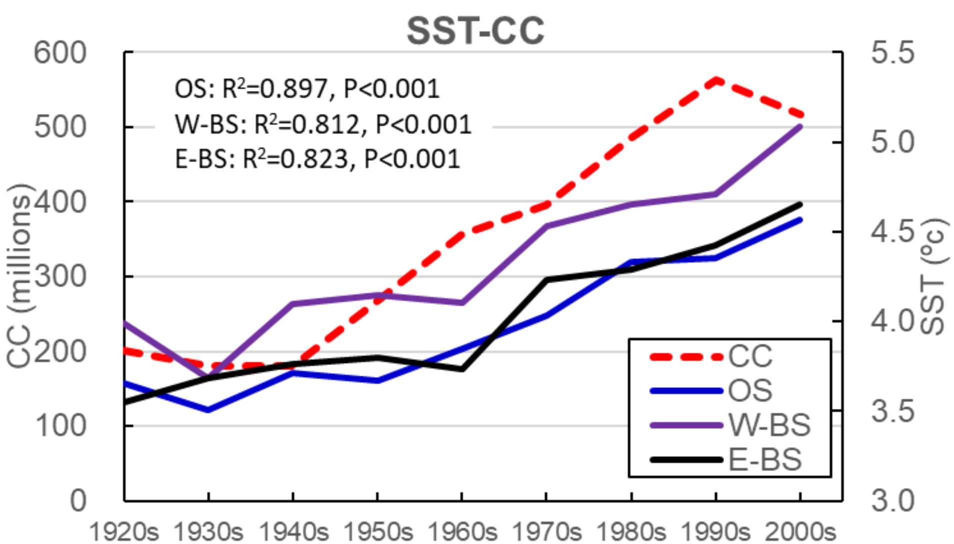


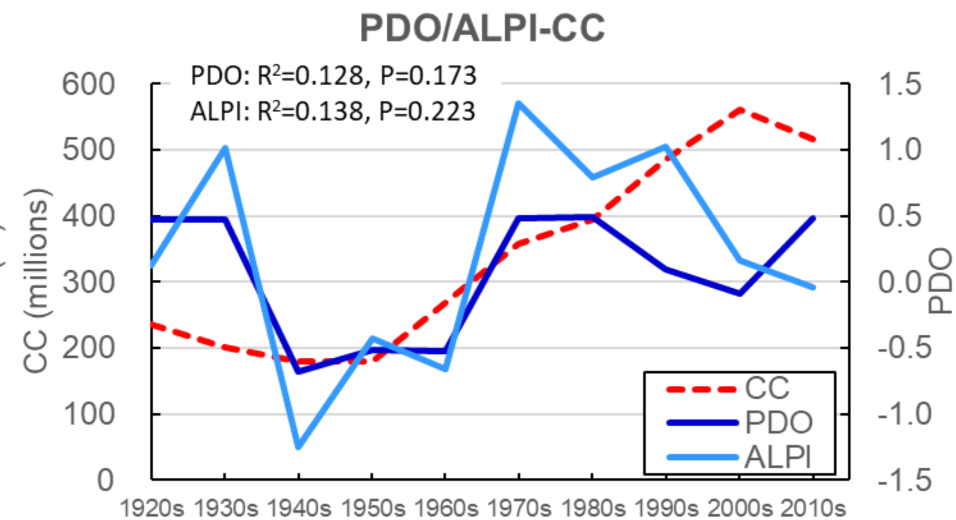


Kaeriyama (2019)

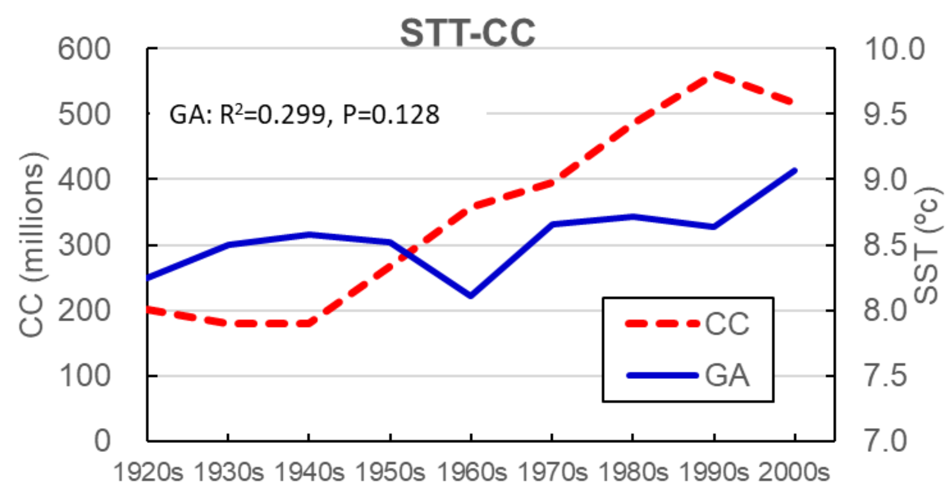
● Temporal changes in the decadal mean of SST, climate change indices and carrying capacity of Pacific salmon

OS: Okhotsk Sea, W- & E- BS: Western and Eastern Bering Sea, GA: Gulf of Alaska, CC: carrying capacity, PDO: Pacific Decadal Oscillation, ALPI: Aleutian Low Pressure Index





- The carrying capacity links to the SST in the Okhotsk Sea and the Bering Sea
- The carrying capacity does not correlate with the PDO and the ALPI (and the SST in the Gulf of Alaska)



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- Loka-Volterra equations for evaluating the inter- and intra-specific interaction among Pacific salmon

$$\frac{dN_1}{dt} = r_1 N_1 \left[1 - \frac{N_1 + \alpha_{12} N_2}{K_1}\right]$$

$$\frac{dN_2}{dt} = r_2 N_2 \left[1 - \frac{N_2 + \alpha_{21} N_1}{K_2}\right]$$

$$\downarrow$$

$$N_1 = K_1 - \alpha_{12} N_2$$

$$N_2 = K_2 - \alpha_{21} N_1$$

$$\downarrow$$

$$\alpha_{12} = \frac{K_1 - N_1}{N_2}$$

$$\alpha_{21} = \frac{K_2 - N_2}{N_1}$$

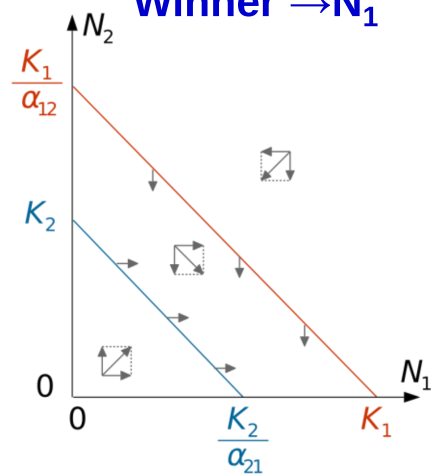
N: population size
K: carrying capacity
α: competition coefficient

K: 1996-2018 catch data (millions)
N: 2016-2018 catch data (millions)

	Pink	Chum	Sockeye
K	296	94	59
N	379	87	73

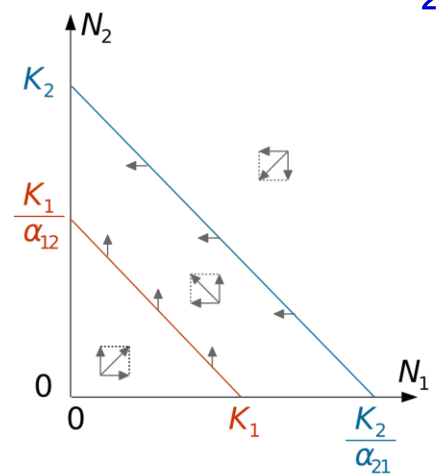
- **$K_2 < K_1/\alpha_{12}$ & $K_1 > K_2/\alpha_{21}$**

Winner →N_1



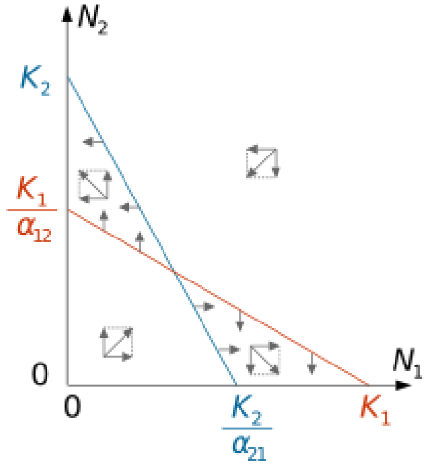
- **$K_2 > K_1/\alpha_{12}$ & $K_1 < K_2/\alpha_{21}$**

Winner →N_2



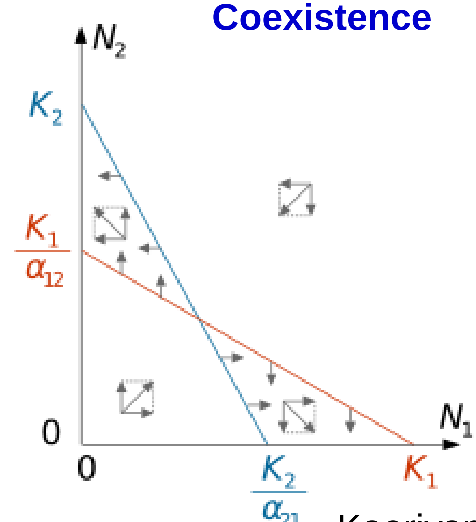
- **$K_2 > K_1/\alpha_{12}$ & $K_1 > K_2/\alpha_{21}$**

Winner, N_0: $N_1 > N_2$ → N1



- **$K_2 < K_1/\alpha_{12}$ & $K_1 < K_2/\alpha_{21}$**

Coexistence



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- Inter- and intra-specific interaction among chum, pink and sockeye salmon based on the Loka-Volterra equation

■ Inter-specific: Pink > Sockeye > Chum

N_1	N_2	K_2 K_1/α_{12}	K_1 K_2/α_{21}	Winner
Chum	Pink	>	<	Pink
Chum	Sockeye	>	<	Sockeye
Pink	Sockeye	>	>	Pink

■ Sockeye: Alaska > Canada >Russia

N_1	N_2	K_2 K_1/α_{12}	K_1 K_2/α_{21}	Winner
Russia	Alaska	>	<	Alaska
Russia	Canada	>	<	Canada
Alaska	Canada	>	>	Alaska

■ Pink: Russia > Alaska = Japan > Canada

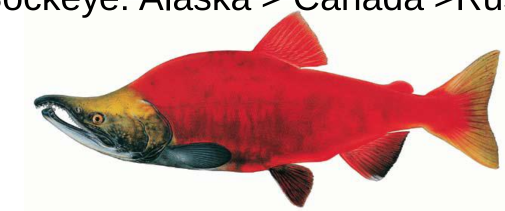
N_1	N_2	K_2 K_1/α_{12}	K_1 K_2/α_{21}	Winner
Japan	Russia	>	<	Russia
Japan	Alaska	<	<	Coexistence
Japan	Canada	>	>	Japan
Russia	Alaska	<	>	Russia
Russia	Canada	<	>	Russia
Alaska	Canada	>	>	Alaska

■ Chum: Alaska > Canada > Russia = Japan

N_1	N_2	K_2 K_1/α_{12}	K_1 K_2/α_{21}	Winner
Japan	Russia	<	<	Coexistence
Japan	Alaska	>	<	Alaska
Japan	Canada	>	<	Canada
Russia	Alaska	>	<	Alaska
Russia	Canada	>	<	Canada
Alaska	Canada	>	>	Alaska

No. 1. Pink: Russia > Alaska = Japan > Canada

No. 2. Sockeye: Alaska > Canada >Russia



No. 3. Chum: Alaska > Canada > Russia = Japan

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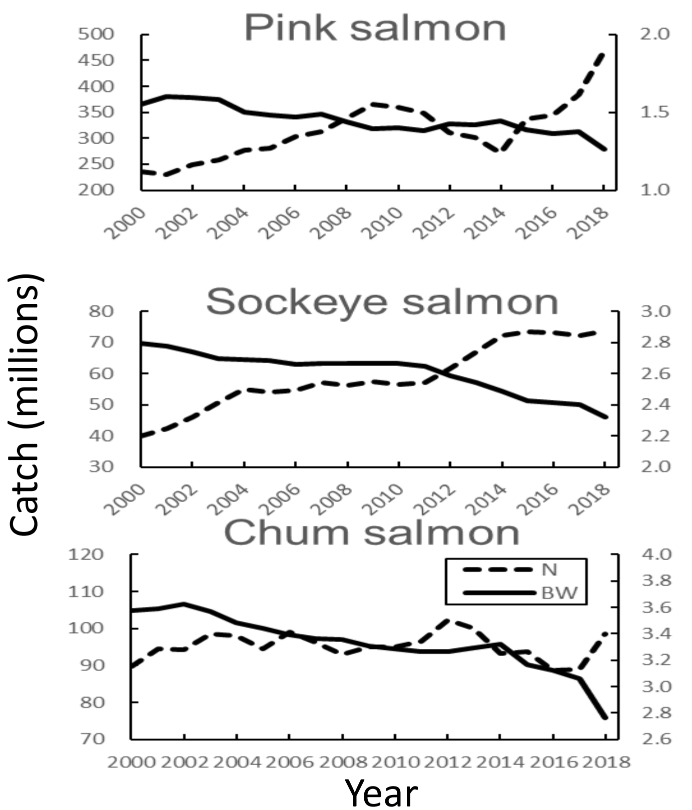
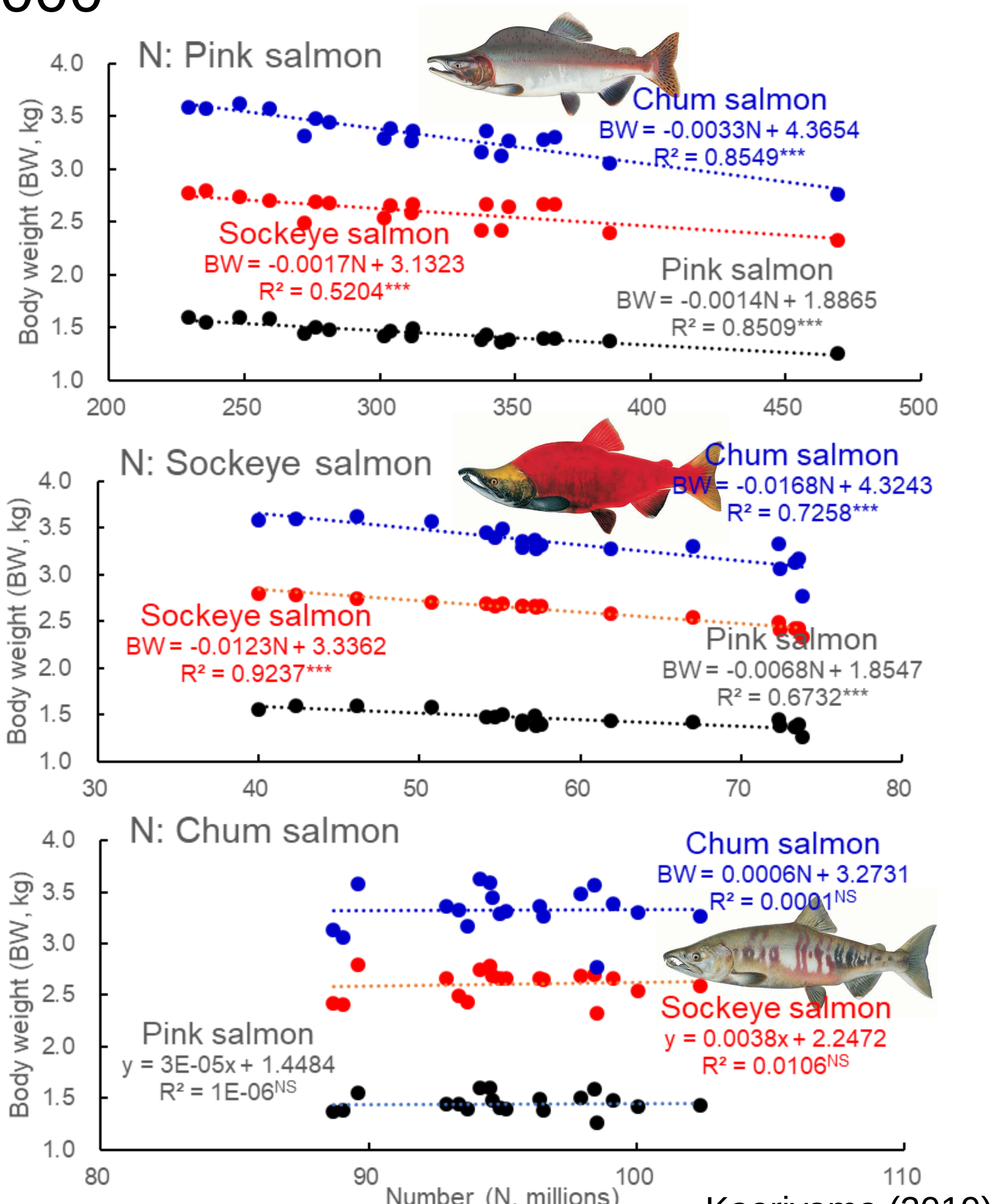
● Relationship abundance and body size for pink, sockeye and chum salmon since 2000





Inter- & intra-specific interaction of 3 species

Density-dependent effect

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SUMMARY & CONCLUSION

- Chinook salmon occupied the highest trophic level, followed by steelhead , sockeye, coho, pink and chum salmon in the North Pacific Ocean.
- Chum salmon will avoid the competition among Pacific salmon without the competitive exclusion principle.
- The feeding pattern of Pacific salmon will be defined as “Species specificity and plasticity” based on their trophic level and structure of each ecosystem in the North Pacific Ocean.
- The total carrying capacity of chum, pink and sockeye salmon seems to link with the SST in the Okhotsk and Bering Seas, despite no-correlation with climatic indices.
- Increase in June SST in the Okhotsk and Bering Seas will serve as a trigger of the high survival rate of Russian chum and pink salmon.
- Japanese chum salmon will be difficult to migrate to the Okhotsk Sea, and to attain full growth at the offshore migration in the coastal seas with progress of the global warming.
- Regarding interspecific competitive interactions among pink, chum and sockeye salmon based on the Lotka-Volterra equation, the pink salmon is strongest, followed by sockeye and chum salmon.
- The interspecific interaction of 3 species will cause the density-dependent effect.

Kaeriyama (2019)