Trophic Link Between *Neocalanus* Copepods and Pink Salmon in the Western Subarctic North Pacific Based on Long-Term Nitrogen Stable Isotope Analysis

Sanae Chiba[1], **Hiroya Sugisaki**[2], **Kazuaki Tadokoro**[3] and **Toru Nagasawa**[4]

[1] *Research Institute of Global Change, JAMSTEC, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan*
[2] *National Research Institute of Fisheries Science, FRA, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan*
[3] *Tohoku National Fisheries Research Institute, 3-27-5, Shinhama-cho, Shiogama, Miyagi 985-0001, Japan*
[4] *Hokkaido National Fisheries Research Institute, 2-2 Nakanoshima, Toyohiraku, Sapporo, Hokkaido 062-0922, Japan*

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We have been conducting analyses of long-term changes in the lower trophic level ecosystems of the western North Pacific using the Odate Collection, a historical zooplankton sample and data set (Odate and Maita 1994). We detected a significant correlation between zooplankton biomass and the decadal water temperature anomaly from winter to spring, which was closely related to Pacific Decadal Oscillation (Chiba et al. 2006). Zooplankton biomass and Japanese pink salmon (*Oncorhynchus gorbuscha*) catch markedly increased in the 1990s (Chiba et al. 2008; Yatsu et al. 2008), roughly coinciding with the 1988/89 regime shift and wintertime warming. In this study, we investigated the possible link between decadal variation of zooplankton and pink salmon abundance using nitrogen stable isotope analyses.

It is well documented that the amount of nitrogen stable isotope ($\delta^{15}N$) contained in plants and animals indicates the trophic position of an organism in the ecosystem because the concentration increases approximately 3.4‰ with the increase of one trophic level. Assuming that pink salmon feed on copepods, we expected that the time-series variation in $\delta^{15}N$ of copepods and salmon might indicate the trophic interaction between them and the bottom-up control of pink salmon production. We measured $\delta^{15}N$ in four dominant copepods species, *Neocalanus cristatus, N. plumchrus*, *N. flemingeri* and *Eucalanus bungii,* from the Odate Collection and in pink salmon scales collected in the offshore area west of 180°. Interannual variation in the amount of $\delta^{15}N$ was compared for the years 1960 to 2002. We used whole pink salmon scales collected from maturing females (age-.1). Thus the concentration of nitrogen stable isotope was the average accumulated during the life span until the time of capture.

The time-series of the averaged $\delta^{15}N$ anomaly for copepods and pink salmon showed a marked decline in the 1990s by 2~3 ‰ (Fig. 1). This decline coincided with the timing of increase in the biomass of copepods and fish, which indicates a possible bottom-up control mechanism for the enhanced salmon production in the 1990s. Considering the $\delta^{15}N$ in the four copepods species varied in a similar manner, we think it is plausible that declines in copepod $\delta^{15}N$ was a response to common environmental forcing rather than from a species-specific ecological or biological trait. These copepod species are reported to shift their feeding strategy to more omnivory, depending on ambient

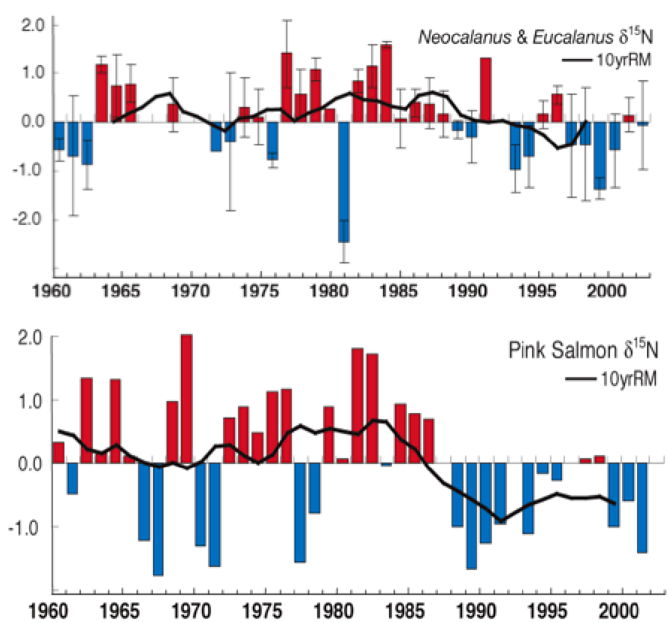

Fig. 1 Time-series anomaly and 10-year running mean of average $\delta^{15}N$ contained in four copepods species, N*eocalanus cristatus, N. flemingeri, N. plumchrus and Eucalanus bungii* (upper panel) and in pink salmon scales collected in the western North Pacific (lower panel).

All correspondence should be addressed to S. Chiba
e-mail: chibas@jamstec.go.jp

phytoplankton availability (Kobari et al. 2003). As a 3 ‰ decline of $\delta^{15}N$ is equivalent to a decline of roughly one trophic level, our results suggested copepods might have fed more heavily on phytoplankton in the 1990s, as compared to the previous decade, due to increased phytoplankton abundance. Did phytoplankton abundance really increase in the 1990s?

After the 1988/89 regime shift, the wintertime conditions in the western North Pacific were warm with a shallow mixed layer depth. Water column stability and light availability increased during winter and this condition was thought to trigger an earlier phytoplankton bloom. We observed increased wintertime Chl *a* and decreased springtime and annual mean Chl *a* in samples from the 1990s (Chiba et al. 2008; Fig. 2). An early bloom and a continuous moderate supply of phytoplankton might be a better match with reproduction and survival of copepods, and other herbivorous zooplankton prey of salmon, that results in benefits to pink salmon production.

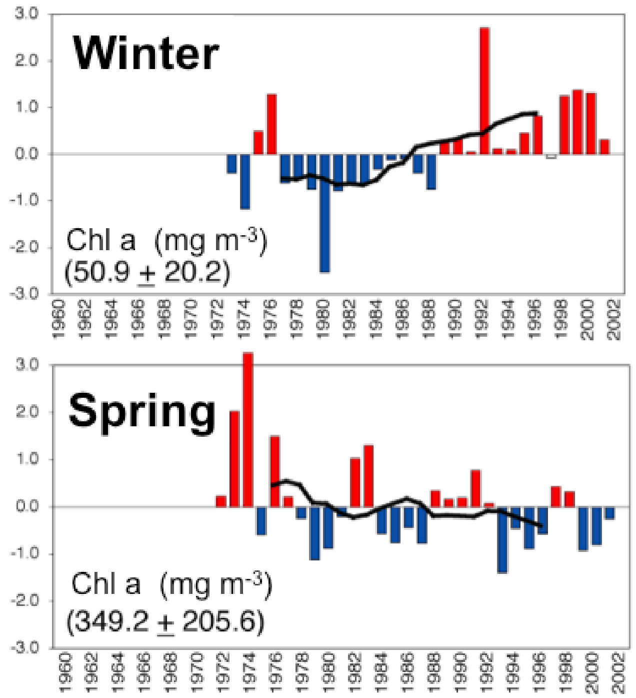

Fig. 2 Time-series anomaly of phytoplankton abundance (Chl a: mg m-3) during winter (upper panel) and spring (lower panel) in the western North Pacific.

This study revealed possible bottom-up control of pink salmon production that is driven by decadal climatic forcing over the North Pacific. We demonstrated the usefulness of measuring $\delta^{15}N$ in zooplankton and fish as an indicator of the linkage between lower and higher trophic levels. However, there is a problem in applying conventional methods of $\delta^{15}N$ determination. The $\delta^{15}N$ concentration in zooplankton varies not only by changes in trophic position, but also varies depending on environmental factors, such as source water concentration of nitrate and/or ^{15}N, physiological state of phytoplankton, and other factors. This deficiency often makes it difficult to interpret results from this type of analysis. Methods for amino-acid analysis of $\delta^{15}N$ concentration has recently been developed to solve this problem by producing results solely based on the trophic level of an organism, rather than environmental and physiological factors (Chikaraishi et al. 2009). Extensive monitoring of zooplankton in the subarctic North Pacific by ships equipped with a continuous plankton recorder (CPR) has been conducted every year since 2000. As a recommendation, we propose future routine analysis of amino acid $\delta^{15}N$ of zooplankton collected by CPR and salmon samples to obtain a better understanding of the mechanism of interannual salmon stock variation in the North Pacific.

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