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A short review of the effects of environmental factors on distribution, migration and recruitment of Pacific saury

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Summary

The purpose of this paper is to provide a summary of previous insights into the effects of the environmental factors on the distribution, migration and recruitment of Pacific saury. The distribution and migration route of Pacific saury in autumn fluctuated from west to east depending on the period. In general, a suitable environment for the distribution of Pacific saury is formed along the Oyashio in autumn, thus they migrate through Oyashio. The mechanism of the eastward shift of the distribution and migration route in autumn has recently been explained by two factors: 1) the change of the pathway of Oyashio making it difficult to form a suitable habitat of Pacific saury in the waters around east of Hokkaido, and 2) eastward shift of the distribution of Pacific saury in early summer. Many studies on the relationship between recruitment fluctuations of Pacific saury and the environmental variations have been conducted. All of them found correlations between the environmental factors in the spawning and nursery grounds (or climatic indices that affect them) and the recruitment. In recent years, several studies have shown that the different environmental factors could correlate with recruitment in different periods. This may be related to the complexity of the life history of Pacific saury such as the interannual change of dominant seasonal cohorts. When considering the environment in stock management of Pacific saury, we need to note the possibility that environmental indicators that are correlated with recruitment in one period may become uncorrelated in another.

1. Introduction

Pacific saury is a kind of small pelagic fishes. As with other small pelagic fishes, its ecology is considered to be greatly affected by environmental variations. It would be beneficial to understand the relationship between the environment and ecology correctly to improve the accuracy of stock assessment. The purpose of this paper is to provide a summary of previous insights about the effects of the environmental factors on the distribution, migration and recruitment of Pacific saury. For more information on the life history and ecology of Pacific saury, which is the premise of this short review, see Fuji et al. (2019).

2. Relationship between fishing ground formation and environmental factors

Pacific saury migrate southwestward in autumn from offshore subarctic area in the western and central North Pacific Ocean (Fig. 1, Fukushima 1979, Suyama et al. 2012, Miyamoto et al. 2019, Kakehi et al. 2020). It has been known for a long time that the fishing grounds of Pacific saury in autumn tend to be formed around the southernmost head of the Oyashio because cold water of Oyashio provide suitable temperature habitat there (Uda 1936). In recent years, many environmental information other than water temperature has become available through satellites, and research on the relationship between the distribution of Pacific saury and environmental factors has progressed. Many studies described the characteristics of the Pacific saury habitat by the abiotic factors, such as sea surface temperature (SST) and its horizontal gradient, etc., and the biotic factors, such as chlorophyll *a* concentration and indices of primal productivity (net primary production NPP, etc.) (Table 1). These findings suggest that Pacific saury generally form high-density schools in highly productive waters with SST between 10°C and 19°C, and in close to SST fronts (where SST change rapidly). It is thought that Pacific saury migrate seasonally through waters where environmental conditions are favorable for their distribution (Kakehi et al. 2020). Such environmental conditions would be distributed along Oyashio during autumn fishing season for Pacific saury. However, it is important to note that their suitable environment varies with season, size and/or age (e.g., Tseng et al. 2013, Chang et al. 2019, Kakehi et al. 2020, Hashimoto et al. 2021).

During June and July, it has been pointed out that the distribution of Pacific saury has shifted to the east and a considerable decrease of the stock in the western side since 2010 (Hashimoto et al. 2020, Hashimoto et al. 2021). The detailed cause of this distribution shift in this season is not yet known.

The annual variation in the migration route of Pacific saury in autumn has been the subject of many studies because it is closely related to the formation of fishing grounds. In some years, fishing grounds of Pacific saury form mainly in eastern waters, while in other years they form close to the coast of Japan (Yasuda and Watanabe 1994). The shift of fishing grounds to the east has occurred in the 1930s, 1980s, and since 2010 (Aizawa and Fukushima 1978, Yasuda and Watanabe 1994, Kuroda and Yokouchi 2017). This phenomenon was historically associated with the dynamics of the Oyashio (Uda 1936, Fukushima 1979). In the seas around Hokkaido, the Oyashio divides into two branches, which are called the first and second branches in accordance with their proximity to the Hokkaido coast (Fig. 1). It was believed that, in years when the first branch is strong, fishing grounds tend to form in the waters close to Japan, and in years when the first branch is weak and the waters around Japan are dominated by warm water, fishing grounds tend to form further east (Uda 1936, Yasuda and Watanabe 1994, Yasuda and Watanabe 1996). Yasuda and Watanabe (1994) used the position of the Oyashio Offshore Front (OOF) as an index to indicate this relationship between the Oyashio and fishing grounds. However, Kuroda and Yokouchi (2017) extended this analysis to 2014 and pointed out that the eastward shift of the fishing grounds after 2010 cannot be explained by the position of OOF. Several studies have shown that Oyashio pathway changed from along-slope direction to offshore direction in the upstream region along Hokkaido, resulting in a decrease of the area of the suitable SST for Pacific saury, which may have contributed to the recent offshore shift of the fishing grounds (Kuroda and Yokouchi 2017, Prants et al. 2021). In addition, Kuroda and Yokouchi (2017) pointed out that the recent eastward shift of Pacific saury distribution in June and July (Hashimoto et al. 2020) may have contributed to the decrease in the abundance of fish coming to this area. The schools of Pacific saury that begin their southwestward migration from more easterly waters in summer might take a more easterly route than those that begin from the west (Fig. 1). In summary, the mechanism of the eastward shift of the distribution and migration in autumn has recently been explained by two factors: 1) change of the pathway of the Oyashio, making it difficult to create a suitable habitat in the seas around Japan, and 2) an eastward shift in the distribution of Pacific saury in early summer.

Chang et al. (2019), as well as Kuroda and Yokouchi (2017), showed that, suitable habitat for Pacific saury have become less likely to form in the seas around Japan since 2010, and that such a trend may be related to the El Niño - Southern Oscillation (ENSO) index of Niño 3.4. They proposed a mechanism whereby an El Niño event increases SST in the waters along Hokkaido and weakens the Oyashio, making it more difficult for fishing grounds to form (Chang et al. 2019). On the other hand, Hsu et al. (2021) reported that the eastward shifts in distribution and migration routes after 2013 could not be explained by a single environmental index or a combination of them. They pointed out that untested factors such as changes in the distribution of prey species (e.g., *Neocalanus* copepods, Miyamoto et al. 2020) and/or the increase of competing species (e.g., Japanese sardine *Sardinops melanostictus*) in the seas around Japan might have influenced the distributional shift.

3. Relationship between recruitment and the environment

Recruitment mechanism and spawning grounds of Pacific saury

Recruitment of many pelagic fishes, including Pacific saury, are thought to be determined by survival during the larval stage associating with environmental variations (Watanabe et al. 2003), as well as the amount of spawner. It has been pointed out that the growth of larval Pacific saury tends to improve with higher SST and/or more prey (Oozeki et al. 2004). The growth dependent survival mechanism was confirmed in larval Pacific saury (Nakaya et al. 2011). These studies suggest that recruitment of Pacific saury would be higher in years when the environment in the spawning and nursery ground is favorable for larval growth (and vice versa). Oozeki et al. (2015) suggested that larval transportation pathway by Kuroshio is also the important factor affecting the recruitment of Pacific saury. All previous studies on the relationship between abundance fluctuations of Pacific saury and the environmental factors have focused on the environment of the spawning and nursery grounds of Pacific saury or the climate indices that may affect it (Table 2, also see Table 3 for descriptions of the climate indices). The spawning and nursery grounds of Pacific saury are formed in the Kuroshio area (KA), Kuroshio recirculation area (KRA) and the Kuroshio-Oyashio Transition and Kuroshio extension (TKE) from autumn to spring (Fig.1, Iwahashi et al. 2006, Fuji et al. 2021), so the environment of these areas and season or related climate indices are of interest.

Relationship between changes in Pacific saury abundance and environmental variations

Tian et al. (2003) and Liu et al. (2019) focused on the environmental factors in winter KA, on the other hands, other researchers investigated on the broader areas, the KRA and/or TKE (Yasuda and Watanabe 2007, Ichii et al. 2018, Yatsu et al. 2021). Most of the studies examined the SST and/or the mixed layer depth (MLD, an indicator of primary production) as an environmental factor of spawning and nursery grounds (Table 2). Most of studies showed positive correlations between SST/MLD and abundance index as the proxy of recruitment. Higher SST and/or higher prey abundance (higher productivity) in the spawning and nursery ground can lead to higher growth and survival of larvae (Ichii et al. 2018). In addition, the environment factors of these areas could be the indicator of the Kuroshio position, which may affect the transport route of the larvae. Nakayama et al. (2021) pointed out that Kuroshio position index (KPI) has potential to be used to predict the recruitment of Pacific saury. This may indicate that recruitment is affected by changes in the Kuroshio current pathway through changing the larval transportation, as Oozeki et al. (2015) also suggested. Correlations have been found between climatic indices and environmental factors in spawning and nursery grounds, suggesting that recruitment fluctuations of Pacific saury could be affected by a decadal climate change (Tian et al. 2003, Liu et al. 2019).

Recently, some studies suggested that different environmental factors may affect the recruitment of Pacific saury in different periods; Ichii et al. (2018) explored the relationship between the survey CPUE and the environmental factors, and found that from 1976 to 2006, except for 1994-2002, the CPUE was positively correlated with the previous year's winter SST in the KRA, and in 1994-2002, it was correlated with the previous year's spring MLD in TKE. Yatsu et al. (2021) also showed that winter SST in the KRA, winter NPGO, and winter SOI were correlated with fishery CPUE of Pacific saury in 1980-1989, 1990-2009, and 2010-2018, respectively. Ichii et al. (2018) discussed about the results associating with the long spawning season of Pacific saury (10 months). The main spawning season of Pacific saury is winter (Watanabe and Lo, 1989). Ichii et al. (2018) also considered that the winter-spawned cohort constituted the main body of the Pacific saury population because the winter environmental factor and recruitment were correlated for the majority of the study period. On the other hand, the spring-spawned cohort is known to have large inter-annual variability in recruitment, and recruitment can be very large in some years (Watanabe et al. 2003). Therefore, a correlation between environmental factors in the spring and recruitment will be found when the spring-spawned cohort has a series of favorable years for recruitment (Ichii et al. 2018).

In addition, the meaning of the climate index itself may change with periods. Litzow et al. (2020) found that a late-1980s North Pacific climate shift resulted in changing correlations between large-scale climate patterns and the PDO and NPGO, and widespread weakening in relationships between the PDO/NPGO and regional physical and ecological processes. These findings suggest that understanding based on observed correlations with PDO/NPGO variability may have limited utility when applied to different time periods. When considering the environment in stock management of Pacific saury, we need to note the possibility that environmental indicators that are correlated with recruitment in one period may become uncorrelated in another (see also Myers (1998)).

4. Conclusions and future works

Many studies showed that the environment influences the distribution, migration, and stock fluctuations of Pacific saury. Correct consideration of these factors will greatly contribute to improving the accuracy of resource assessment and management. However, it should be noted that the relationship between environmental factors and the ecology of Pacific saury may not be consistent in the long term, given the complex life history of saury. In addition, we should also note that specific processes for most of the environmental influences presented in this review have not been verified by the field observation. For example, as described above, most of research on the mechanism of stock fluctuation in Pacific saury has been conducted based on fishery information, and correlation analysis suggests that the environment influences the stock of Pacific saury. On the other hand, due to the lack of field observations, it has not been possible to show a direct relationship between the environment and the survival of larval Pacific saury and the amount of spawning by the spawners. The information of physical environment and plankton production are fundamental for understanding the mechanisms of variation in the growth and recruitment of Pacific saury, but still lacking. It is necessary to promote research and observation using research vessel surveys as well as fishery information to clarify the mechanisms of variation in the abundance of Pacific saury to achieve more accurate stock assessment and management that considers environmental factors.

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Table 1. Summary information on potential environmental factors being suggested to affect distribution of Pacific saury

Categories	Factors	References
Abiotic factor	Sea surface temperature (SST)	Tseng et al. (2013), Chang et al. (2019), Hua et al. (2020), Hashimoto et al. (2021), Fuji et al. (2021)
	SST gradient/front	Tseng et al. (2014), Hua et al. (2020)
	Temperature at 50 m	Kulik et al. (2019)
	Sea Surface Height (SSH)	Chang et al. (2019), Hua et al. (2020)
	Sea surface salinity (SSS)	Chang et al. (2019)
Biotic factor	Net primary production (NPP)	Tseng et al. (2013), Chang et al. (2019)
	Chl *a* concentration	Tseng et al. (2013)

Table 2. Summary information on potential oceanographic factors and periods being suggested to affect recruitment of Pacific saury (modified and expanded from Ichii et al. (2018) and Yatsu et al. (2021)).

Studies	Potential environmental indices affecting recruitment (key period)	Study period
Tian et al. (2003)	Winter SST in Kuroshio region Annual mean SOI	1951-2000
Watanabe (2009)	Spring SST in TKE (1988-1991)	1978-2005
Yasuda and Watanabe (2007)	Winter MLD in KRA	1955-2000
Yatsu and Watanabe (2017)	Winter SST in Kuroshio Extension Sardine recruitment Winter NPGO	1981-2014
Ichii et al. (2018)	Winter SST in KRA (1981-1993, 2003-2006) Spring MLD in TKE(1994-2002)	1981-2006
Krovnin et al. (2018)	Winter NPGO with a lag of 5 years.	1994-2016
Liu et al. (2019)	Winter meridional position of 19℃ in KA Annual SOI Winter MOI	1950-2017
Yatsu et al. (2021)	Winter SST in KRA (1980-1989) Sardine biomass Winter NPGO (1990-2009) Winter SOI (2009-2018)	1982-2018
Nakayama et al. (2021)	KPI in winter and spring	1994-2019

SST: sea surface temperature, MLD: mixing layer depth. KA: Kuroshio Area, KRA: Kuroshio Recirculation Area, TKE: Kuroshio-Oyashio transition and Kuroshio Extension. See table 3 for other abbreviations of environmental indices.

Table 3. Descriptions of environmental indices.

Index	Description	Reference
Niño 3.4	The Niño 3.4 SST anomaly index is an indicator of central tropical Pacific El Niño conditions. It is calculated with SSTs in the box 170°W - 120°W, 5°S - 5°N.	https://stateoftheocean.osmc.noaa.gov/sur/pac/nino34.php
PDO index	Pacific decadal oscillation (PDO) indices are projections of monthly mean SST anomalies onto their first EOF vectors in the North Pacific (north of 20ºN).	http://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo.html
SOI	The Southern Oscillation Index (SOI) is a standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia.	https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/
NPGO index	The North Pacific Gyre Oscillation (NPGO) is a climate pattern that emerges as the 2nd dominant mode of sea surface height variability (2nd EOF SSH) in the Northeast Pacific.	http://www.o3d.org/npgo/
MOI	The MOI is defined as the difference in the SLP between Irkutsk (Russia) and Nemuro (Japan), representing conditions of the winter Asian monsoon	Tian et al. (2004)
KPI	An indicator of Kuroshio axis position and formation of meander, calculated from the anomaly of sea-level difference between Nakanoshima (29°51'N, 129°51'E) and Nishinoomote (30°44'N,131°0'E)	Nakayama et al. (2021)

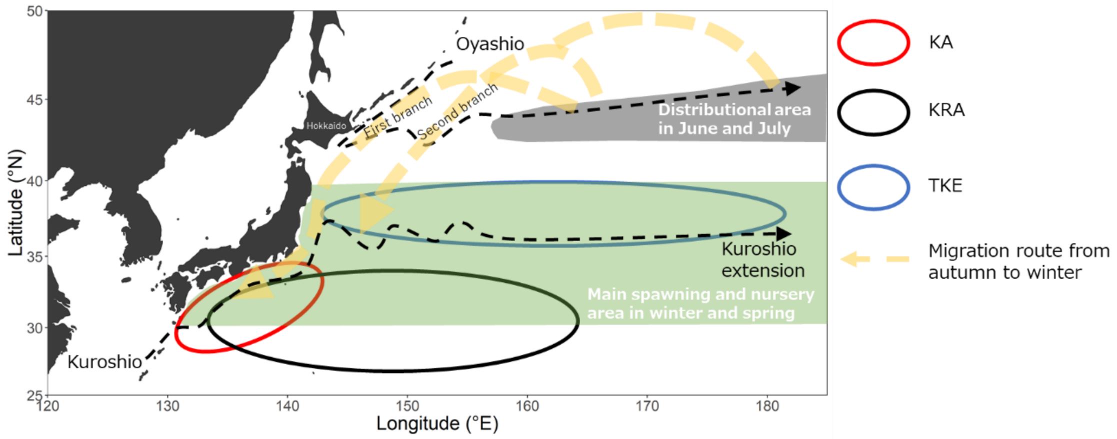

Figure 1. Major oceanographic structures and schematic representation of distribution and migration of Pacific saury in the Northwestern Pacific Ocean between early summer and winter. KA: Kuroshio Area (Liu et al. 2019), KRA: Kuroshio Recirculation Area (Ichii et al. 2018), TKE: Kuroshio-Oyashio Transition and Kuroshio Extension (Ichii et al. 2018).