박사학위논문

Multi-decadal changes in fish assemblages and sustainable fisheries management in the Korea Strait

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2021년 2월

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이 논문을 이학 박사학위 논문으로 제출함

2020년 12월

이경환의 이학 박사학위 논문을 인준함

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2020년 12월

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Abstract

This study showed 1) the multi-decadal changes in fish assemblages in relation to oceanic environment change in the Korea Strait, and 2) biological reference points and current fishing level for sustainable fisheries of Pacific anchovy and chub mackerel representing the dominant species in the Korea Strait.

Chapter 1, I evaluated spatio-temporal changes of the fish-assemblage structure in the Korea Strait (KS, 126°-129°5'E, 33°5'-35°N) and its relationship with oceanic conditions from 1986 to 2010. Hydrographic data include depth-specific water temperature, salinity and inflow indices of the Tsushima Warm Current (TWC) and Korea Strait Bottom Cold Water (KSBCW). Spatio-temporal changes of the fish-assemblage structure and relationship with oceanic conditions evaluated by Correspondence analysis (CA) and canonical correspondence analysis (CCA). Anchovy was the most dominant species in the KS from 1986 to 2010. Shift in the fish assemblage was detected between 1990 and 1991. Sardine and filefish dominated from 1986 to the early-1990s, and chub mackerel and squid dominated from the early-1990s to 2010. Annual changes in fish assemblages were significantly correlated surface water temperature at 0-20 m depths. Regime shift in surface water temperature was detected shift in 1987. Among the significant oceanic conditions, water temperature delayed by 1 year showed the most significant correlation with change in fish assemblage structure. I conclude that 1) fish assemblage structure dramatically shift in the 1990-1991, 2) the KS is an intermediate area between the waters off Ieodo and the East Sea with respect to the timing of shift in fish assemblage structure, 3) the shift of fish assemblage structure in the KS was highly influenced by climate shift of surface water temperature in the late-1980s.

Chapter 2, I developed and applied a simulation-based yield-per-recruit analysis that considered temperature-dependent growth and size-dependent mortality from egg to adult stages of anchovy. I projected changes in fisheries yield and egg production of anchovy with respect to varying biological reference points of 1) the instantaneous fishing mortality (F), 2) the minimum fork length of anchovy allowed to catch for protecting smaller anchovy ($L_{c,min}$), and 3) the maximum fork length allowed to catch for protecting bigger anchovy ($L_{c,max}$). Simulation showed that the anchovy yield will be maximized at ca. 1.4×10^6 tons when $L_{c,min}$ ranges between 42-60 mm or at ca. 0.8×10^6 tons when $L_{c,max}$ ranges from 88-160 mm. At $L_{c,min}$=30 mm, the present minimum length of catch, simulation indicated that the anchovy yield can reach a maximum of 1.3×10^6 tons in the long-term when $F_{0.1}=0.028$ day^{-1}. I expect that this yield-per-recruit model can be applied to other commercially-important small pelagic species in which the traditional Beverton-Holt Y/R model is difficult to apply.

Chapter 3, to provide the biological reference points for management of chub mackerel stock, I applied a simulation-based yield-per-recruit analysis that considered 1) temperature-dependent growth in early life stage, 2) size-dependent mortality. I estimated fisheries yield with respect to varying biological reference points and environmental conditions such as 1) the instantaneous fishing mortality (F), 2) the length at first capture (L_c), and 3) spawning water temperature. The result of simulation showed that the yield-per-recruit (Y/R) could be greater when the L_c ranges from 19-27 cm and F ranges from 1.48-2 yr^{-1}. Y/R with respect to varying spawning water temperature from 15 to 23°C showed an increasing trend with increasing temperature. I suggest targeting an L_c of 17 cm (age=0.6 years) at F=0.48 yr^{-1}, which is the current fishing mortality, for maximizing the chub mackerel harvest.

General introduction

Global fisheries

Global fishery production was 16.7 million tons (86% of total world fish production) in 1950. It increased dramatically to 87.7 million tons in 1996, and then declining to stabilize at about 80 million tons (FAO, 2011). Global fishery production was 82.6 million tons in 2011 and 79.7 million tons in 2012. In these years, the Northwest Pacific had the highest production with 26% of the global fishery production, followed by the Southeast Pacific (15%), the Western Central Pacific (14%) and the Northeast Atlantic (9%) (FAO, 2014). Especially the Pacific and Atlantic Oceans, where showed high fishery production and consumption, require establishment of fisheries resource management plan (Zhang and Kim, 1996).

Korean fisheries

Total catch in Korean coastal waters averaged 1.25 million tons from 1970 to 2018. Catch began to increase from 0.72 million tons in 1970, the largest catch of 1.73 million tons occurred in 1986. After that it steadily decreased until recent year (MOF, 2020). Fishery production in Korean waters steadily decreased, and trophic levels meaning ecosystem structure also decreased with decreasing fishery production (Zhang, 2006). The Korean coastal waters are divided into the three regions, 1) the East Sea, 2) the Korea Strait and 3) the Yellow Sea. Catch of coastal fisheries in the Yellow Sea from 1990 to 2010 showed the highest catch (71,000 tons) before late-2000s. Since late-2000s, the Korea Strait (81,218 tons) showed the highest catch compare with other seas (Yoon et al., 2014).

Cause of changes in fisheries resources

Distribution and abundance of pelagic and demersal fish species are known as influenced by climate change (Gong et al., 2007; Gong et al., 2010; Perry et al., 2005; Reid et al., 2001; Tian et al., 2011). Overfishing also is known to affect changes in fisheries resource together with climate change (Kim et al., 2007). In Korean waters, it is difficult to estimate the total biomass by species because various fish species inhabit with together (Zhang and Kim, 1996). Thus, studies on evaluating 1) the long-term change in fish assemblage and 2) the current fishing level by fish species are needed to determine whether climatic change or fishery was the major cause of the variation in fishery production in Korean waters.

Summary

This study evaluated 1) long-term changes in fish assemblages in relation to climate change in the Korea Strait, and 2) biological reference points for suitable fisheries management of anchovy and chub mackerel representing the dominant species in the Korea Strait.

Long-term changes in fish assemblages in the Korea Strait

In Chapter 1, I evaluated long-term changes in fish assembles in the Korea Strait. The Korea Strait is a mixed area of the Korea Strait Bottom Cold Water (KSBCW) flowing southward and the Tsushima Warm Current (TWC) flowing northward. The Korea Strait is commercially important area because 1) fisheries production was the highest among the

Korean waters from late-2000s and 2) small pelagic species with high consumption are widely distributed. I estimated spatio-temporal changes in fish assemblage structure by applying CA, and relationship with changes in oceanic conditions by applying CCA.

Yield-per-recruit analysis of anchovy

In Chapter 2, I evaluated the yield-per-recruit of anchovy. Yield-per-recruit analysis diagnosis the fisheries stock and suggest biological reference points for sustainable use of fishery resources. However, traditional method of the Beverton and Holt method is difficult to apply to anchovy because of biological characteristics of anchovy. Thus, I estimated and compared the commercial yield by simulation considered the biological characteristics of anchovy at the two fishing conditions of 1) the minimum length allowed to catch and 2) the maximum length allowed to catch.

Yield-per-recruit analysis of chub mackerel

In Chapter 3, I evaluated the yield-per-recruit of chub mackerel. Growth rate of fish is the most high in early life stage and is affected by changes in water temperature. Thus, I applied a simulation-based yield-per-recruit model that considered 1) temperature-dependent growth in early life stage, 2) size-dependent mortality. I evaluated fisheries yield with respect to varying biological reference points and environmental conditions, including 1) the instantaneous fishing mortality (F), 2) the length at first capture (L_c), and 3) water temperature.

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Chapter 1

Long-term changes in dominant fish species and relationship with climate change in the Korea Strait from 1986 to 2010

Abstract

I evaluated the spatio-temporal changes in fish assemblages, and its relationship with oceanic conditions in the Korea Strait (KS, 126°-129°5'E, 33°5'-35°N) from 1986 to 2010. I used the inflow indices of the Korea Strait Bottom Cold Water (KSBCW) and the Tsushima Warm Current (TWC), water temperature and salinity data from 1986 to 2010. Correspondence analysis (CA) detected a shift in the fish assemblage between 1990 and 1991. Sardine and filefish were dominant species from 1986 to 1990, and thereafter chub mackerel and squid became dominant. Surface temperatures at 0-20 m depths, especially with a time lag of 1 yr, were significantly correlated with the 1990-1991 shift in fish assemblage structure. I hope that further multidisciplinary studies between regional oceanographers and fisheries scientists will contribute to development of fisheries policies by understanding interactions between oceanographic processes and fishes at the regional scale in adaptation to climate change.

Key words: correspondence analysis; canonical correspondence analysis; climate change; fish assemblage; regime shift

Introduction

Climate change and regime shift in the North Pacific

A regime shift is a large, decadal-scale switch in the structure of the marine ecosystem, which is associated with changes in the climate systems (Beaugrand, 2004; Reid et al., 2001; Rodionov and Overland, 2005). In the North Pacific, climate regime shifts were reported to have occurred in 1976/1977, 1988/1989 and 1998/1999 (Hare and Mantua, 2000; Minobe, 2000; Overland et al., 2008; Watanabe et al., 2005). Among various climate indices, the Pacific Decadal Oscillation and the Artic Oscillation were particularly related with the shifts (Chiba et al., 2006; Mantua et al., 1997; Rodionov and Overland, 2005).

Impacts of climate change on marine fishes

Climate change affects the biology, recruitment, spatial distribution, migration and human exploitation of marine fishes (Drinkwater, 2005; Kell et al., 2005; Lehodey et al., 2006). Many small pelagic species such as sardine (*Sardinops sagax*), anchovy (*Engraulis japonicus*) and chub mackerel (*Scomber japonicus*) have a direct relationship with climate regime shift (Gong et al., 2007; Gong et al., 2010; Reid et al., 2001). These environmental changes also effect on distribution and abundance of demersal species inhabiting deep waters of more than 200 m such as Pacific cod (*Gadus macrocephalus*) and flathead flounder (*Hippoglossoides dubius*) (Perry et al., 2005; Tian et al., 2011; Tu et al., 2015). Among these, demersal or less mobile species are more vulnerable to changes in the marine environment than short-live pelagic and cephalopods, because 1) they have been adapted to relatively stable environment, and 2) have limitation in migration to suitable habitat for growth and spawning (Yatsu et al., 2013).

Korea Strait (KS)

The Korea Strait (KS) is located southward of Korea, and connects the East China Sea and the East Sea. The KS is approximately 280-km length and 200-km wide with depths up to 150 m (Cho and Kim, 1999; Yi, 1966).

The major currents in the KS

The Tsushima Warm Current (TWC) and the Korea Strait Bottom Cold Water (KSBCW) are major currents in the KS (Na et al., 2010). The TWC, a branch of the Kuroshio, flows northeastward from west of Kyushu into the southern portion of the East Sea through the upper layer, and the KSBCW flows southwestward from the East Sea into the KS through the bottom layer (Na et al., 2010; Yi, 1996).

The Tsushima Warm Current (TWC)

The TWC transports high-temperature water and fish larvae from the East China Sea into the East Sea through the KS (Beardsley et al., 1985; Hsueh et al., 1996; Isobe, 1999; Isobe et al., 1994; Lie and Cho, 1994; Lim and Chang, 1969; Na et al., 2010; Yi, 1966). The TWC is divided into two branches at the KS, one branch flows to the East Sea and another branch flows to the Japanese northern coast (Cho and Kim, 1999). Surface-current speed of the TWC exceeds 80 cm s^{-1} near the Korean coast and 40 cm s^{-1} near the Japanese coast, and the total volume transport is high in summer and autumn and low in winter and spring (Isobe et al., 1994).

The Korea Strait Bottom Cold Water (KSBCW)

The Korea Strait Bottom Cold Water originated from the deeper East Sea (Cho and Kim, 1998; Na et al., 2010; Sudo, 1986). It flows near the shallow within 50 km and shows seasonal variations in the volume transport (Cho and Kim, 1998). Its temperatures are below 10℃ and salinities range from 34.0-34.4 (Lim and Chang, 1969; Na et al., 2010). The cold water of the KSBCW appears in the KS from Jun to February and the bottom temperature becomes lowest in August (Lim and Chang, 1969).

Ecology in the KS

Primary productivity and phytoplankton

In the KS, the nutrients for phytoplankton are supplied from the bottom layer to the mixed layer by physical processes such as the TWC in spring and typhoon in summer and autumn (Chang et al., 1996; Gong et al., 1996; Jang et al., 2013; Shiah et al., 2000). Primary productivity in the western channel of the KS is higher in spring (3.42-6.68 mg C m^{-3} h^{-1}) and autumn (9.24-13.05 mg C m^{-3} h^{-1}) than in summer (0.57-0.79 mg C m^{-3} h^{-1}) and winter (0.75-1.77 mg C m^{-3} h^{-1}) (Chin and Hong, 1985). The annual phytoplankton species composition depends on thermohaline structures which is largely divided into mixed periods (December-May) and stratified periods (Jun-November). Diatoms dominate during the mixed periods while nanoplankton group dominate during the stratified periods (Shon et al., 2008).

Zooplankton

Zooplankton transfer energy between producer and consumer in the ocean (Jang et al., 2012). In the KS, the species diversity of zooplankton increased from spring to autumn and decreased from autumn to winter (Moon et al., 2010). Copepods are the most abundant, but their dominance tend to decrease with increasing abundance of salps (Jang et al., 2012; Kang et al., 2019), which compete for phytoplankton food with copepods and fish larvae (Kang et al., 2000; Kashkina, 1986).

Fish

Small pelagic fish species such as anchovy, Pacific sardine, chub mackerel and common squid dominate the fisheries catches from the KS (Kim and Kang, 2000). Many small pelagic fish use the KS as a migration route between the East China Sea and the East Sea as well as spawning and nursery grounds (Kim, 2003). In addition, filefish (*Thamnaconus modestus*), hairtail (*Trichiurus lepturus*), Pacific cod and yellow croaker (*Larimichthys polyactis*) are major demersal fishes harvested in the KS (Jung et al., 2013c; Chung et al., 2013). The changes in the distribution and catch of fish in the KS were mostly explained by variation of surface and bottom water temperature in relation with the regime shifts in the North Pacific (Beamish, 2008; Jung et al., 2013c).

Past studies on impact of climate change and regime shift of commercial fish assemblage in Korean waters

Past studies evaluated and related long-term changes in the composition and distribution of fisheries species in the adjacent seas of Korea with climate change. Kim and Kang (2000) documented the change in the physical environments during the past 30 years in the KS and its impact on the low and high trophic levels. Gong et al. (2007) and Kim et al. (2007) studied the relationship between climate/environmental variables such as climate regime shift, El Niño and responses of major fisheries species in the adjacent seas of Korea. Jung et al. (2013c) reported latitudinal shifts of major fisheries species in relation to fluctuations of water temperature, salinity and dissolved oxygen in Korean Waters. Hwang and Jung (2012), Jung et al. (2013b) and Jung (2014) evaluated multi-decadal changes in composition of major fisheries species in relation to fluctuations of ocean environmental factors in the adjacent seas of Korea.

Problems

Despite the KS showed highest fisheries production compared with the adjacent seas of Korea from late 2000s, studies on changes in fish community of pelagic and demersal fisheries species related with climate change are in shortage. Most of the studies regarding fish assemblage have been conducted in the inshore waters of the KS without utilization of the data of commercial fisheries catch from the offshore waters (Cha et al., 2007; Huh and Kwak, 1998; Jeong et al., 2013; Kim et al., 2000; Kim et al., 2003a, Kim et al., 2003b; Kim and Gwak, 2006; Kwak et al., 2008). In addition, studies on regional changes of fish assemblages were conducted in the adjacent seas of Korea, but regional comparisons of the changes have not yet conducted.

Goal and objectives

I evaluated the long-term shifts of fish assemblage structure in relation with changes in oceanic conditions in the KS driven by the regime shifts in the North Pacific to provide scientific basis in developing fisheries policies for adaptation to climate change and global warming. For this purpose, I also evaluated changes and shifts in the oceanography and fisheries assemblages of the KS to be compared with the other adjacent seas of Korea.

Data and methods

Hydrographic data

To evaluate annual changes in oceanic conditions in the KS (126°-129°5'E, 33°5'-35°N), I used the inflow indices of the TWC and the KSBCW, water temperature and salinity data from 1986 to 2010 (Fig. 1-1). I utilized the data of the inflow index values of the TWC and KSBCW provide by Na et al. (2010), and the data of water temperature and salinity provided by the Korea Oceanographic Data Center (KODC, http://www.nifs.go.kr/kodc/soo_list.kodc) that has compiled the survey data from the bimonthly cruises conducted by the National Institute of Fisheries Science (NIFS).

The KODC line 208 was selected to evaluate the annual changes of water temperature and salinity at the depths ranging from 0 to 125 m in the KS, because the inflow indices of the TWC and the KSBCW were also calculated based on the data from the line

208 (Jung et al., 2013b; Na et al., 2010). I excluded the December data for all years to avoid unbiased evaluation, because the cruise survey was not conducted in December of 1991 and 1992.

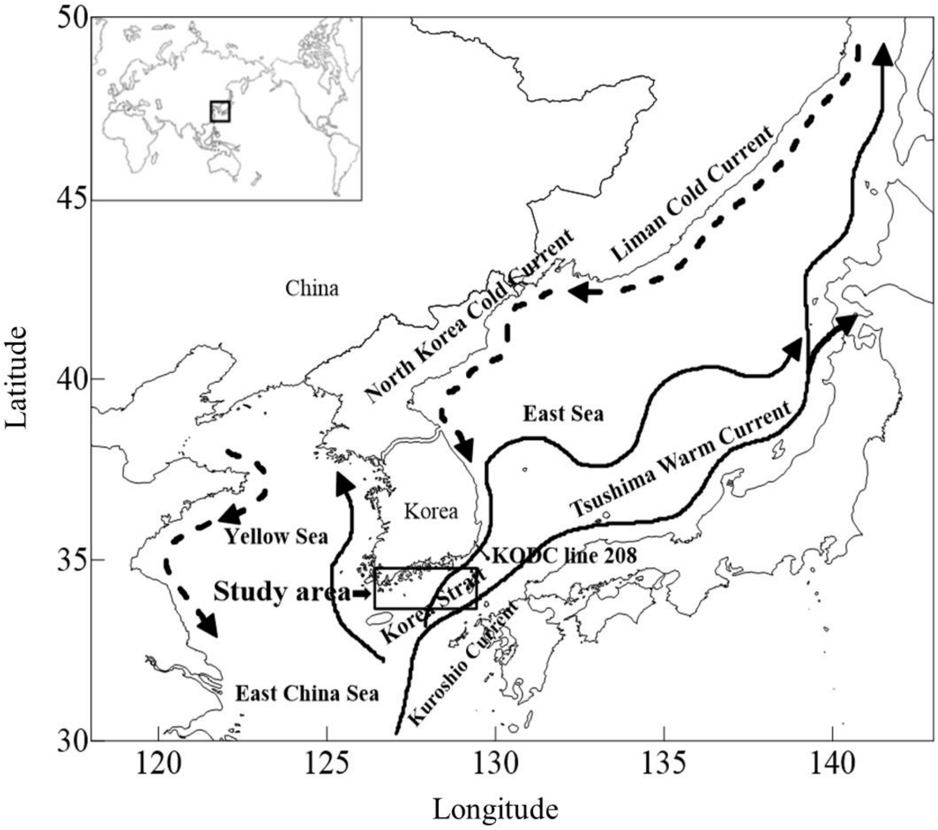

Fig. 1-1. The study area and its major currents (dotted line: cold current, solid line: warm current).

Fisheries data

To evaluate long-term changes in fish assemblages in the KS, I used monthly commercial fisheries catch data from 1986 to 2010 provided by NIFS. The data composed 1) year, 2) month, 3) fishing location (fishing block with latitude and longitude) and 4) catch (kg in wet weight). I evaluated the spatial and temporal variations of fish assemblage structure based on the biomass composition of catch by fish species. I aggregated the monthly catch data to bimonthly data to be compatible with the bimonthly KODC data.

Analyses

Detection of oceanic regime shift in the KS

To detect temporal shifts in the oceanic conditions of the KS, I applied a sequential t-test of regime shift (STARS) developed by Rodionov (2004) to the annual time series of the depth-specific water temperature and salinity and the inflow indices of the two major currents. A regime shift in STARS was defined by the following three criteria: 1) significance level, 2) cut-off length (L) and 3) Huber's weight parameter (H). Significance level is the probability of Type I error. Cut-off length (L) is the minimum time length of the regimes and Huber's weight parameter (H) acts as controlling the weighting value assigned to the outliers. More detailed descriptions are explained at www.beringclimate.noaa.gov (Keevallik, 2011; Rodionov, 2006). To detect at least one shift of all oceanic conditions and consider all outliers, I set significance level=0.3 and H=1. I set L=7.5 because the velocity and discharge of the Kuroshio Current showed long-term cycle of 6-9 years (Gong et al., 2010; Miita and Tawara, 1984).

Changes in fish assemblages and its relationship with oceanic conditions

Commercial fisheries catch data comprised a total of 137 fish species. I selected the top-10 dominant species in total catch which occupied more than 1% in the total catch from 1986 to 2010. I aggregated the remaining species into a single category (’others’) to summarize annual, monthly and spatial changes of the dominant fish species in the KS.

To evaluate spatio-temporal changes of the fish-assemblage structure in the KS by three categorical variables 1) year, 2) month, and 3) fishing block, I graphically summarized the species compositions in biomass of the commercial fisheries catch data by correspondence analysis (CA) from 1986 to 2010 (Hwang and Jung, 2012; Ter Braak, 1986).

I calculated the correlation coefficients between the averaged environmental factors using the water column at each station and the sum of total catch for bimonthly in each year from 1986 to 2010 in the KS. Then, I selected the two stations where the correlation coefficient was the most significant for water temperature and salinity. Additionally, I calculated the cross-correlation coefficients with the time lags of 1 and 2 years for each station to evaluate possible delayed effects of the environmental variables on the fish assemblage structure.

I correlated the first and second dimensions extracted from our CA with the environmental variables (annually averaged depth-specific water temperature and salinity at the selected two stations and the annual inflow of the TWC and the KSBCW) to apply canonical correspondence analysis (CCA) (Ter Braak, 1986). I selected the environmental variables whose correlation coefficient was significant with respect to the first or the second dimension to be shown in the CCA graphics. The CA and CCA were run by the “vegan” package in the R software (3.6.3) (Oksanen, 2018).

Results and discussion

Temporal variability and spatial distribution of fish assemblage structure

Annual change

My CA showed that fish assemblage in the KS dramatically shifted in 1990-1991, and thereafter it was stabilized from 1993 to 2010 (Fig. 1-2). The variability of species biomass composition in fish assemblage during 1986-2010 was mostly explained by two dimensions (44.19% and 21.93%).

From 1986 to 1990, anchovy (36.62%) was the most dominant, followed by sardine (17.67%), filefish (16.04%), chub mackerel (11.24%) and hairtail (5.65%) (Fig. 1-3, a). The dominant fish species from 1991 to 2010 were anchovy (55.8%), chub mackerel (10.53%), squid (7.61%) and hairtail (6.3%) (Fig. 1-3, a).

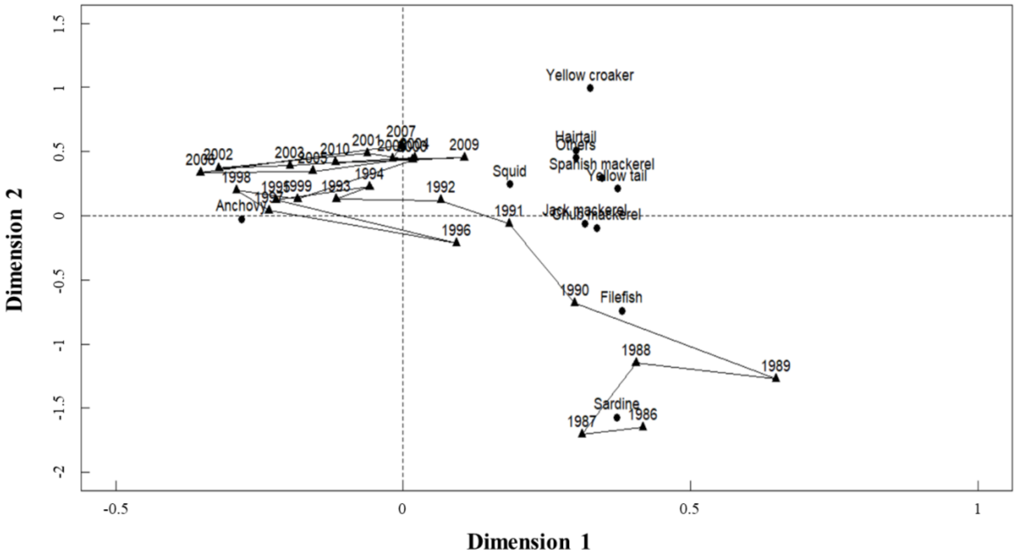

Fig. 1-2. Correspondence analysis of biomass composition of the dominant 11 species from fisheries catches in the Korea Strait (126°-129°5'E, 33°5'-35°N) with respect to species and year from 1986 to 2010. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

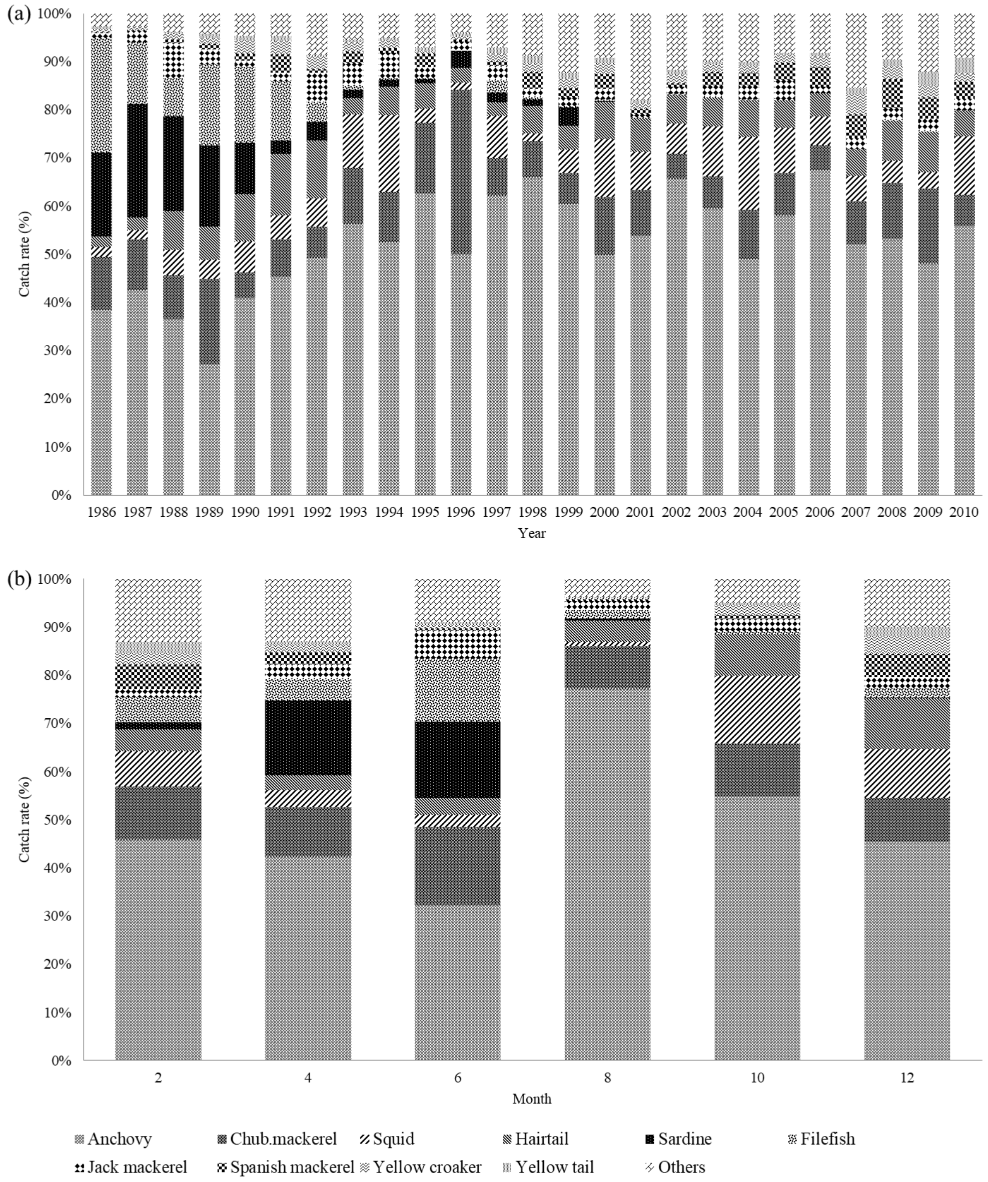

Fig. 1-3. Species composition in biomass of the fisheries catches in the Korea Strait (126°-129°5'E, 33°5'-35°N) from 1986 to 2010 by (a) year and (b) month. The data were provided by National Institute of Fisheries Science (NIFS).

Monthly change

My CA divided the monthly compositions of species biomass into three seasonal groups; 1) Spring (from April to Jun), 2) Summer (August) and 3) Autumn-Winter (from October to February) (Fig. 1-4). The dominant species were anchovy (37.26%), sardine (15.68%), chub mackerel (13.39%) and filefish (8.78%) in spring; anchovy (77.26%) and chub mackerel (8.81%) in summer; anchovy (48.71%), squid (10.53%), chub mackerel (10.38%) and hairtail (7.86%) in autumn-winter (Fig. 1-3, b). Anchovy, sardine, squid and filefish particularly showed greater seasonal variability.

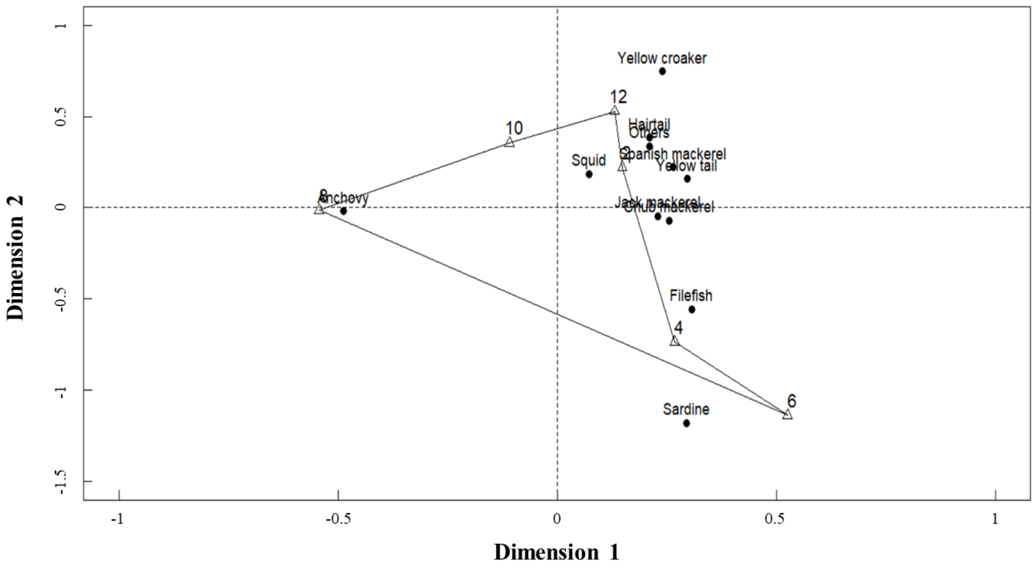

Fig. 1-4. Correspondence analysis of biomass composition of the dominant 11 species from fisheries catches in the Korea Strait (126°-129°5'E, 33°5'-35°N) with respect to species and bi-month from February to December. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

Spatial distribution in fish assemblage

I could the entire study area into 4 Areas based on the similarity in species composition summarized by my CA (Fig. 1-5). Anchovy mainly distributed in Area I. Yellow croaker mainly distributed in Area II. Squid, jack mackerel and Spanish mackerel mainly distributed in Area III. Sardine and filefish mainly distributed in Area IV. Chub mackerel mainly distributed in Area III and IV, and hairtail mainly distributed in Area II and III (Fig. 1-6).

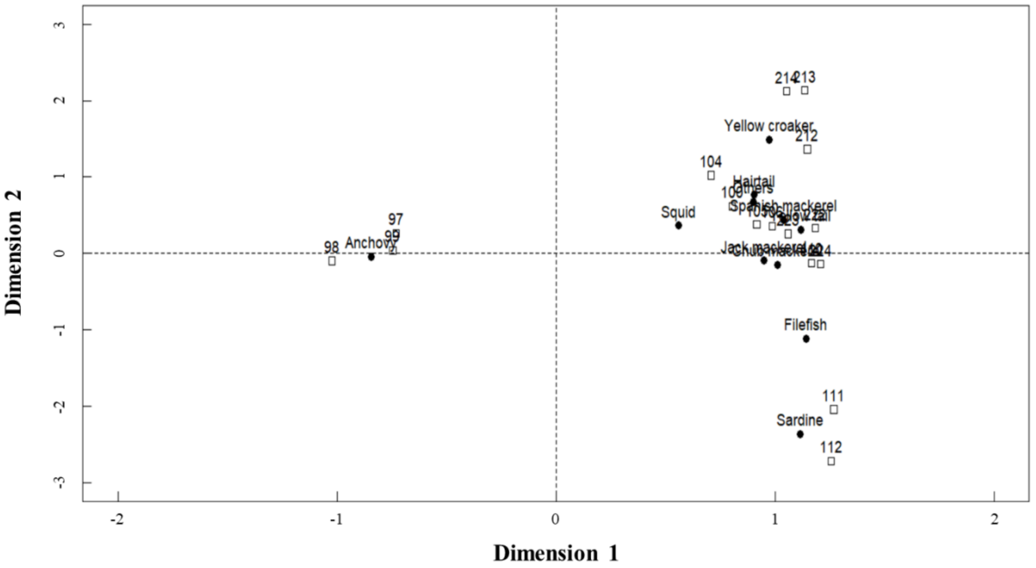

Fig. 1-5. Correspondence analysis of biomass composition of the dominant 11 species from fisheries catches in the Korea Strait (126°-129°5'E, 33°5'-35°N) with respect to species and fishing block. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

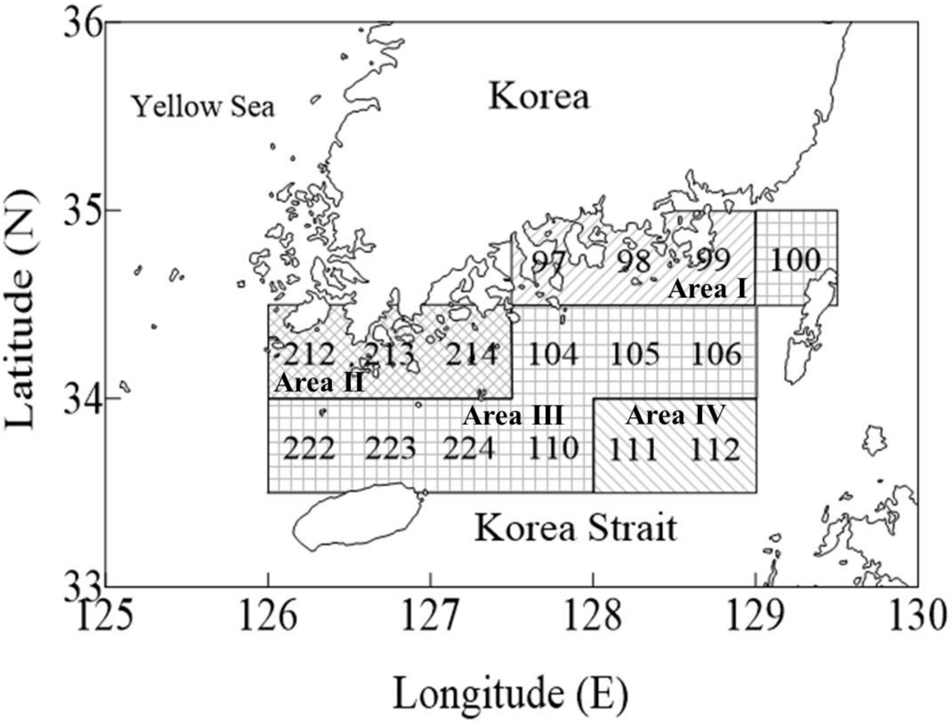

Fig. 1-6. Classification of fishing blocks based on correspondence analysis of biomass composition of the dominant 10 species from fisheries catches in the Korea Strait (126°-129°5'E, 33°5'-35°N) from 1986 to 2010.

Grouping of species based on spatio-temperal variability

Sardine and filefish which dominate in spring were sharply decreased after the early-1990, and mainly distributed far away from the coast. Anchovy was mostly caught in summer in near the Southeast coast of Korea, and the annual catch of anchovy steadily increased from 1986 to 2010. Squid and hairtail dominated in autumn-winter. Squid showed high variability in annual catch compare with other species, and hairtail dramatically decreased in 1993 and then steadily increased to 2010. The two species mainly distributed from the Northern part of Jeju Island to the Southeast sea of Korea. Chub mackerel that was constant of annual and seasonal catch from 1986 to 2010, mainly distributed along with sardine, filefish, squid and haritail (Fig. 1-6). Yellow croaker, jack mackerel and Spanish mackerel showed less than 5% in total catch by season.

Impact of oceanic condition on the fish assemblage

The relationship between changes in oceanic conditions and fish assemblages

As a result of cross-correlation between changes in oceanic conditions and fish assemblages, water temperature of 208-4 station and salinity of 208-1 station showed the highest correlation with total catch. However, we applied salinity data at 208-4 station because 208-1 station is shallower than other stations and the difference in correlation coefficient was small between stations (Table 1-1).

Table 1-1. Correlation coefficient of the monthly water temperature and salinity, averaged over the water column up to 120-m depth at the stations along the KODC 208 line with respect to the bimonthly total catch in the Korea Strait from 1986 to 2010. The values in underline demote $p<0.05$.

Station	208-1	208-2	208-3	208-4
Water temperature	<u>0.259</u>	0.157	<u>0.182</u>	<u>0.307</u>
Salinity	<u>-0.419</u>	<u>-0.397</u>	<u>-0.397</u>	<u>-0.397</u>

I conducted cross-correlation and CCA to evaluate the relationship between the oceanic conditions and fish assemblages. Annually-averaged index of KSBCW, surface water temperature at 0-20 m and bottom salinity at 125 m were significantly correlated with first dimension (Table 1-2 and Fig. 1-7~10). KSBCW and surface water temperature showed negative correlation with first dimension while bottom salinity showed positive correlation. Among the significant oceanic conditions, the correlation of water temperature at 10 m depth showed highest value, followed by KSBCW and salinity at 125 m.

Table 1-2. Correlation coefficients between the first dimension from correspondence analysis and the environmental variables with time lags of 0-2 yr. The coefficients in underline denote $p<0.05$ (TWC: Inflow index of Tsushima Warm Current, KSBCW: Inflow index of Korea Strait Bottom Cold Water, T: water temperature, S: salinity, 0-125: depth in meter)

	Lag0	Lag1	Lag2
	Dimension 1	Dimension 1	Dimension 1
TWC	0.079	0.274	0.286
KSBCW	-0.422	-0.471	-0.507
T0	-0.408	-0.519	-0.504
T10	-0.465	-0.502	-0.422
T20	-0.399	-0.416	-0.208
T30	-0.278	-0.29	-0.094
T50	-0.014	-0.041	-0.009
T75	0.033	-0.022	0.035
T100	0.064	0.106	0.231
T125	0.309	0.216	0.222
S0	0.258	0.247	0.186
S10	0.341	0.309	0.263
S20	0.383	0.31	0.174
S30	0.195	0.3	0.207
S50	0.154	0.295	0.161
S75	0.303	0.248	0.043
S100	-0.054	-0.047	-0.154
S125	0.41	0.35	0.192

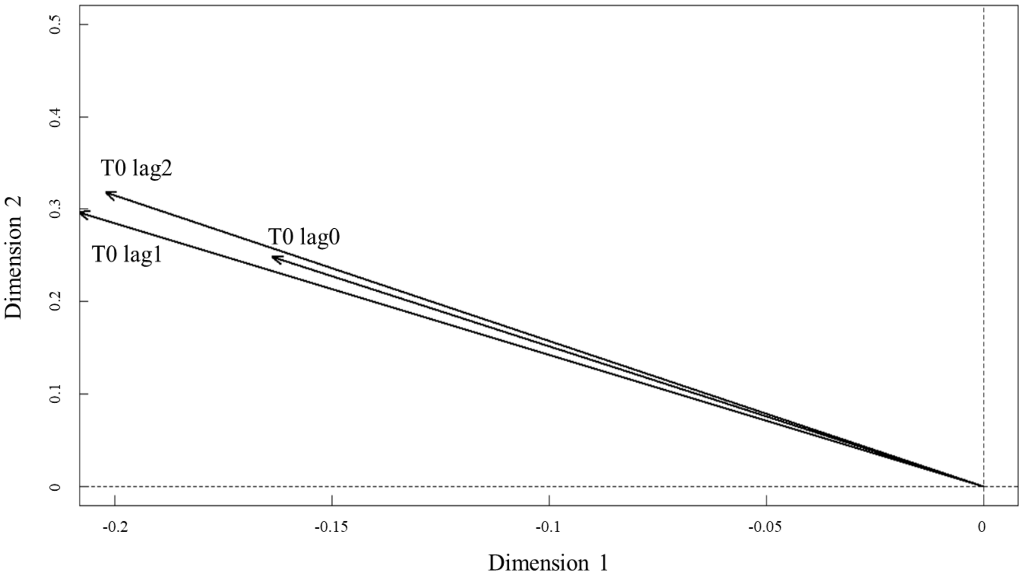

Fig. 1-7. Canonical correspondence analysis on annual fish assemblage in the Korea Strait and water temperature at 0 m depth with time lags of 0-2 yr. Oceanic conditions that were not significantly correlated at 95% confidence interval are omitted. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

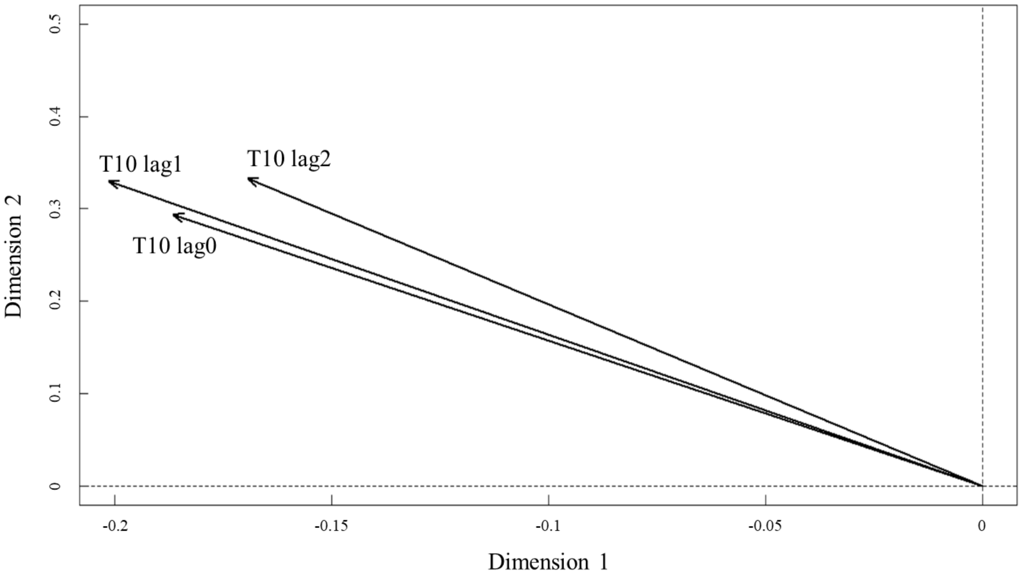

Fig. 1-8. Canonical correspondence analysis on annual fish assemblage in the Korea Strait and water temperature at 10 m with time lags of 0-2 yr. Oceanic conditions that were not significantly correlated at 95% confidence interval are omitted. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

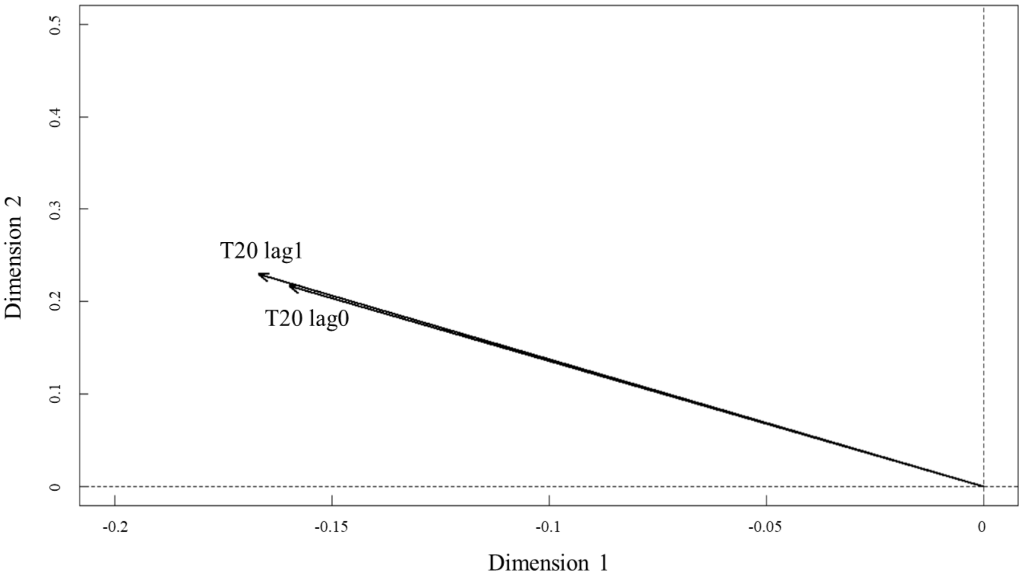

Fig. 1-9. Canonical correspondence analysis on annual fish assemblage in the Korea Strait and water temperature at 20 m depth with time lags of 0-2 yr. Oceanic conditions that were not significantly correlated at 95% confidence interval are omitted. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

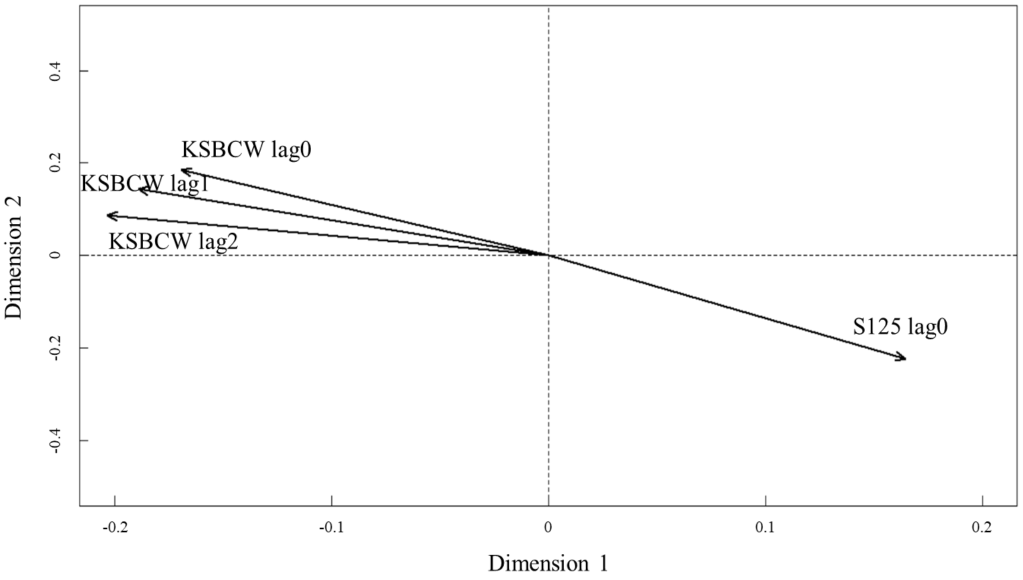

Fig. 1-10. Canonical correspondence analysis on annual fish assemblage in the Korea Strait and the inflow index of KSBCW and bottom salinity at 125-m depth with time lags of 0-2 yr. Oceanic conditions that were not significantly correlated at 95% confidence interval are omitted. Fig. 1-2, 1-4~5 and 1-7~10 can be overlapped for graphical interpretation.

Relationship between changes in oceanic conditions and fish assemblage structure with varying time lags

Cross-correlation and CCA showed the influences of changing oceanic conditions on fish assemblage structure varied by time lags. Fluctuations of the KSBCW before 2 years and surface water temperature before 1 year showed the most significant correlation with annual changes in fish assemblages (Table 1-2, Fig. 1-7~10). Salinity showed the most significant correlation with fish assemblages at the same time (time lag0) (Table 1-2, Fig. 1-10).

Cause of the most significant correlation between catch by fish species and one-year delayed surface water temperature

Correlation coefficients between annual catch of the dominant species with the annual-averaged surface water temperatures at 0-20 water depths were the most significant at a time lag of 1 yr. This can be explained by the three factors: 1) The mean age at first catch was 1 yr, 2) the fish species spend their early-life stages (egg and larval stages) in the surface layer of the KS (Choi et al., 2004; Hwang et al., 2006; Jung, 2008a; Jung et al., 2013a; Kramer, 1960; Lee et al., 2013; Sassa and Konishi, 2006; Zhang, 1996; Zhang and Lee, 2001), and 3) variability in temperature-dependent growth and mortality during the early-life stages is critical in determining the subsequent recruitment levels (Go et al., 2020; Houde, 1989; Jung et al., 2008).

Hydrography

I selected only the environmental factors that showed significant correlations with the two dimensions of our CA to evaluate long-term changes in oceanic conditions and their influences on the fish assemblage structure in the KS.

Annual inflow index of the KSBCW showed three regime shifts during 1986-2010 (Fig. 1-11). The inflow index of the KSBCW showed decreasing shift in 1986-1987 and maintained low values form 1987 to 1992. A shift to higher value was detected in 1993 and decreased again in 2001.

Water temperatures at 0-20 m depths steadily increased from 1986 to 2010 with a increasing shift in 1986-1987 and were particularly high in 1990 (Fig. 1-12), which was also reported in the past studies (Hwang and Jung, 2012; Jung, 2008b; Jung et al., 2013c). Additional increasing shift was detected at 0 and 10 m depths in 1996 and 1997. We speculate that the unexpected increase in water temperatures at 0 and 10 m depths in 1990 was the start of the warming trend of the surface layer in the KS.

Salinity at 125 m depth showed a decreasing shift in 1998 (Fig. 1-13). The KSBCW showed an increasing shift in the 1992-1993 with an increasing trend from 1989 to 1996.

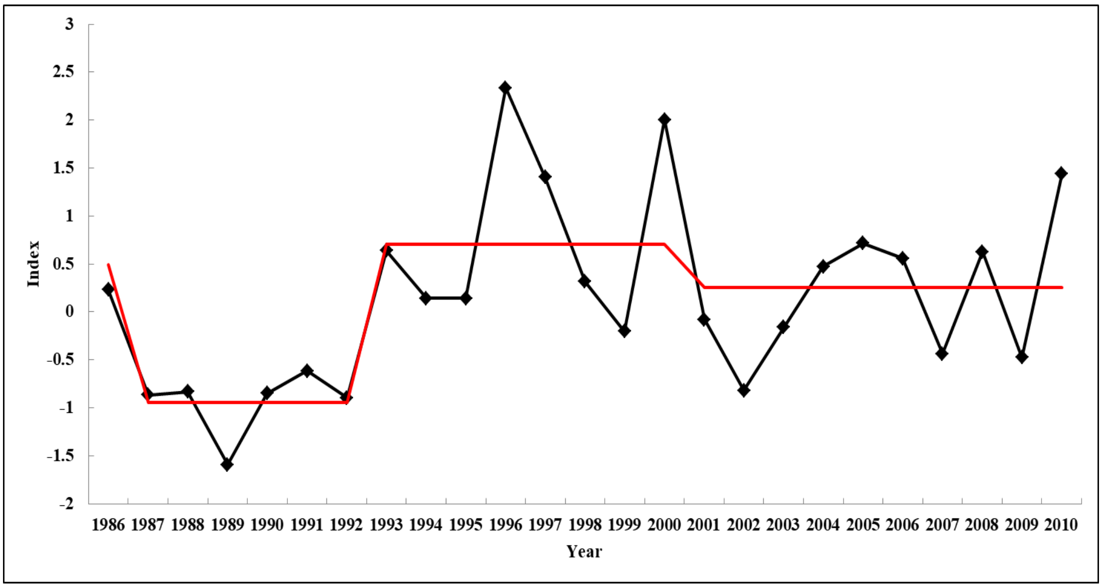

Fig. 1-11. Annual inflow index of the Korea Strait Bottom Cold Water estimated in the KODC line 208 from 1986 to 2010 (black line). The red line represents the step changes detected.

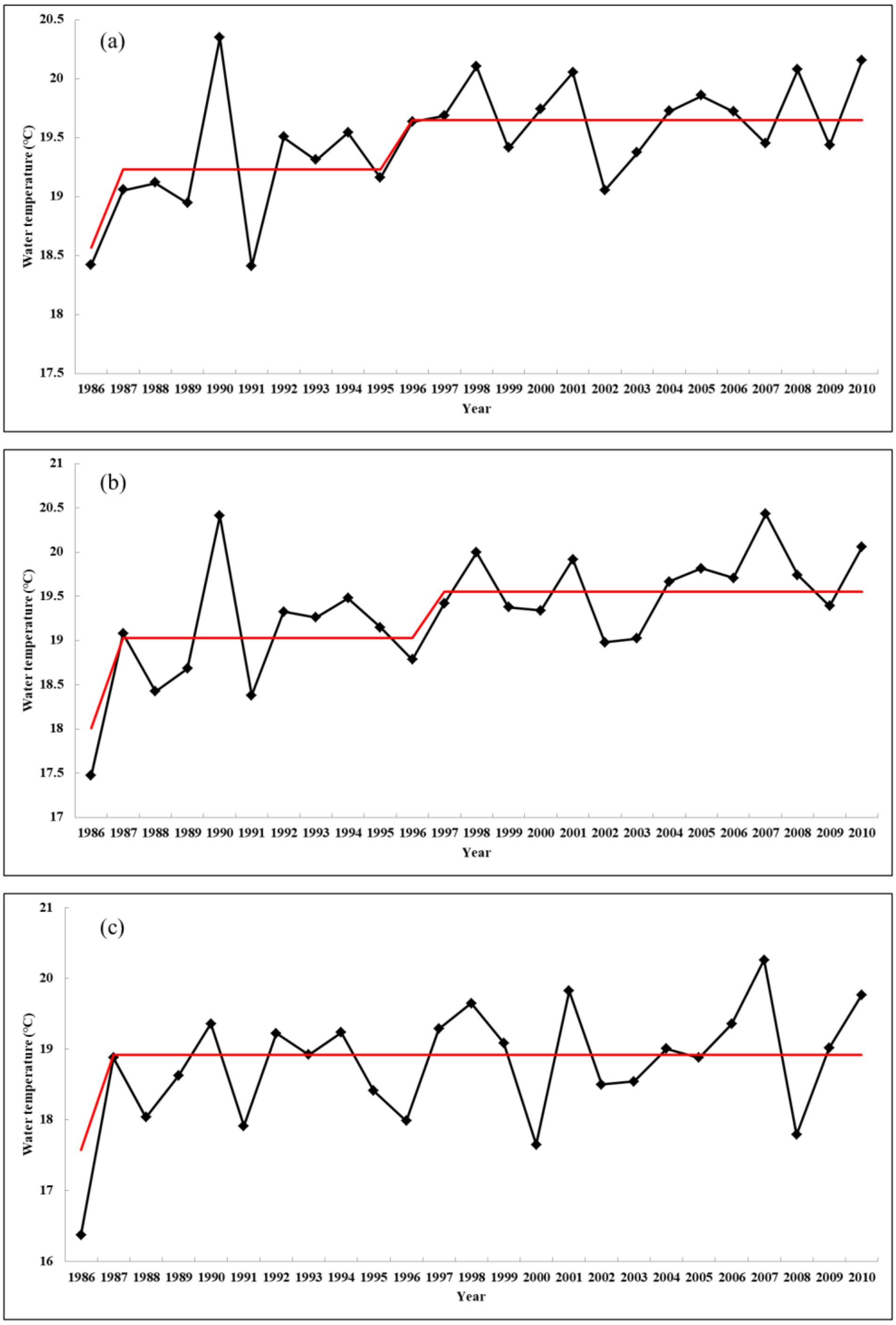

Fig. 1-12. Annually-averaged water temperature at (a) 0, (b) 10 and (c) 20 m depths in the Korea Strait from 1986 to 2010. The red line represents the step changes detected.

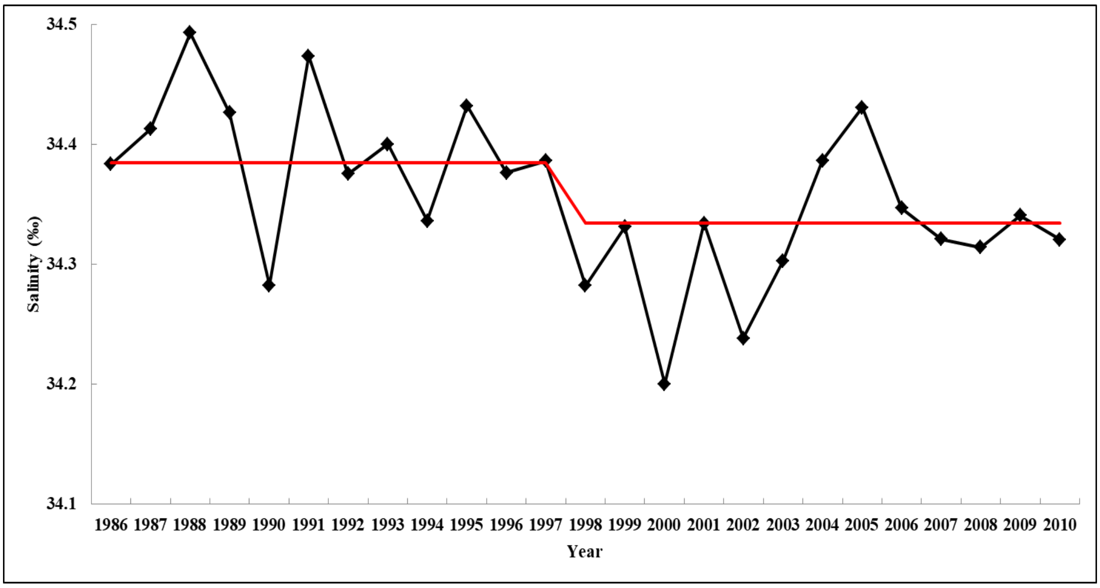

Fig. 1-13. Annually-averaged salinity at 125-m depth in the Korea Strait from 1986 to 2010. The red line represents the step changes detected.

Changes in oceanic conditions and fish assemblages in the late-1980s

Thus, I speculated that the 1990-1991 shift of fish assemblage structure in the KS was triggered by the 1986-1987 shift in surface water temperature. The subsequent shift in the 1992-1993 shift in the KSBCW was followed by the 1997-1998 shift in bottom layer salinity. On the other hand, Jung (2014) and Na et al. (2010) reported that the shift of the dominant species in the southwestern East Sea in the late-1980s were influenced by the cooling of the bottom water and the warming of the surface water caused by the extending the KSBCW. The relationships between the oceanic conditions of surface and bottom layer in the KS related with the TWC and KSBCW require further oceanographic studies.

Correlation between environmental fluctuations by depth and fish species

After selecting the time lag with which the correlation was the most significant, we conducted cross-correlation analyses between the environment variables and annual catches of the dominant fish species.

Annual catch of anchovy in the KS was positively correlated with the inflow index of the KSBCW and water temperature at 0-10 m depths, and negatively correlated with salinity at 125 m depth. Catch of sardine was negatively correlated with water temperature at 0-10 m depths, and positively with salinity at 125 m depth (Table 1-3). Catches of anchovy and sardine showed an opposite trend with respect to changes in water temperature, salinity and KSBCW. Annual catches of hairtail, Spanish mackerel and yellowtail were positively correlated with surface water temperatures at 0-20 m depths. Catches of filefish were negatively correlated with water temperatures at 0-10 m depths. Catches of yellow croaker were positively correlated with water temperature at 0-10 m depths while they showed negative correlations with salinity at 125 m depth. Chub mackerel, squid and jack mackerel did not show significant correlations with water temperature and salinity (Table 1-3).

Table 1-3. Cross-correlation coefficients of the annual catch of fish species in the Korea Strait with the inflow index of the Korea Strait Bottom Cold Water (KSBCW), depth-specific water temperature (T) and salinity (S) at the KODC 208-4 station from 1986 to 2010. The coefficients of underline denote $p<0.05$, and the number in parenthesis denote the time lag in year. The digits 0-125 denote depth in meter.

	Anchovy	Chub mackerel	Squid	Hairtail	Sardine	Filefish	Jack mackerel	Spanish mackerel	Yellow croaker	Yellowtail
KSBCW (2)	0.475	-0.108	-0.254	-0.318	-0.166	-0.301	-0.361	0.161	0.042	0.281
T0 (1)	0.484	-0.087	0.093	0.258	-0.609	-0.448	-0.234	0.441	0.409	0.408
T10 (1)	0.496	-0.039	0.099	0.426	-0.694	-0.51	-0.108	0.65	0.532	0.39
T20 (1)	0.317	-0.155	0.112	0.203	-0.501	-0.336	0.017	0.499	0.395	0.203
S125 (0)	-0.522	0.076	-0.281	-0.23	0.413	0.325	0.346	-0.276	-0.435	-0.382

Comparison of annual changes in dominant fish species in the KS with other seas, the East Sea and the Northern East China Sea

I compared dominant fish species in the KS with past studies in the adjacent seas of Korea from 1980s to 2010. I could identify two groups of representative fish species in the adjacent seas of Korea from the Northern East China Sea to the East Sea: Sardine and filefish from the 1980s to the early-1990s, and chub mackerel, yellow croaker and horse mackerel from the early-1990s to 2010.

Dominant species before and after regime shifts in the early-1990s in the adjacent seas of Korea

Fish assemblage structure in the adjacent seas of Korea including the KS showed that dominant fish species dramatically shifted in the early-1990s. Table 1-4 shows the starting year of the shift in fish community structure by region from the east to west in the Korean waters, proposed by the past and the present studies with respect to the 1988-1991 regime shift (Hwang and Jung, 2012; Jung et al., 2013b; Jung, 2014). The regional comparisons indicate that the southwestern East Sea showed the earliest response to the regime shift, followed by the KS, the waters off Jeju Island and the waters of Ieodo. Detailed mechanisms explaining these delayed responses from the east to the west need further studies.

Table 1-4. Reported start year of shift in fish assemblage structure by region in the Korean waters from 1986 to 2010

Region	East Sea	Korea Strait	Waters off Jeju Islnad	Waters off Ieodo
Shift year	1988	1990	1990	1991

Limitations and problems

Among 85 stations in the KS, I selected environmental data at the single 208-4 station to evaluate the annual changes of water temperature and salinity. More comprehensive methods of evaluating the spatio-temporal variability of the oceanographic conditions to represent the whole area of the KS are needed.

Climate regime shift was reported to occur three times in the North Pacific during the 1970s-1990s (Hare and Mantua, 2000; Watanabe et al., 2005). Fish assemblage in the KS was markedly changed corresponding to the increase in KSBCW and surface water temperature in the late-1980s, but did not show a significant response to the regime shift in the late-1990s. To specifically evaluate the impact of climate change in the late-1990 to the marine ecosystems of the Korean adjacent seas, more comprehensive researches covering all of the components from primary producers to high trophic levels are required.

Further Studies

Several studies on long-term spatio-temporal changes in dominant fish species were conducted at regional scale in the Korean waters, but the Yellow Sea has received less attention (Hwang and Jung, 2012; Jung et al., 2013b; Jung, 2014). For sustainable fisheries management in Korea, further researches need to cover the Yellow Sea to synthesize the regional studies on spatio-temporal variability in fish assemblage structure and its response to the climate regime shift.

The 1992-1993 shift in the inflow index of the KSBCW was preceded by the 1990-1991 shift in fish assemblages and the 1986-1987 shift in the surface water temperature. I hope that regional physical oceanographers will study and explain the time-lagged interactions between the surface temperatures and the KSBCW, which were not detailed in my present study. Multidisciplinary co-works between oceanographers and fisheries scientists will contribute to understanding of bio-physical interactions at the regional scale in response to climate change in the Korean waters.

Conclusion

I showed that the fish assemblage structure of the KS was shifted in 1990-1991, driven by 1988-1989 regime shift in the North Pacific, which could have corresponded to the 1986-1987 shift in the surface water temperatures detected in my study. Comparisons of my results with the past regional studies in the Korean waters suggested that the KS is an intermediate area between the waters of Ieodo and the East Sea with respect to the timing of shift in fish assemblage structure (Table 1-4). The regional shifts were characterized by the replacement of dominant fish species from sardine and filefish to chub mackerel and squid.

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Chapter 2

Simulation-based Yield-per-recruit Analysis of Pacific Anchovy *Engraulis japonicus* in the Korea Strait

Abstract

Pacific anchovy *Engraulis japonicus* is one of the most commercially important species in the Korea Strait. I developed and applied a daily simulation-based yield-per-recruit model of anchovy that considered 1) temperature-dependent growth, and 2) size-dependent mortality, including the life cycle from egg to adult stages. I estimated fisheries yield and egg production with respect to varying biological reference points of 1) the instantaneous fishing mortality, and 2) the length at first capture in fork length (L_c) with the two alternative fisheries regulation scenarios 1) a minimum $L_{c,min}$ to protect larval and juvenile anchovy, 2) a maximum $L_{c,max}$ to protect adult anchovy. Results showed that fisheries yield could be maximized when the minimum $L_{c,min}$ ranges between 42-60 mm (annual catch = ca. 1.2 million tons) and the maximum $L_{c,max}$ > 88 mm (annual catch = ca. 0.8 million tons). The study results suggest that to protecting small size population is more efficient than to protecting big size population for fishery management.

Key words: Pacific anchovy, *Engraulis japonicus*, Yield-per-recruit analysis, Stock assessment

Introduction

Anchovy

Pacific anchovy *Engraulis japonicus* is a warm water small pelagic fish geographically widespread in the Northwest Pacific and Central Pacific. It mainly distributed from 24 to 170 m depths and 6.5-22℃ degree celsius water temperature. Anchovy have biological characteristics of high growth rates, early maturity, seasonal migrations, spawning pelagic eggs and schooling behavior (Bacha and Amara, 2009; Oh et al., 2009; Yamada et al., 2007; Yasue et al., 2010).

The role of the anchovy in marine ecosystem

Pacific anchovy is an economically important species in Korea. It is also an essential element of marine ecosystem because of occupy the intermediate part of the food web, playing a connecting the low and high trophic levels by becoming a major prey for fish of high trophic level (Kim et al., 2013; Pauly et al., 1998; Zhao et al., 2003; Zhou et al., 2015).

Fisheries of anchovy

Pacific anchovy was caught throughout the Korean coastal waters, most commercial fisheries concentrated in Tongyeong of the Southern coast of Korea. Anchovy fisheries of drag net, trawl and draft gill net occupy half of the annual total catch (Jung, 2008; Jung et al., 2016; Kim et al., 2015). Annual catches began to increase from $11x10^4$ tons in 1992, it maintained more than $19x10^4$ tons until 2015. The highest catch of $29x10^4$ tons in 2011.

Annual catches of anchovy dramatically decreased in 2016 (MOF, 2017). There have been attempts to include anchovy as a target fish species for fisheries management due to continuous inter industry and regional conflicts, but studies on evaluation and management of anchovy resource are shortage.

Past studies

Studies on anchovy conducted in Korea

Past studies on biological characteristics of anchovy were conducted related with growth, spawning, distribution of egg and larval, and food organisms (Cha, 1990; Hwang et al., 2006; Hwang et al., 2007; Kim, 1983; Kim et al., 2013; Kim et al., 2017; Kim and Choi, 1988; Kim and Kang, 1992; Lee and Go, 2002; Park and Cha, 1995). Cho and Kim (2006), Kim et al. (2004) and Oh et al. (2009) reported genetic diversity of anchovy in Korean waters based on genetic structure. Jung et al. (2008) reported changes in growth and number of spawned egg and mortality depending on water temperature. Regarding the change in biomass of anchovy, studies on relationship biomass-temperature and predicting change in distribution were conducted (Choi et al., 2001; Choi and Kim, 1988; Jung, 2008; Jung et al., 2016; Kim et al., 2002; Kim et al., 2015). Kim and Lo (2001) reported seasonal egg production and spawning participation rate of adult anchovy.

Studies on anchovy conducted in a foreign country

Studies of conducted in a foreign country on the anchovy near the Korean waters are divided into two population groups: 1) the Tsushima Current stock is distributed from the

East China Sea to Yellow Sea and 2) the Pacific stock is distributed in the Eastern Sea of the Japan. Zheng et al. (2015) and Zhou et al. (2015) reported genetic analysis of the populations, and the relationship between pacific decadal oscillation and changes in anchovy populations of the anchovy distributed from the East China Sea to Yellow Sea. Hayashi et al. (2016), Suhara et al. (2013), Takeshige et al. (2015) and Yasue et al. (2016) reported reproduction characteristic, distribution of egg-larvae and impact of change in the marine environment on the early life stage of anchovy in the Eastern Sea of the Japan.

Problems

Most Studies have been conducted on the effect of environmental change and the biological characteristics of anchovy. However, Studies on evaluation of anchovy resource for solving the industry and regional conflicts and estimation of biological reference points for fishery management are shortage.

Goal

In Korea, the fisheries resources of the yellow croaker, hairtail, variously coloured abalone and cod were evaluated by applying the yield-per-recruit analysis, but studies on fish with biological characteristics of high growth rates, a short life span and early maturity are shortage (Cha and Jung, 2012; Ko et al., 2008; Park et al., 2000; Zhang et al., 1992). Thus, I applied the yield-per-recruit analysis to estimate the biological reference points of anchovy for fisheries management.

Yield-per-recruit analysis

Traditional yield-per-recruit analysis

Yield-per-recruit analysis evaluates commercial yield with respect to varying biological reference points of 1) the instantaneous fishing mortality and 2) length at first capture for sustainable use of fishery resources. This method assumes the following hypothesis: 1) changes in the marine environment appear high variability in the annual scales, but it is constant in the long term time scales and 2) annual reproduction is constant. Traditional yield-per-recruit analysis have been applied the method suggested by Beverton and Holt (1957), and the equation is as follows.

$$\frac{Y}{R} = F\exp(-M(t_c - t_r))W_\infty \sum_{n=0}^{3}\left(\frac{U_n \exp(-nK(t_c - t_0))}{F + M + nK}[1 - \exp(-(F + M + nK)(t_L - t_c))]\right)$$

·· (1)

The parameters in this equation are as follows: F (instantaneous rate of fishing mortality), M (instantaneous rate of natural mortality), t_c (first catch age), t_r (age of recruitment), W_∞ (asymptotic weight), K (the growth coefficient), t_0 (a time used to calculate size at age 0), t_L (maximum age) and U_0=1, U_1=-3, U_2=3, U_3=-1.

Limitation of applying the yield-per-recruit analysis to anchovy

There are problems in applying the Beverton and Holt (1957) method to estimate the yield-per-recruitment of anchovy. 1) In the Eq. (1), the natural mortality is constant which cannot reflect the changes in natural mortality depending on length and age in the natural condition and 2) traditional method evaluate targeting fish more than 1 age and having a specific spawning period. Therefore, Beverton and Holt (1957) method is difficult to apply to anchovy because of a short life span, early maturity and large fluctuations in natural mortality (Jung, 2008; Jung et al., 2008). Traditional method cannot be used to provide a biological reference point on the condition of the maximum fork length allowed to catch for protecting adult fish because of its premise of the minimum length of allowed catch.

Objectives

This study is to develop a simulation-based yield-per-recruit model (Y/R) that considering the temperature-dependent growth and size-dependent mortality from egg to adult stages, and evaluate changes in fisheries yield and egg production of anchovy in the Korea Strait (KS) with respect to varying the instantaneous fishing mortality (F) and length at first capture (L_c). I also evaluated the fisheries yield and egg production on the two fishing conditions of 1) the minimum length allowed to catch ($L_{c,min}$) and 2) the maximum length allowed catch ($L_{c,max}$) to evaluate which fishing strategy is better for sustainable anchovy fisheries.

Data and methods

Study area

To evaluate the yield-per-recruitment (Y/R) of anchovy in the KS, I selected the Sothern Waters of Korea, which showed the highest catch among the adjacent seas of Korea (Fig. 1, b of Jung et al., 2008). Biological characteristics of anchovy and monthly fluctuations of water temperature applied the results of past studies in the same area.

Simulation parameters

I used the result of Jung et al. (2008) to evaluate the monthly fluctuations of water temperature, temperature-dependent growth and size-dependent mortality. Length-weight relationship and fecundity were evaluated by applying the parameters estimated from Choi and Kim (1988) and Kim and Kang (1992).

Approach

I evaluated the Y/R of anchovy using the equation of size-dependent instantaneous natural mortality reported by Cha and Jung (2012) and Jung et al. (2008), and traditional method of Beverton and Holt (1957).

Hypothesis

This simulation assumed the following hypothesis.

1) Maximum age of anchovy is 3 years (Jung, 2008).
2) Growth and incubation time of eggs are affected by water temperature (Jung et al., 2008).
3) The instantaneous natural mortality of hatched anchovy is inversely proportional to body length (Jung et al., 2008).
4) Spawning participation rate and egg production of anchovy is constant every year.
5) The sex ratio of hatched eggs is 1:1 (Jung et al., 2008).
6) The larvae and adult fish are separated by 80 mm fork length (Kim and Lo, 2001) and only adult fish participate in spawning.

Based on this hypothesis, I projected changes in commercial yield and egg production of anchovy for 3 years with respect to varying the instantaneous fishing mortality (F=0-0.05 day^{-1}) and length at first capture on the two fishing conditions of $L_{c,min}$ and $L_{c,max}$ (0-160 mm). $L_{c,min}$ means that smaller and young anchovy are protected and, $L_{c,max}$ means, bigger adult anchovy are protected.

Daily simulation

The simulation was conducted in a daily for 3 years from January 1 to December 31. In this simulation, d and i mean day (1-1,095 days, 3 years) and daily cohort (i=1-365 th daily cohort) respectively.

Water temperature and growth of anchovy

Hatching of egg and growth of anchovy calculated daily and were affected by fluctuation of water temperature.

Water temperature

Daily water temperature in the KS were evaluated by applying the equation which calculated water temperature using the Korea Oceanographic Data Center (KODC) data of the 204-207 and 400 lines at 10 m depth in 1996 reported by Jung et al. (2008).

$$T_d = 18.28 - 5.67\sin[2\pi(d+31.4)/365] \cdots\cdots\cdots\cdots\cdots \quad (2)$$

T_d is water temperature (°C) on the day d.

Growth

Hatching time with respect to varying water temperature

Hatching time of anchovy egg with respect to varying water temperature was calculated from following equation reported by Kim and Lo (2001). In the Eq. (3), h_i is the hatching time of i th daily cohort and T_i is the same as T_d in the Eq. (2).

$$h_i=40.46\exp(-0.1167*T_i)*9^{1.14}/24 \cdots\cdots\cdots\cdots\cdots \quad (3)$$

Age-length relationship

Temperature-dependent growth of anchovy was evaluated using von Bertalanffy growth equation. I applied the parameters of growth equation reported by Jung et al. (2008). Equations to evaluate growth and growth coefficient are as follows.

$$K_d=0.00044+0.00017*T_d \cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

$$L_{i,d+1}-L_{i,d}=\begin{cases} K_d*(L_\infty-L_{i,d}) & \text{if } d\geq h_i \\ 0 & \text{if } d<h_i \end{cases} \quad \cdots\cdots\cdots \quad (5)$$

K_d is growth coefficient on the day d, L_∞ is asymptotic length of anchovy, $L_{i,d}$ is length of i th daily cohort on the day d. If d is less than h_i, it is distinguished pre-hatching stage and the growth rate is 0. L_0 is diameter of eggs of Pacific anchovy which was assumed 1.5 mm (Jung et al., 2008).

Length-weight relationship

Weight of hatched larva is affected by length and evaluated by using the equation of length-weight relationship reported by Choi and Kim (1988). In the Eq. (6), $W_{i,d}$ is wet weight (g) of *i* th daily cohort on the day *d*.

$$W_{i,d}=0.004*(L_{i,d}/10)^{3.2748} \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

Instantaneous rate of natural mortality and total mortality

According to the hypothesis (3), the instantaneous natural mortality (M) of hatched anchovy is inverse proportion to body length. I applied the coefficient of equation reported by Jung et al. (2008) for estimating size-dependent instantaneous natural mortality.

$$M_{i,d}=1.24 \text{ mm day}^{-1}/L_{i,d} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

$M_{i,d}$ is the instantaneous natural mortality of *i* th daily cohort on the day *d*. I evaluated the instantaneous total mortality (Z) following the two equations.

$$Z_{i,d} = \begin{cases} M_{i,d} + F & \text{if } L_{i,d} \geq L_{c,\min} \\ M_{i,d} & \text{if } L_{i,d} < L_{c,\min} \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots \text{(8-1)}$$

$$Z_{i,d} = \begin{cases} M_{i,d} + F & \text{if } L_{i,d} \leq L_{c,\max} \\ M_{i,d} & \text{if } L_{i,d} > L_{c,\max} \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots \text{(8-2)}$$

$Z_{i,d}$ is the instantaneous total mortality of *i* th daily cohort on the day d. Eq. (8-1) means that fishing is prohibited when $L_{i,d}$ smaller than $L_{c,min}$ for protecting immature fish whereas Eq. (8-2) means that fishing is prohibited when $L_{i,d}$ bigger than $L_{c,max}$ for adult fish.

Spawning fraction

Initial number of eggs were used number of eggs spawned by an average matured female anchovy during a year (N_0=159,586) (Jung et al., 2008). I estimated daily spawning fraction rate (P_i, i=1-365 days) of adult female anchovy based on spawning fraction for each month reported by past studies (Kim and Kang, 1992; Kim and Lo 2001) (Fig. 2-1).

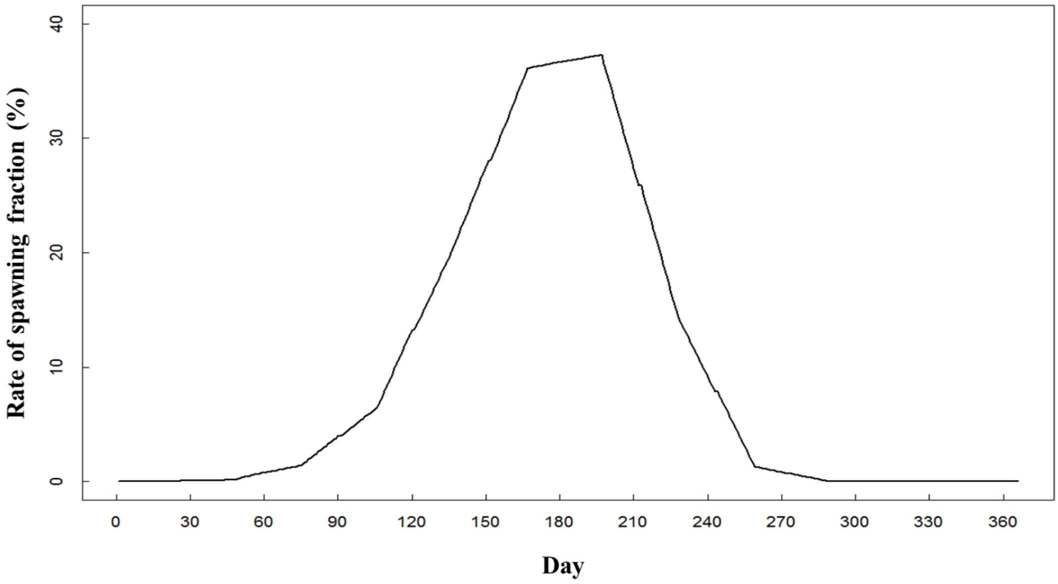

Fig. 2-1. Estimated daily spawning fraction rate of Pacific anchovy *Engraulis japonicus* in the Korea Strait.

Population dynamics by cohort

Initial population applying daily spawning fraction rate were estimated by Eq. (9).

$N_{i,0}=N_0*P_i$ ………………… (9)

$N_{i,0}$ is initial population of i th daily cohort and N_0 is number of eggs spawned by an average matured female anchovy during a year (Jung et al., 2008). P_i is spawning fraction rate of i days (Fig. 2-1).

Changes in total biomass and catch biomass

Changes in daily population and catch in the daily cohort were estimated by Eqs. (10) and (11).

$N_{i,d+1}=N_{i,d}*S_{i,d}$ ………………… (10)

$S_{i,d}=\exp(-Z_{i,d})$ ………………… (11)

$N_{i,d+1}$ and $N_{i,d}$ are population of anchovy on the day $d+1$ and d days. $S_{i,d}$ is survival rate of i th daily cohort on the day d. Catch of anchovy was estimated by catch equation of the Gulland's (1965) (King, 2007).

$N_{catch,i,d}$=(F/$Z_{i,d-1}$-$N_{i,d-1}$exp(-$Z_{i,d-1}$))⋯⋯⋯⋯(12)

$N_{catch,i,d}$ is catch (n) of *i* th daily cohort on the day *d*. I estimated catch of anchovy by daily cohort for 3 years by applying Eq. (13) based on hypothesis (2).

$$N_{\text{total catch}} = \sum_{i=1}^{365}\sum_{d=i}^{1095} N_{\text{catch},i,d} \quad \cdots\cdots\cdots\cdots (13)$$

Yield-per-recruitment (Y/R)

Anchovy yield (g) by daily cohort was estimated by Eq. (14) (Cha and Jung, 2012).

$Y_{i,d}$=$N_{catch,i,d}$*$W_{i,d-1}$⋯⋯⋯⋯⋯⋯(14)

$Y_{i,d}$ is Y/R of *i* th daily cohort on the data *d* based on wet weight. Y (tons) is the Y/R simulated for 3 years which is using Eq. (15).

$$Y = \sum_{i=1}^{365}\sum_{d=i}^{1095} Y_{i,d} / 10^6 \quad \cdots\cdots\cdots\cdots\cdots (15)$$

Egg production

I estimated body weight dependent fecundity among female anchovies more than 80 mm body length by Eq. (16) (Kim and Kang, 1992).

$$e_{i,d} = \begin{cases} 42.813 * W_{i,d}^{1.883} & \text{if } L_{i,d} \geq 80 \text{ mm} \\ 0 & \text{if } L_{i,d} < 80 \text{ mm} \end{cases} \quad \cdots\cdots\cdots\cdots\cdots (16)$$

$e_{i,d}$ is fecundity of an matured female anchovy of *i* th daily cohort on the data *d*. Egg production ($E_{i,d}$) by daily cohort applying daily spawning fraction rate (Fig. 2-1) was estimated by Eq. (17).

$$E_{i,d}=e_{i,d}*N_{i,d}*P_d \cdots\cdots\cdots\cdots\cdots (17)$$

Yield-per-egg production (Y/E: n) for 3 years was estimated by Eq. (18).

$$E = \sum_{i=1}^{365}\sum_{d=i}^{1095} E_{i,d} \quad \cdots\cdots\cdots\cdots\cdots (18)$$

Correction of yield-per-recruitment and egg production

Estimated Y/R and Y/E were corrected by applying correction factor. I used adult anchovy biomass in summer during 1990-1994 in the southern water of Korea (490×10^3 mt, Table 10 of Kim and Lo, 2001) as the correction factor.

$$B=\sum_{i=1}^{365}\sum_{d\in\{196,561,926\}} N_{\text{adult},i,d} * W_{i,d} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(19)}$$

$$N_{\text{aduult},i,d}=\begin{cases} N_{i,d} & \text{if} \quad L_{i,d}\geq 80 \text{ mm} \\ 0 & \text{if} \quad L_{i,d}<80 \text{ mm} \end{cases} \quad \text{where } d=196,561,926\ (0\text{-}2 \text{ age}) \quad \cdots\cdot \text{(20)}$$

d is day of July 15 representing summer at age 0-2. *B* is adult biomass more than 80mm body length of July 15 when no catch.

$R=SSB/B\cdots\cdots\cdots\cdots\cdots\cdots$ (21)

R is correction factor and *SSB* is adult anchovy biomass in summer reported by Kim and Lo (2001). Y/R_{total} was estimated by Eq. (22).

$Y_{\text{total}}=R*Y\cdots\cdots\cdots\cdots\cdots\cdots$ (22)

Y_{total} is Y/R_{total} (tons) applying correction factor. Total egg production was estimated by Eq. (23). E_{total} is total Y/E_{total} (n) applying correction factor.

$E_{total}=R*E$ ……………… (23)

Biological reference points in the yield-per-recruit analysis

Biological reference points in the Y/R distinguished into F_{max}, $F_{0.1}$, Y_{max} and $Y_{0.1}$ were estimated by varying instantaneous fishing mortality (F, 0-0.05 day^{-1}) and length at first capture ($L_{c,}$ 0-160 mm) on the two fishing conditions of 1) the minimum fork length of anchovy allowed to catch ($L_{c,min}$) and 2) the maximum fork length allowed to catch ($L_{c,max}$). F_{max} is a reference point of the instantaneous fishing mortality where the slope of the Y/R curve equals zero and Y_{max} is the corresponding catch. $F_{0.1}$ is a reference point of the instantaneous fishing mortality where the slope of the Y/R curve corresponds to 10% of the initial slope at the origin and $Y_{0.1}$ is the corresponding catch.

Results

Yield-per-recruitment

Daily spawning fraction rate (P_i) of anchovy was high in summer from Jun to August (150-210 days) (Fig. 2-1). Fig. 2-2 showed Y/R_{total} with respect to varying F (0-0.05 day^{-1}) and L_c (0-160 mm). Y/R_{total} in the fishing condition $L_{c,min}$ was maximized at 1.5-1.59 million tons when minimum fork length ranged between 42-60 mm and F was more than 0.03 day^{-1}, and the when $L_{c,min}$ was more than 120 mm it showed 0 regardless of F (Fig. 2-2, a). Y/R_{total} in the fishing condition $L_{c,max}$ was maximized at 0.8 million tons when minimum fork length ranged between 88-160 mm and F was less than 0.02 day^{-1}, and the when $L_{c,max}$ decreased, it decreased regardless of F (Fig. 2-2, b).

Estimation and comparison of F_{max} and $F_{0.1}$

Based on current fishing regulation to protecting immature fish ($L_{c,min}$=30 mm, Jung, 2008), $Y_{0.1}$ showed about 1.22 million tons when $F_{0.1}$ was 0.016 day^{-1} and Y_{max} showed about 1.31 million tons when F_{max} was 0.028 day^{-1} (Fig. 2-3, a). $Y_{0.1}$ in the fishing condition $L_{c,max}$ showed about 0.24 million tons when $F_{0.1}$ was 0.028 day^{-1} and Y_{max} showed about 0.25 million tons when F_{max} was 0.038 day^{-1} (Fig. 2-3, b).

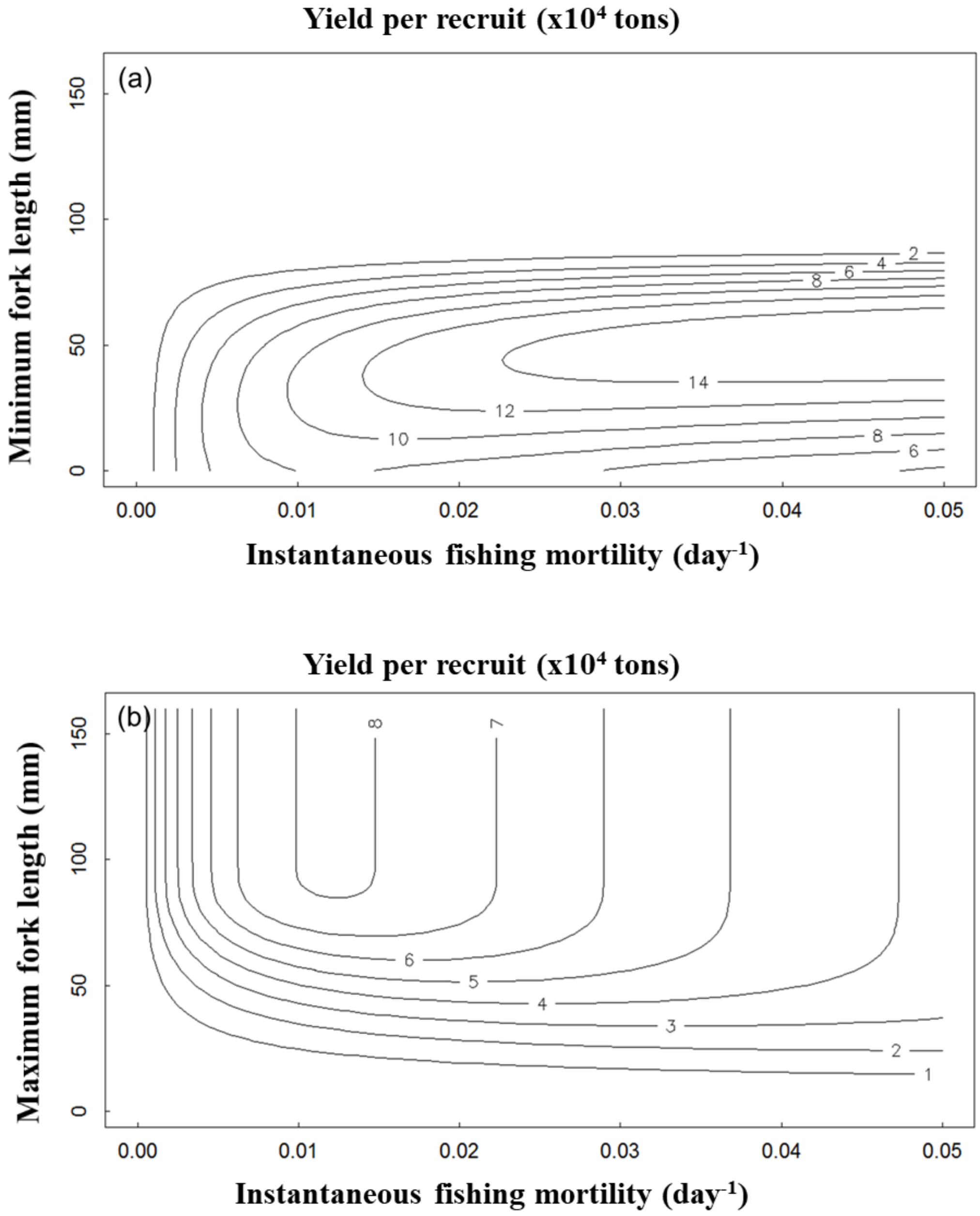

Fig. 2-2. Yield per recruit of Pacific anchovy *Engraulis japonicus* with varying instantaneous fishing mortality and varying (a) minimum fork length of allowed catch (smaller fish are protected and bigger fish are allowed for commercial catch); (b) maximum fork length of allowed catch (bigger fish are protected and smaller fish are allowed for commercial catch).

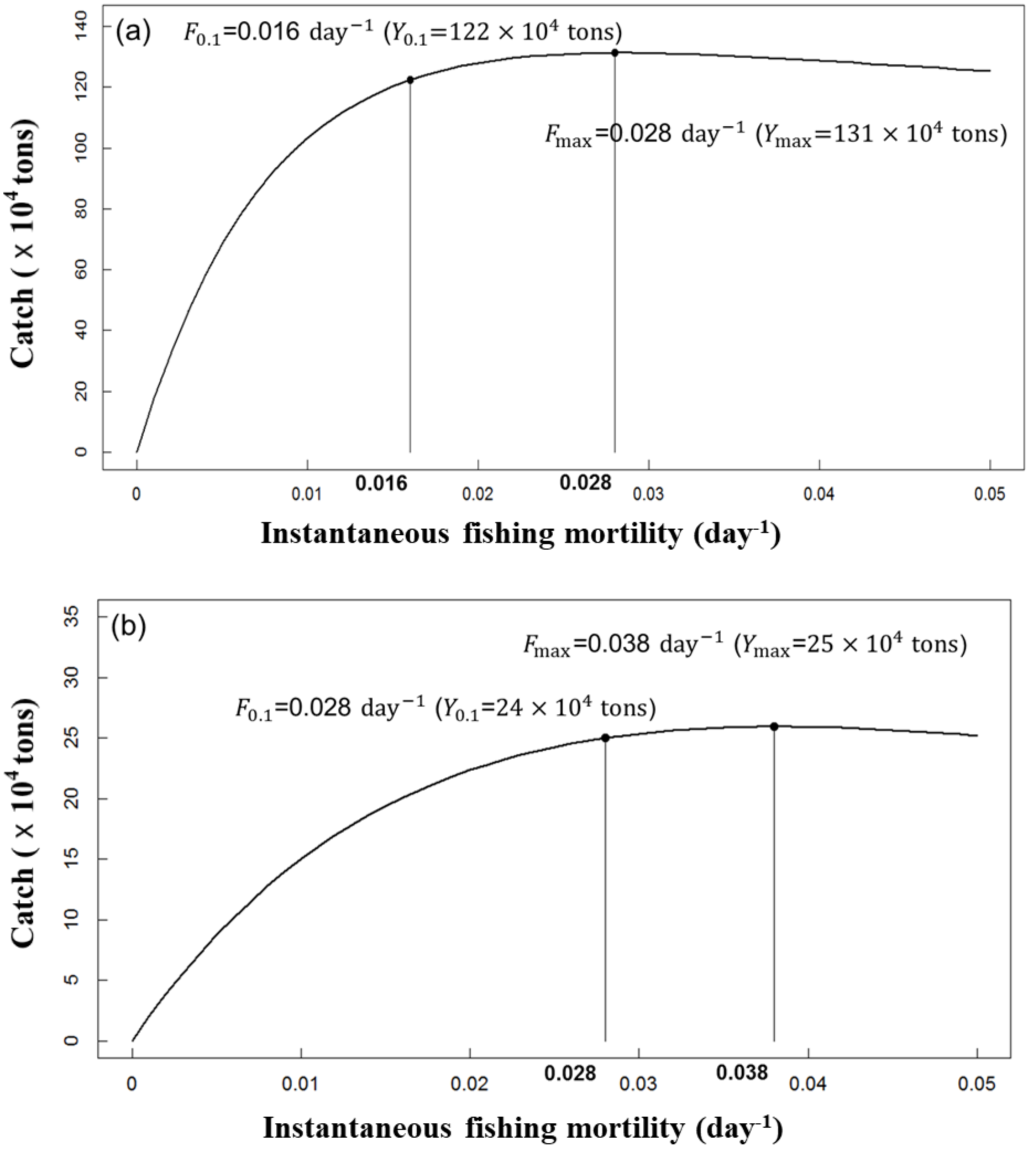

Fig. 2-3. Yield per recruit curves of Pacific anchovy *Engraulis japonicus* with varying instantaneous fishing mortality when (a) minimum fork length of allowed catch=30 mm; (b) maximum fork length of allowed catch=30 mm. $F_{0.1}$ is a reference point of instantaneous fishing mortality where the slope of the yield per recruit curve corresponds to 10% of the initial slope at the origin and $Y_{0.1}$ is the corresponding catch; F_{max} is a reference point of instantaneous fishing mortality where the slope of the yield per recruit curve equals zero and Y_{max} is the corresponding catch.

Yield-per-egg production

Y/E_{total} of the two fishing conditions showed about 8 billion eggs when no catch (F=0, T_c=0). Egg production in the fishing condition $L_{c,min}$ increased according to decreased of F and increased of $L_{c,min}$. Egg production in the fishing condition $L_{c,max}$ increased according to decreased of F and $L_{c,max}$ (Fig. 2-4). Based on current fishing regulation to protecting immature fish ($L_{c,min}$=30 mm, Jung, 2008), egg production showed 800-8,000 million eggs with respect to varying F. Egg production in the fishing condition $L_{c,max}$ showed 0.02-8,000 million eggs with respect to varying F.

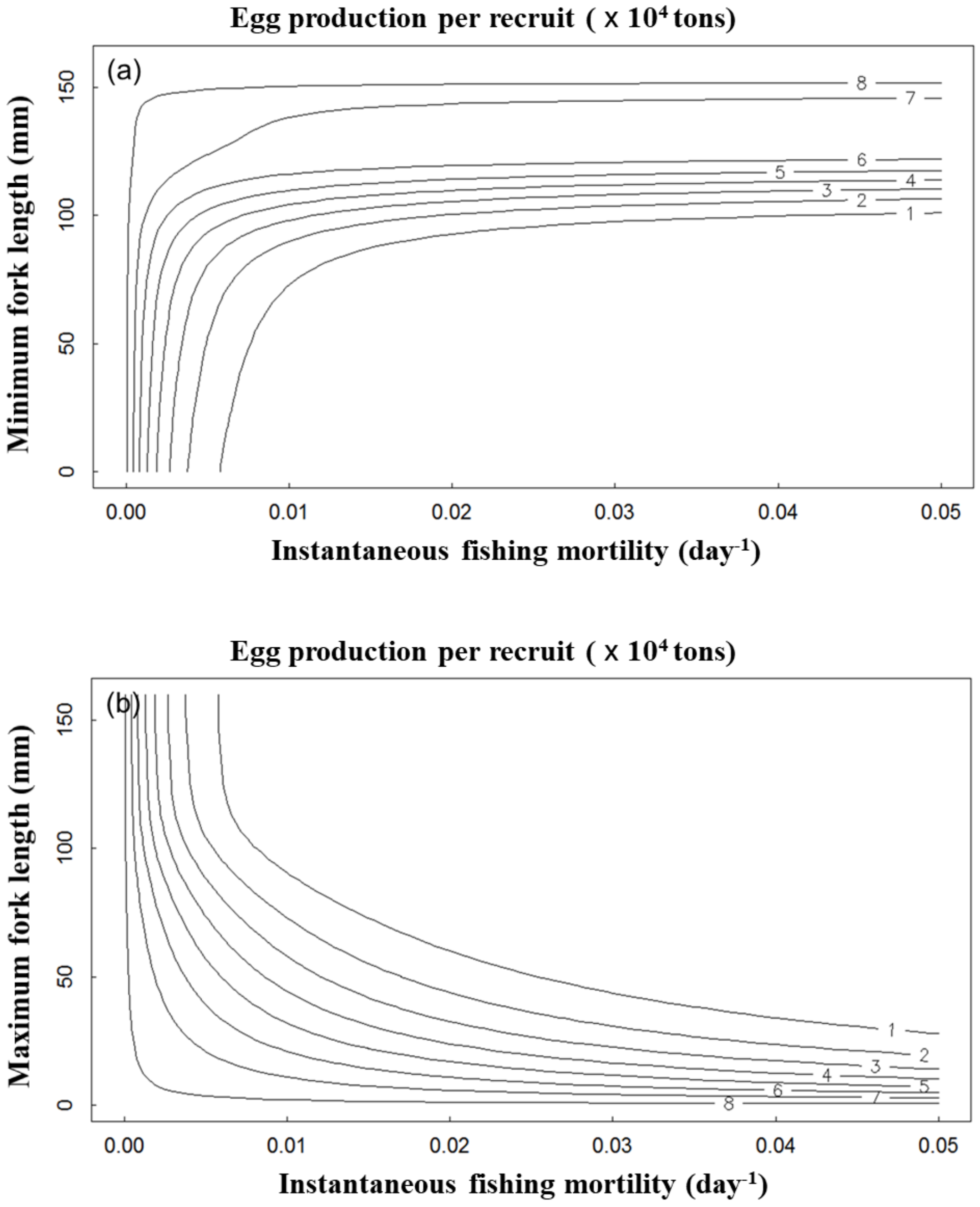

Fig. 2-4. Egg production per recruit of Pacific anchovy *Engraulis japonicus* with varying instantaneous fishing mortality and varying (a) minimum fork length of allowed catch (smaller fish are protected and bigger fish are allowed for commercial catch), (b) maximum fork length of allowed catch (bigger fish are protected and smaller fish are allowed for commercial catch).

Discussion

Yield-per-recruitment of the two fishing conditions

I estimated the $\mathrm{Y/R_{total}}$, $\mathrm{Y/E_{total}}$, $Y_{\max}$ and $Y_{0.1}$ on the two fishing conditions of 1) $L_{\mathrm{c,min}}$ for the protecting immature fish and 2) $L_{\mathrm{c,max}}$ for the protecting adult fish. $\mathrm{Y/R_{total}}$ on the fishing condition $L_{\mathrm{c,min}}$ was maximized at 1.5-1.59 million tons when minimum fork length ranged between 42-60 mm and increased when F increased. $\mathrm{Y/R_{total}}$ on the fishing condition $L_{\mathrm{c,max}}$ was maximized at 0.8 million tons when maximum fork length ranged between 88-160 mm. Fishing condition $L_{\mathrm{c,min}}$ showed about twice as higher maximum yield than $L_{\mathrm{c,max}}$ (Fig. 2-2). Thus, I evaluate that protecting immature fish is more advantageous method to increasing the anchovy catch over the long term than protecting adult fish.

Comparisons of yield-per-recruitment varying fishing conditions

Protecting immature fish condition

I compared the yield at $F_{0.1}$ of the two fishing conditions. $Y_{0.1}$ on the fishing condition $L_{\mathrm{c,min}}$ increased about 10 % when first catch length 30 mm increased 10 mm and decreased about 12 % when first catch length decreased 10 mm (First catch length 20 mm: $F_{0.1}$=0.013 day^{-1}, $Y_{0.1}$=1.07 million tons, first catch length 40 mm: $F_{0.1}$=0.02 day^{-1}, $Y_{0.1}$=1.35 million tons) (Fig. 2-2, a).

Protecting adult fish condition

$Y_{0.1}$ of the fishing condition $L_{c,max}$ increased about 42 % when first catch length at 30 mm increased 10 mm and decreased about 38 % when first catch length decreased 10 mm (First catch length 20 mm: $F_{0.1}$=0.044 day^{-1}, $Y_{0.1}$=0.15 million tons, first catch length 40 mm: $F_{0.1}$=0.02 day^{-1}, $Y_{0.1}$=0.36 million tons) (Fig. 2-2, b).

Comparisons of $Y_{0.1}$ at first catch length 30 mm

I compared $Y_{0.1}$ of the two fishing conditions at L_c=30 mm. $Y_{0.1}$ on the fishing condition $L_{c,min}$ showed 1.22 million tons when $F_{0.1}$ was 0.016 day^{-1} and $Y_{0.1}$ on the fishing condition $L_{c,max}$ showed 0.25 million tons when $F_{0.1}$ was 0.028 day^{-1}. Thus, protecting immature anchovy showed about 80 % higher yield than protecting adult anchovy (Fig. 2-3).

Cause of difference in yield of the two fishing conditions

Fishing condition $L_{c,min}$ showed higher yield than $L_{c,max}$ in all catch length. I expect that difference in yield of the two fishing conditions caused by catch biomass of adult fish because 1) yield was calculated by applying individual weight (Eq. 13) and 2) $L_{c,min}$ mainly caught adult fish.

Comparisons of yield-per-egg production varying fishing conditions

Y/E_{total} maximized at 800 million eggs when no catch. Fishing condition $L_{c,min}$ showed higher egg production than $L_{c,max}$ (Fig. 2-4). Egg production on the fishing condition $L_{c,min}$ increased according to increase of first catch length and decrease of F, but on the fishing condition $L_{c,max}$ increased according to decreased of F and $L_{c,max}$.

Cause of difference in egg production of the two fishing conditions

I expect that difference in egg production of the two fishing conditions caused by rate of spawning participation of adult fish. Because, spawning population increased when first catch length increase in fishing condition $L_{c,min}$ whereas it decreased in $L_{c,max}$. Thus, I evaluate that protecting immature fish is more advantageous regulation to increasing egg production of anchovy over the long term than protecting adult fish.

Management of anchovy stock based on yield-per-recruit analysis

Yield-per-recruit analysis to evaluate the Y/R on the condition of protecting immature fish was generally conducted using developed by Beverton and Holt (1957) method. This study evaluated changes in fisheries yield and egg production of anchovy on the two fishing conditions by applying simulation based on Beverton and Holt (1957) method. I conclude that current fishing regulation of protecting immature fish can product higher commercial yield and egg than protecting adult fish.

Comparisons result of simulation and present catch biomass of anchovy in Korea

I compared fisheries yield at F_{max} when L_c=30 mm ($L_{c,min}$) with average catch biomass 0.22 million tons of anchovy in Korea in 2010 (MOF, 2017). The current F level was estimated to 0.001 day^{-1}, which need additional effort about 28 times to reach maximum commercial yield 1.31 million tons (F=0.028 day^{-1}). Simulation result showed that even if the fishing effort was increased, more catches could be obtained without overfishing. However, anchovy fisheries tend to be concentrated on the shallow coastal areas, not conducted throughout the Korea Strait. I expect that this tendency was affected by socio-economic factors such as fuel costs for maximizing the profit return on cost (Fig. 5, b of Jung et al., 2016). Thus, I speculate that the current fishing effort would be difficult to increase by 28 times, unless increasing the anchovy price.

Limitations and problems

Changes in yield and egg production with respect to varying length at first catch

I applied the biological characteristics and daily water temperature reported by past studies to evaluate Y/R and Y/E. Changes in yield and egg production were highly affected by adult biomass of anchovy. Thus, additional study is required to determine length of adult based on recent studies for growth of anchovy.

Necessity of representative value of biologic parameters of anchovy

The distribution of anchovy is changed depending on body length and spawning period. Difference in habitat environment affects the growth and fecundity of regional population. There are uncertainties in the studies on natural mortality and fecundity, because biological characteristics of anchovy were evaluated based on the results of a survey conducted 20 to 30 years ago (Jung, 2008; Lee et al., 1995; Takasuka et al., 2005). To quantify the natural mortality, stock and spawning characteristics of anchovy, recent survey of egg-larvae and adult anchovy collected form the adjacent seas of Korea is need (Takasuka et al., 2005).

Further Studies

Studies on evaluation of yield-per-recruit analysis considering economic cost

This simulation evaluated the yield with respect to varying fishing mortality and length at first catch length with the exception of economic cost such as fuel cost. Smaller anchovy is more valuable than larger anchovy. The price per dry weight of anchovy is most profitable for the 30-45 mm length (Jung et al., 2008). To evaluate the economic value of Y/R, a study on the value of production that reflect the economic value by size of anchovies is needed. To suitable use of anchovy resources, additional studies on 1) estimation of the range of instantaneous fishing mortality and 2) fishing regulation of minimum catch length reflecting recent biological data are need.

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Chapter 3

Simulation-based Yield-per-recruit Analysis of Chub Mackerel *Scomber japonicus* in Korean Waters

Abstract

Chub mackerel *Scomber japonicus* is an economically important pelagic species in the western North Pacific. In the last 50 years, the annual total catch showed large fluctuation ranging from 100 to 420x10^3 tons in Korean waters. I applied a simulation-based yield-per-recruit model that considered 1) temperature-dependent growth in early life stage, 2) size-dependent mortality to provide the biological reference point for management of chub mackerel. I estimated fisheries yield with respect to varying biological reference points and environmental conditions. The result of simulation showed that the yield-per-recruit (Y/R) could be maximized when the L_c ranges from 19 to 27 cm and F ranges from 1.48 to 2.00 yr^{-1}. Y/R with respect to varying water temperature from 15 to 23°C showed an increasing trend with increasing temperature. I suggest the L_c=17 cm (age=0.6 years) at the current F=0.48 yr^{-1} for maximizing the harvest of chub mackerel.

Key words: Chub mackerel, Potential yield, Fisheries management, Stock assessment

Introduction

Chub mackerel

Chub mackerel *Scomber japonicus* is one of the small pelagic fish distinguished by economically important fish in Korea, Japan and China, and mainly distributed on the continental shelf of the warm and temperate waters from 10 to 100 m depths and about 15℃ degree celsius water temperature (Yamada et al., 2007; NFRDI, 2010). Chub mackerel in the adjacent seas of Korea is divided into two stocks of 1) the Tsushima Current stock and 2) Pacific stock. The Tsushima Current stock widely distributes in the East China Sea, the Yellow Sea and the East Sea, and the Pacific stock distributes in the Pacific coast of Japan (Watanabe et al., 2002). The Tsushima Current stock in the adjacent seas of Korea migrates northward to the Yellow Sea and the East Sea during spring and summer for feeding, and moves back to the East China Sea during winter and autumn for spawning and wintering (Hiyama et al., 2002; NFRDI, 2010; Yamada et al., 2007). Chub mackerel is known to have a fast growth rate and matured about 1 year after hatching (Hwang et al., 2008b; Yoon et al., 2008).

Fisheries of chub mackerel

Catches of small pelagic species such as chub mackerel, jack mackerel *Trachurus japonicus* and sardine *Sardinops melanostictus* showed large interannual fluctuations depending on the biological characteristic and environment of fishing ground (Cha et al., 2002; Watanabe et al., 2002). Chub mackerel in Korea has been applied to the total allowable catch (TAC) in order to achieve sustainable fisheries from 1999. In the Northern East China Sea to the Southeastern Coast of Korea, chub mackerel was mainly caught by large purse seine fishery. The total catches of chub mackerel from 1970 to 1995 showed $100x10^3$-$200x10^3$ tons. It increased until $420x10^3$ tons in 1996, then decreased to $150x10^3$ tons in 2000s (Cha et al., 2002; Lee and Kim, 2011; Oh et al., 2016). Fishing ground of chub mackerel in Korean coastal waters was formed in the coast of Jeju Island from May to Jun and in the middle area of the Yellow Sea in August. In December, fishing ground in the Yellow Sea disappeared and it moved to the southern part of the East Sea (Cha et al., 2002; Lee and Kim, 2011). This seasonal movement of fishing ground was expected to be affected by variations in water temperature and the Kuroshio Current extension (Jung et al., 2014; Lee and Kim, 2011).

Past studies

Biological characteristic

Past studies on biological characteristics of chub mackerel were conducted related with growth, maturity and spawning, and feeding habits (Cha et al., 2002; Choi et al., 2000; Hwang et al., 2008b; Yoon et al., 2008). Regarding early life stage, Hwang et al. (2008a), Jung et al. (2013), Lee et al. (2016) and Park et al. (2008) reported that distribution of egg and larva, effects of water temperature and salinity on early life stage, and changes in buoyancy and vertical distribution with growth.

Temporal and spatial fluctuations in biomass

Cho et al. (1984), Hiyama et al. (2002), Kim et al. (1999) and Lee and Kim (2011) reported long-term variations in population biomass of mackerel and its relationship with the marine environment. Chen et al. (2009) and Jung et al. (2014) evaluated habitat suitability index and latitudinal shifts of distribution. Yukami et al. (2009) estimated the spawning grounds of chub mackerel. Kamimura et al. (2015) evaluated the relationship between growth of juvenile fish and recruitment.

Estimation of biological reference points

Choi et al. (2004a) estimated the survival rate, first catch length and instantaneous coefficient of mortality of chub mackerel. Choi et al. (2004b) estimated maximum sustainable yield (MSY) and optimal fishing effort for sustainable use of mackerel resources.

Problems

Many Studies of chub mackerel have been conducted on the early life stage, the biological characteristics and the relationship between biomass and marine environment. However, Studies on evaluation of biological reference points for fishery management are shortage.

Objectives

Adult fish can choose the ideal habitat. However, distribution, recruitment and growth of early life stages of egg and larva are largely influenced by changes in marine environment such as ocean current, water temperature and salinity because of vulnerable to changes in marine environment and weak swimming ability (Brochier et al., 2009; Gilbert et al., 2010; Kim et al., 2011).

Thus, to provide the biological reference point for fisheries management of chub mackerel, I applied a simulation-based yield-per-recruit model that considered 1) temperature-dependent growth in early life stage, 2) size-dependent mortality. I evaluated fisheries yield with respect to varying biological reference points and environmental conditions, including 1) the instantaneous fishing mortality (F), 2) the length at first capture (L_c), and 3) water temperature.

Data and methods

Approach

To evaluate the yield-per-recruit (Y/R) of chub mackerel, I estimated growth of larva and juvenile-adult stages respectively using the growth equation reported by Go et al. (2018) and Hwang et al. (2008b), and evaluated fisheries yield with respect to varying L_c and water temperature.

Simulation of yield-pre-recruit analysis

To compare the Y/R at ranges from length at L_c=15-30 cm (length at first capture) and F=0-2 yr^{-1} (instantaneous fishing mortality), I applied following conditions, and estimated $F_{0.1}$ and F_{max} distinguished by biological reference point in the yield-per-recruit analysis. $F_{0.1}$ is a reference point of the instantaneous rate if fishing mortality where the slope of the yield per recruit curve corresponds to 10% of the initial slope at the origin, and F_{max} is a reference point of the instantaneous fishing mortality where the slope of the Y/R curve equals zero (Beverton and Holt, 1957; Deriso, 1987).

1) Y/R is evaluated with respect to varying L_c and F at the averaged spawning temperature 20°C (NFRDI, 2010).

2) Y/R is evaluated with respect to varying L_c at F=0.48 yr^{-1} known as current instantaneous rate of fishing mortality (NFRDI, 2005).

3) Y/R is evaluated with respect to varying spawning water temperature ranged from 15-23 °C at first catch length 15 cm (NFRDI, 2010).

Hypothesis

This simulation assumed the following hypothesis.

1) Maximum age of chub mackerel is 6 years (NFRDI, 2010).

2) Growth of larval stage is affected by water temperature (Kim et al., 2011).

3) Larval stage and juvenile-adult stages are distinguished by standard length 1.5 cm (Hunter and Kimbrell, 1980).

4) The instantaneous natural mortality coefficient of hatched chub mackerel is inversely proportional to body length (Jung et al., 2009).

5) Initial egg numbers are assumed 10,000 for simulation.

Daily simulation

The simulation was conducted in a daily for 6 years (0-2,190 days, 6 years). The biological characteristics applied to the simulation were estimated through the following method.

Growth

Growth of larval stage and juvenile-adult stages were estimated using parameters of growth equation reported by Go et al. (2018) and Hwang et al. (2008b).

The growth of larval stage was estimated using Gompertz equation (Nancy, 1983) and the growth coefficient (α) was applied parameter reported by Go et al. (2018). Go et al. (2018) evaluated the growth of larval stage reflected the hypothesis (2) using Hunter and Kimbrell (1980) data.

$$L_t=L_\infty/(L_0/L_\infty)^{\exp(-\alpha * t)} \cdots\cdots\cdots\cdots\cdots (1)$$

$$\alpha=0.0028*e^{0.0971*T} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

L_∞ is asymptotic length (cm) of chub mackerel, L_t is length at t day (Fork Length, cm), t is day (t=0-2,190 days), α is growth coefficient reported by Go et al. (2018) and L_0 is length at 0 age. I assigned the value of L_∞ as the estimated parameter of juvenile-adult stages by applying the von Bertalanffy growth model (VBGM). I assigned the value of L_0 as the reported length at hatch of mackerel egg, 3.1 mm, by Hunter and Kimbrell (1980).

To evaluate the growth of mackerel reflecting water temperature, Go et al. (2018) defined the growth coefficient α as a function of water temperature, where T is water temperature (°C). Length during larval stage was estimated by the Gompertz equation differentiated by time (t) (Eqs. 3, 4). Length of the L_{t+1} at $t+1$ day was evaluated following equations.

$$dL/dt=\alpha * L_t * \ln(L_t/L_\infty) * \ln(L_\infty/L_0)/\ln(L_0/L_\infty) \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

$$L_{t+1}=L_t+(dL/dt) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

α is the same as α in the Eq. (2), length at $t+1$ was evaluated using length at t day and the rate of change of the length (dL/dt) by day. I adopted VBGM to evaluate the changes in length (FL) with age (day) during juvenile-adult stages based on data of Hwang et al. (2008b).

$$L_t=L_\infty * (1-\exp(-K * (t-t_0))) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Here, L_t, L_∞ and t are the same as parameters of the Gompertz equation and K is growth coefficient of juvenile-adult stages. Hypothetical age at which a fish would have been zero length (t_0) is evaluated by the following equation (Jung et al. 2009).

$t_0=1/K*\ln(1-L_0/L_\infty)$ ………………… (6)

Here, L_0 is the same as L_0 in the Eq. (1). I adopted VBGM not considered change of water temperature to evaluate the juvenile-adult stages, because immature and adult fish can move to favorable habitat. Length during juvenile-adult stages was estimated by the VBGM differentiated by time (t).

$dL/dt=K*(L_\infty-L_t)$ ………………… (7)

Length-weight relationship

Weight was evaluated using length–weight relationship equation reported by Choi et al. (2000). In Eq. (8), W_t is weight (g) of length at t day.

$W_t=0.0044*L_t^{3.362}$ ………………… (8)

The instantaneous rate of natural and total mortality

The instantaneous natural mortality (day^{-1}) was evaluated by Eq. (9) based on hypothesis (4).

M_t=0.1009/L_t d^{-1} ······················ (9)

M_t is the instantaneous natural mortality (day^{-1}) at t day. The instantaneous fishing mortality (day^{-1}) was evaluated by Eq. (10).

$$F_t = \begin{cases} F/365 & \text{if} \quad L_t \geq L_c \\ 0 & \text{if} \quad L_t < L_c \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots \text{(10)}$$

Here, F_t is the instantaneous fishing mortality at t day and L_c is length at first catch. F_t (yr^{-1}) reported by NFRDI (2005) was converted to F_t (day^{-1}) by Eq. (10). The instantaneous total mortality (day^{-1}) was calculated by Eq. (11). Z_t is the instantaneous total mortality (day^{-1}) at t day.

$$Z_t = \begin{cases} M_t + (\ F/365) & \text{if} \quad L_t \geq L_c \\ M_t & \text{if} \quad L_t < L_c \end{cases} \cdots\cdots\cdots\cdots \text{(11)}$$

Population dynamics and yield

Fish population by day was evaluated by Eq. (12).

N_t=N_{t-1}*exp(-Z) ·················· (12)

N_t is daily population at t day. Yield (day^{-1}, g) was evaluated by catch equation of the Gulland's (1965) equation and it was converted to the wet weight (g) (King, 2013).

$Y_t=(F/Z)*N_t*(1-\exp(-Z))*W_t$ ········ (13)

Y_t is yield (day^{-1}, g) at t day. Total yield-per-recruitment (Y/R, yr^{-1}, g) simulated for 6 years was evaluated by Eq. (14).

$\mathrm{Y}=\sum_{\mathrm{d}=0}^{2,190}\mathrm{Y_t}$ ················ (14)

Results

Yield-per-recruit

At averaged spawning ground temperature at 20°C, Y/R (yr^{-1}) was maximized to 1,830-1,925 g when L_c ranges from 19 to 27 cm and F ranges from 1.48 to 2 yr^{-1}, and showed less than 200 g when F was less than 0.04 yr^{-1} regardless of L_c (Fig. 3-1). At L_c ranges from 15 to 17 cm, Y/R increased with increasing F and decreased when F was more than 1.67. At L_c ranges from 18 to 30 cm, Y/R steadily increased with increasing F (Fig. 3-1).

At L_c =15, 20, 25, 30 cm, $F_{0.1}$ showed 0.83, 1.02, 1.27, 1.56 yr^{-1} and increased with increasing L_c. F_{max} showed 1.76, 1.8, 1.97 yr^{-1} when L_c ranges from 15 to 17 cm and showed more than 2 yr^{-1} when L_c ranges from 18 to 30 cm (Fig. 3-2). Y/R with respect to varying L_c showed 905-1,244.7 g at current fishing regulation (F=0.48 yr^{-1}, NFRDI, 2005), and maximized to 1,244.7 g when L_c=17 cm (Fig. 3-3).

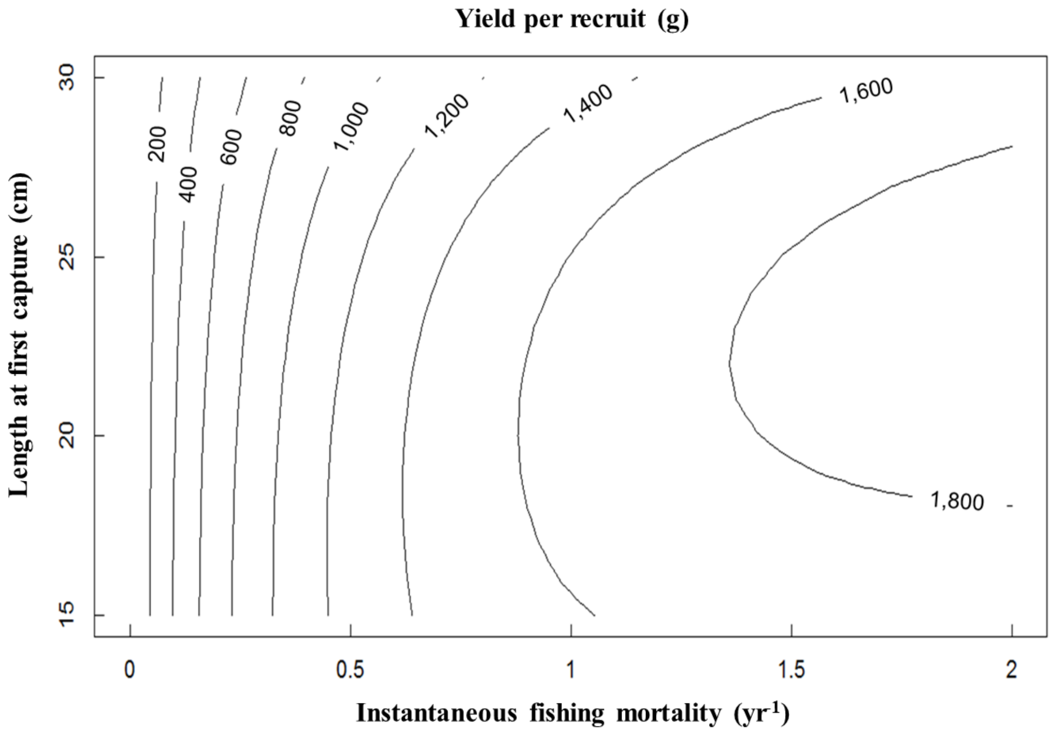

Fig. 3-1. Yield per recruit of chub mackerel *Scomber japonicus* with the varying length at first capture (L_c) and instantaneous fishing mortality (F) when water temperature is assumed to be 20℃ for the growth during the larval stage (< 1.5 cm in standard length).

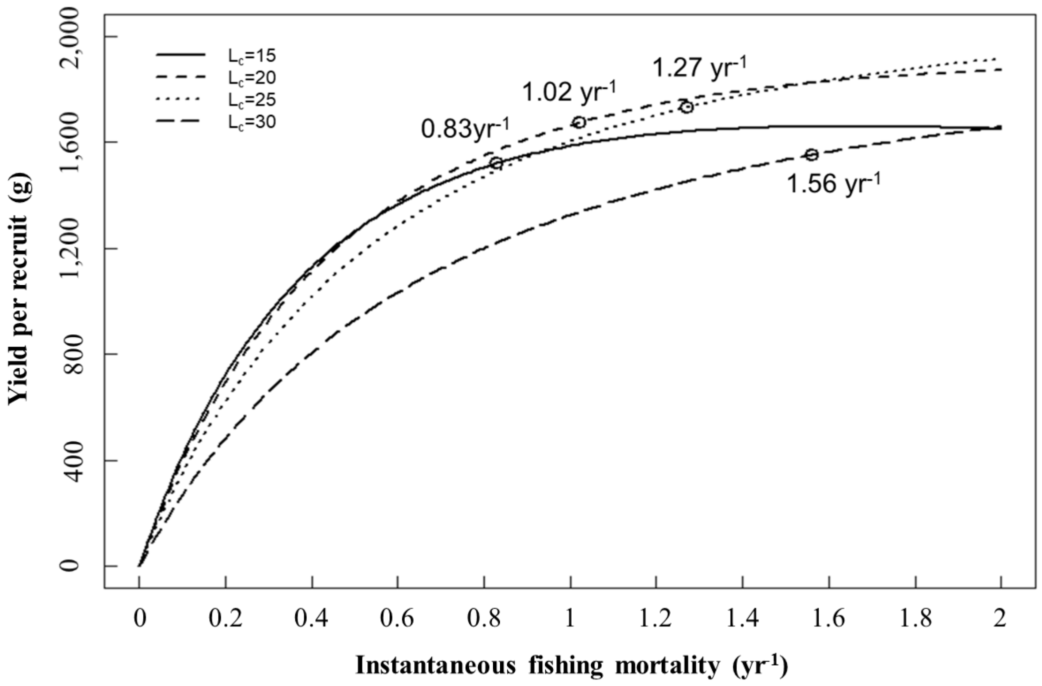

Fig. 3-2. Yield per recruit curve of chub mackerel *Scomber japonicus* varying with the length at first capture (L_c=15, 20, 25, 30 cm) and the corresponding values of $F_{0.1}$. $F_{0.1}$ is the value of F at which the corresponding slope of yield-per-recruit curve equals to the 10% of the initial slope at the origin (F = 0).

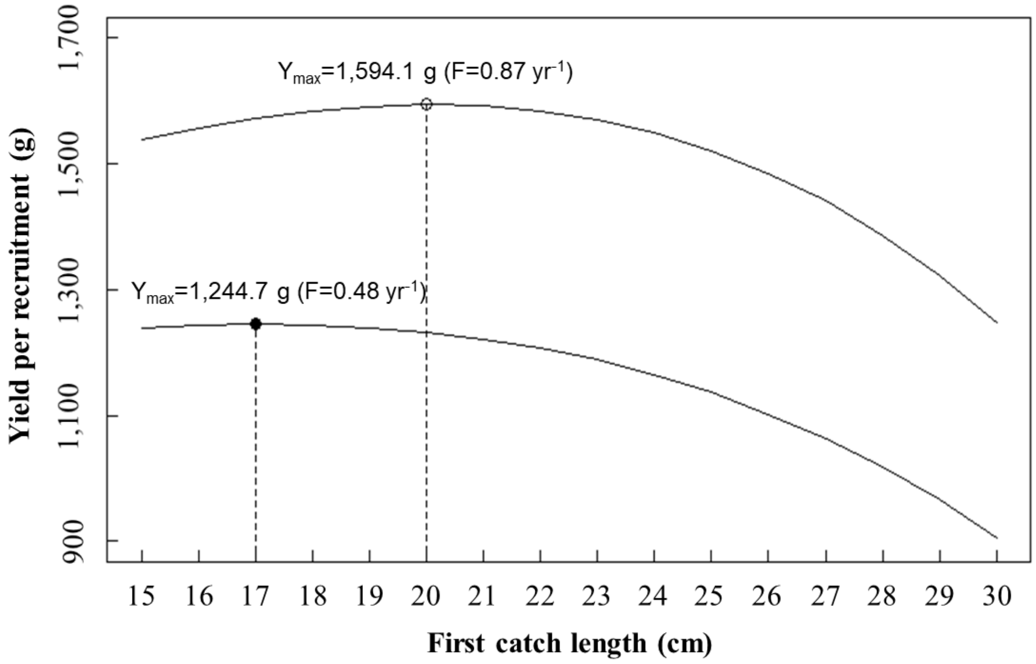

Fig. 3-3. Yield-per-recruits of chub mackerel *Scomber japonicus* at the reported fishing mortality of 0.48 yr^{-1} and 0.87 yr^{-1} with the varying length at first capture ranging from 15 to 30 cm in fork length. Y_{max} is the maximum yield.

Yield-per-recruit with respect to varying water temperature

At L_c=15 cm, on the temperature ranges from 15 to 23°C known as spawning water temperature (NFRDI, 2010), Y/R increased with increasing water temperature and F. Y/R showed 200-800 g when water temperature ranges from 15 to 18°C and maximized to 3,702 g when water temperature at 23°C (Fig. 3-4). At the lowest temperature of spawning at 15°C, $Y_{0.1}$ showed 208 g when F=0.83 yr^{-1} and Y_{max} showed 227 g when F=1.65 yr^{-1}. $Y_{0.1}$ and Y_{max} are yields corresponding to the instantaneous fishing mortality (F) at $F_{0.1}$ and F_{max}. At the suitable temperature of spawning at 17°C and 18°C, $Y_{0.1}$ showed 519, 765 g when F=0.83, 0.84 yr^{-1} and Y_{max} showed 567, 833 g when F=1.65 yr^{-1}. At the highest temperature of spawning at 23°C, $Y_{0.1}$ showed 3,390 g when F=0.83 yr^{-1} and Y_{max} showed 3,702 g when F=1.65 yr^{-1}. Yield at points of $F_{0.1}$ and F_{max} increased with increasing water temperature (Fig. 3-5).

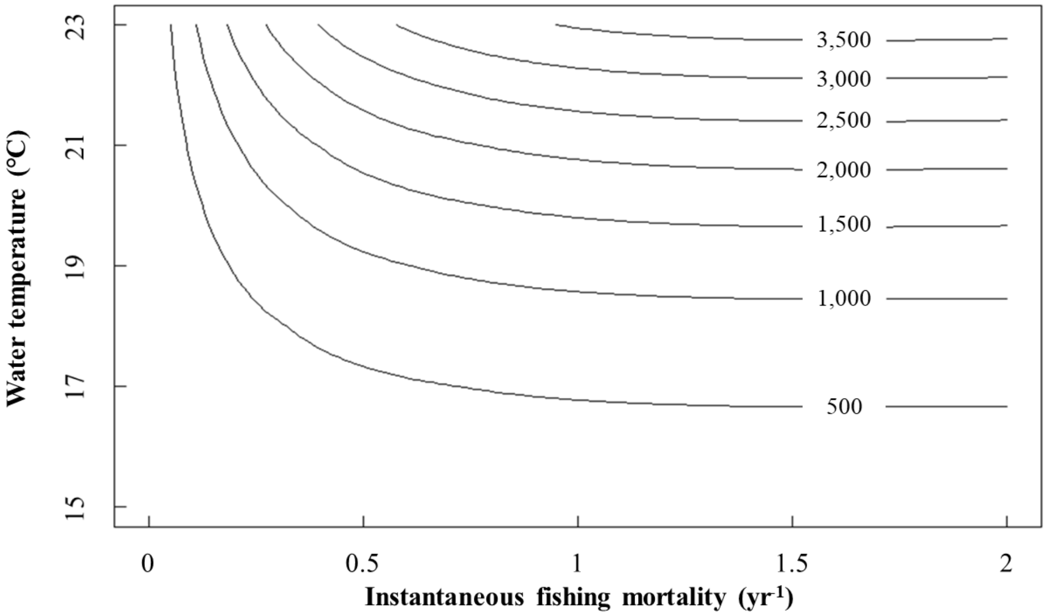

Fig. 3-4. Yield of chub mackerel *Scomber japonicus* with varying water temperature and instantaneous fishing mortality (*F*). when the length at first capture=15 cm and the maximum length of the larva, whose growth is assumed temperature-dependent, is assumed to be 1.5 cm.

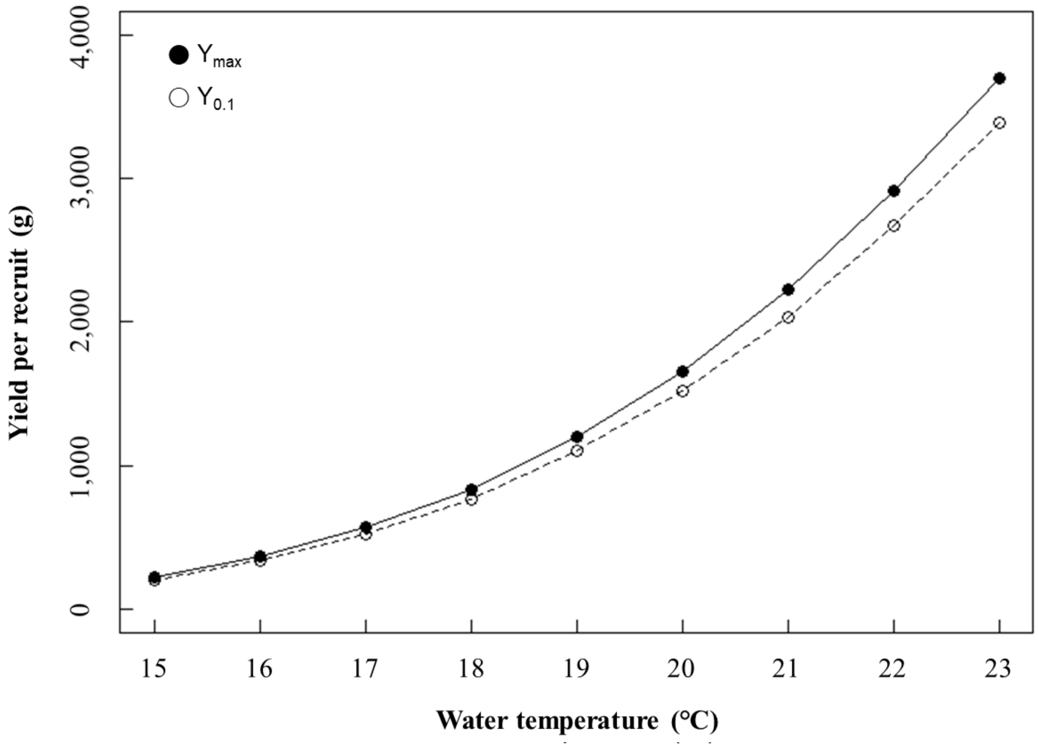

Fig. 3-5. Yield ($Y_{0.1}$ and Y_{max}) of chub mackerel *Scomber japonicus* with varying water temperature. $Y_{0.1}$ and Y_{max} are the yields corresponding to the instantaneous fishing mortality (F) are $F_{0.1}$ and F_{max}. $F_{0.1}$ is the value of F at which the corresponding slope of yield-per-recruit curve equals to the 10% of the initial slope at the origin (F=0). F_{max} is the value of F at which the yield-per-recruit is maximized.

Discussion

Comparison of yield-per-recruit with respect to varying first catch length

I estimated the Y/R, $Y_{0.1}$ and Y_{max} of chub mackerel with respect to varying L_c ranges from 15 to 30 cm and F ranges from 0 to 2 yr^{-1} using the past studies on biological characteristics of chub mackerel and yield-per-recruit analysis. Y/R was maximized to more than 1,800 g when L_c ranges from 19 to 28 cm and F ranges from 1.36 to 2 yr^{-1}. Y/R increased with increasing L_c when F was more than 0.36 yr^{-1}. At current instantaneous fishing mortality F=0.48 yr^{-1}, Y/R was maximized to 1,244.7 g when L_c=17 cm. L_c=17 cm showed 37 % high yield compared with L_c=30 cm when F=0.48 yr^{-1}.

Comparison of $F_{0.1}$and F_{max} with respect to varying first catch length

I evaluated the $F_{0.1}$ and F_{max} at L_c=15, 20, 25, 30 cm to compare the difference in yield with respect to varying L_c. $F_{0.1}$ showed the highest yield of 1.730 g when L_c=25 cm (F=1.27 yr^{-1}). Yield at $F_{0.1}$ increased between L_c=15 cm and 25 cm with increasing L_c, but it decreased at more than L_c=25 cm. F_{max} showed the highest yield of 1,659 g when L_c=15 cm (F=1.65 yr^{-1}). F_{max} at L_c=20, 25, 30 cm will be increased additionally with increasing L_c because it was expected to more than 2 yr^{-1}.

Estimation of suitable catch length and age of chub mackerel

I used VBGM of chub mackerel reported by Choi et al. (2000) and Hwang et al. (2008b) to estimate the age at L_c=17 cm who estimated the growth of chub mackerel from early to adult life stages using VBGM.

Age at L_c=17 cm was predicted to 0.4 and 1 age based on growth equation reported by Choi et al. (2000) and Hwang et al. (2008b). Age at L_c=17 cm using the growth equation applied in this simulation was estimated age 0.6 which showed slower growth than Choi et al. (2000) on the contrary faster growth than Hwang et al. (2008b). Thus, I expect that the maximum yield at F=0.48 yr^{-1} can be obtained when fishing from more than L_c=17 cm and age 0.6.

Comparison of first catch age for producing maximum yield-per-recruit

Choi et al. (2004b) reported that yield of chub mackerel was maximized when F=0.87 yr^{-1} and first catch age is 2.67 which showed 2.07 age higher than my result. I speculate that difference in first catch age for maximum yield was caused by difference in L_C. In Y/R simulation, L_C for maximizing yield increased with increasing F. Thus, I expect that L_C in the Choi et al. (2004b) study for maximum yield was high compare with my result (Fig. 3-3).

Comparison of yield-per-recruit with respect to varying water temperatures

In the spawning water temperature ranges from 15-23°C, yields were showed about 200 g when the lowest spawning temperature 15°C, and about 3,600 g when the highest temperature 23°C. Difference in yield was expected as a result of the difference in growth rate depending on a parameter α during the early life stages. Growth rate increased and the instantaneous natural mortality decreased when higher water temperature by Eqs. (2) and (9).

Thus, I expect that number of catch and yield will increase because of the instantaneous natural mortality decrease and growth rate increase with increasing water temperature.

Comparisons of $F_{0.1}$ and F_{max} with respect to varying water temperature at spawning ground

I compared yield at $F_{0.1}$ and F_{max} when water temperature at 15, 17, 18 and 23°C. $F_{0.1}$ and F_{max} showed 0.83-0.84 yr^{-1}, 1.65 yr^{-1} varying L_c. $F_{0.1}$ and F_{max} showed a constant value, however yield increased with increasing water temperature (Table 3-1, Fig. 3-4).

Yield at $F_{0.1}$ and F_{max} points showed 1,519.88 g ($Y_{0.1}$) and 1,659.27 g (Y_{max}) when averaged spawning temperature 20°C. $Y_{0.1}$ and Y_{max} will decrease about 86% when water temperature of spawning ground decreases to 15°C, while will increase about 123% when water temperature of spawning ground increases to 23°C (Fig. 3-5).

Table 3-1. Variation of $F_{0.1}$, F_{max} and $L_{c,max}$ with respect to varying water temperature condition (15, 17, 18, 23°C) during the early life stages of chub mackerel *Scomber japonicas*. $F_{0.1}$ is the instantaneous fishing mortality (F) at which the corresponding slope of yield-per-recruit curve equals to the 10% of the initial slope at the origin (F=0). F_{max} is the value of F at which the yield-per-recruit is maximized. L_c is the fork length at first capture and $L_{c,max}$ is the value of L_c at which the yield-per-recruit is maximized when F=0.48 yr^{-1} (NFRDI, 2005) and 0.87 yr^{-1} (Choi et al., 2004b).

Water temperature (°C)	$F_{0.1}$ (yr^{-1}) (at L_c=15 cm)	F_{max} (yr^{-1}) (at L_c=15 cm)	$L_{c,max}$ (at F=0.48 yr^{-1})	$L_{c,max}$ (at F=0.87 yr^{-1})
15	0.83	1.65	17 cm	20 cm
17	0.83	1.65	17 cm	20 cm
18	0.84	1.65	17 cm	20 cm
23	0.83	1.65	17 cm	20 cm

Comparison of L_c with respect to varying water temperature at spawning ground

I compared $L_{c,max}$ at F=0.48 yr^{-1} and 0.87 yr^{-1} when the water temperature 15, 17, 18, 23℃ to estimate the difference in L_c by water temperature. $L_{c,max}$ is the L_c at the point of maximized yield when F=0.48 yr^{-1} and 0.87 yr^{-1}. $L_{c,max}$ was estimated to 17 cm and 20 cm on the two fishing mortality. $L_{c,max}$ was constant regardless of water temperature, but yield at $L_{c,max}$ increased with increasing water temperature (Table 3-1). Variation of L_c to maximize the yield was affected by F than water temperature and it will increase with increasing F.

Limitations and problems

This study evaluated the suitable first catch length at the current fishing mortality, and compared with past studies. Choi et al. (2000) and Hwang et al. (2008b) evaluated the growth of chub mackerel larva and juvenile-adult stages using the VBGM, whereas I separately evaluated the growth of larval stage (Gompertz equation) and juvenile-adult stage (VBGM) using the growth equation considering the water temperature at spawning ground. Despite using the same data, estimated age of L_c=17 cm showed a difference in Hwang et al. (2008b) and this study. Thus, additional studies on Y/R and biological reference point such as first catch length and age using the growth equation divided by growth stages are needed to compare with result of this study.

Further studies

This study estimated Y/R with growth of initial population excluding egg reproduction by adult stage fishes. Therefore, additional studies are needed considering the spawning characteristic and reproduction process. I will assess Y/R including economic value of chub mackerel by length for 1) preventing overfishing of immature fish and 2) providing more detailed biological reference points to use the chub mackerel stock sustainably.

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General conclusion

Changes of catch, distribution and biological characteristic of fisheries resources are affected by climate change and fisheries. I evaluated the long-term changes in fish assemblages and relationship with climate change in the Korea Strait (Chapter 1). I also evaluated the yield of chub mackerel and anchovy by applying yield-per-recruit analysis to provide biological reference points and evaluate the current fishing level (Chapter 2 and 3).

Long-term changes in fish assemblages in the Korea Strait

Fish assemblage in the KS dramatically shifted in 1990-1991. Anchovy was dominant species in the KS from 1986 to 2010. Sardine and filefish were dominant species from 1986 to 1990, and thereafter chub mackerel and squid became dominant. Anchovy was mainly distributed near the Southeast coast of Korea and the pelagic fish species increasing after regime shift was mainly distributed from the Northern part of Jeju Island to the Southeast sea of Korea (Chapter 1).

Yield-per-recruit analysis of anchovy and chub mackerel

Y/R_{total} and Y/E_{total} of anchovy were evaluated on the two fishing conditions ($L_{c,min}$ and $L_{c,max}$) when F=0-0.05 day^{-1} and L_c=0-160 mm during 3 years. The summarized yield-per-recruit model to derive Y/R_{total} and Y/E_{total} is shown in Fig. A-1. On the fishing condition $L_{c,min}$, Y/R was maximized at 1.5-1.59 million tons when minimum fork length ranged between 42-60 mm and F was more than 0.03 day^{-1}. Y/R on the fishing condition $L_{c,max}$ was maximized at 0.8 million tons when minimum fork length ranged between 88-160 mm and F

was less than 0.02 day^{-1}. At the current fishing regulation at $L_{c,min}$=30 mm, annually-averaged catch of 0.22 million tons from 2000to 2016 was evaluated to 0.001 day^{-1} level. To reach maximum yield 1.31 million tons (F=0.028 day^{-1}), additional fishing effort is needed about 28 times. Fishing condition $L_{\mathrm{c,min}}$ showed higher Y/R$_{\mathrm{total}}$ and Y/E$_{\mathrm{total}}$ than $L_{\mathrm{c,max}}$.

Thus, I suggest that current fishing regulation of $L_{c,min}$ is more advantageous regulation to increasing yield and egg production of anchovy over the long term than $L_{\mathrm{c,max}}$. Additionally, I expect that even if the fishing effort is increased, more catches can be obtained without overfishing (Chapter 2).

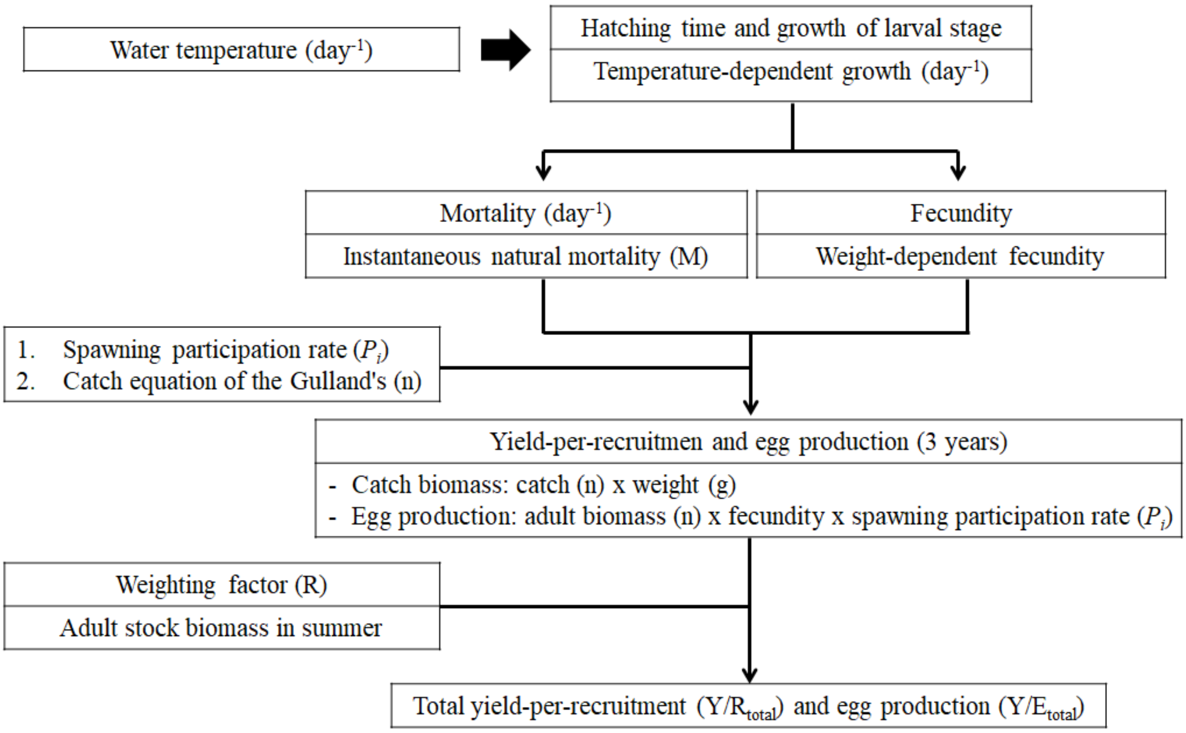

Fig A-1. Flower chart of yield-per-recruit analysis of anchovy.

The result of Y/R simulation of chub mackerel ranges from L_c=15-30 cm and F=0-2 yr^{-1} during 6 years was maximized to 1,830-1,925 g when L_c ranges from 19 to 27 cm and F ranges from 1.48 to 2 yr^{-1}. The yield at $F_{0.1}$ point considered as a biological reference point was maximized at L_c=25 cm ($F_{0.1}$=1.27 yr^{-1}, $Y_{0.1}$=1,730.65 g). At the current fishing level (F=0.48 yr^{-1}), I expect that the maximum yield can be obtained when L_c=17 cm and first catch age 0.6 (Chapter 3).

Correlation between changes in oceanic conditions and fish assemblage structure

Surface water temperature (0-20 m depths), KSBCW and bottom salinity (125 m) were significantly correlated with the local fisheries production and fish distribution (Chapter 1). Among the oceanic conditions, surface water temperature 1 year ago (0-20 m depths) showed highest correlation with changes in fish assemblage structure in the KS (Table 1-2 and Fig. 1-8). Detailed mechanisms were not detected relationship between KSBCW, bottom salinity and changes in fish assemblage structure. Thus, I speculate that changes in fish assemblage structure of the KS are most affected by surface water temperature.

Current fishing level of anchovy and chub mackerel in the Korea Strait

I expect that even if the current fishing effort in the Korea Strait was increased, more catches could be obtained without overfishing based on results of Chapter 2 and 3. Thus, despite the Northwest Pacific region known to show higher rate of fishing effort than other area, I evaluate that the current fisheries in the Korea Strait use the fisheries resource without overfishing.

Lastly, I conclude that change in fisheries resource at the current fishing level is more affected by changes in oceanic environment than fisheries based on results of chapter 1-3.

대한해협 수산 어종 장기 변동과 모의실험을 통한 멸치와 고등어 가입당 생산 분석

이경환

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요약

우리나라 연근해어업 생산량은 1970년 72만 톤에서 점차 증가하여 1986년 173만 톤으로 최대 생산량을 나타냈으며, 이후 최근까지 감소하여 90-100만 톤을 유지하고 있다. 과거 연구를 통해 수산자원 변동과 감소는 크게 기후변화에 따른 해양환경 변화와 남획에 영향을 받는 것으로 평가되었다.

해양환경 변화가 수산어종 분포에 미치는 영향을 평가하기 위해 해양환경 장기 변동을 어종별 분포 및 어획량 변동과 연결하여 평가하는 연구가 지속적으로 시도되고 있다. 우리나라 주변 해역을 대상으로 해양환경 변동이 수산어종에 미치는 영향을 평가한 연구에 따르면 1980년대 후반 해양환경 체제변환이 1990년 초에 나타난 쥐치류와 정어리 자원의 급격한 감소와 관련이 있는 것으로 나타났으며, 멸치-정어리의 주요 어종 교체 현상 또한 해양환경 변동과 연관되어 있는 것으로 나타났다. 일부 어종에 대해 가입당 생산량 분석과 같은 어획수준을 평가한 연구는 진행 되었지만, 어획과 어종별 자원량 변동의 관계를 뚜렷하게 평가하지 못해 남획이 우리나라 주요 수산어종의 자원량 감소의 원인으로 평가하기에는 부족하다.

따라서, 이 학위논문의 연구 목적은 1) 우리나라 주변 해역 중 대한해협을 대상으로 어류 군집 장기 변동과 해양환경 변동의 관계를 평가하고, 2) 대한해협 주요 수산어류 구분되는 멸치와 고등어를 대상으로 어류 자원의 지속적인 이용을 위한 생물학적 기준점을 제시하기 위해 가입당 생산분석을 적용하여 어획조건에 따른 가입당 생산량과 현행 어업수준을 평가하는 것이다.

대한해협 1986-2010년 우점종 변동과 해양환경 변동의 관계를 평가하기 위해 대응분석을 이용하여 연도별, 월별 우점종 변동과 어획지점에 따른 해구번

호별 어종 분포를 평가하고 정준대응분석을 이용하여 해양환경 변동이 연도별 우점종 변동에 미치는 영향을 평가하였다. 평가결과 대응분석을 통한 대한해협 어류군집은 1990-1991년 사이에 1번의 유의한 우점종 변동을 나타냈다. 1990s 초에 나타난 어류군집 우점종 변환을 기준으로 1986-1990년은 멸치, 쥐치, 정어리가 우점하는 것으로 나타났으며, 1991-2010년은 멸치, 고등어, 오징어가 우점하는 것으로 나타났다. 해구별 어종 분포 평가 결과 멸치는 남해동쪽 연안에 우점하는 것으로 나타나며, 고등어, 오징어, 갈치는 제주도 북쪽 해역에서 남해 동쪽으로 연결되는 가장 넓은 해역에 분포하는 것으로 나타났다. 정준대응분석을 통해 연도별 어류군집 변동은 표층수온 (0-20 m) 변동에 가장 큰 영향을 받는 것으로 나타났다.

멸치 연간어획량은 1992년 11만 톤 이후 2015년까지 19만 톤 이상의 어획량을 나타냈으나 2016년 11만 톤으로 감소하였다. 멸치의 가입당생산량을 평가하기 위해 수온 의존적인 성장과 체장 변화에 따른 자연사망률을 반영하여 알-성어 단계까지 평가하였다. 멸치는 1) 짧은 생애주기와 2) 빠른 성숙 연령, 3) 연중 산란하는 생물학적 특성 때문에 일반적으로 사용하는 Beverton and Holt (1957)의 방법을 적용 하기에 문제점이 있다. 따라서, 멸치 생물학적 특성과 Beverton and Holt (1957)의 방법을 고려한 모의실험을 통해 1) 순간어획사망계수(F)와 2) 어획개시체장(L_c) 변동에 따른 가입당생산량을 평가하였다. 또한, 현행 어업 규정으로 적용하고 있는 1) 미성어를 우선 보호하며 어획하는 최소어획체장($L_{c,min}$=L_c 이상의 개체를 어획 하는 경우)과 2) 성어를 우선 보호하며 어획하는 최대어획체장($L_{c,max}$=L_c 이하의 개체를 어획 하는 경우) 조건에 따른 가입당생산량을 평가하고 비교하였다. 평가결과 $L_{c,min}$가 42-60 mm 일 때 최대 가입당

생산량은 1.4×10^6 톤으로 나타냈으며, $L_{c,max}$가 88-160 mm 일 때 최대 가입당 생산량은 0.8×10^6 톤으로 나타났다. 현행 $L_{c,min}$ 규제 기준으로 보고된 30 mm일 때 최대 가입당생산량은 13.1×10^6 톤(F=0.028 yr^{-1})으로 1990-2016년 멸치 평균 어획량 2.2×10^6 톤(F=0.001 yr^{-1})과 비교하면 최대 생산량에 도달하기 위해 현재보다 약 28배의 추가적인 노력량이 필요한 것으로 평가된다. 어획조건에 따른 최대생산량 차이는 미성어를 보호하며 어획할 경우 성어를 우선으로 보호하며 어획하는 것 보다 약 1.9배 가입당 생산량이 높은 것으로 나타났다. 따라서, 미성어를 우선으로 보호하는 어획하는 최소어획체장 적용이 성어를 우선 보호하며 어획하는 최대어획체장 적용 보다 장기적으로 멸치 어획고를 증대시키는데 유리한 규제 방볍으로 평가되며, 지금보다 어획노력량을 늘려도 멸치 자원의 감소 없이 더 많은 생산량을 얻을 수 있을 것으로 평가된다.

고등어는 1999년부터 연간 어획할 수 있는 어획량을 설정하여 자원을 관리하는 총 허용어획량(total allowable catch, TAC) 대상 어종이다. 1970년대부터 1995년까지 연간 약 10-20만 톤의 어획량을 나타냈으며, 1996년에 약 42만톤까지 증가하였으나 2000년 약 15만톤 수준으로 감소하여 연도별 어획량 변동이 크게 나타났다. 고등어 자원의 적정 어획을 위한 생물학적 기준점($F_{0.1}$과 F_{max})과 현행 어획수준을 평가하기 위해 1) 수온을 반영한 초기 성장과 2) 체장 변화에 따른 자연사망률을 고려하여 Beverton and Holt (1957)의 가입당 생산량 분석 방법을 기반으로 한 1) 순간어획사망계수(F)와 2) 어획개시체장(L_c) 변동에 따른 가입당 생산량을 평가하였다. 평가결과 L_c=19-27 cm, F=1.48-2 yr^{-1}일 때, 약 1,830-1,925 g으로 최대생산량을 나타냈으며, L_c변동에 따른 $F_{0.1}$지점의 생산량은 L_c=25 cm, F=1.27 yr^{-1}일 때 1,730 g으로 가장 높은 생산량을 나타냈다.

산란 수온 범위로 알려진 15-23℃ 범위에서 수온이 높을수록 가입당생산량이 증가하는 것으로 나타났다. 현행 어업 수준인 F=0.48 yr^{-1}에서 고등어 가입당 생산량은 L_c=17 cm 일 때 가장 높은 생산량을 얻을 수 있을 것으로 나타났으며, 이 때의 연령은 0.6세로 평가되었다. 현행 고등어 어업 수준을 평가하기 위해 L_c=25 cm일 때 F=0.48 yr^{-1} 과 1.27 yr^{-1} ($F_{0.1}$) 지점의 생산량을 비교하면 F=0.48 yr^{-1}일 때 생산량(1,136 g)이 F=1.27 yr^{-1}일 때 생산량 보다 낮기 때문에 지금보다 어획노력량을 늘려도 고등어 자원의 감소 없이 더 많은 생산량을 얻을 수 있을 것으로 평가된다.

대한해협 어류군집 장기변동 평가결과 해양환경 요인 중 표층 수온 변동이 주요 어종 변동에 가장 큰 영향을 미치는 것으로 나타났으며, 멸치와 고등어 가입당 생산분석을 통해 현행 어업 수준에서 어획노력량을 늘려도 자원 감소 없이 더 많은 생산량을 얻을 수 있을 것으로 나타났다. 따라서, 현행 어업 수준에서 나타나는 수산자원 변동 및 감소는 어획보다 해양환경 변동에 더 큰 영향을 받는 것으로 예상된다.