What caused the collapse of walleye pollock population in Korean waters?

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ABSTRACT

Walleye pollock (pollock hereafter) in Korean waters was one of the most important fishery species economically, and the majority of population located in North Korean waters. Catch records have been changed dramatically since commercial fisheries begun in the early 20th century: the highest catch in 1930s, sudden decrease during 1940s~1960s, another boom in 1970s~1980s, and a continuous decrease in 1990s until they collapsed completely in 2000s. Three plausible hypotheses were introduced for such collapse: overfishing on pollock in high biomass period, warming of seawater, and changes in ecosystem structure and function. Those hypotheses reviewed would give us clues how Korean pollock population survive in ecosystem, and such theoretical backgrounds should be the basis for the establishment of conservation measures with precautionary concept when pollock return to Korean waters again. Intensive interdisciplinary collaboration between South and North Korea is recommended for predicting their re-visiting and for better management under changing environment.

Keywords: walleye pollock, fishery collapse, Korean waters, climate change, marine ecosystems

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1. Introduction

Walleye pollock Gadus chalcogrammus (pollock hereafter) is a semi-demersal species residing in cold and deep water of water column over the continental shelf and slope areas (> 200 m) along the Asian and North American coasts (NFRDI, 2010). In the northwestern Pacific, Korean Peninsular is regarded as the southern boundary of their distribution (Kim and Kang, 1998). Due to its enormous biomass, pollock is regarded as the most important fish species in North Pacific marine ecosystem ecologically. Pollock resource is frequently centered at marine foodweb, because they feed on zooplankton and small nekton, and many carnivorous predators such as Pacific cod, arrowth flounder, and stellar sea lion consume pollock (Incze et al., 1988; Kim and Gunderson, 1988). The statistics of the Food and Agriculture Organization (FAO) of the United Nations also indicates that commercial catch on pollock as a single species used to be the highest in the world (Kim, 1987).

Pollock is one of the important fish species culturally and economically in Korean history. Pollock has been an important seafood for Korean since the early 19th century (Park, 1978), and became a major commercial fishery from the early 20th century in Korean waters occupying two third of monetary value in total fishery production during the 1930s (Kang, 2009). Most fishing activities were carried out off the eastern coast of the North Korea until this time, but recent official catch records were only from the Republic of Korea (i.e., South Korea) due to the separation of political regimes after the completion of Japanese Imperialism in 1945. After the peak of pollock yield in the late 1930s, fishing activity was much depressed during the 1940s~1960s. Annual catches of pollock were increased again in 1970s, peaked in 1981 showing about 166 thousand metric tons (MT) of pollock production (Fig. 1). Mean pollock catch was 107 thousand MT during 1976~1985, which was equivalent to 44% of total fishery yield of the eastern coastal areas (Kang, Park, and Kim, 2013). The catch of pollock had shown a tremendous decline since the late 1980s through 1990s, and the pollock stocks were completely collapsed in Korean waters since 2000s.

Pollock was ubiquitous species in the East Sea, and maintained high biomass until the 1980s there. In general, about 7 million MT of pollock biomass were estimated in the entire East Sea during the early 1980s and the pollock biomasses as well as the fishery yields were higher in the western part than eastern one (Schuntov et al., 1993). The Wonsan Bay of North Korea was the most representative spawning ground in Korean waters (Fig. 2), and pollock fishery usually targeted on spawning population in winter actively. Areal distribution of pollock fishery in Korea, however, indicated that the strong fishing activity occurred even in the southern part of the Korean Peninsula during cold years such as 1980s. In the mid 1970s through mid 1990s when pollock resource was relatively high, the Korean government especially allowed fishermen to fish juvenile pollock (ages 1-2, called nogari or called small pollock in Korean statistics), and tremendous amounts of juveniles were caught in Korean waters during this period (Kang, Park, and Kim, 2013).

Biology and ecology of Korean pollock were not much investigated except some

basic information such as length-weight relationship, ageing, spawning and maturation (Park, Hue, and Kim, 1978 and 1979; Oh, Sakuramoto, and Lee, 2004). Due to the lack of quantitative analysis on feeding biology, ecology, growth rate estimation, and recruitment processes, the forecasting of stock condition was very limited. Only simple time-series analysis was carried out for the prediction of pollock catch (Park and Yoon, 1996). The investigation on ecological processes under changing environment is the essential part of fisheries oceanography to predict the year-class strength of future stocks.

Various sources of fishing information indicated that pollock stocks were much abundant in North and South Korean waters in 1980s (Schuntov et al., 1993; NRC, 1981; Kim and Kang, 1998). As mentioned above, pollock stocks were completely collapsed in 2000s, but no clear explanation on this collapse has been made. In this paper, therefore, we review the history and status of pollock fishery, and the distribution and migration patterns in the East Sea were speculated. Based on fisheries and ecological information, three hypotheses were introduced for explaining why pollock population collapsed in Korean waters recently. Reviewing such hypotheses would give us some clues how Korean pollock populations survive in ecosystem and how they interact with other species when they return to Korean waters again in the future.

2. Materials and methods

Fishery statistics and seawater temperatures from South Korea were analyzed using the data sets in the Korean Fisheries Yearbook and the Korea Oceanography Data Center of the National Fisheries Research and Development Institute, respectively. Additional information on local fisheries collected by the National Federation of Fisheries Cooperative was used for the temporal distribution of fishing areas in the western part of the East Sea. North Korean data reported to the FAO were excluded because of the reliability issue. The summary of biological characteristics of pollock was extracted from some early research papers that described the relationship between pollock catch, areal distribution and climate changes (Gong and Zhang, 1983; Kim, 1984; Kim and Kang, 1998). Note that most historic data and information were re-cited or re-examined from Park's pioneering works (Park, 1978).

3. Pollock in Korean history

Although there was no clear and precise description on pollock fishery in our history, it seemed to be started in the late Koryo Dynasty dating back to about 600 years ago, and the Korean's fishing history targeting on this species might be the longest in the world. Pollock has been called in different names in history books and folk tales. Mutaeo, which was thought as another name of pollock, was shown in 16th century history book, and the name Myung-Tae was shown in 17th century first time. The current official Korean name of pollock is Myung-Tae which appeared

firstly in history book, Sung-Jeong-Won-Il-Gi, published in 1652. The name Myung-Tae was originated as 'fished by Mr. Tae in Myung-Cheon Province' (Park, 1978). In Korean history for last 600 years, we could find some written records on presence/absence of pollock in a specific period. Pollock appeared in folk tales in 14th century, but no records were existed for 200 years (Fig. 3). Pollock has at least 20 different names and dialects currently, and various ways of cooking have been developed using all parts of pollock body (Kim, Kang, and Kim, 2014). Also, dried pollock is the necessity in memorial service for ancestors in ordinary family and for an exorcism by a shaman. Due to such a wide utilization of pollock in our common as well as dietary life, pollock became the intimate fish species for Korean in cultural aspects traditionally.

One history book (Song-Nam-Jab-Sik3 written by Jae-Sam Cho) indicated that pollock was shown in the Yellow Sea in 1858 (Park, 1978). Considering there are no pollock fisheries in the statistics from the Yellow Sea of the South and North Korea currently, we could infer that pollock moved into the Yellow Sea from the East Sea via off the southern coast of the Korean Peninsula. Even in our recent climate history over the Korean Peninsula, there were several events of 'little ice period' (Fig. 3). If the isotherms in ocean would move down to the south during these periods or the earlier period in the past, some fish species in the East Sea ecosystem might expand their territory to the Yellow Sea. In case of pollock, they became extinct due to possibly the unfavorable ocean environments or no suitable spawning and nursery grounds in the Yellow Sea, although Pacific cod, which is also the same gadoid group with pollock, is still important in the Yellow Sea fisheries. Fluctuation of fish biomass is a natural phenomenon, and the presence and absence of pollock resource has been repeated in Korean history books. On the other hand, climate over the Korean Peninsula also showed the alternation of cooling and warming phases over time. Figure 3 demonstrates the relationship between pollock resource and climate in Choson Dynasty (Kim, 1984). Roughly speaking, match and mismatch of catch record of pollock with climate variability indicates that cool temperature seems to provide a favorable condition for pollock stocks in Korean waters, and vice versa.

4. Distribution and migration of Korean stock

Pollock distributes the most coastal areas along the rim of the East Sea, and it is generally known that there are four major spawning stocks (Fig. 2) (Kim and Kang, 1998): the Tartar Strait (Russia), the Peter the Great Gulf (Russia), the western coastal areas off the Hokkaido and Honshu (Japan), and the Wonsan Bay (Korea). The spawning ground of the Wonsan Bay is regarded as the biggest among them. Different research, however, argued that three groups off the Japanese Islands and one in Korean waters consisted of pollock stocks in the East Sea (Oh, Sakuramoto, and Lee, 2004). Based on tagging experiment in 1932, on the other hand, the possibility of migration between the Wonsan Bay and the western Hokkaido was suggested, because 13 pollock out of 47,810 tagged from the Wonsan Bay were re-captured

off the Hokkaido coast later, and one pollock tagged from the Hokkaido was found near the Korean Peninsula (Gong and Zhang, 1983; Iwata, 1975).

It was speculated that pollock stock off the Korean Peninsula had two types of seasonal migration pattern: north-south and east-west migration. The north-south migration along the coastline indicates that they spawn at the Wonsan Bay during winter, and move up and down in north-south direction seasonally along the coast. Especially, the juveniles spawned at the Wonsan Bay during winter migrate into the southern waters for feeding and growth during spring through fall, and they return to spawning area in early winter. On the other hand, migration behavior of adults in the local areas off the South Korea showed the east-west migration which explains the spawning at coastal areas along the Korean coast during winter. After spawning, pollock spawners move to the deeper depth in open sea, and stay there until the next spawning period. However, it is believed that the population sizes of local stock would be small if there are some (Kang, Park, and Kim, 2013).

5. Three hypotheses for recent collapse

The collapse of pollock stock off the Korean Peninsula was one of the biggest disasters for Korean fisheries industry and fishers in the recent fishery history. Due to the practical difficulties to overcome the complicated political situation between the South and North Korea, there has been no intensive scientific investigations. Actually, the major spawning ground locates in the North Korea, and the limitation in oceanographic and fisheries surveys existed. Even there was no agreement on fisheries management and fishery data exchange between two regimes, so that no logical explanation on why Korean pollock population collapsed in recent years can be made. Here, based on observations from anthropogenic activity, environmental variability, and foodweb alteration, we introduce three plausible hypotheses for the collapse of pollock in 2000s: overfishing on pollock including juveniles and spawners in high biomass period, confined fishing areas with cold water mass off the coast in warm period, and changes in ecosystem structure and function.

5.1 Overfishing on pollock

Overfishing as an anthropogenic activity can deteriorate stock condition severely. One typical characteristic of the pollock fishery in Korea is the inclusion of immature juvenile pollock. Severe fishing pressure on juveniles was common during the 1975-1997 period, and therefore a large portion of pollock catch was juveniles. The proportion of juvenile pollock catch in weight was higher than 85~90% in the late 1970s, and it decreased continuously to 18% in 1988, then increased to 63% in 1990 (Fig. 4). The number of juvenile pollock caught from Danish seine and drift gill net fisheries during the same period, however, was 16 billion pollock occupying about 91.2% of total number caught (Kang, Park, and Kim, 2013). Such high fishing pressure on juvenile pollock might cause recruitment overfishing.

Because there was no bilateral agreement to protect straddling fish stocks between

the South and North Korea, no conservation measures were established for pollock stocks. In the North Korea, about half of total fishery production was from pollock fishery in the East Sea targeting on spawning adults to produce pollock roe. Pollock yields in the early 1980s reached at about one million MT with the peak of 1.8 million MT in 1983, and a sudden reduction to about 500 thousand MT was followed in the mid-late 1980s (Kim and Kang, 1998). Considering pollock yields from neighboring nations, overfishing on spawning stock seems to be obvious in the North Korea. Therefore, heavy fishing activities on juveniles and spawners in South and North Korea, respectively, might be one of the main reasons of pollock collapse.

5.2 Warming of seawater

Environmental variability is regarded as one of the major controlling factors for the distribution as well as the future recruitment of fishes. As we can see the appearance/disappearance of pollock species depending on climate conditions through Korean history (Fig. 3), recent warming trend of the East Sea might influence on pollock stock. Warming trend in the surface layer (0-50 m) was evident in winter (February) of the eastern Korea during the last four decades (1969-2008) (Seong et al., 2010). The increasing trend of sea surface temperature (SST) was clearly bigger in winter (0.047℃/year) than in summer (0.010℃/year) (Fig. 5a). Because pollock spawners move to shallow areas for spawning in Wonsan Bay, and eggs and larvae stay in the surface layer. Higher SST in main spawning season (i.e., winter) might affect the spawning behavior of pollock negatively. In Japanese waters, pollock decreased in abundance and the regions in which their abundance remained high became greatly reduced in extent during warm period (Tian et al., 2008). It has been frequently reported that the warming of the seawater temperature would be detrimental to stock's survival in the southern boundary of the species' distribution (Drinkwater et al., 2009; Rijnsdorp et al, 2009).

In Korean waters, there is a negative correlation between pollock catch and local seawater temperatures (Kim et al., 2007), which reveals that pollock as a coldwater species would have a difficult environmental situation due to warming of the East Sea. Although warming of the surface layer is conspicuous in the East Sea, deeper depth near the coastal areas where fishing activities on pollock were concentrated showed consistently low temperature forming a narrow cool band along the coastline (Chung, Kim, and Kang, 2014). Even, temperature at 100m depth showed a cooling trend in recent years (Fig. 5b), and pollock as a demersal species resides deeper than 100m. Therefore, the habitat temperature found in the coastal areas would be suitable for pollock regardless surface warming phenomenon during the last four decades. On the other hand, the fishing areas for pollock should be restricted to coastal areas apparently because pollock would avoid higher temperature in the open sea (Fig. 5c). Such narrow fishing zone may accelerate the depletion of remaining fishable pollock. For example, the spatial distribution of fishing areas on pollock varied depending on stock condition as well as water temperature. In 1970s, the period of high biomass and cool temperature, the fishing areas were spread over the relatively broad area, while those in 1990s and 2000s had been decreasing near the coastal areas as stock reduced and water temperature warmed (Fig. 6).

5.3 Ecosystem consideration

All life forms are linked by prey-predator relationship in marine foodweb. Climate change causes not only the changes in physical property of seawater but also the structure and function in marine ecosystems. Abrupt phase transitions of physical as well as biological components in marine ecosystem were frequently found in world ocean (Hare and Mantua, 2000; Hunt et al., 2011), and ecosystem function will be adjusted by the modification of ecosystem structure and productivity. In the North Pacific, there were two big climate regime shifts in 1976/77 and 1988/89, which resulted in changes of mixed layer depth (MLD), chlorophyll concentration, zooplankton biomass and fish abundance. Primary productivity in spring is determined by the relationship between the MLD and critical depth (Svedrup, 1953), and secondary productivity influence consequently on fish production through foodweb interaction, and the East Sea ecosystem also responded to those climate events (Kang, Kim, and Bae, 2000; Zhang et al., 2000).

Alternation of dominant fishery species had been reported from demersal species regime to pelagic one during the 1988/89 regime shift (Zhang et al., 2000). Historically, pollock and common squid have been important fish species in Korean waters and their catches showed oscillatory pattern of dominance related to water temperature (McFarlane et al., 2009; PICES, 2004). Roughly speaking, the combined catch of both species consisted of a half of total production from the eastern coastal fisheries (Fig. 7). For example, our estimation indicated that pollock catch accounted for 41.8% of total catch in weight during 1977-1986, while those from common squid only 10.6%. However, in 1987-1997, the proportion of pollock was dropped to 7.8%, but common squid became dominant species occupying 37.9% of total catches. Various ecological niches involve in ecosystem function, and the responses of marine populations including pollock to climate/environmental variability would be expressed by the trophodynamics in foodweb. Understanding the mechanism of this cyclic pattern in fish community, and the collapse and re-visiting of pollock population in Korean waters could be answered from the light of ecosystem changes.

6. Further consideration and suggestion

In order to predict stock condition and fishing availability with high precision, we need to improve our understanding on pollock ecology (de Young et al., 2010; Moloney et al., 2010). The recruitment mechanisms including vulnerability of pollock to climate change, prey-predator relationship and food availability under rapidly changing environmental conditions should be quantified through the process-orient and modeling works. As mentioned above, however, the different political regimes between South and North Korea hinder cooperative research at this moment. To improve ecological understanding on pollock, it is our hope that the political negotiation between South and North Korea can be achieved to utilize such valuable protein resource near future. Joint oceanographic research and data exchange in fisheries would be the first step toward this target. We also need a preparatory dialogue between policy-mak-

ing and science groups in case of revisiting of pollock populations in Korean waters.

Currently, adult as well as juvenile pollock were rarely found in Korean waters. Korean government has operated 'Stock rebuilding program of fishery resources' over 10 years in Korean waters. For the recovery of pollock resources, we need to establish awareness programs for ordinary and fisherman urgently to protect large spawning pollock that can produce more eggs. Furthermore, if pollock could appear in Korean waters once again, we need to establish the early-warning system to prevent overfishing situation by applying the strict conservation measures and the declaration of moratorium until stock condition becomes stable. The intensive interdisciplinary researches among related subjects, the establishment of ecosystem-based fisheries management, and the reliable estimation of total allowable catch (TAC) through scientific investigation are necessary actions for better management of pollock resource.

In general, the favorable temperature condition for coldwater species would be cool temperature. In 1970s~1980s, cool temperatures of surface layer prevailed off the east coast of the Korean Peninsula, and high anomaly of pollock catches was common (Kim et al., 2007). On the other hand, pollock catch was much reduced and common squid, which prefers warm temperature, became dominant since the 1990s when warm temperatures appeared. The water temperature in the region might be too warm for pollock since the early 1990s, and such uncomfortable conditions would be the main reason of their collapse. When the temperature becomes suitable for pollock stock, they might visit to Korean waters again near future (Bulatov, 2014). However, no mechanistic explanation has been made on the relationship between seawater temperature and recruitment success of pollock and common squid. We observed frequently in the past ecosystem history that coldwater species used to be flourish in warm temperature unless water temperature exceeds to a certain range. For example, pollock in the eastern Bering Sea showed the very strong year-class in 1978 when the warm water temperature was observed (Mueter et al., 2006).

A large range of uncertainty arisen from model structure and ecological parameters will result in vague conclusion on the expected impacts on ecosystem productivity. The future climate should be clearly projected in fine scale using global circulation models (GCMs) to predict marine ecosystems including fish resources (Hollowed et al., 2013; Kim et al., 2014). Generally speaking, due to the global warming, we expect that the East Sea would be warmed-up in this century continuously, as recent observations indicated a rapid warming of Korean waters (Belkin, 2009). The trend of climate change over the Korean Peninsula should be refined, and the GCMs with a delicate downscaling technique provide credible projections for the spatial distribution of regional ocean temperature. The uncertainty in GCM outputs on and the physical characteristics such as seawater temperature and salinity of its surrounding water should be reduced especially for the predicting the destiny of Korean pollock populations.

7. Acknowledgments

References

Belkin, I.M. (2009) Rapid warming of large marine ecosystems. Progress in Oceanography 81:207-213.

Bulatov, O. (2014) Walleye pollock: global overview. Fisheries Science 80:109-116.

Chung, S., S. Kim, and S. Kang (2014) Ecological relationship between environmental factors and Pacific cod (*Gadus macrocephalus*) catch in the southwestern East/Japan Sea. Animal Cells and Systems 17(5):374-382.

de Young, B., F.E. Werner, H. Batchelder, F. Carlotti, Ø. Fiksen, E.E. Hofmann, S. Kim, M.J. Kishi, and H. Yamazaki (2010) Dynamics of marine ecosystems: integration through models of physical-biological interactions. In: M. Barange, J.G. Field, R.P. Harris, E.E. Hofmann, R.I. Perry, and F.E. Werner (eds.) Marine ecosystems and global change. Oxford University Press, New York, pp.89-128.

Drinkwater, K.F., F. Mueter, K.D. Friedland, M. Taylor, G.L. Hunt Jr., J. Hare, W. Melle (2009) Recent climate forcing and physical oceanographic changes in Northern Hemisphere regions: A review and comparison of four marine ecosystems. Progress in Oceanography 81:10-28.

Gong, Y., and C.I. Zhang (1983) The walleye pollock (Theragra chalcogramma) stock in Korean waters. INPFC Ground Fish Symposium, Paper No. P-2. 27 p.

Hare, S.R., and N.J. Mantua (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47(2-4):103-145.

Hollowed, A.B., M. Barange, R. Beamish, K. Brander, K. Cochrane, K. Drinkwater, M. Foreman, J. Hare, J. Holt, S-I. Ito, S. Kim, J. King, H. Loeng, B. MacKenzie, F. Mueter, T. Okey, M.A. Peck, V. Radchenko, J. Rice, M. Schirripa, A. Yatsu, and Y. Yamanaka (2013) Projected impacts of climate change on marine fish and fisheries. ICES Journal of Marine Science 70(5):1023-1037.

Hunt, G.L., K.O. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E. Overland, P.H. Ressler, S. Salo and P.J. Stabeno. (2011) Climate impacts on eastern Bering Sea foodwebs: a synthesis of new data and an assessment of the Oscillating Control Hypothesis. ICES Journal of Marine Science 68(6):1230-1243.

Incze, L.S., C.M. Lynde, S. Kim, and R. Strickland (1988) Walleye pollock in the eastern Bering Sea. In W.S. Wooster (ed.) Species synopsis: Life history of selected fish and shellfish of the northeast Pacific and Bering Sea. Washington Sea Grant Publication, University of Washington, Seattle, USA. pp.55-69,

Iwata, M. (1975) Population identification of walleye pollock, *Theragra chalcogramma,* PALLAS), in the vicinity of Japan. Memoirs of the Faculty of Fisheries, Hokkaido University, 22:193-258.

Kang, J-s. (2009) The dispute over the pollock fishing spot in Hamkyeongnamdo under Japanese Imperialism: a controversy about motor boat. The Daegu Historical Review 96:85-115. (in Korean with English abstract)

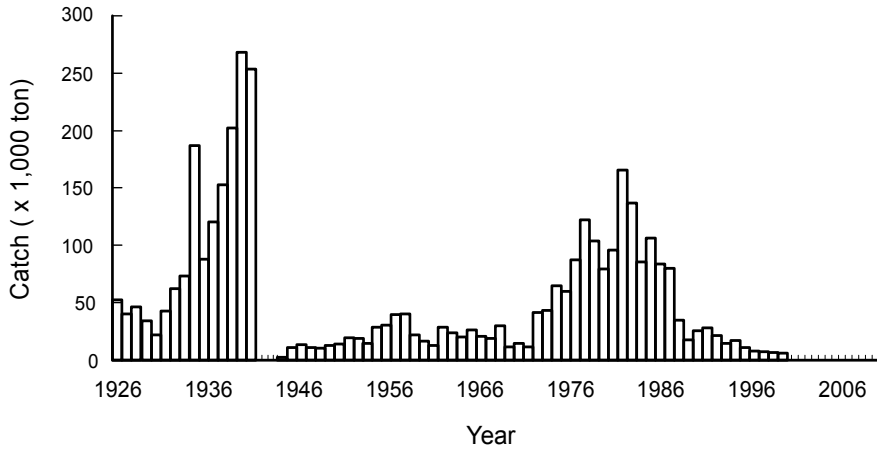Kang, S. S. Kim, and S.-W. Bae (2000) Changes in ecosystem components induced by

climate variability off the eastern coast of the Korean Peninsula during 1960-1990. Progress In Oceanography 47:205-223.

Kang, S., J.H. Park, and S. Kim (2013) Size-class estimation of the number of walleye pollock *Theragra chalcogramma* caught in the southwestern East Sea during 1970s-1990s. Korean Journal of Fisheries and Aquatic Science 46(4):445-453. (in Korean with English abstract)

Kim, D-H., S. Kang, and S. Kim (2014) Market and consumption of walleye pollock in Korea. Fisheries Science 80:213-218.

Kim, S. (1987) spawning behavior and early life history of walleye pollock, *Theragra chalcogramma,* in Shelikof Strait, Gulf of Alaska, in relation to oceanographic factors. Ph.D. Dissertation, University of Washington, Seattle, WA, 220 p.

Kim, S., and D.R. Gunderson (1988) Walleye pollock, Theragra chalcogramma, in the Gulf of Alaska. *In* W.S. Wooster (ed.) Species synopsis: Life history of selected fish and shellfish of the northeast Pacific and Bering Sea. Washington Sea Grant Publication, University of Washington, Seattle, USA. pp.70-82,

Kim, S., A.B. Hollowed, M. Barange, and B.R. MacKenzie (2014) ICES and PICES strategies for coordinating research on the impacts of climate change on marine ecosystems. Oceanography 27(4):160−167.

Kim, S., S. Kang, C-I. Zhang, H. Seo, M. Kang, and J.J. Kim (2012) Comparison of fisheries yield and oceanographic features at the southern boundaries of the western and eastern Subarctic Pacific Ocean. ICES Journal of Marine Science. 69(7):1141-1147.

Kim, S., and S. Kang (1998) The status and research direction for fishery resources in the East Sea/Sea of Japan. Journal of Korean Society of Fisheries Resources 1:44-58. (in Korean with English abstract)

Kim, S., C-I. Zhang, J-Y. Kim, J-H. Oh, S. Kang, and J.B. Lee (2007) Climate variability and its effects on major fisheries in Korea. Ocean Science Journal 42:179-192.

Kim, Y.O. (1984) Climate in Korea during the Little Ice Age. Journal of Geography and Geography Education 14:1-16. (written in Korean).

McFarlane, G.A., C. Zhang, J.R. King, S. Kim, R.J. Beamish, and J.H. Oh (2009) Contrast in life histories of commercially exploited marine fishes off the coasts of Canada and east Korea. Ocean Science Journal 44:43-60.

Moloney, C.L., A. Jarre, S. Kimura, D.L. Mackas, O. Maury, E.J. Murphy, W.T. Peterson, J.A. Runge, and K. Tadokoro (2010) Dynamics of marine ecosystems: ecological processes. In: M. Barange, J.G. Field, R.P. Harris, E.E. Hofmann, R.I. Perry, and F.E. Werner (eds.) Marine ecosystems and global change. Oxford University Press, New York, pp.179-218.

Mueter, F., C. Ladd, M.C. Palmer, and B.L. Norcross (2006) Bottom-up and top-down controls of walleye pollock (*Theragra chalcogramma*) on the Eastern Bering Sea shelf. Progress in Oceanography 68:152-183.

NFRDI. 2010. Ecology and fishing ground of fisheries resources in Korean waters. NFRDI SP-2010-FR-009. 405 p. (in Korean)

NRC (1981) Pacific pollock (*Theragra chalcogramma*) resources, fisheries, products and

markets. Natural Resources Consultants, A report prepared for the National Marine Fisheries Service Contract No. 81-ABC-00289, 131 p.

Oh, T-G., K. Sakuramoto, and S-G. Lee (2004) The relationship between spawning area water temperature and catch fluctuation of walleye pollock in the East Sea/Sea of Japan. Journal of Korean Society of Fisheries Resources 6:1-13. (in Korean with English abstract)

Park, B.H., J.B. Hue, and H.K. Kim (1978) Age and growth of Alaska pollack, *Theragra chalcogramma,* in the Eastern Sea of Korea. Bulletin of Fishery Research and Development Agency 20:33-42. (in Korean with English abstract)

Park, B.H., J.B. Hue, and H.K. Kim (1979) Spawning and maturity of Alaska pollack, *Theragra chalcogramma* (PALLAS), in the Eastern Sea of Korea. Bulletin of Fishery Research and Development Agency 22:33-38. (in Korean with English abstract)

Park, H-H., and G-D. Yoon (1996) Prediction of walleye pollock, *Theragra chalcogramma,* landings in Korea by time series analysis: AIC. Bulletin of Korean Society of Fishery Technology 32:235-240. (in Korean with English abstract)

Park, K-B. (1978) History of the Korean Alaska pollack fisheries. Theses Collection of National Fisheries University at Busan 20:25-51. (in Korean with English abstract)

PICES (2004) Marine Ecosystems of the North Pacific. PICES Special Publication 1, 280 p.

Rijnsdorp, A.D., M.A. Peck, G.H. Engelhard, and C. Mollmann (2009). Resolving the effect of climate change on fish population. ICES Journal of Marine Science 66:1570-1583.

Schuntov, V.P., O.S. Volkov, O.S. Temnikh, and E.P. Dulepova (1993) Walleye pollock in ecological systems of Far-Eastern Sea. Pacific Research Institute of Fisheries and Oceanography (TINRO), 426 pp. (in Russian)

Seong, K.T., J.D. Hwang, I.S. Han, W.J. Go, Y.S. Suh, and J.Y. Lee (2010) Characteristic for long-term trends of temperature in the Korean waters. Journal of Korean Society of Marine Environment and Safety 16:353-360.

Svedrup, H.U. (1953) On conditions for the vernal blooming of phytoplankton. Journal du Conseil Perm. Int. Explor. Mer. 18:287-295.

Tian, Y., H. Kidokoro, T. Watanabe, and N. Iguchi (2008) The late 1980s regime shift in the ecosystem of Tsushima warm current in the Japan/East Sea: evidence from historical data and possible mechanisms. Progress in Oceanography 77:127-145.

Zhang, C.I., J.B. Lee, S. Kim, and J.-H. Oh (2000) Climatic regime shifts and their impacts on marine ecosystem and fisheries resources in Korean waters. Progress In Oceanography 47:171-190.
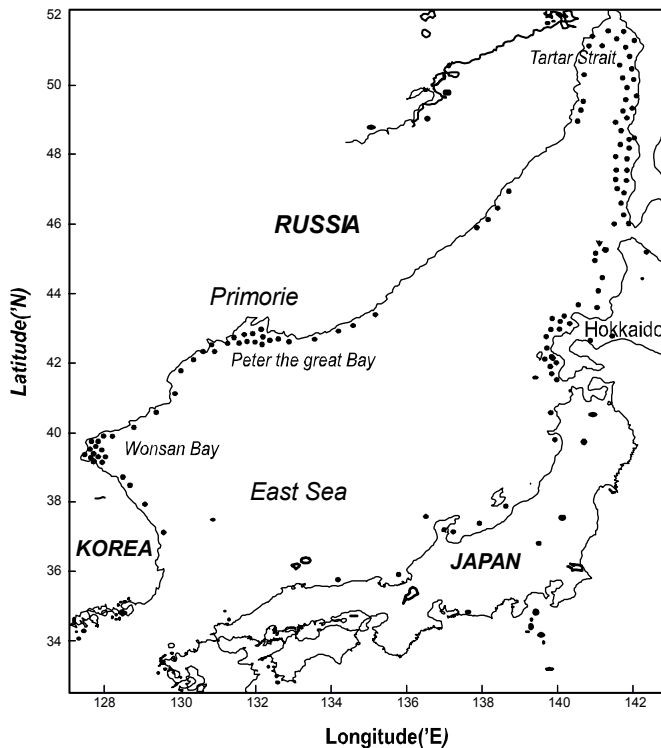
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Figure 1. Catch of walleye pollock (1926-2014). Notice that pollock catches in the first part of the 20th century were mostly from the North Korean waters, while those since 1946 were only from the South Korean waters.

Figure 2. Spawning areas of walleye pollock (Gadus chalcogrammus) in East Sea. Four major spawning stocks located in the Wonsan Bay, the Peter the Great Bay, Tartar Strait, and off the western Hokkaido, and several local stocks along the rim of the coast are indicated by dots (Kim and Kang, 1998).

Figure 3. Pollock records in various history books and Cooling Index (i.e., frequency of cooling events) during Choson Dynasty. Pollock records were drawn based on Park (1978), and Cooling Index was from Kim (1984).

Figure 4. Catch variability of walleye pollock adult and juvenile in Korean waters. (a) Relative catches in ton, (b) Relative catches in number, (c) Absolute catches in ton, and (d) Absolute catches in number (Kang, Park, and Kim, 2013).

Figure 5. Warming trend in sea surface temperature of the East Sea since 1968. (a) Sea Surface Temperature in February, (b) Water temperature at 100 m depth, and (c) Spatial distribution of temperature at 100 m depth (Seong et al., 2010).

Figure 6. Changes in fishing area of walleye pollock during 1970s~2000s.

Figure 7. Changes in species composition of two major commercial species from the eastern coastal fisheries of Korea.
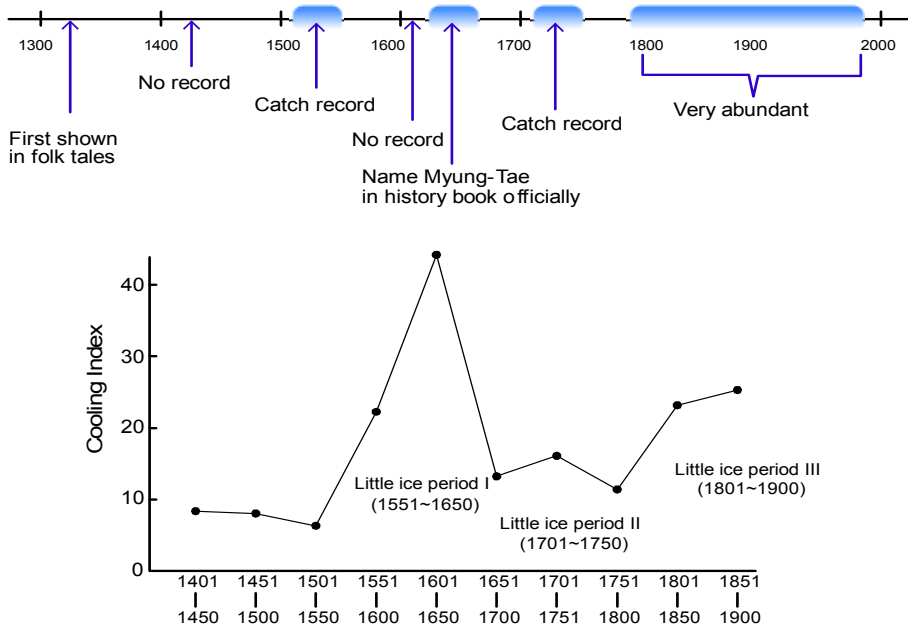
Figure 1. Catch of walleye pollock (1926-2014). Notice that pollock catches in the first part of the 20th century were mostly from the North Korean waters, while those since 1946 were only from the South Korean waters.
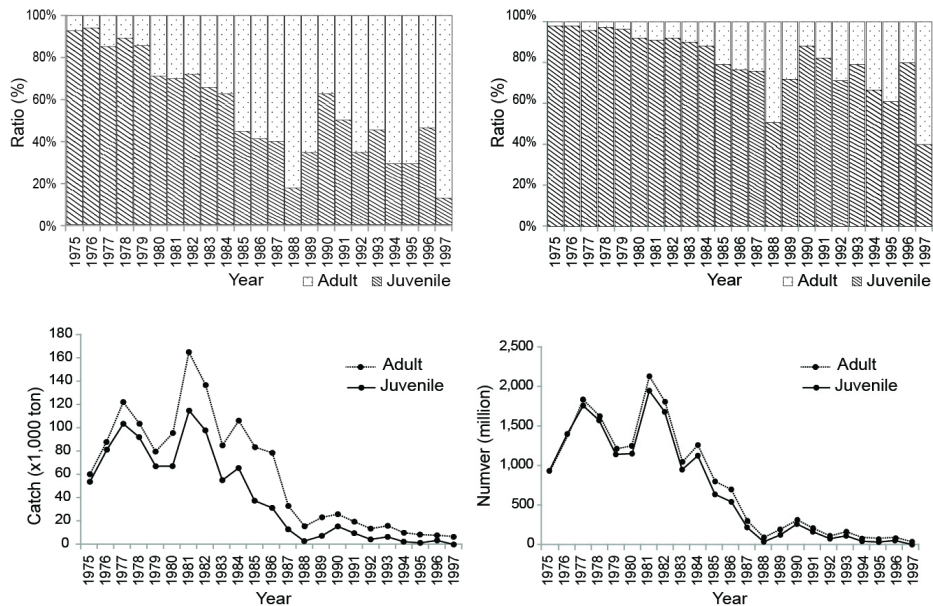

Figure 2. Spawning areas of walleye pollock (Gadus chalcogrammus) in the East Sea. Four major spawning stocks located in the Wonsan Bay, the Peter the Great Bay, Tartar Strait, and off the western Hokkaido, and several local stocks along the rim of the coast are indicated by dots (Kim and Kang, 1998).

What caused the collapse of walleye pollock population in Korean waters?   **55**
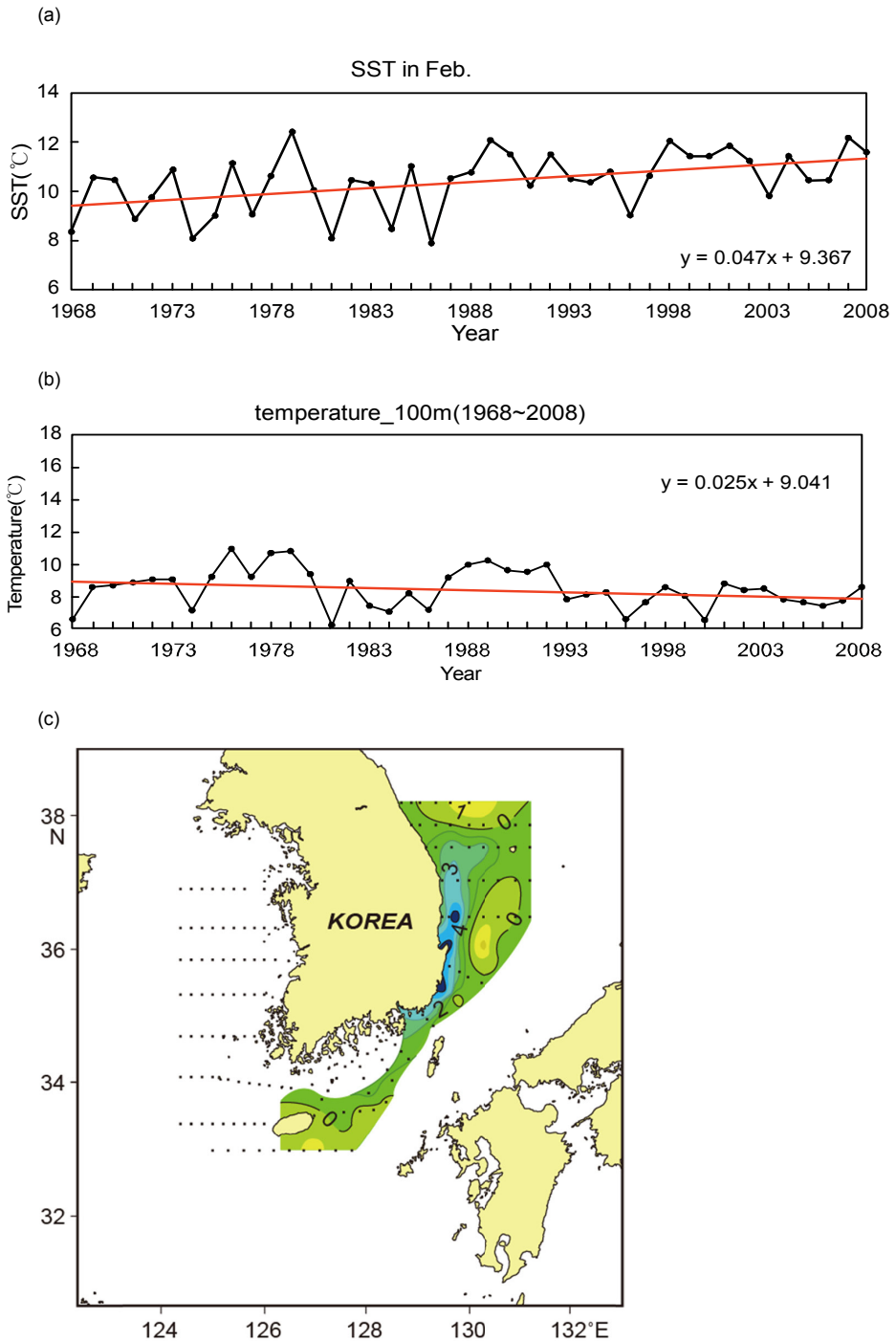
Figure 3. Pollock records in various history books and Cooling Index (i.e., frequency of cooling events) during Choson Dynasty. Pollock records were drawn based on Park (1978), and Cooling Index was from Kim (1984).
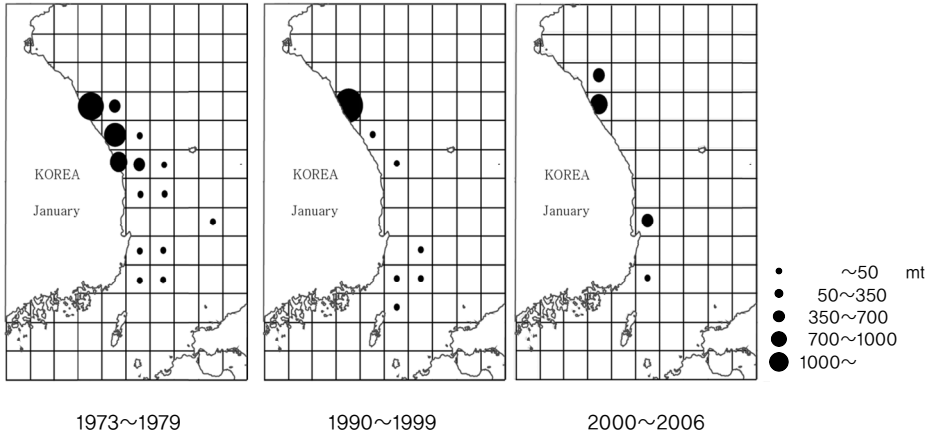

Figure 4. Catch variability of walleye pollock adult and juvenile in Korean waters. (a) Relative catches in ton, (b) Relative catches in number, (c) Absolute catches in ton, and (d) Absolute catches in number (Kang, Park, and Kim, 2013).

Figure 5. Warming trend in sea surface temperature of the East Sea since 1968. (a) Sea Surface Temperature in February, (b) Water temperature at 100m depth, and (c) Spatial distribution of temperature at 100m depth (Seong et al., 2010).

(a)

(b)

(c)

What caused the collapse of walleye pollock population in Korean waters?   **57**

Figure 6. Changes in fishing area of walleye pollock during 1970s~2000s.

1973~1979   1990~1999   2000~2006

Figure 7. Changes in species composition of two major commercial species from the eastern coastal fisheries of Korea