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The Long-Term Dynamics of Walleye Pollock Stocks in Relation to Oceanographic Changes in the East Sea

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Abstract: The decline in walleye pollock (*Gadus chalcogrammus*) stocks in Korean waters is a major concern for fishery conservation and management. However, the causes and mechanisms of this collapse remain unclear. This study investigated the complex dynamics influencing the abundance of walleye pollocks in the East Sea of Korea over several decades, by analyzing data from long-term changes in biological factors including composition of length and sex, catch, and oceanographic condition. Prior to the mid-1980s, the catch ratio of juveniles was higher than that of adults, with a higher proportion of females in both juvenile and adult catches compared to males. Especially, high fishing pressure on female individuals can be an important factor contributing to declining reproduction. Consequently, after the mid-1980s, there was a sudden decline in juvenile pollock catches. In the late 1980s, there was a rapid increase in sea surface temperature (SST) in the spawning grounds, resulting in a decrease in both the duration of suitable temperature for spawning and the regional proportion for suitable spawning conditions. Consequently, the decline in pollock stocks after the late 1980s due to overfishing of pollock in the mid-1980s was further exacerbated by the effects of SST warming after the late 1980s. These findings highlight the impact of overfishing and environmental factors on pollock stocks and indicate the need for appropriate fishery management practices to ensure the sustainable use of fishery resources.

Keywords: East Sea; walleye pollock; fisheries management; overfishing; oceanographic condition

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1. Introduction

Walleye pollock (*Gadus chalcogrammus*), referred to as "pollock" hereafter, is a semidemersal, cold-water species widely distributed across the North Pacific Ocean, ranging from Korea to the central coast of California [1,2]. As of 2020, the global annual pollock catch stood at approximately 3544 thousand tons, making it the second-ranked species in global fish catches [3]. Notably, fluctuations in the total catch of this species were higher than those of other demersal species [3]. Pollock plays a crucial role in the marine food web, acting both as a predator of zooplankton and small fish and as prey for demersal fish, seabirds, and marine mammals [4,5].

Long-term changes in pollock production worldwide have exhibited a decreasing trend since the late 1980s, attributed to global warming and overfishing of both juvenile and adult individuals [6–8]. However, pollock production in Japan and Russia has either remained stable or slightly increased after 2000 [8], while the pollock catch in the United

States and Canada, situated in the North Pacific, has not continued to decline since 2000 but has instead maintained a stable level [8]. In Korean waters, pollock fisheries have also undergone a drastic decline since the late 1980s, with catches plummeting below 1000 tons, nearly reaching extinction since 2000, in contrast to production in other countries [7–11].

Within Korean waters, the primary habitat of pollock is located in the southwestern part of its North Pacific distributional range, with the main fishing area situated in the western part of the East Sea [12,13]. During the 1970s and 1980s, pollock ranked as the second-largest catch among all fisheries in Korea. The pollock catch in Korea peaked in 1981 at approximately 170,000 metric tons but rapidly declined to a few hundred metric tons after the late 1980s [7,14]. Since the 2010s, pollock has ceased to be a commercial fishery resource in Korea, as catches fell below one metric ton [7,15,16]. To determine the cause of changes in catches of fisheries, it is essential to consider the simultaneous impacts of human activities such as overfishing and changes in the physical environment of habitats and spawning grounds. Recent studies aiming to understand the fluctuations in pollock catch have focused on changes in the oceanic and biological conditions around spawning grounds [9,17].

Donghan Bay (DB) in North Korea is the primary spawning ground for pollock in Korean waters [11,18]. Pollock aggregate to spawn during winter, from January to March, and the eggs released during this period remain in the surface layer [19,20]. The optimal spawning temperature associated with low mortality typically falls within the 2–5 °C range in the continental shelf area [9,21–23]. Following hatching, juvenile pollocks move from their vertical distribution to deeper layers as they grow [24,25], and their dietary preferences evolve, transitioning from mesozooplankton to mesopelagic fish, as evidenced by stomach content analysis [26,27]. Larger pollocks are generally found in deep water, characterized by consistently cold temperatures (below 5 °C) with minimal seasonal variation [28–30].

The collapse of pollock stocks poses a significant concern in the conservation and management of fishery resources, given its importance in commercial fisheries. Understanding the underlying causes and mechanisms of this collapse is crucial to mitigate the risk of further collapses in other fishery species. Previous studies have posited that overfishing and environmental changes in habitats due to climate change are the primary drivers of changes in pollock stocks. Three potential hypotheses have been suggested to elucidate the collapse of pollock stocks in Korean waters: (1) overfishing during periods of high biomass [11]; (2) ocean warming in their habitat grounds [7,9,10]; and (3) food availability impacting growth, survival, and recruitment [31,32]. However, these hypotheses are primarily based on simple correlation analyses of individual parameters affecting changes in total pollock catch, such as water temperature and zooplankton biomass [29]. Additionally, these hypotheses lack ecological information, such as size and sex composition, for each period. To gain a more comprehensive understanding of the drivers behind changes in fishery resource biomass, it is imperative to consider varying responses to oceanic conditions and overfishing at each life stage and their corresponding mechanisms [7,10,30].

To address this knowledge gap, this study aimed to analyze the responses of pollock stocks to changes in oceanic conditions in both spawning and habitat grounds and assess the impact of these ecological responses at each life stage on the collapse of pollock stocks. Our specific objectives were to: (1) identify the effect of spatial and temporal changes in the spawning ground; (2) analyze long-term shifts in ecological responses to oceanic conditions in the habitat using a long-term dataset (1970s, 1980s, 1990s, and recent years) that includes biological information on Korean pollock; and (3) investigate the causes underlying the accumulation of caught juvenile pollock and their effects on pollock resources. Based on our findings, we evaluated the potential mechanisms and causes underlying the collapse of pollock stocks in Korean waters.

2. Materials and Methods

2.1. Pollock Statistical Data

Long-term changes in the catches of adult and juvenile pollocks were estimated using data from the Korean statistical yearbook (Korean Statistical Information Service; KOSIS; https://kosis.kr/eng/ (accessed on 5 January 2023)). This yearbook does not provide information on the size of individual pollocks, and data on juvenile pollock catches are available only for 22 years, spanning from 1975 to 1997. Prior to 1975, pollock catch data were not categorized by age, and post-1997, fishing for juveniles was prohibited to preserve resources. Using this dataset, a correlation coefficient with a time lag was analyzed to ascertain the relationship between changes in adult and juvenile pollock catch.

2.2. On-Site Pollock Catch Data around the Main Fishing Ground in Korean Waters

Pollock sampling was conducted in the mid-eastern waters of Korea (Figure 1) during the winter months (January to March). Samples were collected using gill net fishery techniques over four distinct periods by the National Institute of Fisheries Science (NIFS): Period A (1973–1979), Period B (1980–1985), Period C (1991–1995), and Period D (2016–2018) (Table 1 and Appendix A). The total lengths (TL) and weights of the specimens were measured to the nearest 0.1 cm and 0.1 g, respectively (Figure 2). To determine changes in the catch ratio between adult (≥37 cm) and juvenile (<37 cm) pollock during each time period, a total length (TL) of 37 cm was adopted as the standard for differentiation [14,33]. To compare the differences in the biological condition between each period, the condition factor was calculated for each period using the formula: $K = 100\ W/L^3$ [34], where W and L represent body weight (g) and total length (cm), respectively. The age of the pollock was estimated using: $\text{Age} = (-\text{Ln}((654-\text{TL} \times 10)/654) - 0.0555716)/0.223$ [35].

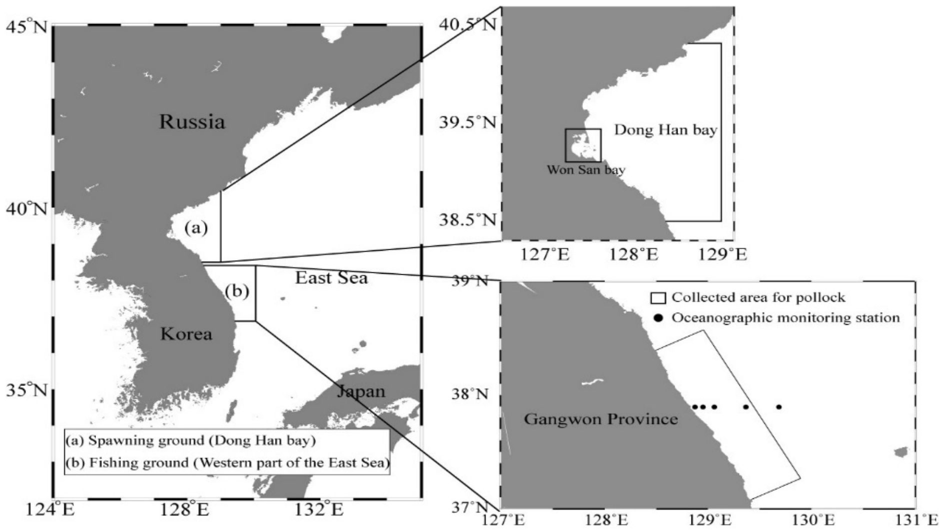

Figure 1. Map of the study area: (**a**) spawning ground, (**b**) sampling area of pollock specimens and oceanographic monitoring station.

Table 1. Number of specimens included in this study.

	Number of Specimens			
	Period A	**Period B**	**Period C**	**Period D**
Total specimens	1144	1118	795	834
Female	673	704	551	441
Male	471	414	244	393

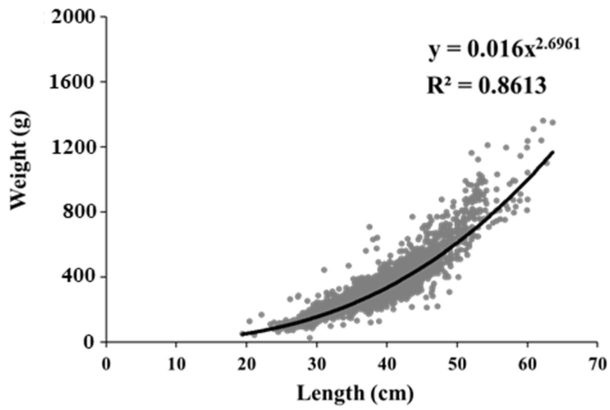

Figure 2. The length-weight relationship for pollock analyzed in this study (n = 3891).

2.3. Long-Term Changes in Oceanic Conditions around Spawning and Fishing Grounds

In situ observation data and satellite data were used to examine long-term trends in oceanographic conditions of fishing and spawning grounds. Oceanic conditions in the DB located in North Korea were obtained using satellite data sets for the periods from 1982 to 2022, while oceanic conditions in the fishing grounds located in the western part of the East Sea were acquired through in situ observation data for the periods from 1973 to 2018. The climate regime shift (CRS) that occurred in the late 1980s was associated with a step change in oceanic and atmospheric conditions in the Northern Hemisphere, such as the Arctic Oscillation (AO), Siberian High Pressure (SH), East Asian Winter Monsoon (EAWM), and El Niño-Southern Oscillation (ENSO). This shift is noted in graphs depicting longer-term changes in oceanic conditions and pollock catch [7,36–38].

The sea surface temperature (SST) around DB, recognized as a spawning ground for pollock in Korean waters, was analyzed using data from 1982 to 2022 from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) [39]. OSTIA provides daily global-scale sea surface temperature and sea ice data in a 0.05° lattice, which are reanalyzed for public consumption based on field observations of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) [40] and data from the Advanced Very High-Resolution Radiometer (AVHRR) (http://www.nodc.noaa.gov/SatelliteData/ (accessed on 5 January 2023)) as well as from Along-track Scanning Radiometer (ATSR) (http://neodc.nerc.ac.uk/ (accessed on 5 January 2023)). Most pollock spawn between January and March, with the eggs remaining in the surface layer after release as pelagic eggs [16,41]. The suitable temperature range for spawning grounds falls between 2–5 °C, considering the known optimal spawning temperature [21] and its correlation with low mortality [9,10,17,22,23]. Hence, changes in the spatiotemporal distribution of the spawning grounds were estimated using the following methods: (1) Assessing changes in the duration of suitable temperature (2–5 °C) for spawning (DTS) and its horizontal distribution at each decade using daily SST data, and (2) Analyzing long-term changes in the regional proportion for suitable spawning conditions (2–5 °C) (RPS) relative to the total area of DB.

To assess the long-term changes in oceanic conditions in the western part of the East Sea, recognized as a fishing ground for pollock in Korean waters (Figure 1), water temperature data from five fixed stations during winter (February) were collected from the Korea Oceanographic Data Center at the NIFS (https://www.nifs.go.kr/kodc/index.kodc (accessed on 10 March 2023)). This water temperature data is provided by year and standard depth (0 m, 10 m, 20 m, 30 m, 50 m, 75 m, 100 m, 125 m, 200 m, 250 m, 300 m, 400 m, and 500 m), and the water temperature in February during each period (period A, B, C, and D) was averaged by depth. Specifically, long-term changes in water temperature were analyzed in the upper layer (up to 100 m), intermediate layer (100–300 m), and bottom layer (greater than 300 m) to determine the relationship between changes in the water column structure and the size composition of pollock.

3. Results

3.1. Long-Term Changes in Catches of Juvenile and Adult Pollock

Long-term changes in the total catch of pollocks, based on the statistical yearbook, indicate a distinct regime shift. However, juvenile and adult pollocks exhibited different regime-shift timings (Figure 3). For juveniles, the total catch averaged 83,000 metric tons from 1975 to 1983. After 1984, it decreased rapidly to 11,000 metric tons (Figure 3a). Conversely, the total catch of adult pollock diverged from that of juveniles and has shown a decreasing trend since the late 1980s (Figure 3b). The correlation coefficient between juvenile and adult pollock catches suggests that fluctuations in juvenile pollock catches precede those in adult pollock catches by 3–4 years (Figure 3c). Thus, the high fishing pressure on juveniles was closely associated with decline in pollock resources. Additionally, sudden changes in oceanographic conditions of habitats and spawning grounds, combined with the effects of fishing pressure on immature fish, may further exacerbate the decline in pollock resources.

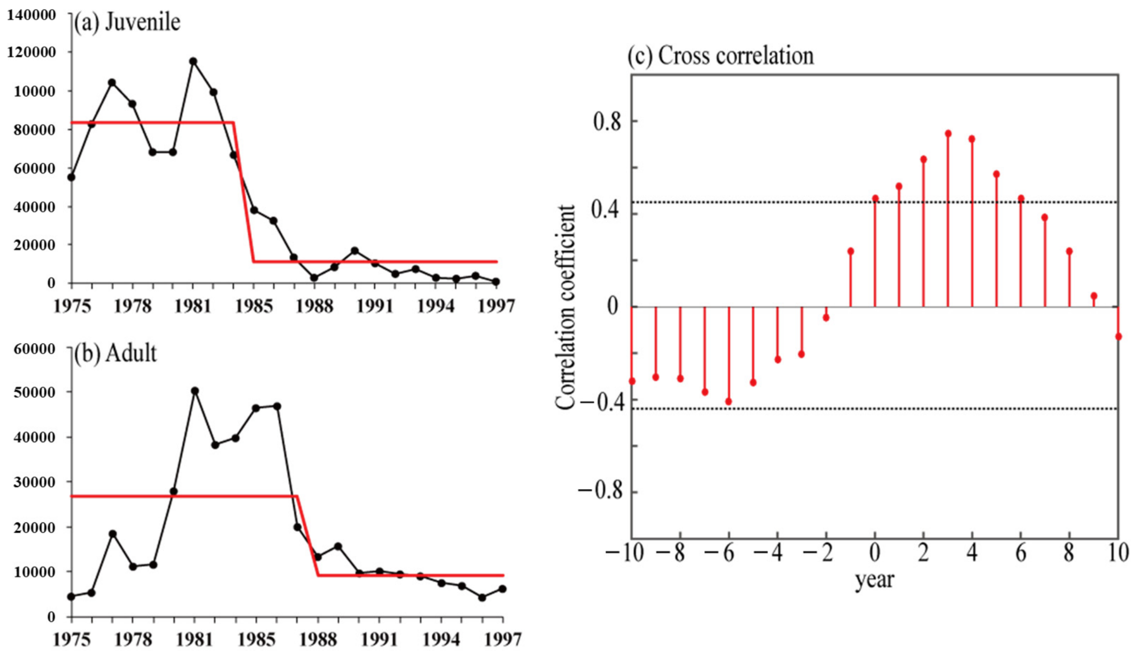

Figure 3. Long-term changes in catches of juvenile (**a**) and adult (**b**) pollock, and (**c**) cross-correlation between juvenile and adult pollock (The red line represents the step changes estimated by the sequential *t*-test analysis of regime shifts).

3.2. Long-Term Changes in the Sex Composition of Pollock

Long-term changes in the composition of juvenile and adult pollocks exhibited diverse patterns across different periods (Figure 4). Notably, the composition of females in the adult group remained consistently higher than that in the juvenile group throughout most of the experimental period (Figure 4). However, during certain periods, such as period C, the proportion of females in the adult group was notably lower compared to other periods (Figure 4). While the proportion of females in the juvenile group was relatively higher than that of males, females did not constitute a large proportion of the adult group (Figure 4).

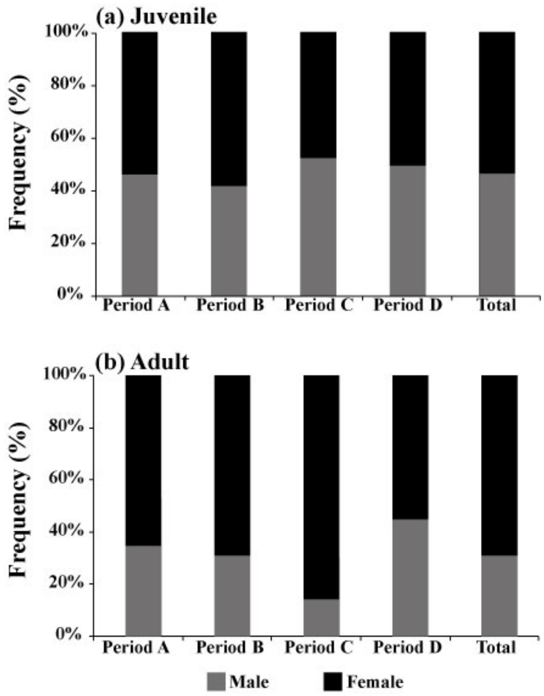

Figure 4. Composition of juvenile and adult pollock in the male (**a**) and female (**b**) groups in each period.

3.3. Long-Term Changes in the Size Spectrum and Condition Factor of Pollock

Long-term changes in the size composition exhibited distinct patterns during each period (Figure 5). During Period A, juveniles accounted for 57.7% of the population, whereas adults comprised 42.3%. Notably, the size composition exhibited a single-peak curve, with the highest representation observed in the 34–37 cm size group (41%) (Figure 4). In Period B, a similar trend was observed, with a higher proportion of juveniles (57.1%) than adults (42.9%). A single-peak curve characterized the size distribution, with the most significant proportion found in the 36–39 cm size range (52.2%). However, in Period C, a different pattern emerged compared to Periods A and B. The proportion of juveniles decreased by 43.2%, whereas that of adults increased by 56.8% (Figure 5). The size spectrum displayed a bimodal curve with peaks at 28–29 cm (8.8%) and 42–43 cm (16.1%). Finally, during Period D, the composition of juveniles and adults became more balanced, with juveniles representing 51.1% and adults representing 48.9% of the population. The size distribution exhibited a bimodal curve with peaks at 28–31 cm (25.8%) and 40–43 cm (15.5%) (Figure 5). Additionally, the proportions of individuals smaller than 30 cm and larger than 50 cm was 19.4% and 10.8%, respectively, which were higher than those of other periods (Figure 5).

The condition factor, a metric reflecting both the weight and length of pollock and serving as an indicator of energy storage, provided insights into the biological state of pollock over time (Figure 6). Across Periods A, B, and C, the condition factor remained relatively stable, exhibiting consistent values ranging from K = 0.51 to 0.53 and standard deviations from 0.8 to 0.1. Notably, Period B stood out with the lowest recorded value of 0.51, indicating potential fluctuations in the energy reserves of the pollock during that period (Figure 6). However, in Period D, there was a slight increase in the condition factor, with a rise to K = 0.6, suggesting a potential improvement in the biological condition of the pollock. This increase was accompanied by a maintained standard deviation of 0.1, indicating a consistent trend within the observed data (Figure 6).

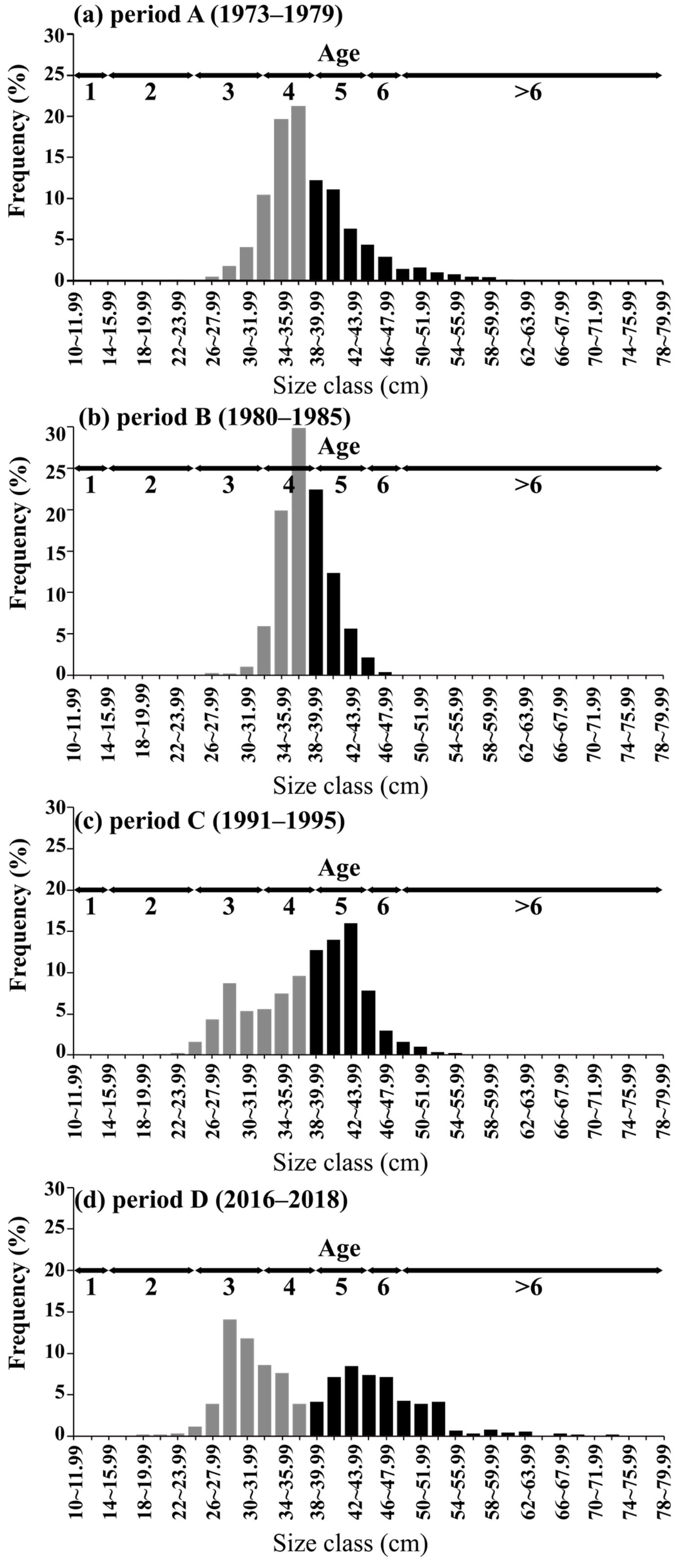

Figure 5. Size spectrum of pollock in each period. (The gray and black vertical bars indicate the juvenile and adult groups, respectively).

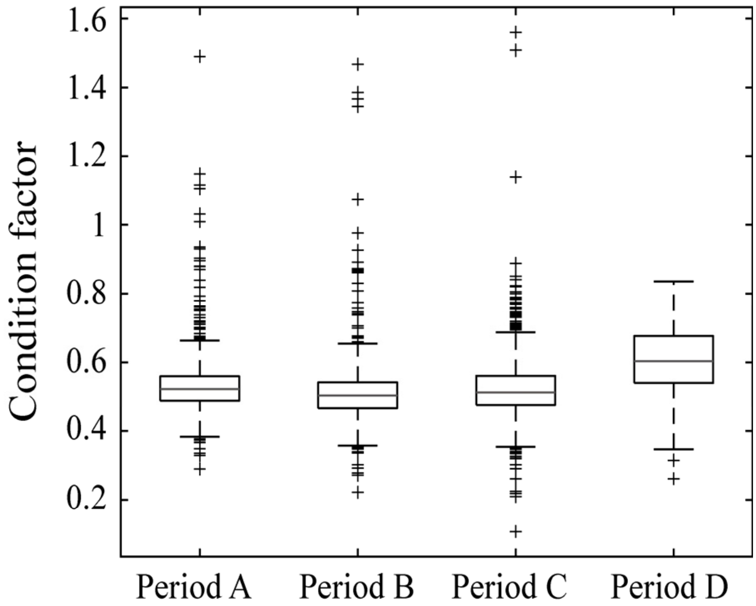

Figure 6. Condition factor for pollock in each period.

3.4. Water Temperature Structure in the Western Part of the East Sea

In the western part of the East Sea, the vertical water temperature structure varied across different time periods, showing distinctive patterns in the changes in the intensity of stratification and the temperature difference between the upper layer (0–100 m) and intermediate layer (100–300 m) during each period (Figure 7).

During Period A, the water temperature in the upper layer ranged from 5.9 to 8.8 °C, with average temperatures of 7.5 °C in the coastal area and 8.4 °C in the offshore area (Figure 7a). In the intermediate layer, the water temperature ranged from 1.4 to 6.8 °C, with average temperatures of 3.1 °C in the coastal area and 4.3 °C in the offshore area (Figure 7a). In Period B, the water temperature in the upper layer exhibited a greater decrease (3.5–8.4 °C) compared to Period A, with average temperatures of 6.2 °C in the coastal area and 7.5 °C offshore (Figure 7b). The intensity of stratification was weaker than that in Period A, and the water temperature in the intermediate layer was the lowest among all periods (Figure 7b). In the intermediate layer, the water temperature ranged from 0.9 to 6.5 °C, with average temperatures of 1.9 °C in the coastal area and 2.8 °C offshore (Figure 7b). During Period C, the water temperature in the upper layer increased rapidly (4.0–9.3 °C) compared to Period B, with average temperatures of 7.7 °C in the coastal area and 8.7 °C offshore (Figure 7c). The intensity of stratification was stronger than that in Period B. In the intermediate layer, the water temperature ranged from 1.4 to 7.2 °C, with average temperatures of 2.6 °C in the coastal area and 4.7 °C offshore (Figure 7c). In Period D, the water temperature in the upper layer ranged from 2.7 to 10.1 °C, with average temperatures of 7.6 °C in the coastal area and 9.5 °C offshore (Figure 7d). In the intermediate layer, the water temperature ranged from 1.1 to 5.8 °C, with average temperatures of 1.9 °C in the coastal area and 2.9 °C offshore (Figure 7d). Notably, the water temperature in the deep layer (≥300 m) did not exhibit significant changes and remained consistently below 2 °C throughout all the periods (Figure 7d).

Long-term observations of the vertical water temperature structure in the ground habitat revealed varying fluctuations between the upper and intermediate layers. Notably, in the 1980s (Period B), the water temperature in the upper layer was lower than that of other periods. Subsequently, there was a continuous upward trend in the water temperature in the upper layer. In contrast, the water temperature in the intermediate layer decreased during Periods C and D (Figure 8).

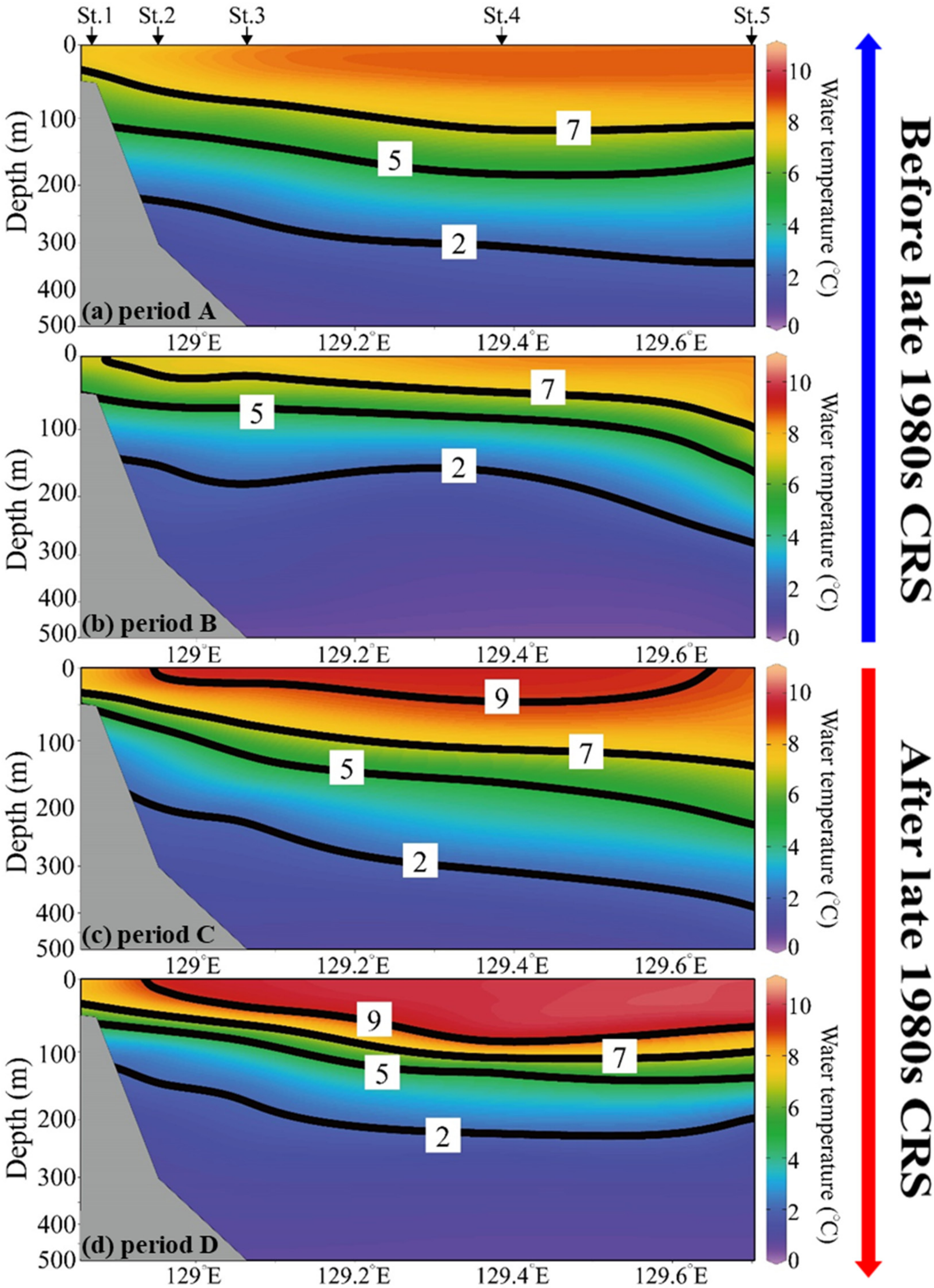

Figure 7. Vertical structure of water temperature in the western part of the East Sea in each period.

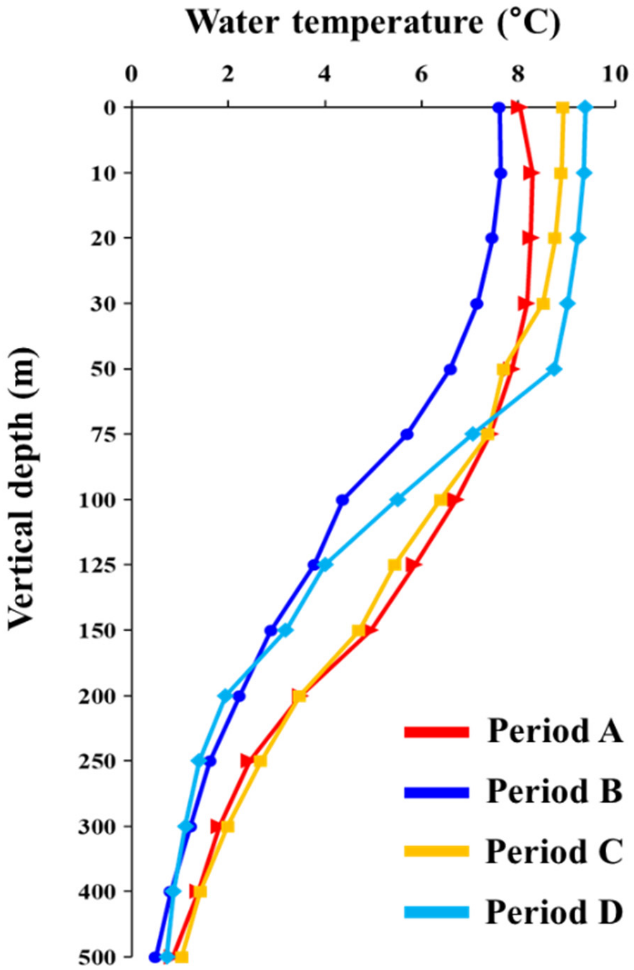

Figure 8. Vertical profile of water temperatures in the western part of the East Sea in each period.

3.5. Long-Term Changes in Oceanic Conditions of the Spawning Ground

The monthly variations in SST in the pollock spawning ground showed a decreasing pattern after December, reaching its lowest values in January and February (Figure 9).

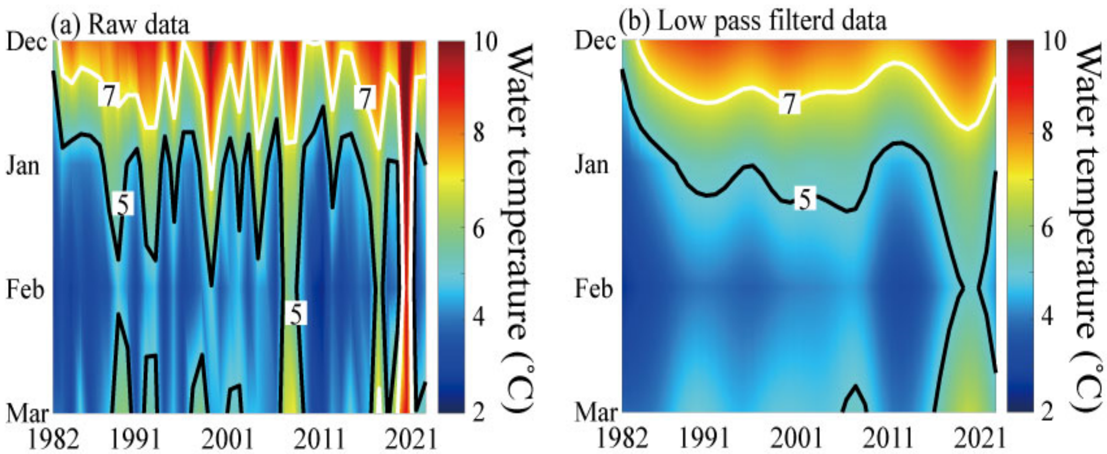

Figure 9. Long-term changes in sea surface temperature (SST) in the spawning ground.

From 1982 to 2022, the SST in December ranged between 5.5 °C and 12.2 °C (mean 8.2 °C) and did not provide a suitable temperature range for spawning (2–5 °C). The SST decreased continuously after December. In January and February, SST ranged between 3.2–10.5 °C (mean 4.8 °C) and 2.3–9.1 °C (mean 3.9 °C), respectively (Figure 9). The SST slightly increased from March onward, ranging between 2.9–9.1 °C (mean 4.8 °C) (Figure 7). The winter SST around the spawning grounds showed a consistent increase. Suitable oceanic conditions for spawning were observed from January to March after the 1990s, and from February to March after the 2010s. Additionally, due to the rising SST, the duration of temperatures exceeding 7 °C has expanded from December to January. These fluctuation patterns were related to changes in the duration of the formation of suitable oceanic conditions for spawning (Figure 9).

3.6. Long-Term Changes in the Duration of Suitable Temperature for Spawning (DTS) and Regional Proportion for Suitable Spawning Conditions (RPS)

Up to 1987, the DTS spanned approximately 79 days (Figure 10). However, after 1988, this duration reduced to approximately 45 days, attributable to a rapid increase in SST. From 2010 onward, the DTS exhibited an upward trend for approximately 68 days before experiencing a sharp decline in late 2010 (Figure 10). The horizontal distribution of DTS also exhibited different fluctuation patterns across different periods (Figure 11). During the 1980s, the primary locations with DTS exceeding 70 days were distributed across a broad area encompassing the inshore and northern parts of the DB, including Wonsan Bay (Figure 11). In contrast, in the 1990s the principal area with DTS surpassing 70 days witnessed a rapid decline and shifted to the northern part of the coastal zone within the DB. These regions expanded during the 2000s with a decrease in SST and were situated in the northern coastal area of the DB (Figure 11). In the 2010s, these regions were located in the northern part of the DB. However, in the 2020s, these regions were not included in the DB (Figure 11). Variations in RPS were also linked to changes in SST (Figure 12). Prior to the late 1980s, RPS constituted approximately 56.9% of the total DB area; subsequently, it rapidly declined to approximately 28.6% after the late 1980s. Following the late 2000s, the RPS increased again to 51.6%; however, after the late 2010s, it decreased to 17.9% (Figure 12).

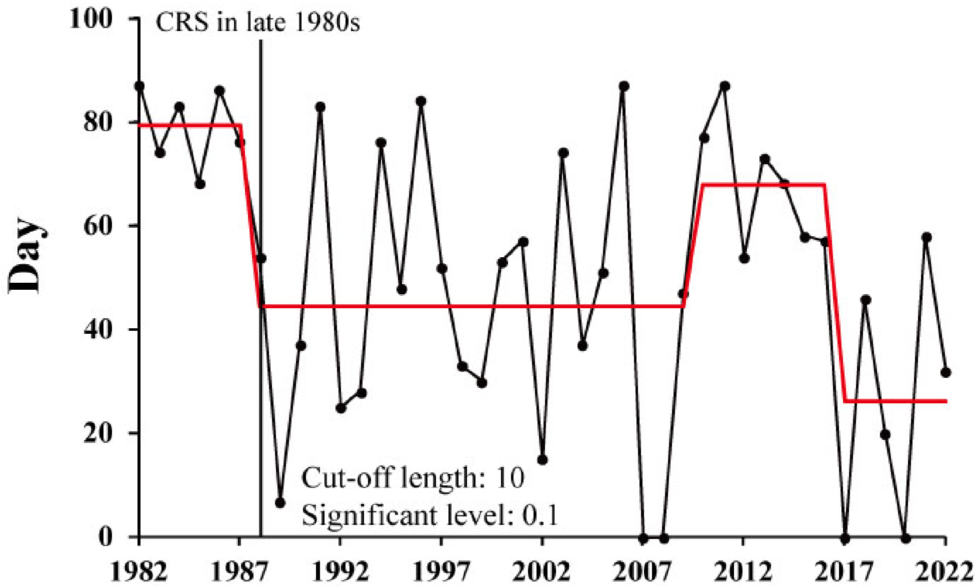

Figure 10. Long-term changes in the duration of suitable temperature for spawning (The red line represents the step changes estimated by the sequential t-test analysis of regime shifts).

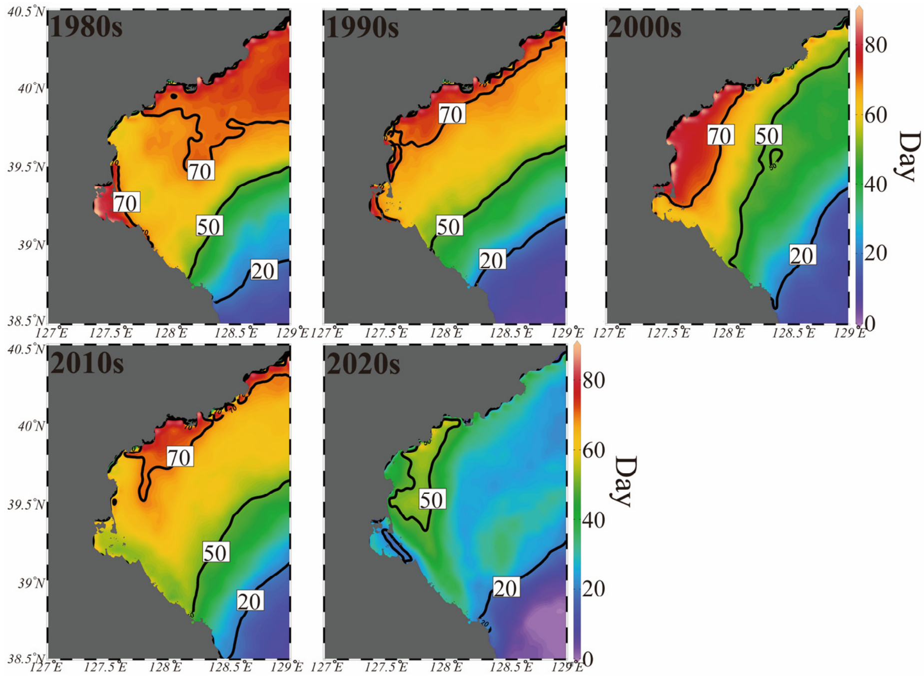

Figure 11. Horizontal distribution of the duration of suitable temperature for spawning (DTS) in each decade. (The number indicates the duration of suitable temperature for spawning measured in days).

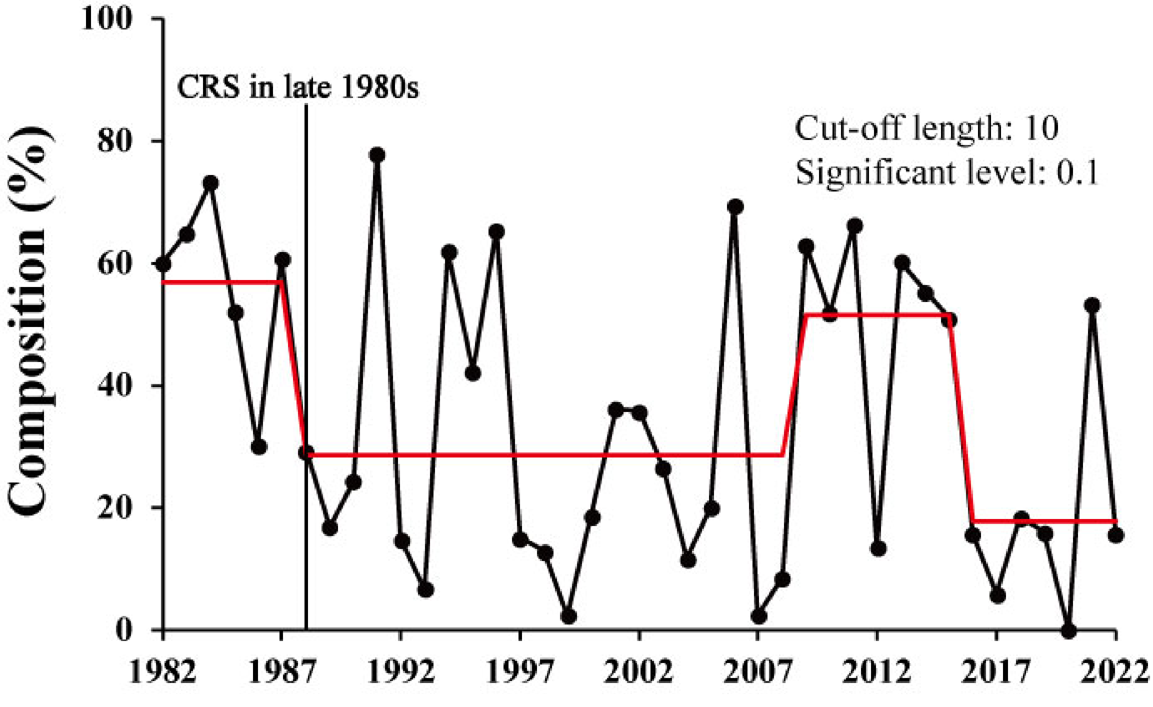

Figure 12. Long-term changes in the regional proportion for suitable spawning conditions (The red line represents the step changes estimated by the sequential t-test analysis of regime shifts).

4. Discussion

The collapse of the pollock fishery was simultaneously influenced by anthropogenic activities, such as overfishing, and natural factors such as climate change. Furthermore, the effects of these factors on changes in pollock biomass showed distinct timing.

Pollocks exhibit distinct biological characteristics at each stage of life. Pollock eggs and larvae are typically distributed near the surface layer [16,42]. Subsequently, during the juvenile and adult stages, they change their vertical habitat range, transitioning from the upper layer to deeper ones [43]. Furthermore, changes in oceanic conditions in their habitats also significantly influence the size of individual pollocks. Pollocks exhibit distinct habitat preferences based on their preferred habitats.

Large groups of pollock, depending on their size, predominantly inhabit specific temperature ranges. Larger pollocks prefer temperatures between 2–6 °C, whereas smaller pollocks primarily inhabit the temperature range of 4–12 °C [14,27,29,30]. These variations in the oceanic conditions of their preferred habitats, based on size and growth patterns, play a crucial role in their survival strategies. Relatively smaller individuals favor environments conducive to higher metabolic rates for growth, whereas larger individuals prefer environments suitable for lower metabolic rates to enhance energy efficiency. Therefore, larger pollock tend to inhabit deeper and cooler areas [44,45].

Previous studies have highlighted that warming water temperatures resulting from climate change are a critical factor contributing to the collapse of pollock fisheries [7,46]. In particular, the warming trend observed after the late 1980s has been linked to significant changes in the ecosystem dynamics of the East Sea of Korea [36,46]. Cold-water species such as pollock, which were the most abundant species during the 1980s, became a minor component of catches after the late 1980s. Conversely, warm-water species, such as the common squid (*Todarodes pacificus*), have emerged as major components of catches since the late 1980s [7,46]. However, in the 1990s and 2010s, following a decline in pollock biomass, water temperatures in the upper layer exhibited a rapidly increasing pattern. In contrast, in the intermediate layer where both small and large individuals inhabit, water temperatures decreased. This created oceanic conditions suitable for the habitats of small and large individuals. Furthermore, it is recognized that the primary prey source for juvenile pollock, euphausiids [27,28], prefer colder water temperatures within the range of 7–9 °C. The decrease in water temperature in the intermediate layer likely resulted in an increase in the abundance of these prey organisms [26,27]. Throughout the entire pollock life cycle, the early stage is most affected by environmental changes in the upper layer. Pollock mortality is highest during the early life stages. Therefore, a sudden rise in water temperature in the upper layer of the East Sea after the late 1980s, resulting from climate change, negatively affected the survival rate of pollock during the early stage more than in other life stages.

For the Alaska Pollock inhabiting the Alaska region, the mortality rate within the first five months after hatching is 66–88% [19]. In Korean waters, the rate of warming in the upper layer, which serves as the primary habitat for larvae and eggs, is higher than that of the intermediate and deep layers where adult pollocks reside [47]. These changes in oceanic conditions in spawning grounds affect mortality during the early life stages [10,48,49]. Specifically, the timing of creating suitable oceanic conditions for spawning and hatching [50], advection of eggs and larvae [17,51], and food sources are important factors influencing changes in survival rates and mortality during the early life stages [4,52].

Fluctuations in SST around the DB have not only impacted suitable conditions for pollock spawning but also the spatial distribution of spawning grounds [9,10,17,30]. Since the late 1980s, there has been a significant decrease in both the DTS and RPS, leading to suitable spawning conditions. These environmental changes in pollock spawning grounds are key factors influencing the hatching and survival rates of juvenile pollock [9,53]. The developmental rate of pollock eggs appears to be slower at lower temperatures, whereas hatching rates are higher [10,54–57]. During the early stages, juvenile pollocks exhibit more vigorous energy metabolism under higher temperature conditions, leading to faster growth compared to colder sea temperatures [58]. However, as metabolic rates increase, a constant supply of abundant food is required. Failure to consume food quickly under high-temperature conditions can lead to an increased mortality rate [22]. Although hatching and juvenile survival are possible under high-temperature conditions, lower-temperature conditions yield even higher hatching and juvenile survival rates. Spatial changes in pollock spawning grounds also serve as key factors that influence the hatching and survival rates of pollock juveniles [17]. When pollock spawning grounds are primarily located along the inshore area of the DB, they are more stable in the face of environmental changes caused by external factors such as ocean currents. These changes in oceanic conditions can significantly impact the food web structure, including variations in food source abundance and competition with other species, thereby affecting the survival rate of pollock during their early life stages [36,46]. When the central part of the spawning ground shifts to the northern coast of the DB, a higher likelihood of eggs and juveniles being advected offshore because of factors such as ocean currents exists. Even if the temperature conditions are suitable for growth, the limited food supply in offshore areas could have a negative impact on the survival rate of juveniles. In particular, since the late 1980s, with the increase in volume transport by the East Korean Warm Current, the proportion of eggs and juveniles transported to nursery grounds suitable for growth and survival has decreased. Instead, there has been an increase in the proportion transported offshore or to northern areas [17].

Sudden changes in oceanic conditions in the East Sea since the late 1980s have had a negative impact on the early life stages [10]. This is believed to be a major factor contributing to the decrease in pollock biomass. However, unlike other countries such as Japan and Russia, the total catch of pollock in Korean waters has steadily declined since the late 1980s, recording amounts of less than one ton since the 2000s. The fluctuations in pollock biomass in Korean waters appear to be the result of the cumulative impact of long-term overfishing of juveniles and the effects of climate change since the late 1980s. The climate changes that occurred in the late 1980s are well-documented and have been observed in various oceanic conditions and marine ecosystems in the North Pacific, including the northeast Pacific [59], the subtropical Kuroshio Current region [37], and Korean waters in the East Sea [7]. Long-term changes in the oceanic conditions of the East Sea have been associated with climate factors, indicating atmospheric and oceanic conditions in the North Pacific [7]. Specifically, changes in the intensity of the AO, SH, and EAWM have been identified as major factors influencing the sudden increase in water temperature in the East Sea after the late 1980s [7]. The transition of the AO from a negative to a positive phase in the late 1980s resulted in the strengthening of the Arctic wind vortex, which impeded the southward movement of cold air to mid-latitudes during the positive phase of the AO [60], a phenomenon linked to the weakened SH [7]. Consequently, the change in the pressure gradient force between the central pressures of the SH and Aleutian low pressure affected the weakening of the EAWM and the increase in air temperature around the East Sea [7]. Additionally, the weakened EAWM after the late 1980s and intensified northward warm current might have created unfavorable conditions for the walleye pollock in the late 1980s [17]. Furthermore, during periods of a weak Kuroshio Current combined with El Niño [61,62], the effect of Ekman transport on the Kuroshio Current flowing in the East China Sea was weakened, causing the main axis of the Kuroshio Current to migrate westward with decreased velocity [7,47,61,63]. Consequently, the Tsushima Warm Current, which flows into the East Sea and separates from the Kuroshio Current, was enhanced [7,47,61,63]. As a result, oceanic conditions in the East Sea indicated warmer than normal conditions.

The Korean government initially prohibited the fishing of juvenile pollock but lifted this prohibition after 1974, which led to the continuation of juvenile pollock fishing until the early 1990s [64,65]. During the mid-1970s, juveniles constituted over 80% of the total catch, and this high proportion of juvenile catches persisted until the mid-1980s [18]. The high intensity of juvenile fishing appears to have been influenced by both biological characteristics and advancements in fishing techniques and gear. During the 1970s and 1980s, the primary fishing grounds for pollock in Korean waters were shallow areas near the shore, which served as the primary habitat for juvenile pollock. This can be attributed to two factors: (1) the high abundance of pollock in both inshore and offshore areas, and (2) limitations on fishing activities in deep layers and offshore areas due to the underdevelopment of fishing gear and methods. As a result of fishing activities and the spatial distribution of juvenile pollock, the proportion of juveniles in catches exceeds that of adults. This continued fishing for juvenile pollock for over a decade has likely contributed to overfishing [64]. The ongoing and increased fishing pressure on juvenile pollock has had an impact on adult pollock biomass and recruitment [18]. The highest recorded catch of juvenile pollock was in 1981, with a significant decline in the total catch of juvenile pollock after 1984–1985. Subsequently, the catch of adult pollock also showed a declining trend after 1987–1988, suggesting a time-lag effect in response to changes in the juvenile pollock population. In summary, the high fishing pressure on juveniles is associated with a decline in adult biomass and appears to be a significant factor contributing to decreased reproduction and recruitment [18]. Notably, in Korean waters, there are more female individuals than males, and increased fishing pressure on females has a greater impact on reproduction and recruitment than on males [66–68]. This imbalance in gender ratio may be a response to overfishing of juveniles.

The decline in pollock resources, primarily driven by high catch pressure on juvenile pollocks and climate change, has led to notable changes in body size. Specifically, in the East Sea of Korea, the proportion of juvenile pollock decreased, whereas that of adult pollock increased in the 1990s and in more recent times (2010s), compared with the period of high biomass in the late 1970s and mid-1980s. The decline in the proportion of juvenile pollock is primarily attributed to excessive fishing of juveniles, whereas the increase in the size of adult individuals is believed to be influenced by density-dependent effects [18]. During the 1990s, as pollock biomass rapidly declined, competition for food resources decreased, resulting in accelerated growth and maturation processes. Consequently, the size of adult pollock in the East Sea of Korea significantly surpassed that of the mid-1970s [18,20]. Moreover, advancements in fishing techniques and gear have enabled fishing activities to extend into deeper layers and cover longer distances after the 1990s, facilitating the capture of pollock. Consequently, it is important to consider the possibility of an increased proportion of both larger-sized and smaller-sized pollocks in Period D.

5. Conclusions

The abundance of pollock in the East Sea of Korea has significantly decreased since the late 1980s, with catches dropping below one ton after the 2000s. This decline appears to result from complex interactions between human activities, such as overfishing, and natural factors, such as climate change. Before the early 1980s, the catch ratio of juveniles notably exceeded that of adults and persisted for a decade, primarily due to sustained and excessive fishing of juveniles, leading to a sharp decrease in juvenile abundance in the mid-1980s. Subsequently, in the late 1980s, climatic changes had a significant impact as sea surface temperatures (SST) in spawning grounds rapidly increased, resulting in a reduction in both the suitable region and duration of spawning. The reduced reproduction due to excessive overfishing during the early 1980s, combined with the sudden changes in oceanic conditions of spawning and habitat grounds that occurred in the late 1980s, further worsened the situation. This cumulative impact of both overfishing and environmental changes in habitats and spawning grounds due to climate change served as major factors in exacerbating the decline.

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Appendix A

Table A1. The information of specimens used in this study.

Period	Year	Month	Female					Male				
			Total Length (cm)		Weight (g)		No.	Total Length (cm)		Weight (g)		No.
			Mean	STD.	Mean	STD.		Mean	STD.	Mean	STD.	
A	1973	1	44.28	8.39	483.15	261.55	26	36.33	2.52	256.63	44.42	24
	1973	2	38.69	3.91	307.41	86.93	34	38.23	2.13	301.88	48.36	16
	1973	3	-	-	-	-	-	-	-	-	-	-
	1974	1	41.85	6.13	384.45	140.18	83	39.29	5.70	326.69	119.09	35
	1974	2	41.13	4.36	383.61	126.33	36	41.88	4.55	410.54	111.98	24
	1974	3	38.69	4.64	300.83	134.27	36	38.26	3.18	265.14	48.44	14
	1975	1	41.97	6.73	361.07	146.95	28	38.79	6.30	305.83	164.07	12
	1975	2	44.51	11.05	507.89	285.16	19	39.63	6.25	392.38	193.43	21
	1975	3	40.02	4.99	361.76	161.87	33	41.53	4.12	380.71	92.02	7
	1976	1	37.89	5.07	352.54	181.87	13	37.16	6.25	300.18	177.78	44
	1976	2	-	-	-	-	-	-	-	-	-	-
	1976	3	-	-	-	-	-	-	-	-	-	-
	1977	1	-	-	-	-	-	-	-	-	-	-
	1977	2	39.77	5.21	347.06	155.11	63	39.13	4.72	335.46	133.41	37
	1977	3	-	-	-	-	-	-	-	-	-	-
	1978	1	36.61	2.36	253.68	46.33	31	36.10	2.47	251.24	43.57	29
	1978	2	38.03	2.04	294.22	53.38	27	37.10	1.67	259.27	45.04	33
	1978	3	35.35	2.43	232.79	54.12	29	36.88	2.79	256.35	49.21	31
	1979	1	39.11	5.00	354.61	169.38	56	35.95	3.05	255.14	70.89	64
	1979	2	35.73	1.97	256.41	46.73	78	35.16	2.13	235.32	50.41	41
	1979	3	34.69	3.13	225.87	56.71	81	34.29	2.73	222.79	54.47	39
B	1980	1	37.93	2.20	292.30	43.29	71	36.56	1.98	269.61	56.88	49
	1980	2	38.40	2.51	302.62	61.42	66	37.49	2.41	268.50	49.31	54
	1980	3	-	-	-	-	-	-	-	-	-	-
	1981	1	38.41	2.61	291.88	69.52	69	38.37	3.05	280.12	63.74	51
	1981	2	39.39	3.24	279.21	49.47	38	38.21	2.81	252.73	46.22	22
	1981	3	-	-	-	-	-	-	-	-	-	-
	1982	1	37.98	3.04	266.36	62.82	67	38.48	3.06	274.12	65.83	33
	1982	2	37.28	2.85	267.22	54.03	49	37.34	2.38	258.94	53.48	51
	1982	3	-	-	-	-	-	-	-	-	-	-
	1983	1	38.07	2.51	277.31	52.30	75	36.84	2.34	268.88	47.27	25
	1983	2	36.86	2.15	263.40	50.47	45	36.91	2.83	265.95	53.81	65
	1983	3	-	-	-	-	-	-	-	-	-	-
	1984	1	37.18	3.52	264.88	62.88	67	36.38	2.36	244.85	48.95	33
	1984	2	38.08	3.54	285.00	72.59	69	36.48	3.63	259.15	53.21	20
	1984	3	-	-	-	-	-	-	-	-	-	-
	1985	1	37.86	3.03	265.50	52.85	88	36.45	2.34	246.45	55.80	11
	1985	2	-	-	-	-	-	-	-	-	-	-
	1985	3	-	-	-	-	-	-	-	-	-	-

Table A1. *Cont.*

Period	Year	Month	Female					Male				
			Total Length (cm)		Weight (g)		No.	Total Length (cm)		Weight (g)		No.
			Mean	STD.	Mean	STD.		Mean	STD.	Mean	STD.	
C	1991	1	42.63	3.02	397.27	90.67	113	41.24	2.14	381.80	67.77	15
	1991	2	38.90	6.36	302.59	120.43	63	32.07	6.01	186.23	93.83	35
	1991	3	36.11	5.55	252.58	99.05	62	35.71	5.97	246.08	108.40	37
	1992	1	41.31	5.65	345.13	113.75	77	31.84	5.34	173.30	77.74	23
	1992	2	39.33	6.25	334.90	134.02	60	35.23	5.84	224.37	94.06	38
	1992	3	37.22	4.59	333.38	116.01	63	30.71	4.93	217.11	114.69	37
	1993	1	-	-	-	-	-	-	-	-	-	-
	1993	2	-	-	-	-	-	-	-	-	-	-
	1993	3	34.48	3.36	211.46	73.13	32	33.96	3.05	195.28	37.84	39
	1994	1	-	-	-	-	-	-	-	-	-	-
	1994	2	41.97	4.39	386.56	117.79	39	39.07	7.09	332.44	191.22	12
	1994	3	-	-	-	-	-	-	-	-	-	-
	1995	1	40.49	3.25	387.25	148.51	42	36.99	3.98	286.85	105.66	8
	1995	2	-	-	-	-	-	-	-	-	-	-
	1995	3	-	-	-	-	-	-	-	-	-	-
D	2016	1	45.67	6.97	550.10	271.45	30	42.35	5.91	424.96	189.48	21
	2016	2	44.08	9.13	529.36	268.57	13	46.17	6.31	570.44	261.47	15
	2016	3	44.92	7.23	517.05	290.44	19	40.29	7.57	395.71	186.78	15
	2017	1	42.39	8.97	512.90	290.64	59	41.67	7.76	457.02	223.34	38
	2017	2	39.14	9.71	384.13	282.10	37	39.32	7.28	359.95	169.28	29
	2017	3	38.36	10.84	420.34	340.50	41	38.29	7.18	350.49	180.54	38
	2018	1	41.55	8.76	510.66	277.29	48	39.47	7.53	408.29	194.96	35
	2018	2	40.97	7.42	452.71	217.74	55	39.24	7.62	389.69	201.44	48
	2018	3	32.74	6.57	254.94	180.87	139	34.27	5.32	258.99	131.95	154

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