VOLUME 11 Issue 1
JULY 2026

E-ISSN: 2622-3384
P-ISSN: 2527-9939

JURNAL MEdu Mangifera Edu

The life cycle transformation of Pacific Cod fish mechanism

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ABSTRACT

Pacific cod (Gadus macrocephalus) is a key commercial and ecological species in the North Pacific, supporting valuable fisheries and marine ecosystems. However, its distribution, population dynamics, and responses to climate change and fishing pressure remain incompletely understood. This study integrates 20 years of bottom trawl survey data from the Southwestern Bering Sea (2000–2020) with ecological modelling, stock assessment records, satellite-tagging data, socioeconomic indicators, and international fisheries datasets to evaluate Pacific cod biology and fisheries management. Long-term trawl surveys revealed seasonal and depth-related shifts in abundance, size composition, and spatial distribution, indicating dynamic habitat use across life stages. Environmental modelling showed that increasing bottom-water temperatures may reduce suitable spawning habitat because of the species' narrow thermal tolerance. Satellite-tag data confirmed seasonal migrations between feeding and spawning grounds, highlighting the importance of habitat connectivity. Stock assessments indicated that biomass and recruitment were influenced by both environmental variability and fishing intensity, emphasizing the need for adaptive management. Socioeconomic analyses demonstrated the importance of Pacific cod fisheries to regional livelihoods and the potential impacts of declining stock productivity. Overall, this integrated assessment provides scientific evidence to support ecosystem-based fisheries management, sustainable harvest strategies, and long-term conservation of Pacific cod populations in the North Pacific.

ARTICLE INFO

Keywords
Ecological species, Fish, *Gadus macrocephalus*, Migratory behaviour shifts, Tagging data

Received
November 11, 2025

Revised
June 22, 2026

Accepted
June 30, 2026

Published
July 31, 2022

How to cite
Ibrahim, N.A. (2026). The life cycle transformation of Facific Cod fish mechanism. *Jurnal Mangifera Edu*, *11*(1), 19-26. https://doi.org/10.31943/mangiferaedu.v11i1.250.

INTRODUCTION

Pacific Cod (Gadus macrocephalus) is found in Northern Pacific waters with brown to gray spots, can grow up to 3.7 feet long and weigh up to 50 pounds, and lives up to 13 years. This study used data from bottom trawl surveys conducted in the southwestern Bering Sea during 2000-2020, covering the spring, summer, and autumn hydrological seasons (Terentyev, 2025). The study also analyzes density or vertical (depth) distribution, the size of large Pacific cod, the size composition of Pacific Cod (Gadus macrocephalus), and inferences about migratory behavior in that region. This 20-year dataset provides a long-term, empirical view of cod distribution or migration in the Southwestern Bering Sea (Terentyev, 2025).

The study combines statistical models of Pacific Cod distribution based on decades of survey and environmental data (Stone et al., 2025). It also includes socioeconomic data from Alaska coastal communities to assess how climate-driven changes in Cod distribution could impact human

communities. The study reported on the official stock assessment for Pacific cod (Gadus macrocephalus) in the Gulf of Alaska to integrate multiple sources of data from federal and state catch records, size or age composition data from commercial fisheries, bottom trawl, and post-sampling data for Catch length distribution (Stone et al., 2025). This paper investigates how warming bottom water temperatures in the eastern Bering Sea may affect where Pacific cod can successfully produce eggs and larvae. They have narrow temperature. Bottom temperatures are suitable for successful cod egg hatching (Bigman et al., 2025).

Pop-up satellite archival tags were deployed on 38 individuals of Pacific cod in the northern Bering Sea during summer 2019, when the cod were foraging (Nielsen et al., 2025). For 31 of those tagged cod, the reconstructed seasonal movements (using geolocation from tag data: depth, temperature, light) were used to track where fish moved during winter spawning, based on location probability modeling. This study analyzed data from Taiwanese longline fisheries between 2010 and 2023, focusing on length, age composition, and catch volume of adult Pacific bluefin tuna landed by Taiwanese fleets (Lin et al., 2025). This article evaluates whether sustainable fisheries and ocean management efforts have succeeded in improving the overall status of marine fisheries worldwide (Cheung et al., 2025). Thus, this paper also identifies emerging and intensifying threats that complicate fisheries sustainability.

Thus, the study gap is a comprehensive overview of seasonal or vertical cod distribution trends, climate-driven shifts, ecological modeling, and global fisheries pressures. The study's problem statement is a limited understanding of seasonal and vertical distribution trends. The existing dataset provides partial insights but has not been integrated into a long-term assessment. Thus, Pacific cod distribution is changing in response to warming waters, and the ecological consequences of these shifts remain unclear. Therefore, there is an insufficient linkage between biological changes and management implications. The study aims to provide a comprehensive assessment of Pacific cod (Gadus macrocephalus) distribution, population dynamics, and ecological responses to climate and fisheries pressures in the Northern Pacific.

METHOD

The study will focus on the Northern Pacific, including the Southwestern and Northern Bering Sea, the Gulf of Alaska, and surrounding North Pacific waters. This study uses a frame survey or vessel registry to validate data completeness for the catch, effort, and fleet data. Secondary data sources utilize published market reports as an industrialized database, similar to a company's annual report. To assess fishery management practices, ecological impacts, and compliance, stock assessment or management advice data are needed to evaluate stock status, mortality, recruitment, catch advice, and sustainability. Therefore, it integrates both sets of data to derive a comprehensive picture of ecological health, fishery practices, compliance, and management effectiveness of Pacific cod.

RESULTS AND DISCUSSION

It was found that the Bering Sea and Gulf of Alaska are not overfished, and the Aleutian Islands and Pacific Coast stocks have not been assessed. Although these conditions are implied, management

measures are in place. Season A refers to the timeframe from January to April for the winter season, when Pacific cod migrate to their spawning grounds (Laurel et al., 2023). Season B runs from April through November, when cod actively feed. Thus, the total allowable catch for the year is divided by these seasons and gear types. There is a 43% increase in Season A over Season B for Pacific cod to migrate and find their spawning grounds, helping protect the fish, support population cycles, and maintain biodiversity and sustainable fisheries in 2025.

Therefore, the total cooperative quota is more than double for a specific program in the Atlantic. Further, the key management areas are in Alaska, which include the Bering Sea and Aleutian Islands and the Gulf of Alaska. It was found that harvesting Pacific cod at more than double the sustainable rate, which is overfishing, will lead to potential population collapse and long-term negative impacts on the entire marine ecosystem. There is a specific regulation for a very niche processing method within a cooperative fishery management area to utilize a quota share. This study compiled and analyzed archival data on UK seafood imports and domestic landings from 1900 to 2020 to evaluate ecological, socio-economic, and sustainability issues, revealing that the weighted average distance traveled by seafood imported into the UK increased by 18–32% over time; consequently, scientific surveys and stock assessments employed bottom trawl surveys to estimate Pacific cod abundance (Heard et al., 2025).

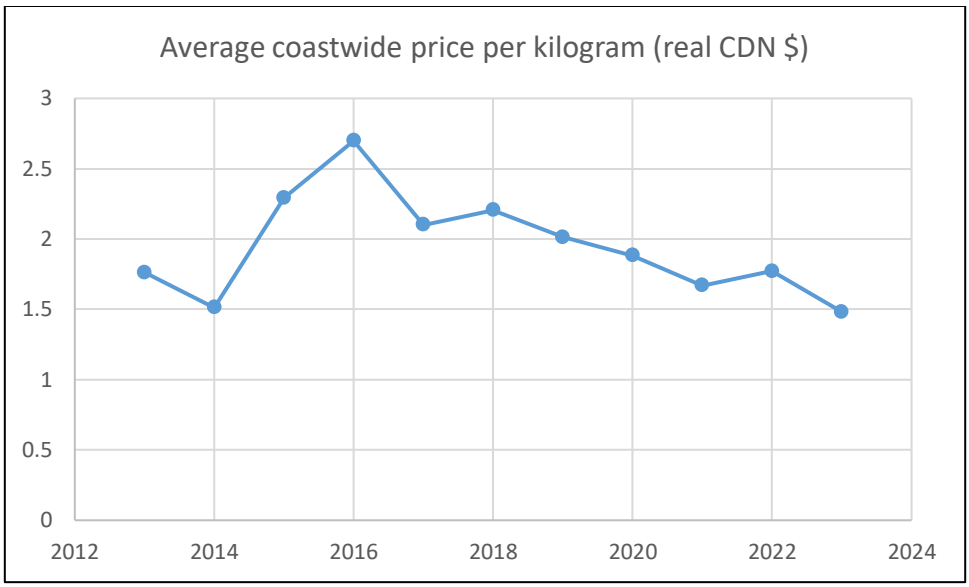

Figure 1. Coastwide average price of Pacific Cod per kilogram over time

The global cod fish market was valued at USD 1,678.9 million in 2023 and is projected to increase to USD 1,899.6 million in 2025, reaching USD 3,667.6 million by 2035. In 2025, fresh and frozen cod are expected to account for 62.1% of the market, while breaded and processed products represent the remaining 37.9%. This projected market growth highlights the importance of responsible fishing practices to ensure long-term sustainability, reduce environmental pressure, and minimize supply risks (Lucintel, 2026). According to the Archive Market Research Report, the global Pacific cod market is projected to grow at a compound annual growth rate (CAGR) of approximately five perceant between 2025 and 2033 (Gurunule, 2025). Measures should be taken to support aquaculture growth and sustainable sourcing and processing efficiencies without overexploiting wild

stocks. Secondary data sources include published market reports and company annual reports as an industrialized database.

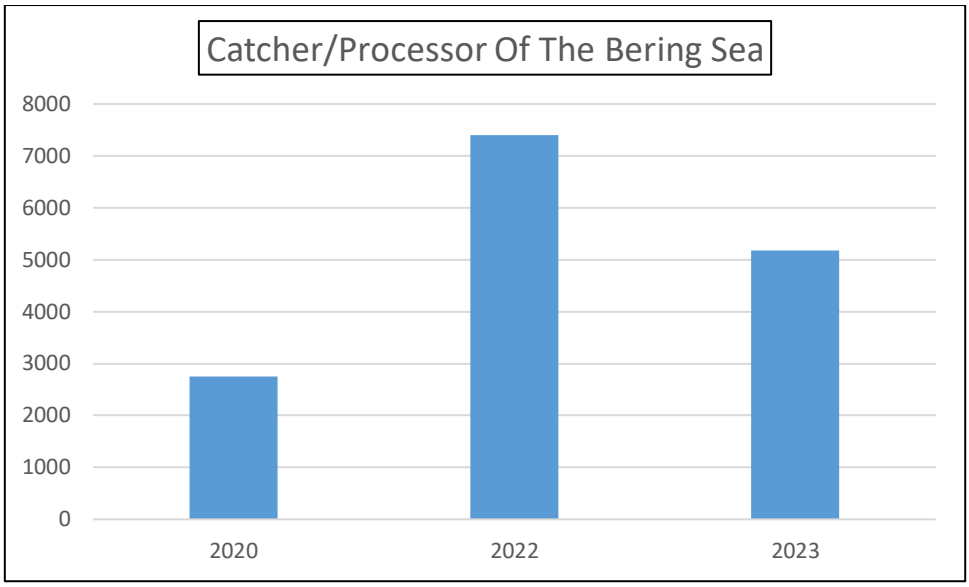

Figure 2. Number of catchers or processors of the Bering Sea (Metric/tonnes)

Attempts to commercialize Atlantic cod (*Gadus morhua*) through aquaculture have produced both successes and failures across Norway, the United Kingdom, New England (USA), and Atlantic Canada from the late 1980s to 2012. Despite technological advances that enabled the establishment of hatcheries and commercial farms in all four regions, sustainable cod aquaculture continues to depend on a comprehensive understanding of the species' biology and the optimization of production techniques (Nardi et al., 2021). This paper investigates how changing thermal conditions affect the early life history of Pacific cod in the eastern North Pacific (notably the Gulf of Alaska and nearby regions). Thus, this paper highlights the need for long-term, multi-life-stage monitoring, as there is also uncertainty about future climate trajectories (Laurel et al., 2023).

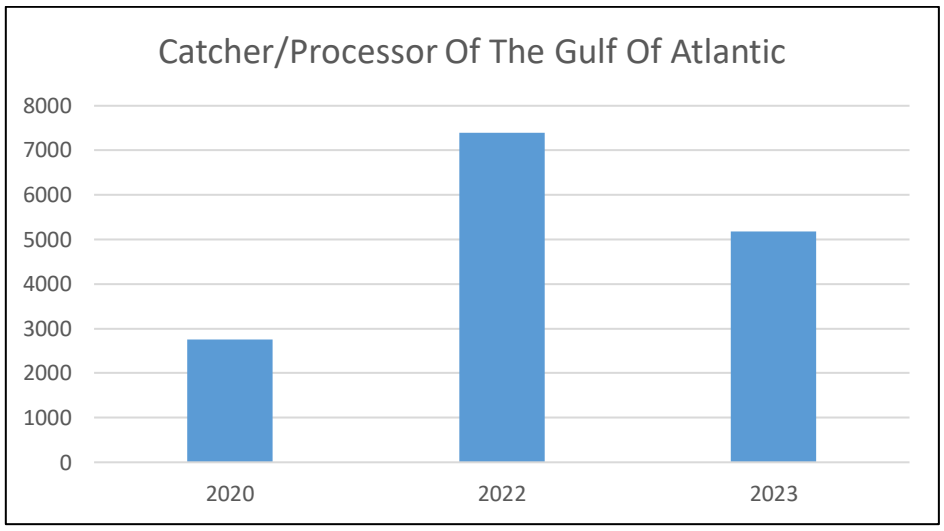

Figure 3. Number of catchers and processors of the Gulf of Atlantic (Metric/tonnes)

The Pacific cod population available for commercial fishing in the Kuril Islands (both northern and southern parts) shows dynamics comparable to those projected over 1975–2020 in parts of the

southeastern Bering Sea and other Russian shelf or bay regions (like Karagan or Olyutor bays) (Zolotov et al., 2020). This includes changes in gear use, fishing zones, and temporal patterns of catch. The size distribution of Pacific cod (Gadus macrocephalus) has varied in space and time across the North Pacific, covering regions from the northern Kuril Islands through the Aleutian Islands to southeast Alaska. The observed loss of large fish in heavily exploited regions may have altered the population structure for ecological reproduction (Charbonneau et al., 2019). Given this persistent low abundance under minimal fishing mortality, the update triggered a formal review of stock status even though no new catch advice has yet been reviewed for 2023 (DFO, 2024).

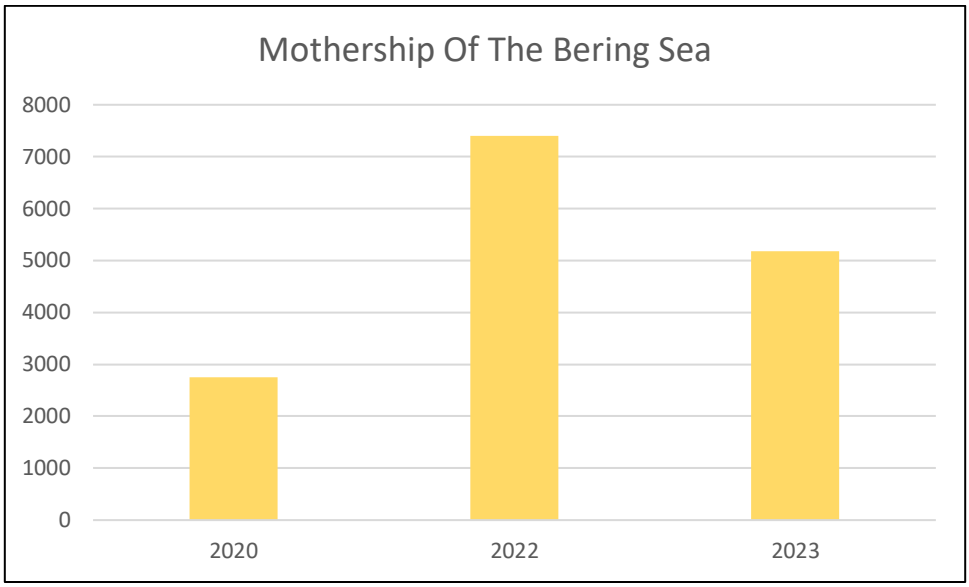

Figure 4. Count of vessels to operate as mothership for Pacific Cod of the Bering Sea (Metric/tonnes)

Pacific cod in the Eastern Bering Sea show spatial heterogeneity in size and age; thus, this study provides a rare empirical test using real-world fisheries data by providing a stock assessment for the redistribution of the gap in the sampling method (Puerta et al., 2019). In response to declining biomass, the recommended biological catch for 2023 was reduced by approximately 25% relative to 2022, while the stock assessment incorporated changes in natural mortality associated with environmental stress to support climate-responsive fisheries management (Hulson et al., 2022). There is a high upfront cost and infrastructure demands due to the lack of institutional and regulatory practices. There is incomplete integration of the circular economy in end-of-life vessel decommissioning, material reuse, or systemic waste management (Utama et al., 2025).

The data are on the fishery and stock status of Pacific Cod (Gadus macrocephalus) in the northwestern Bering Sea from 1968 to 2024 (Datsky et al., 2023). The surge is attributed to improved feeding conditions and favorable environmental conditions, as well as increased bioavailability. Given the cooling trend since 2021, future fishery management should account for these population dynamics and ecological shifts when making harvesting decisions (Datsky et al., 2023). In Pacific cod, the most recent data (2017 and 2018) found unexpectedly large numbers much farther north in the Northern Bering Sea (Spies et al., 2020). Based on these findings, climate change is altering species behavior and abundance, as well as their fundamental geographic distribution.

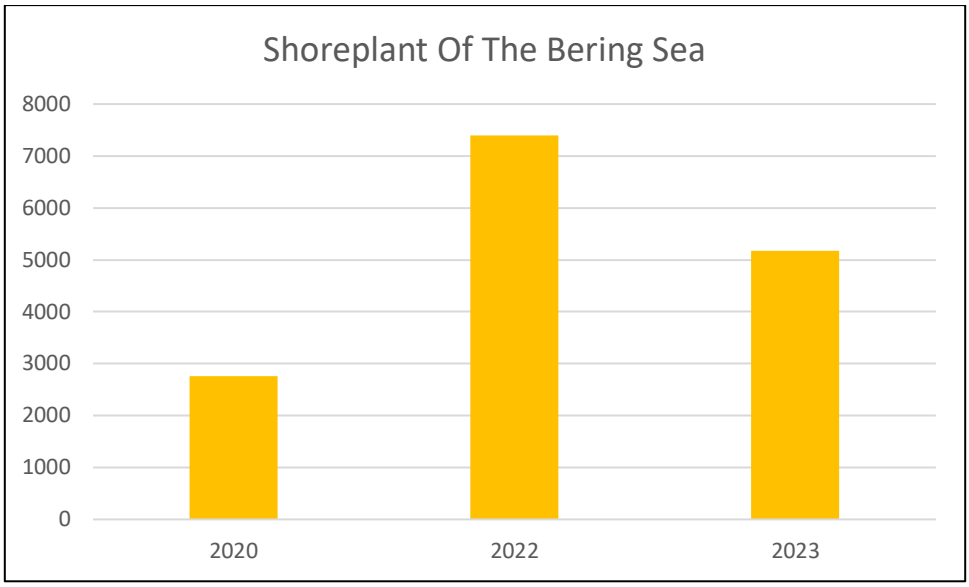

Figure 5. Number of shore plants for Pacific Cod fish of the Bering Sea (Metrics/tons)

The Ocean Atlas in 2017 provided a comprehensive, data-driven overview of the ocean's condition and information on the ocean's health for a stable climate, biodiversity, and human well-being (Ambsdorf et al., 2017). Preventing biological invasions is more effective than managing established invasions; therefore, horizon scanning is essential to identify species that pose a realistic invasion risk, particularly those currently classified as having high to moderate risk and prioritized for near-term reevaluation of their invasive potential (Pratt et al., 2025). However, there is a limited capacity for broad-scope risk scanning due to resource constraints.

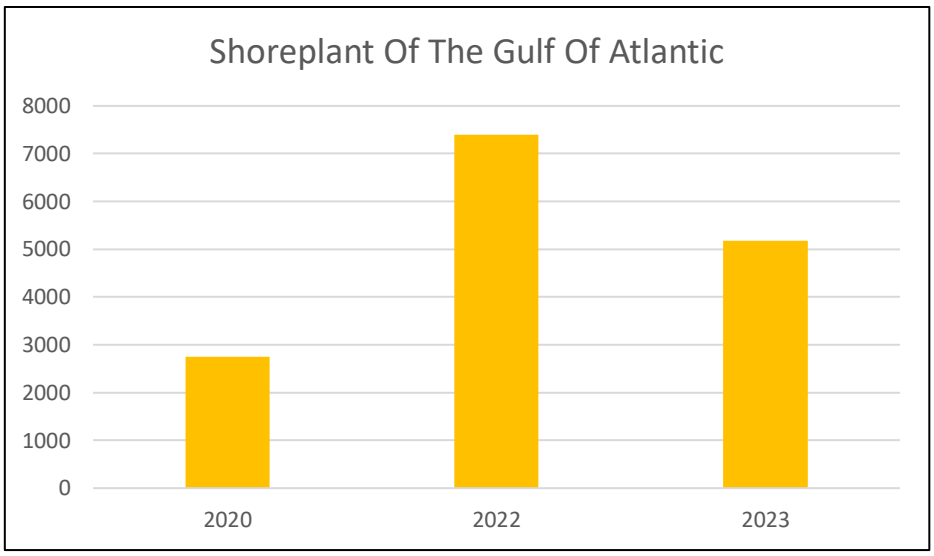

Figure 6. Number of shore plants for Pacific Cod fish of the Gulf of Atlantic (Metrics/tons)

Cod exhibit a range of biological traits that enable them to withstand harsh environmental conditions and inhabit both shallow and deep waters. Their complex reproductive strategy, characterized by high fecundity and population genetic structuring, enhances adaptive capacity and provides a foundation for sustainable fisheries management. Despite these adaptations, cod populations remain highly susceptible to overfishing, particularly when spawning aggregations are intensively exploited. Furthermore, increasing ocean temperatures have driven a northward shift in

cod distribution, reflecting the growing influence of climate change on their population dynamics and habitat suitability (Reddy, 2025). The findings underscore that static stock assessments may be insufficient and that dynamic, spatially explicit management is needed to accommodate migration, distribution shifts, and environmentally driven recruitment variability (Rand et al., 2024).

CONCLUSION

Cod fisheries management integrates seasonal biology, reproduction cycles, and spatial distributions. However, overfishing threatens population structure, ecosystem stability, and biodiversity. Bottom trawling is an essential monitoring method for stock assessment. Aquaculture offers a biologically viable alternative to wild-capture fisheries. Overall, biological understanding of cod life history and ecosystem interactions is crucial for sustainable fisheries, population recovery, and biodiversity conservation. Future directions include effective monitoring and tracking changes in abundance, size structure, and distribution. Alongside wild capture management, cod aquaculture provides a supplement that may reduce pressure on wild stocks. Therefore, there is a need for a deep understanding of cod's biological life history, behavior, and ecosystem interactions.

ACKNOWLEDGMENT

The author is thankful for this wonderful opportunity to contribute to biological references and studies to be shared among other researchers.

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