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Multispecies fisheries management in Japan’s offshore waters: the case of Hokkaido Pacific offshore trawl

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Abstract

Multispecies fisheries management in Japan's offshore waters:
the case of Hokkaido Pacific offshore trawl

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Japan is currently implementing its reformed fisheries policy. The new Fisheries Act passed by the Diet in 2018 stipulates that output control through Total Allowable Catch (TAC) is the principle for fisheries resource management. This is a turning point for Japan, which has traditionally managed fish stocks primarily through input control and voluntary management by fishermen. TACs will be set to individual stocks using a harvest control rule, pre-determined through stakeholder dialogue. Japan lands a wide variety of fish and faces a difficult task of managing multispecies fisheries while balancing ecological, social, and economic objectives. This research aims to gain insight into the multispecies fisheries management under the new fisheries policy using a case study of the Hokkaido Pacific offshore trawl, which has a traditional Japanese-style co-management system and is scheduled to introduce TAC for cod. First, this study assessed the current co-management system using the Fishery Performance Indicator. The results showed that the fishery was performing high in the community aspect, especially regarding the "human" aspect, suggesting that Japan's co-management system can work effectively in the complex environment of a multispecies fishery and return the benefits to the local community. Meanwhile, the ecology and economy performed moderately. This study then simulated the effects of various harvest scenarios with a multispecies bioeconomic model. It revealed that achieving a stock recovery policy for decreased cod would lead to a significant socioeconomic loss. The new fisheries policy in Japan expects to improve ecological performance by strengthening the management of individual stocks. However, the key to success will be better understanding the impact of new management systems on fishermen's behavior and facilitating discussions with stakeholders by showing what would be improved and what risks are involved in not acting.

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I dedicate this work to my child here in Seattle.

Chapter 1: Introduction

1.1 Fisheries policy reform in Japan

Japan is currently implementing its reformed fisheries policy. In 2018, the Japanese Diet approved amendments to the Fisheries Act to strengthen science-based fisheries management and improve the profitability of the fishing industry through proper fisheries management. Under the reform, the number of stocks assessed will be expanded from 50 in 2018 to around 200 in 2023. Following stock assessment and stakeholder dialogue, each stock will have a harvest control rule (HCR) set to achieve the desired biological reference point. Then, based on the HCR, each stock will be managed by its Total Allowable Catch (TAC). The coverage of the TAC will increase from 60% of the marine capture fishery production in 2018 to 80% in 2023 (FAJ, 2023). The Fisheries Agency of Japan (FAJ) aims to recover the marine capture fishery production, which peaked at 11.5 million mt in 1984 and declined to 3.4 million mt in 2020, to 4.4 million mt in 2030, by strengthening science-based management (FAJ, 2023). In response to these drastic changes, there are vigorous discussions taking place among industry, academia, and public institutions on how to view the status of Japan's fisheries and fisheries management and what they should be in the future (Council for Regulatory Reform, 2019; Japan Economic Research Institute, 2022; Katayama & Nakata, 2020; Science Council of Japan, 2017).

Japan faces the challenge of how to achieve sustainability in multispecies fisheries. Most fisheries catch multiple species simultaneously and unavoidably, whereas achieving optimal utilization of all species with different productivity and stock status is impossible. Seeking to maximize landings from multispecies fisheries will result in overfishing of some species (Worm et al., 2009). Species with low quota (called “choke species”) could restrict fishing opportunities for high quota species (Mortensen et al., 2018; Schrope, 2010), leading to social impacts such as loss of fishing jobs and closure of processing plants (McQuaw & Hilborn, 2020).

In Japan, the introduction of catch limits for bluefin tuna in 2015 resulted in numerous social disruptions, notably in set nets with low selectivity, including in-season closures, significant overages of allocations, revenue losses, and heavy labor workloads to release fish exceeding quota. Fisheries managers and scientists worldwide have struggled for decades to manage individual species in multispecies fisheries and align them with socioeconomic objectives (Pascoe et al., 2020; Paulik et al., 1967; Ricker, 1958).

Offshore fisheries will likely be affected earliest, as the new management system will begin with stocks having large catch volumes. Japan's fisheries are classified into coastal, offshore, and distant-water fisheries according to the waters they operate, with offshore fisheries accounting for 60% of the marine capture fishery production (FAJ, 2019). Offshore fisheries have historically been under government input controls, including limited entry permits, vessel tonnage limits, fishing season and areas, as well as self-imposed rules by regional or fishery type-specific fishery cooperatives, including seasonal/area closures, fish length limits, and gear restrictions (FAJ, 2019). Since 1997, TACs have been introduced for eight species, and input controls, output controls, and the fishing industry's self-imposed rules are being integrated. Such a system is more layered than coastal fisheries, which local fishermen primarily manage under Territorial User Rights for Fisheries (TURFs), and distant-water fisheries, managed multilaterally under international agreements. The new fisheries policy raises the issue of reconciling biological, economic, and social sustainability in multispecies fisheries because input controls may affect multiple species, whereas output controls focus on controlling the catch of a single species.

The effectiveness of management systems for offshore fisheries has yet to be thoroughly examined (Inomata, 2017; Tokunaga et al., 2019b). The historical input controls have reportedly worked well in controlling fishing capacity (Nagasaki, 1989; Tomioka, 2014). TACs, which started to be applied later, have also been found to have lower exploitation rates for target species compared to non-TAC species (Ichinokawa et al., 2017). Some argue that TACs have not contributed to substantial reductions in fishing capacity and that existing input controls remain effective (Tanaka, 2015). In addition, research from a socioeconomic perspective is still underway. Socioeconomic support remains theoretical, e.g., Inomata (2014), who found that the co-management system combining government and fishermen management is consistent with Ostrom's common pool resource management theory (Ostrom, 1990). Under the new fisheries policy, there is an increasing need to quantitatively examine the management of offshore fisheries from a socioeconomic and resource conservation perspective.

1.2 Objective

This study aims to apply quantitative analysis to multispecies fisheries management in Japan's offshore waters to gain insight into ecologically, socially, and economically sustainable management. As a case study, this study focuses on an offshore trawl on the Pacific coast of Hokkaido, Japan. In Chapter 2, the performance of fishery management there is assessed using the Fishery Performance Indicator (FPI). How well does Japan's multispecies fishery management perform? What are its strengths and weaknesses? This study examines what is needed to improve the sustainability of Japanese fisheries, including the potential impacts of the fisheries policy reform. Chapter 3 uses a multispecies bioeconomic model to simulate the effects of different harvest scenarios on the case study. Are there trade-offs between ecology, economy, and community? Is it possible to balance different objectives? The potential impact of expanding TACs and introducing HCRs on multispecies fisheries under the new fisheries policy is examined.

1.3 Case study

The case study in this paper is the Hokkaido Pacific offshore trawl. Trawl fisheries are typical multispecies fisheries existing all over the world. Japan's offshore trawl fishery has more than 60 home ports across the country (Tominoa, 2014), accounting for 11% of offshore fisheries production (FAJ, 2019). Hokkaido is the largest fishing region in Japan, and one of its primary fisheries is offshore trawl fishery. In the Hokkaido Pacific offshore trawl, the main target species, Alaska pollock (*Gadus chalcogramma*; hereinafter referred to as "pollock”), is managed under TAC, and the fishery-related data are well maintained, providing the conditions for conducting quantitative analyses. The second important species, Pacific cod (*Gadus macrocephalus*; hereinafter referred to as "cod”), is a candidate for TAC under the new fisheries policy (FAJ, 2023). Therefore, this fishery is best suited to evaluate Japan's multispecies fisheries management framework and to analyze how future reforms will affect it.

1.3.1 Overview of the fishery

The fishery operates in the offshore waters within Japan's exclusive economic zone (EEZ), mainly targeting pollock (Figure 1.1). In 2021, it landed 73,000 mt, worth 5.5 billion yen (Figure 1.2). The region has four home ports and 16 fishing vessels operated in 2020. Fishing vessels range from 125 to 182 gross tons (about 30 to 40 m in length), with 14 to 18 crew members per vessel (Tomioka, 2014). There are two types of fishing gear: Danish seines and otter trawls, with Danish seines being dominant. Fishing operations are mainly day trips. The catch is landed at the local home port, traded on the ex-vessel market, and processed mainly within Hokkaido, making it economically crucial to the local community (Tomioka, 2014). Pollock accounts for 85% of the catch and 54% of the value in 2021, 94% of which is processed into surimi for domestic consumption, including small amounts of fresh fish, and 6% is exported mainly to Korea as fresh fish (HTFCF, 2009). In addition, high-priced fish roe is another vital commodity. Exports to Korea accounted for 24% of the total value in 2010 in the Kushiro area, the largest home port (Kushiro Fisheries Revitalization Committee, 2019), yet have declined significantly since the Fukushima nuclear accident in 2011, with China becoming the leading export destination in recent years (Tokyo Fisheries Promotion Foundation, 2017). Cod accounts for 11% of the catch and 27% of the value and is consumed mainly in the domestic market as fresh fish. Japanese flying squid (*Todarodes pacificus*) is the third important species for this fishery, accounting for 1% in volume and 6% in value, but both the volume and value have been declining in recent years due to the stock depression, and its influence in the fishery business is decreasing. The squid is managed by TAC, but the catch by the Hokkaido Pacific offshore trawl represents only 2% of the total catch of the stock in 2021 (Hokkaido Research Organization, 2022; Okamoto et al., 2023). Other catches, including Saffron cod (*Eleginus gracilis*), Sohachi flounder (*Hippoglossoides pinetorum*), and Chestnut octopus (*Paroctpus conispadiceus*), constitute 4% of the total catch.

1.3.2 Management system

Offshore trawlers have been subject to input controls by the FAJ since 1933, including vessel tonnage limits, limited entry permits by tonnage class, and engine power limits (Tomioka, 2014). The fundamental management philosophy is to regulate fishing capacity through tonnage limits because the tonnage of a fishing vessel is a proxy for its fishing capacity. Offshore trawls are relatively large-scale fisheries and have historically conflicted with coastal fisheries because they share fish stocks and fishing grounds (Tomioka, 2014). Therefore, the areas where offshore trawls can operate are designated by permits, and coastal areas are closed to trawling to separate them from coastal fisheries. Offshore trawlers in Hokkaido used to operate in foreign waters.

However, due to the establishment of EEZs by various countries and Russia's reduction of allocations to Japan, they have returned to domestic waters, and vessel reduction programs were implemented twice, in 1977 and 1986 (Itakura, 2004). Since then, the number of vessels has been decreasing.

The Hokkaido Pacific offshore trawl fishermen belong to local fishery cooperatives. The prefecture-level Hokkaido Trawl Fisheries Cooperative Federation (HTFCF) and the national-level National Federation of Medium-Trawler (NFMT) are their umbrella organizations. These cooperatives and federations have introduced various self-imposed rules. There is a seasonal closure from June to August. A move-on-rule is in place to move fishing grounds when pollock less than 34 cm in total length account for more than 20% of the catch (Ishino et al., 2021). The fishermen in Muroran have adopted a pooling system in which all vessels share income and some expenses, and they share fishing ground information (Matsuishi et al., 2013). They also have numerous agreements with coastal fishermen specifying exact hours and locations of operation to avoid fishing gear interaction (Honma Fishery Corporation, 2017). Fishing grounds are also restricted to the vicinity of each home port, which is much smaller than the permitted area, due to coordination with other fishermen and fish stock distribution (Matsuishi et al., 2013).

Pollock has been managed under a TAC by the FAJ since 1997. The FAJ allocates quotas to offshore and coastal fisheries based on the average catch over the past three years (Matsuishi & Kaneiwa, 2014). The offshore quota is set for offshore trawls, and the NFMT, a national organization, receives it first. Then the NFMT allocates them to the regional fishery cooperative federations (HTFCF in Hokkaido) based on historical catches. Since 2008, the HTFCF has been allocating its quota to each local fishery cooperative because a decrease in the TAC threatened to cause catches to exceed the quota (Sakai et al., 2012). Local fishery cooperatives allocate quotas equally to their member fishing vessels (Stable Seafood Supply Organization, 2018). The coastal fisheries catch pollock with gill nets, longlines, and set nets, and its share of the catch is about 40%, with 374 boats active (Hokkaido Research Organization, 2022). In summary, the management system of the Hokkaido Pacific offshore trawl is multilayered, with historic input management and voluntary rules overlain by the TAC.

1.4 Figures

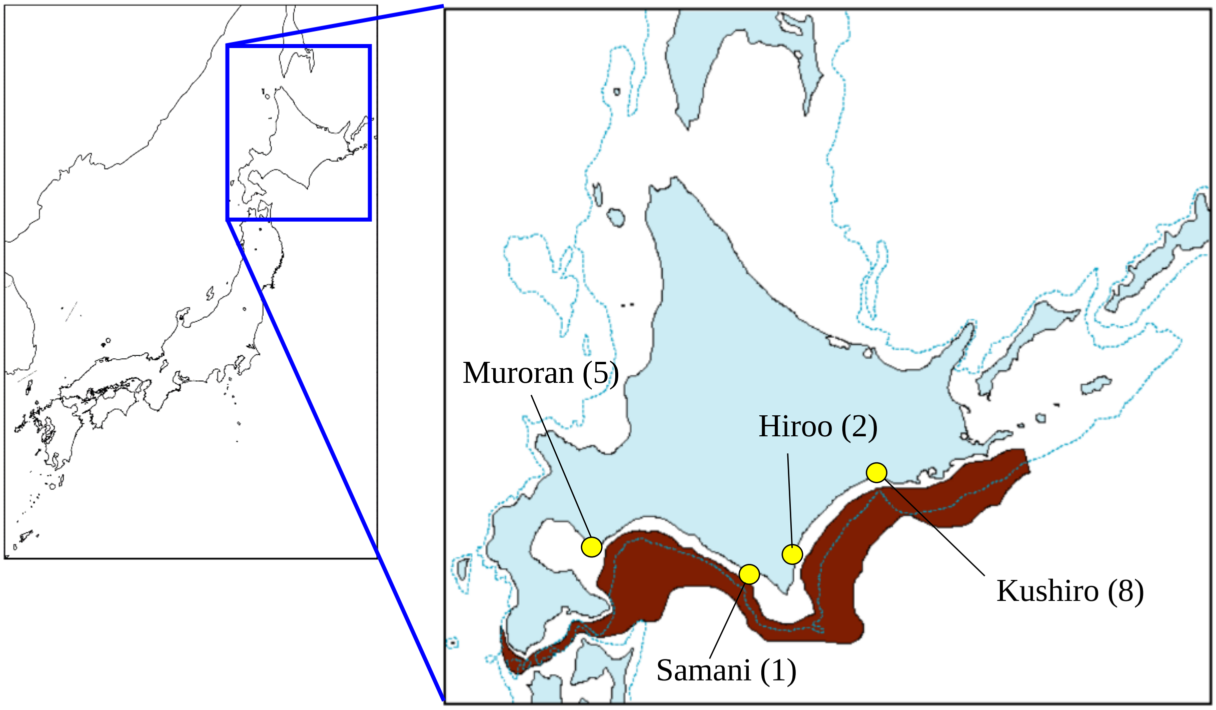


Figure 1.1: Fishing ground for Alaska pollock from Hokkaido Research Organization (2022), adding yellow dots indicating fishing ports of Hokkaido Pacific offshore trawl with the number of active vessels in 2021 in parenthesis. The blue dotted line represents a depth of 200 m.

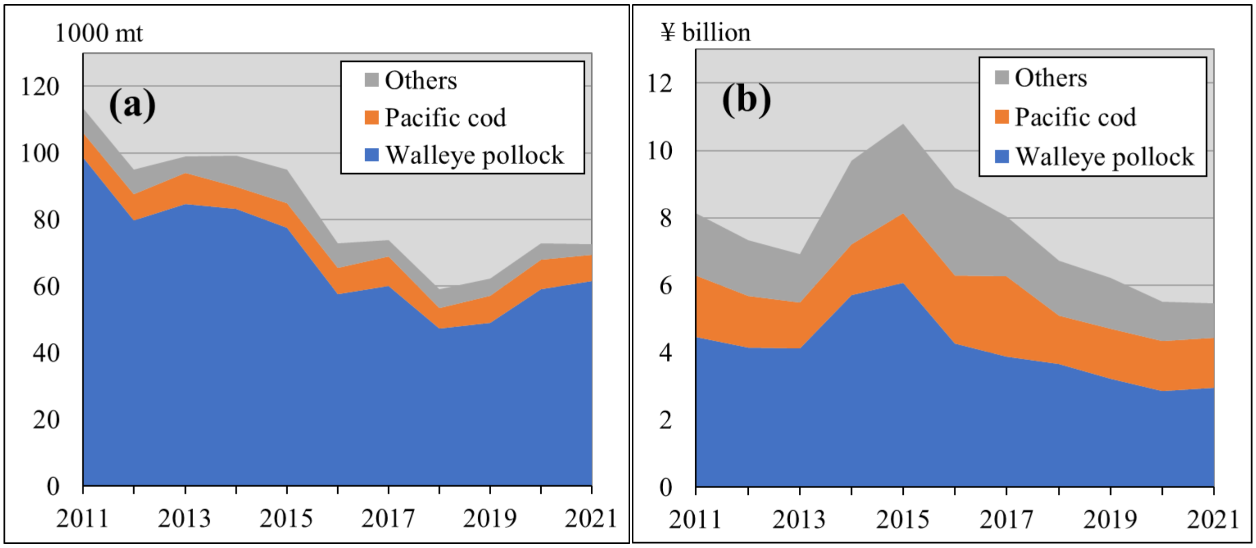


Figure 1.2: Landings volume (a) and landings value (b) by species for Hokkaido Pacific offshore trawl

Chapter 2: The performance of the Japanese multispecies fisheries management

2.1 Abstract

Japan's fisheries are suffering from declining landings, fewer fishermen, and low stock statuses. Efforts to improve their sustainability are deemed urgent. Japan lands a wide variety of fish and faces a difficult task of managing multispecies fisheries while balancing biological, social, and economic objectives. Fishery management in Japan has been relying on co-management in which the fishermen themselves, as resource users, are responsible for planning and implementing resource management supported by public institutions. Several previous studies have reported that such a system meets the conditions for effective management. (e.g., Inomata, 2014; Makino & Sakamoto, 2003) Still, there is room to examine how sustainable individual cases are and what are possible improvements.

This study assessed the performance of fisheries management in a case study of the Hokkaido Pacific offshore trawl, using the Fishery Performance Indicators (FPIs) [Anderson et al., 2015]. The results showed that the fishery was performing well in the community aspect, especially regarding the "human" aspect, such as crew and owner, suggesting that Japan's co-management system can work effectively in the complex environment of a multispecies fishery and return the benefits to the local community. Meanwhile, the ecological and economic performance were moderate. The new fisheries policy in Japan expects to improve ecological performance by strengthening the management of individual stocks. The key to success will be understanding the impact of the new management system on fishermen's behavior in multispecies fisheries and incorporating appropriate complementary systems to maintain or increase economic and social

viability.

2.2 Introduction

Japanese fisheries are suffering. Marine capture fishery production peaked at 11.5 million mt in 1984 and have declined to 3.4 million mt (a 70% decrease) in 2020 (FAJ, 2023). The number of fishermen decreased by 42% between 2003 and 2020. Out of 84 stocks with stock status in 2018, 41 stocks (49%) were assessed to be at low levels (FAJ, 2019). The situation with the world's sixth largest EEZ, yet only the tenth largest catch, is sometimes called underperforming (Katsukawa, 2017; Tokunaga, 2019a). In addition, Japan’s world-leading domestic seafood market is likely to shrink due to the declining population that Japanese society faces. When looking at the overall performance of Japanese fisheries, a sense of crisis about its sustainability is inevitable.

One of the characteristics of Japanese fisheries is the diversity of fish species. For example, in Iceland and Norway, fishing nations located at high latitudes, the number of fish species that accounted for 80% of the catch in 2015 was 5 and 8, respectively, while in mid-latitude Japan, the number of species was 16 (Fujita, 2019). At the Tokyo Metropolitan Central Wholesale Market, the largest seafood market in Japan, more than 600 fish species are distributed (Tokyo Metropolitan Central Wholesale Market, n.d.). In addition, in recent years, as catches of several important fish species such as Japanese flying squid, pacific saury, and chum salmon have plummeted due to climate change, there has been a renewed awareness of the need to increase the resilience of the fishing business by utilizing multiple species (Task Force on the Problem of Poor Fishing, 2021). Therefore, multispecies fisheries management is an essential issue for the sustainability of Japanese fisheries.

Fisheries managers are tasked to balance ecological, economic, and social sustainability, known as the triple bottom line (TBL; Elkington, 1994), which becomes more difficult in multispecies fisheries. Achieving socioeconomically optimal catches while protecting all fish species is unrealistic. There is a trade-off between maximizing landings from multispecies fisheries and avoiding overfishing of some fish species (Worm et al., 2009). Many researchers argue that aligning the triple bottom line of sustainability is not feasible (e.g., Cochrane, 2000; Mardle et al., 2002; Pope, 1997; Symes & Crean, 1995). Various stakeholders usually share fish stocks, and someone's success can be someone else's failure (Hilborn, 2007a). The situation is complicated in multispecies fisheries because the number of stakeholders increases exponentially. In recent years, however, evidence has been found that TBL can complement proper management (Asche et al., 2018; Costello et al., 2016; Danielsen & Agnarsson, 2020).

Japan's fisheries management has been relying on "co-management," a combination of public management by the government and voluntary management by fishermen (Inomata, 2021). Its feature is that fishermen themselves, as resource users, are responsible for formulating and implementing resource management supported by the government's public system (Inomata, 2017; Makino & Sakamoto, 2003). This philosophy dates back to the Taiho Ritsuryo Code in 645, Japan's oldest fishery legislation, which stipulated the principle of resource protection and cultivation by users (Makino & Sakamoto, 2003). In offshore areas, government regulations have focused on input controls, including limited entry permits, vessel tonnage limits, and fishing periods/areas, complemented by self-imposed rules such as seasonal/area closure, length limits, and gear restrictions developed by regional or fishery-type specific fishery cooperatives. The Fisheries Agency states that due to the nature of multispecies and multi-gears, co-management combining various management methods is in place according to the characteristics of fish stocks and fisheries (FAJ, 2010). Such a co-management system is effective in ensuring compliance and reducing monitoring and enforcement costs (Inomata, 2014; Makino & Matsuda, 2005).

Although TACs were introduced in Japan in 1997 with the ratification of the United Nations Convention on the Law of the Sea (UNCLOS) and strengthened the management responsibilities of governments to some extent, the philosophy of management by the resource users themselves persisted After the national government allocates quotas to the coastal and offshore sectors, the details of how the quotas are to be fished, including area, time, and gear, are set by agreement among the fishermen, with the government endorsing them. This management method is described domestically as the "Japanese style" (Inomata, 2017). Inomata (2014) found conformity with Ostrom's (1990) design principles, polycentricity (Ostrom, 2005), and social capital (Ostrom & Ahn, 2003) for offshore fishery management where large proportions of the catch are under TACs, and provided theoretical support that Japanese style co-management could work effectively there. Inomata (2021), from the standpoint of institutional economics, suggested that Japanese style management is reasonable in terms of reduced transaction costs, incentive structures to adjust fishing opportunities, and institutional complementarity between public and voluntary rules. Many studies have also reported the existence of cooperative voluntary management systems, such as pooling systems, rotating operations, and individual quotas, for individual cases in offshore waters (e.g., Higashimura & Onishi, 2018; Matsuishi et al., 2013; Sakai et al., 2022b).

These studies suggest that the Japanese management system provides for good enabling conditions, but it is not certain that such conditions lead to good fishery performance. The system that leaves practical management to the fishermen themselves may lead to the following problems: (1) lack of awareness of scientific and quantitative management, (2) management concentrated on species with high commercial value, (3) impacts on the ecosystem overlooked, and (4) difficulty in reducing fishing pressure when it is excessive (Makino & Sakamoto, 2003). Several researchers are interested in how effective Japanese-style fisheries management is for large-scale, efficiencyoriented, and business-like offshore fisheries (e.g., Inomata, 2021; Ono, 2005, p340; Yamakawa, 2009). In recent years, the topic of how the expanded stock assessment and TACs under the new fisheries policy will affect multispecies fisheries has also attracted interest (e.g., Makino, 2019; Yamakawa, 2019).

This study applies the Fishery Performance Indicator (FPI) to evaluate the performance of the Hokkaido Pacific offshore trawl, which has a Japanese-style management system that combines public and voluntary management. The performance is compared to the average of FPI case studies conducted globally, in developed countries and in Japan. Moreover, as a benchmark for a more specific view, the performance is compared to trawl fisheries worldwide with different management systems. The research questions are: i) How well is Japan's multispecies fishery management performing in the Hokkaido Pacific offshore trawl fishery, and what are its strengths and weaknesses? ii) What systems do other countries adopt to balance TBL, and what can we learn? By identifying these points, this study examines what is needed to improve the sustainability of Japanese fisheries, including the potential impacts of the fisheries policy reform.

2.3 Methods

2.3.1 Fishery Performance Indicator (FPI)

The Fishery Performance Indicator (FPI) is an assessment tool that measures individual fisheries' ecological, economic, and social performance (Anderson et al., 2015). Using 68 output metrics coded on a scale of 1 to 5, the performance of a fishery by triple bottom line is assessed, which is further segmented into 14 dimensions (Figure 2.1). The output metrics also assess performance by stock, harvest, and post-harvest sectors, which are further subdivided into 11 dimensions (Figure 2.1). In addition, 54 input metrics on management approaches and enabling conditions that may affect output performance assess five components of 15 dimensions (Figure 2.2). Details of the scoring methodology are described in the FPI manual (Anderson et al., 2018). Unlike traditional stock assessments conducted on a stock-by-stock basis (Vinther et al., 2004), the fishery-based or fishery management system-based approach of the FPIs can readily apply to multispecies fisheries. Moreover, while fisheries management usually involves complex interactions among environmental factors, fishing techniques, and the historical and social conditions of the community, the standardized and holistic approach of the FPIs allows the case study to be compared with other cases.

The FPIs for the Hokkaido Pacific offshore trawl was scored based on government statistics, literature reviews, and the author's knowledge as a fishery manager. The HTFCF provided annual catch volume and value by species. The scores were compared to the world average, developed country average, and Japanese average. The global average of 147 cases was from the FPI database. The developed countries and Japanese averages came from published studies. The developed country average was added to the comparison because significant differences have been observed in scores between developed and developing countries (Anderson et al., 2015). Thirty-five percent of the database comprises developed countries (Eggert et al., 2021). All metric scores for the Hokkaido Pacific offshore trawl are in Appendix 1 and 2.

2.3.2 Benchmark fisheries

New Zealand hoki trawl, South Africa deep-sea hake trawl, and Faroe Islands demersal trawl were selected from the FPI database as benchmarks to gain a more specific view of the performance of the Hokkaido Pacific offshore trawl. These three benchmark fisheries have similar fishing characteristics to the Hokkaido Pacific trawl because they are trawl fisheries using industrialized fishing vessels in offshore areas and target cod-like species (Gadiformes). On the other hand, the management systems are different. The following is a summary of the management systems in each fishery. An overview of each fishery, including their species compositions, is in Table 2.1.

New Zealand hoki trawl

The fishery is an individual transferable quota (ITQ) fishery in which approximately 95% of the catch consists of species under a quota management system (QMS) [DeepWater Group Ltd., 2013]. Hoki (*Macruronus novaezelandiae*) accounts for 73% of the total catch in this fishery. Stocks managed under the QMS are subject to quota shares, property rights representing the quota holder's share of the allowed commercial catch (FishServe, n.d.). Each year, a catch limit called the Total Allowable Commercial Catch (TACC) is set for each stock. Quota holders receive an Annual Catch Entitlement (ACE), the amount of fish they can catch out of the TACC, based on their share. Quota holders report their catch to the management authority monthly. If the catch exceeds the ACE, they must purchase or receive a transfer of the ACE from another quota holder or pay a fee called Deemed Value as a penalty. Quota shares are also tradable, whereas there are limits on the share that one can be owned (45% for hoki; FishServe, n.d.). Sixty-five percent of the hoki quota is owned by three companies (Fisheries New Zealand, 2010), and there is some degree of consolidation. New entrants can enter the fishery by acquiring a quota share or by leasing ACE from quota holders.

Deemed Value is an essential mechanism for balancing quotas among multiple species under the QMS. In multispecies fisheries, it is not easy to match quotas with the catch for multiple species, yet quota holders can retroactively compensate for overages by paying a Deemed Value. The unit price of the Deemed Value is set on a stock-by-stock basis and generally increases as the overage increases. This prevents quota holders from catching a stock excessively without an ACE

(Peacey, 2002). In addition, the interim Deemed Value during the fishing season is set lower than the annual Deemed Value after the fishing season to encourage quota holders to cover their catch with ACEs during the fishing season. The purpose of the Deemed Values system is to incentivize individual fishermen to obtain ACEs consistent with their catch at flexible times, ensure efficiency through the quota market, and encourage accurate catch reporting (Fisheries New Zealand, 2021).

Other than the QMS, Benthic Protection Areas and Seamount Closures under the Fisheries Act prohibit bottom trawling in approximately 30% of NZ's EEZ (Clement et al., 2013). In addition, spatial and temporal closures called Hoki Management Areas and Hoki Seasonal Spawn Areas have been voluntarily established to protect juvenile and spawning hoki, respectively (Fisheries New Zealand, 2020). The QMS covers 98 species (642 stocks) [Fisheries New Zealand, 2016], and there are no limits on the number of vessels and effort (Sanchirico et al., 2006). In the hoki trawl, non-QMS species account for only about 5% of the catch, and the risk of overfishing is considered low (Clement et al., 2013). Although discarding is prohibited (Fisheries New Zealand, 2010), unreported catch remains an issue (Bremner et al., 2009).

South Africa deep-sea hake trawl

This fishery is unique in that it is under a combination of an ITQ and Total Allowable Effort (TAE) [SADSTIA, n.d.-c]. The TAC of hake began in 1978, and the individual quota followed the next year. Hake consists of deep-water hake (*Merluccius paradoxus*) and shallow-water hake (*M. capensis*), which comprise 57% and 14% of the total catch in this fishery, respectively. Although the two species differ in their distributions by depth, they are difficult to distinguish morphologically and are managed under a single combined TAC. The TAC is fixed at a maximum of 150,000 t, with annual fluctuations limited to 10% increases and 5% decreases (Norman & Japp, 2019), suggesting an aspiration to stabilize catches. Quota transfers require acquisitions or mergers of companies and government approval. (Cooper et al., 2014). Since 1991, TACs have been set based on an Operational Management Procedure (OMP) pre-agreed upon by all key stakeholders, including fishing companies, fisheries managers, and scientists (Field et al., 2013).

The TAE is an effort limit per vessel based on the fishing days adjusted by engine power (Siyema, 2010). It started in 2006 due to concerns about expanding fishing capacity (Cooper et al., 2014; SADSTIA, 2013). After successful capacity downsizing (Cooper et al., 2014), the role of preventing excess fishing for bycatch species after the hake TAC is reached has been emphasized (SADSTIA, n.d.-a; Siyema, 2010). The socioeconomic benefits of bycatch species are widely recognized in this fishery (Cooper et al., 2014; Genesis Analytics Ltd., 2019). Bycatch species such as horse mackerel (*Trachurus capensis*) and snoek (*Thysites atun*) are essential food sources for low-income residents on the West Coast, while kingklip (*Genypterus capensis*) and monkfish (*Lophius upsicephalus*) are highly valued in export markets (Department of Environment, Forestry, and Fisheries, 2020; SADSTIA, 2021b; Siyema, 2010).

Other management measures include precautionary catch limits for the critical bycatch species kingklip and monkfish, and trip limits for these two species and kob (*Argyrosomus japonicus*) [Department of Environment, Forestry, and Fisheries, 2020]. A move-on rule requires fishermen to move at least 5 miles if the catch of these three species exceeds the threshold. Bycatch species other than hake cannot exceed 50% of landings (Siyema, 2010). Since 2004, fishing has been restricted to areas with historical footprints, referred to as "the ring fences" (Norman & Japp, 2019). This started as a voluntary measure by the industry to promote Marine Stewardship Council (MSC) certification and became an official management measure in 2015 (Durholtz, 2019). The industry-funded observer program covers 40% of the fishing grounds and 10% of the effort (Norman & Japp, 2019), and fishery officers monitor all landings (SADSTIA, n.d.-c).

The deep-sea hake trawl fishery is capital-intensive and vertically integrated, with fishing rights holders owning fishing vessels and processing and marketing infrastructure (FEIKE, 2011). The fishery is also horizontally integrated, with significant consolidation of fishing rights holders through mergers and acquisitions. The top three business entities (called "clusters") own 75.7% of the quota and 70% of the active vessels (Cooper et al., 2014). Historically, white people dominated the fishery, however, the establishment of the Democratic administration in 1994 and the subsequent black economic empowerment (BEE) policy, and the enactment of the Marine Living Resources Act in 1998 resulted in additional allocations to Black people (Field et al., 2013; SADSTIA, n.d.-b). However, a small number of large capital firms with vested interests still account for most allocations and have disproportionately large power in the value chain, leading to an unequal competitive environment and excessively high barriers to entry (Mnisi & Lekezwa, 2014; Nielsen & Hara, 2006; Vilakazi & Ponte, 2022).

The adoption of the OMP has enabled the fishery to be certified by the MSC and allowed access to the EU and U.S. markets in various product forms such as fillet, H&G, and fresh fish (Norman & Japp, 2019; SADSTIA, 2021b). Without the MSC certification, the net present value of this fishery is estimated to decrease by 37.6% (Lallemand et al., 2016). The OMP is reviewed every four years in consultation with scientists, NGOs, and fishermen and is considered a successful example of multi-stakeholder involvement in fisheries management (Field et al., 2013). Payne & Bannister (2003) mentioned that throughout the long history of marine science in South Africa since the appointment of the first scientists and advisors in 1896, decision-makers have generally listened to and faithfully followed scientific advice, resulting in clearly successful fisheries management compared to the EU. Payne & Bannister (2003) noted that throughout the long history of marine science in South Africa since the appointment of the first scientists and advisors in 1896, decision-makers have generally listened to and faithfully followed scientific advice, resulting in successful fisheries management compared to the EU.

Faroe Islands demersal trawl

This fishery mainly targets saithe (*Pollachius virens*), cod (*Gadus morhua*), and haddock (*Melanogrammus aeglefinus*) and is managed under the effort quota (EQ) management system. (Note that the Faroe Islands reformed its fisheries policy in 2018-2019, and the demersal trawl fishery shifted to a TAC and ITQ system (Danielsen & Agnarsson, 2018a). However, this paper analysis the fishery based on the situation in 2018 when its FPI was scored.) The EQ system comprises four fleet groups: two demersal trawl fleets (single trawler and pair trawler), longliners, and coastal fisheries. Each year, fishing days are set based on advice from ICES and input from the industry (Baudron et al., 2010), and the fishing days are allocated to each fleet group and assigned equally to each vessel within the group. Fishing days can be transferred permanently or leased annually within the same fleet group. In the last three months of the fishing year, fishing days are transferable between fleet groups, making it challenging to control fishing pressure on a particular stock because each fleet has different target species and catchability (Danielsen & Agnarsson, 2018b). To encourage the transfer of catches from inshore, where small fish live, to offshore, one inshore fishing day is equivalent to three offshore fishing days. Single and paired trawl owners cannot hold over 10% and 20% of the total quota share. An important assumption of the EQ system is that under a properly set effort quota, overfished stocks will naturally recover as fishermen target the most abundant species (Danielsen & Agnarsson, 2020). However, other factors varying by species, such as price, are ignored (Danielsen & Agnarsson, 2018b).

The demersal trawl was under an ITQ for saithe, cod, and haddock from 1994 to 1996. However, it faltered after only two years for the following reasons: i) the TAC was subject to review by a stakeholder committee composed of industry representatives and by the Parliament and deviated from scientific advice; ii) the lease of allocations could only be made once a year and not for two consecutive years; iii) allocations could not be sold permanently; iv) licenses were renewable annually, and access rights were not guaranteed; and v) some demersal stocks, especially cod,increased rapidly right after the introduction of the ITQs, yet the inflexible quota system led to discards and misreporting, resulting in solid industry opposition (Jákupsstovu et al., 2007). Such a mechanism to prevent fleet rationalization was adopted because of political concerns about the social impact of job losses in the early 1990s when the Faroe Islands were in the midst of a severe economic crisis (Danielsen & Agnarsson, 2018b). The unexpected surge in demersal stocks led to a distrust of stock assessments, which became a factor in adopting effort management rather than catch limits (Danielsen & Agnarsson, 2018b).

Several problems have been identified with the EQ system. First, the total fishing days are too many and not substantial constraints. The average effort limit for the 2016 fishing season was 352 days per vessel for single trawlers and 520 days per vessel for pair trawlers when operating offshore (Danielsen & Agnarsson, 2018a&b). Therefore, fleet rationalization has yet to progress (Danielsen & Agnarsson, 2018b). The fishing days were initially set after consultations with stakeholder committees and the Parliament. Even in recent years, politicians have hesitated to reduce fishing days due to concerns about social impacts, especially job losses (Danielsen & Agnarsson, 2018b). Second, as ICES gives scientific advice in terms of catch, the impact of effort limits on stocks is uncertain if the relationship between fishing days and the catch is unclear. In particular, there is evidence that technical creep has increased the catchability of the fleet since the implementation of EQ (Thomsen et al., 2005). Finally, saithe, cod, and haddock catches have exceeded ICES recommended levels in many years and have declined significantly since the early 2000s. Fishing mortalities for saithe and cod are well above target (Danielsen & Agnarsson, 2018b). Baudron et al. (2010) argue that the main problem is not effort management itself but rather the inability to respond to scientific advice and shifts in catchability.

Management measures other than EQ include a bottom trawling prohibition in coastal waters shallower than 200 m and within 12 nautical miles (Hegland & Hopkins, 2014), and a discard ban (Johnsen & Eliasen, 2011).

2.4 Result

2.4.1 The performance relative to the global averages

The FPI output scores of the Hokkaido Pacific offshore trawl are in Figure 2.3. The ecology score (3.86) was higher than the average of all case studies (3.30) while slightly less than the developed country average (4.04) and the Japanese case study average (3.97). The economic performance scored 3.67, which was above all case studies (3.29) and the Japanese average (3.49) and at the same level as the developed countries (3.74), yet this score was the lowest among the TBL scores. Notably, the community performance was very high (4.60) and well above all case studies (3.79) and developed countries (4.05). Japanese fisheries score very high in this category on average. The high performance was due to good scores (≥ 4.5) in all dimensions except Labor Returns.

Figure 2.4 shows the output scores by sector for the Hokkaido Pacific offshore trawl. The harvest sector performed very well, scored of 4.3, which was higher than all case study average, the developed country average, and the Japanese average. This high performance resulted from high scores in the dimensions of Harvest Performance (4.75), Owners (5.00), and Crew (4.88). On the other hand, the post-harvest score was below the Japanese average, close to the developed country average. The products from this fishery are mainly inexpensive surimi for the domestic market, and Market (3.43) and Processing Workers (3.43) dimensions did not score high.

2.4.2 The performance relative to the benchmark trawl fisheries

Figure 2.5 compares the Hokkaido Pacific offshore trawl and the benchmark trawl fisheries based on output scores by TBL indicator (Figure 2.5a) and TBL dimension (Figure 2.5b). The ecology score of the Hokkaido offshore trawl (3.86) was a little higher than the Faroe Islands demersal trawl (3.71), yet lower than the New Zealand hoki trawl (4.38) and South Africa hake trawl (4.50). The lack of third-party certification was a major factor, and the low stock status of some bycatch species also affected the result.

For the economic indicator, the fishery was below all three benchmark fisheries. In particular, Harvest Asset, Risk, and Trade dimensions were the lowest among these fisheries. The Harvest Asset was weak due to low assets relative to landings value and a declining trend in the number of vessels, causing a decrease in total revenues. Fishing permits and catch quotas in this fishery are not tradable, and no assets accumulate. The main assets are fishing vessels, which are generally aging, although some new vessels have been built in recent years. The Risk dimension was low due to high monthly and spatial variability in landings and prices. Pollock is migratory, and Kushiro, located upstream, lands large catches at the beginning of the fishing season, while Muroran, located downstream, catches high-value spawning fish, which were variable factors. The Trade dimension was affected by the facts that i) most of the products are for the domestic market, while other benchmark fisheries are export-oriented, ii) the product is surimi with relatively low added value, and iii) surimi is less competitive than imported products from the U.S. and other countries.

Results for this fishery for Community outperformed the other three and compared favorably with similar fisheries worldwide. In particular, it outperformed all other fisheries in Carrier, Local Ownership, and Management Returns. The high scores for Carrier are due to the age balance of the crew and the skilled crew. The fishery also excels in the locality, as it is not dependent on non-local crews and owners. The offshore trawl fishery and the seafood processing industry are core industries in the region, with high salaries and social status, which increased the Managerial Return.

Figure 2.6 shows the FPI output scores by sector (Figure 2.6a) and sector dimension (Figure 2.6b). The harvest sector performance of the Hokkaido offshore trawl fishery (4.30) was better than the other three fisheries. All fisheries were above the developed country average, which is unsurprising given that these cod fisheries are industrialized and efficient. However, even within these fisheries, the Hokkaido offshore trawl performed well. It scored highly in the dimensions of Harvest, Owners, and Crew. Harvest dimension scored five on Excess Capacity, Season Length, and Safety metrics. Landings Level was also near optimal. High wages and social status support the Owner and Crew dimensions. On the other hand, the Harvest Assets and Risk dimensions were the lowest of the four fisheries, with the factors discussed above. The fishery revealed a mix of strengths and weaknesses in the harvest sector.

The Post-Harvest Sector score (3.94) was similar to South Africa (3.85) while below NZ (4.22) and the Faroe Islands (4.21), with the lowest scores in Market and Processing Workers dimensions among these fisheries. The Market dimension was affected by a lack of products for export, a shortage of processing facilities that meet the U.S. and EU export standards, inadequate pricing power and competitiveness of surimi, and overall low fish prices mainly due to low catches of high-value squid. Processing Workers were rated relatively low regarding wages and social status, relying on foreign workers and part-timers.

Figure 2.7 presents input scores for each fishery. Note that these input scores measure enabling conditions, which may affect output scores, yet higher scores do not necessarily mean "better" (Asche et al., 2018). However, some differences appear by looking at four trawl fisheries side by side, which have similar technical characteristics under different management systems. First, NZ scored highly in the Access Rights and Harvest Rights, which is natural given the fishery's highly developed and flexible ITQ system. The fishery also scores very high in Participation & Support because stakeholders are closely involved in designing fishery management plans, setting voluntary measures, conducting research, and monitoring (DeepWater Group Ltd., 2013), and the Deemed Value payments make revenue for the government. The extensive Marine Protected Area (MPA) and ITQ system also led to high scores in Management Methods. The Faroe Islands have adopted the TAE system and scored very low in Harvest Rights. Participation & Support was not high, yet the demersal fleet is organized and had a relatively high score in Collective Action, consistent with the literature (Danielsen & Agnarsson, 2018b), which points to the industry's lobbying to the TAE system. South Africa is managed under a combination of ITQ and TAE, placing it between NZ and the Faroe Islands in Property Rights. Although the country is a developing country, it scored well in Data and Management Capacity and Participation & Support, consistent with much literature noting the success of science-based fisheries management in the fishery. Japan's Hokkaido Pacific trawl has TACs for pollock and flying squid. However, the quota is not transferable, and there is competition for fish stocks with coastal fisheries and Russia, resulting in medium scores for Access Rights and Harvest Rights. On the other hand, Collective Action and Leadership received high scores, supported by the fact that the offshore trawl industry is highly organized and influential in fisheries management and marketing. In addition, it scored very high in infrastructure, consisting of roads and utilities, refrigeration and freezing capacity, technology, and research facilities. Overall, the FPI input scores captured the differences in the management systems of each fishery.

2.5 Discussion

This study evaluated the performance of the Hokkaido Pacific offshore trawl, using the Fishery Performance Indicators, to understand the degree of success of Japan's multispecies fisheries management in offshore water and to gain insight into what is needed to improve its sustainability. The score was compared to the global average, the developed countries' average, and the Japanese average, as well as to cod trawlers in other countries with different management systems as benchmark. As a result, higher performances than all comparison groups were found in the Community and Harvest sectors. This was due to high scores on metrics related to fishing vessel owners and crews, including wages, social status, experience, age structure, and residents. On the other hand, the ecology, economy, and post-harvest sector performance were moderate, on par with the developed country average, and at the lower end of the benchmark fisheries.

Although the value of offshore trawl has traditionally focused on its mass productivity (e.g., Itakura, 2004; Shibata et al., 2004), the results of this study also highlight a significant contribution to the local community on the " human" aspect, including job, career development, and fair wages. Even though relatively large offshore fisheries often rely more on foreign crews than coastal fisheries (Sasaki, 2020), it is remarkable that the Hokkaido Pacific offshore trawl, which uses the largest vessels and requires many crew members, is operated solely by locals. In this fishery, the excellent working conditions of day-trip fishing and high wages attract the local labor force (JICA & IC Net Co Ltd., 2020; Sasaki, 2020). On the other hand, offshore fisheries are usually multi-day trips, hindering crew recruitment. In addition, the environmental condition of abundant pollock stock is also a factor. The offshore trawl in Aomori Prefecture, located next to Hokkaido, also uses similarly sized vessels but has significantly lower landings due to fewer pollock and relies on foreign crews (NFMT, 2021). The benchmark fisheries catch cod-like species with large biomass, yet local ownership was low for South Africa due to historical racial issues. The Faroe Islands Demersal trawl employs local labor, however, it pays worse than other fisheries and has a relatively high turnover rate (Danielsen et al., 2021).

The favorable working conditions are supported by the co-management system in which fishermen themselves formulate and implement the management, supplemented by the government's public management. First, although the Hokkaido Pacific offshore trawl fishermen can operate in a vast area under their fishing permits, they voluntarily restrict their operations to a narrow area in front of the home port (Matsuishi et al., 2013). This unstated policy started to prevent competitive fishing among offshore trawlers and between offshore trawlers and coastal fisheries, but at the same time, it contributed to a shorter operational period. Second, the government allocates pollock TAC to the offshore trawl sector, and the NFMT and HTFCF effectively manage individual quotas, which provides a cooperative fishing operation. This has prevented the quota overage and race to fish. Finally, the fishery has a move-on rule, where fishermen change fishing ground when the proportion of small pollock exceeds a limit, resulting in meager catches of small fish, which helps to maintain spawning biomass (Ishino et al., 2021). These measures form part of the resource management plan the related fishery cooperatives agreed upon, which the government approves. These facts suggest that even in a complex environment where offshore and coastal fisheries interact and catch multiple species, a Japanese-style co-management system can work effectively and return the benefits to the local community.

Overly strong consideration for the community occasionally leads to a risk of overfishing. For example, in the Faroe Islands demersal trawl, concerns about job loss have created an excessively high an effort quota, and haddock and cod are overfished. The TAE setting process including dialogues with a stakeholder committee and the Parliament, which allowed the quota to deviate from scientific advice. In Japan, the offshore trawl on the Japan Sea side of Hokkaido catches the pollock of Japan Sea stock, using almost the same fishing methods as those on the Pacific side. However, the Japan Sea stock, in contrast to the Pacific stock, is currently in collapse. In the 1990s and 2000s, when the survival of juvenile fish was poor, excessive TACs were set with a priority on maintaining catches, which accelerated the stock decline (Misaka, 2016; Shida, 2013). A feature of Japan's new fisheries policy is that biological reference points for each stock and harvest control rule to achieve them are subject to discussion at stakeholder meetings. Maintaining and increasing the sustainability of stocks while ensuring community considerations remains a critical task.

The high reliance on a single pollock stock, consisting of 54% of the landings value, is one of the risks for the Hokkaido Pacific offshore trawl. Supported by the currently abundant pollock stock, the ecology score of the FPI was moderate. On the other hand, the stock status of pollock is highly dependent on the emergence of the strong year class, which has occurred in 2005 and 2007 since 2000, but recruitment has been at a low level in the last decade (Ishino et al., 2021). Therefore, it is essential to continue accurate and timely monitoring of recruitment and efforts to secure spawning biomass by protecting small fish. The Japan Sea side offshore trawl has still been suffering due to the slump in pollock stock and is seeking to shift away from its dependence on pollock (Yanagawa, 2015). Under the new fisheries policy, the biological target and a harvest control rule for pollock have been set, which would help fishermen to develop business plans from a more long-term perspective.

The single market reliance would also be a risk. Pollack is almost exclusively processed into surimi for domestic consumption. However, consumption of surimi products is declining (Japan Kamaboko Association, n.d.), and its price depends on the international market, and this fishery seeks more price formation power. Furthermore, its grade is lower than imported surimi's, and its price competitiveness needs to be stronger. Therefore, it is essential to diversify the market to increase the economic sustainability of this fishery. The pollock fishery in Alaska, one of the world's leading producers of surimi, has increased its production of higher-value fillets and gained new markets in the EU since the Catch Share program began in 1998 (Northern Economics Inc., 2017). All the benchmark fisheries in this study are export-oriented, and all received higher FPI economic scores than the Hokkaido offshore trawl. In Hokkaido, the Kushiro Trawl Fishery Cooperative Association has recently built a processing facility to produce higher-grade surimi, and fishermen apply high freshness and sanitary treatments to their fish to meet the standards. The cooperative is also leading attempts to expand exports to Thailand, Malaysia, and other East Asian countries, amid difficulties in reviving exports to South Korea (Kushiro Fisheries Revitalization Committee, 2019). The development of collective fishing operations and processing based on fishery cooperatives may be a form of horizontal and vertical integration. The insufficient economic and post-harvest sector scores presented in this study justify those efforts but also highlight challenges to market expansion, such as the lack of third-party certification and the small number of processing facilities that meet EU and U.S. standards.

It would be important to actively utilize bycatch species to improve the economics of this fishery. Non-pollock species account for 15% by weight but 46% by value. Well-developed infrastructures and one of the world's largest domestic seafood markets will be a strength. Indeed, the fishery cooperatives are leading attempts to commercialize non- or under-utilized fish (Kushiro Fisheries Revitalization Committee, 2019). The lack of scientific data on bycatch species can be a factor that discourages the active use of multispecies and is also a reason why this fishery does not meet the MSC certification standard (Matsuishi & Kaneiwa, 2014). Although scientific resource constraints are likely high, improved science-based management through new fishery policies is expected to ameliorate this situation.

The new fisheries policy expects to improve ecological performance by strengthening the management of individual stocks. However, it also poses challenges in multispecies fisheries. For example, what advice should scientists give when multiple stocks show opposite statuses? How should fisheries managers deal with discarding, high-grading, and misreporting issues when more stocks are subject to catch limits? How can the fishing industry improve its economics under new constraints? The benchmark fisheries provided examples of successes and lessons in designing multispecies fisheries management. One of the concepts of the NZ QMS system is to promote the wise use of fish stocks by maximizing the asset value of quota held by quota holders (Mace et al., 2014), and on the FPI scale, this system appears to be achieving its objective. In South Africa, adopting the OMP enabled the fishery to gain the MSC certification, which led to access to European and U.S. markets. On the other hand, the Faroe Islands demersal trawl miscalculated the impact of the EQ system on fishermen's behavior, leading to a decline in the stocks. Understanding fishermen's behavior is essential to successful fisheries management (Hilborn, 2007b). In Japan, analysis of the impacts of new management measures using a multispecies bioeconomic model and review and reconsideration of existing management measures that are folded together and have yet to be fully validated scientifically will be necessary. With these, understanding the impact of management systems on fishermen in multispecies fisheries and incorporating appropriate complementary systems to maintain or increase economic and social viability will be key for Japanese fisheries to succeed in reform.

2.6 Tables

Table 2.1: A summary of benchmark fisheries against the Hokkaido Pacific offshore trawl. The figures for the Japan Hokkaido Pacific offshore trawl are as of 2021. For South Africa hake deep-sea trawl, upper rows are for fresh vessels, and lower rows are for freezer vessels. Source: [*1] Anderson et al., 2019; [*2] FPI database; [*3] FAO, 2023; [*4] Ballara & O'Driscoll, 2021, 64p; [*5] Fisheries New Zealand, 2022, 589p; [*6] Fisheries New Zealand, 2010, 10p; [*7] Andrews, et al., 2022, 28p; [*8] FEIKE, 2011; [*9] Garlock et al., 2020; [*10] SADSTIA, n.d.-d; [*11] SADSTIA, 2021b; [*12] SADSTIA, 2021a; [*13] STATBANK, n.d. ; [*14] Danielsen et al., 2021; [*15] Teyggjan, n.d. ; [*16] Ministry of Fisheries and Natural Resources, n.d.

Fishery (FPI assessment year)	Japan Hokkaido Pacific offshore trawl (2021)	New Zealand hoki trawl (2011)	South Africa hake deep-sea trawl (2018)	Faroe Islands demersal trawl (2018)
Species (volume)	Pollock (85%), Cod (11%), Souhachi-flounder (1%), Flying squid (1%), Saffron cod (1%), Others (1%)	Hoki (73%), Hake (7%), Ling (5%), Silver warehou (4%), Javelinfish (2%), Others (9%)[*1]	Deep-water Hake (57%), Shallow-water Hake (14%), Monkfish (4%), Kingklip (3%), Jacopever (2%), Others (20%)[*7]	Saithe (42%), Greater silver smelt (24%), Mackerel (12%), Cod (5%), Greenland halibut (3%), Others (14%)[*13]
Landings volume (mt)	72,622	130,000 (Hoki)[*2]	132,000 (Hake)[*8]	49,562[*13]
Landings value (USD)	49 million	590 million (Hoki quota value)[*3]	300 million[*9]	65 million[*13]
No. vessels	16	65[*2]	30 (fresh) 21 (freezer)[*9]	33[*14]
Vessel tonnage (GT)	125-160	Highly variable[*4]	600 (fresh) 300-2900 (freezer)[*10]	220-993[*15]
Gear	Danish seine, otter trawl	Otter trawl, twin trawl, midwater trawl[*4]	Otter trawl (fresh), otter trawl (freezer)[*9]	Pair trawl, otter trawl[*14]
Main product	Surimi (pollock)	Fillet (hoki)[*5]	Fillet, HG, fresh (hake)[*11]	Fillet (saithe & cod), HG (cod & halibut), mince (smelt)[*16]
Main market	Domestic	Export (EU, US, Australia)[*6]	Export (58% in value; EU, Australia, US), Domestic (42%)[*12]	Export (EU)[*16]

2.7 Figures

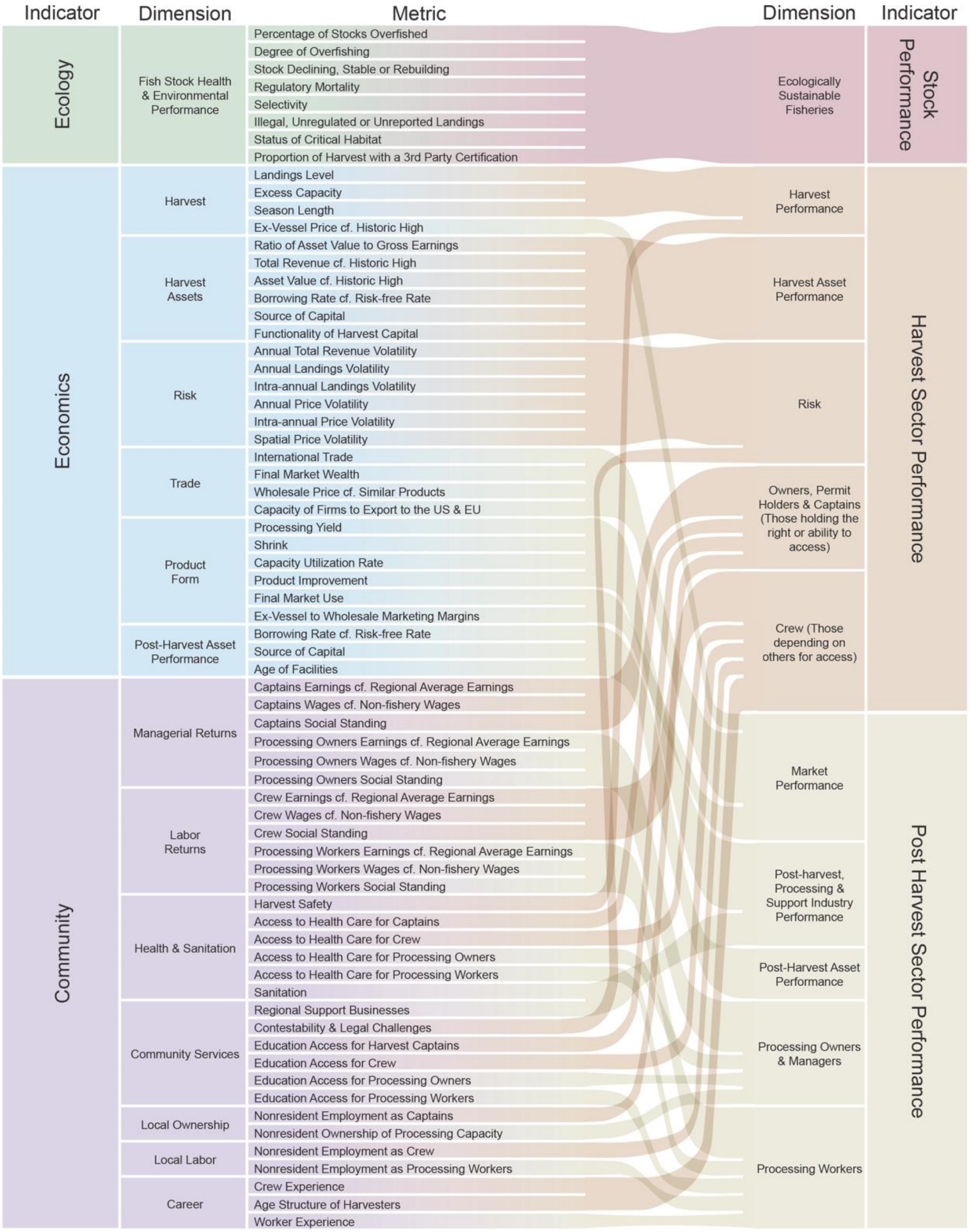
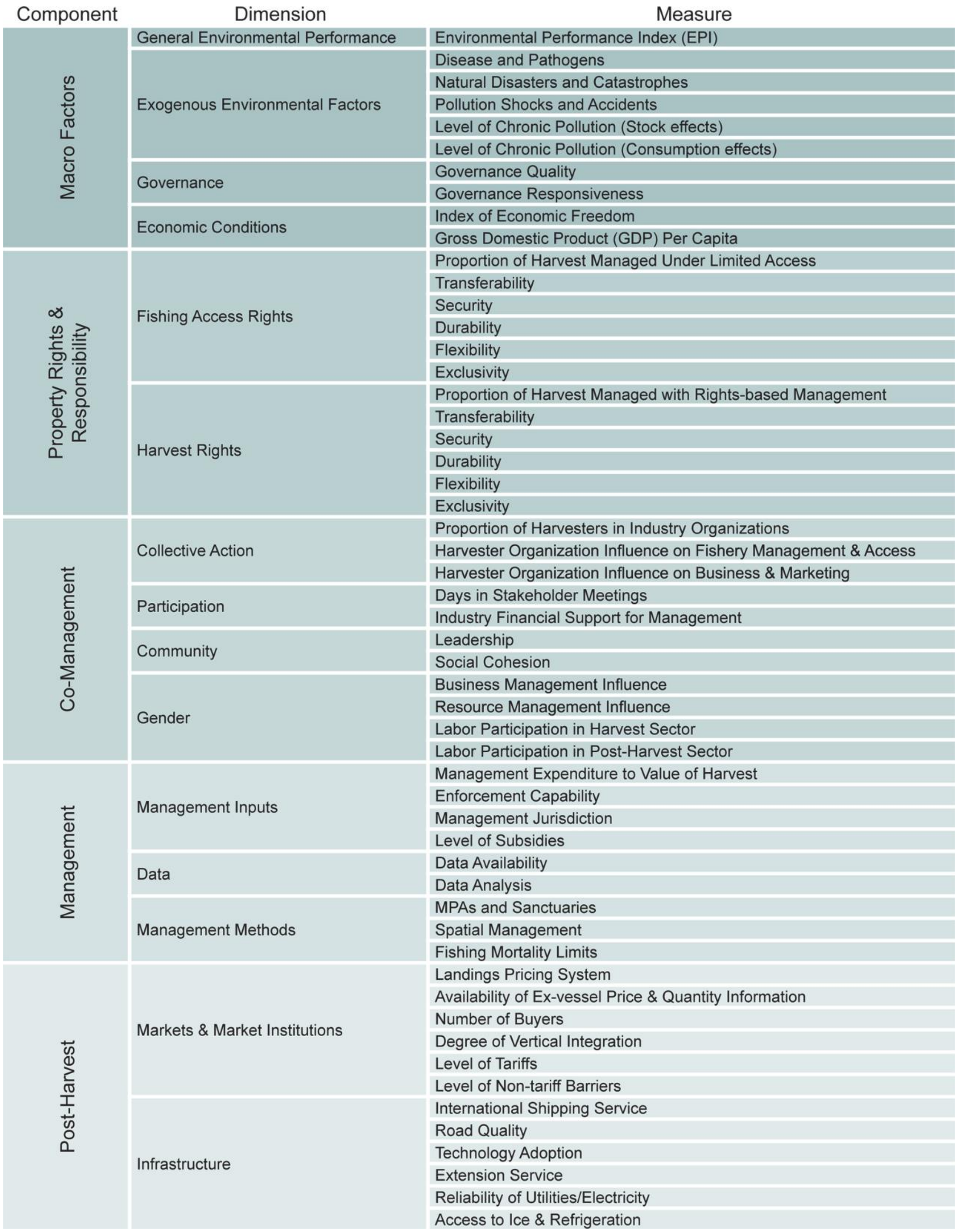


Figure 2.1: FPI output indicators with the associated dimensions and metrics from Anderson et al. (2015).

al. (2015).



Component	Dimension	Measure
Macro Factors	General Environmental Performance	Environmental Performance Index (EPI)
	Exogenous Environmental Factors	Disease and Pathogens
		Natural Disasters and Catastrophes
		Pollution Shocks and Accidents
		Level of Chronic Pollution (Stock effects)
		Level of Chronic Pollution (Consumption effects)
	Governance	Governance Quality
		Governance Responsiveness
	Economic Conditions	Index of Economic Freedom
		Gross Domestic Product (GDP) Per Capita
Property Rights & Responsibility	Fishing Access Rights	Proportion of Harvest Managed Under Limited Access
		Transferability
		Security
		Durability
		Flexibility
		Exclusivity
	Harvest Rights	Proportion of Harvest Managed with Rights-based Management
		Transferability
		Security
		Durability
		Flexibility
		Exclusivity
Co-Management	Collective Action	Proportion of Harvesters in Industry Organizations
		Harvester Organization Influence on Fishery Management & Access
		Harvester Organization Influence on Business & Marketing
	Participation	Days in Stakeholder Meetings
		Industry Financial Support for Management
	Community	Leadership
		Social Cohesion
	Gender	Business Management Influence
		Resource Management Influence
		Labor Participation in Harvest Sector
		Labor Participation in Post-Harvest Sector
Management	Management Inputs	Management Expenditure to Value of Harvest
		Enforcement Capability
		Management Jurisdiction
		Level of Subsidies
	Data	Data Availability
		Data Analysis
	Management Methods	MPAs and Sanctuaries
		Spatial Management
		Fishing Mortality Limits
Post-Harvest	Markets & Market Institutions	Landings Pricing System
		Availability of Ex-vessel Price & Quantity Information
		Number of Buyers
		Degree of Vertical Integration
		Level of Tariffs
		Level of Non-tariff Barriers
	Infrastructure	International Shipping Service
		Road Quality
		Technology Adoption
		Extension Service
		Reliability of Utilities/Electricity
		Access to Ice & Refrigeration

Figure 2.2: FPI input components with the associated dimensions and metrics from Anderson et al. (2015).

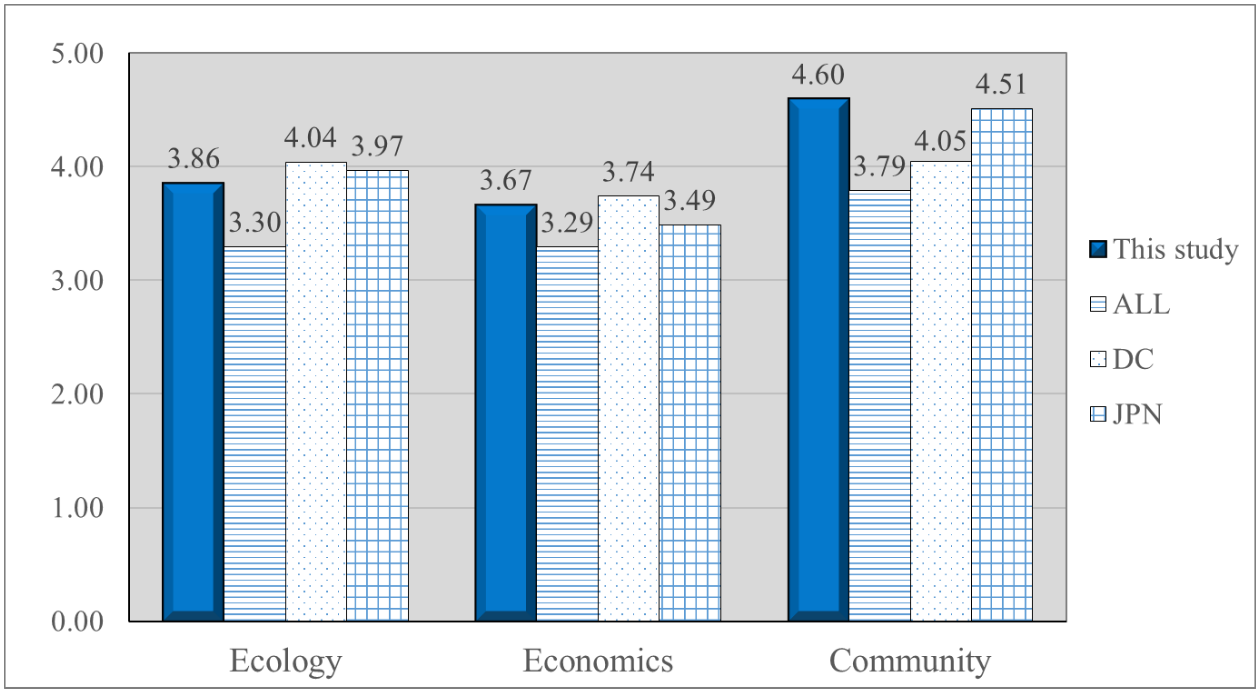


Figure 2.3: FPI output scores by TBL. ALL: the average of all case studies around the world (n = 147) from the FPI database; DC: the average of developed country case studies (n = 52) from Eggret et al. (2021); JPN: the average score of Japanese case studies (n = 12) from Anderson et al. (2015), Garlock et al. (2022), Tokunaga et al. (2019b), and Uchida et al. (2018).

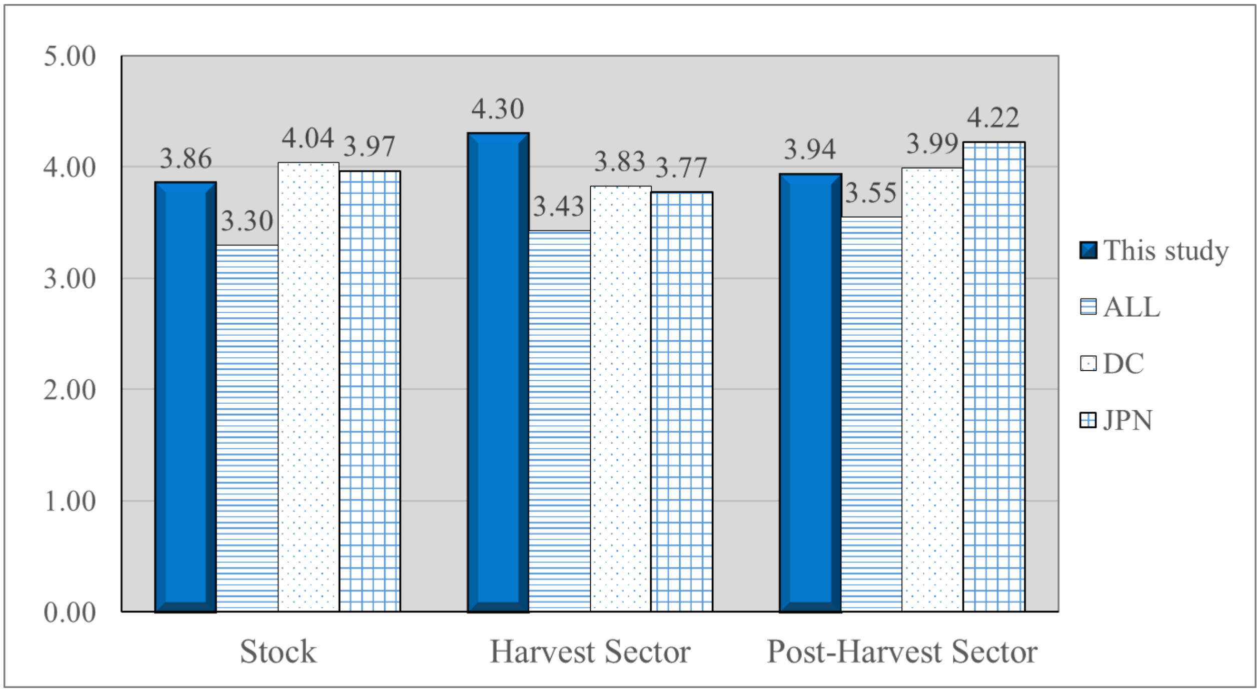


Figure 2.4: FPI output scores by sector. ALL: the average of all case studies around the world (n = 147) from the FPI database; DC: the average of developed country case studies (n = 52) from Eggret et al. (2021); JPN: the average score of Japanese case studies (n = 12) from Anderson et al. (2015), Garlock et al. (2022), Tokunaga et al. (2019b), and Uchida et al. (2018).

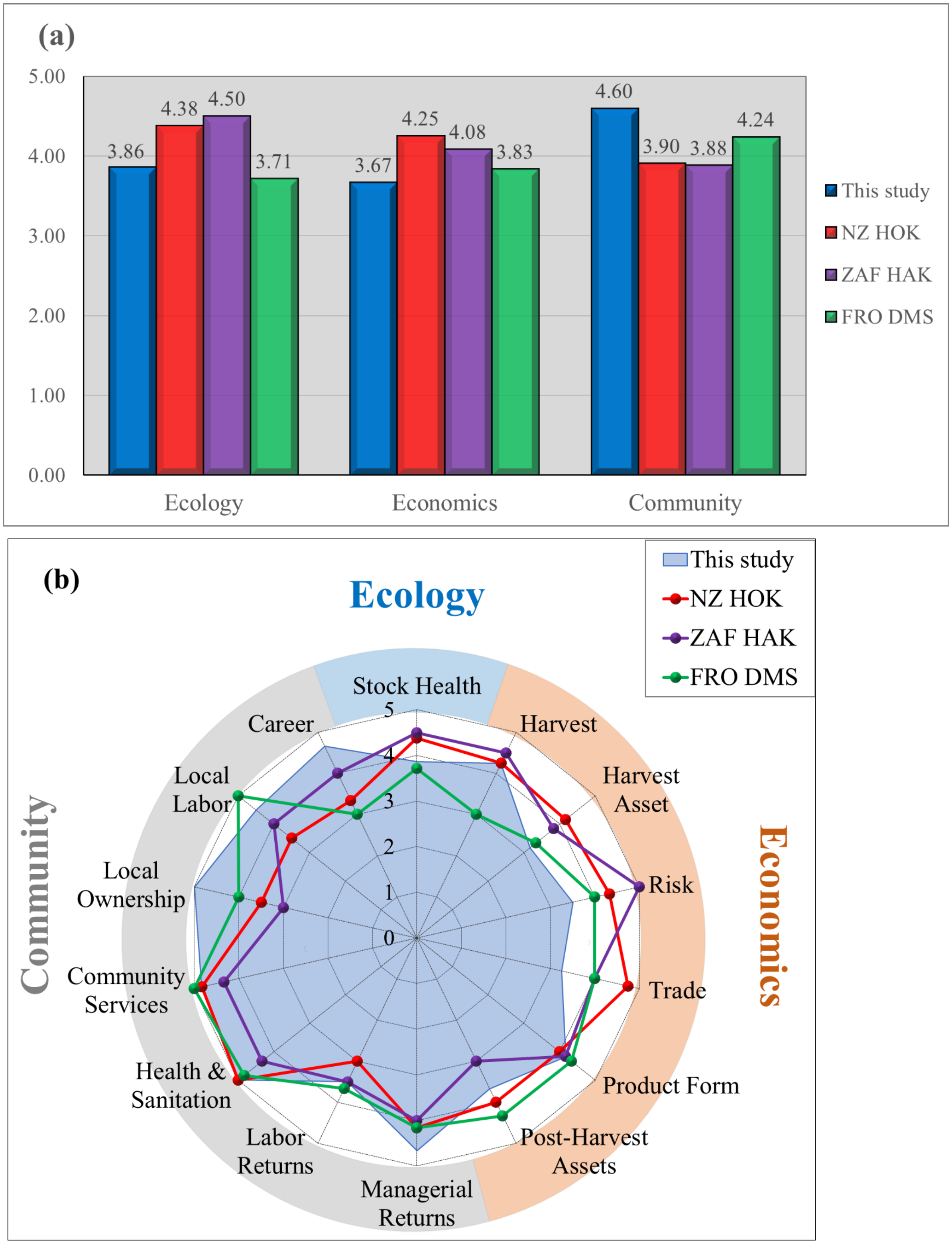


Figure 2.5: FPI output scores by TBL indicator (a) and TBL dimension (b). NZ HOK: New Zealand hoki trawl; ZAF HAK: South Africa hake deep-sea trawl; FRO DMS: Faroe Islands demersal trawl.

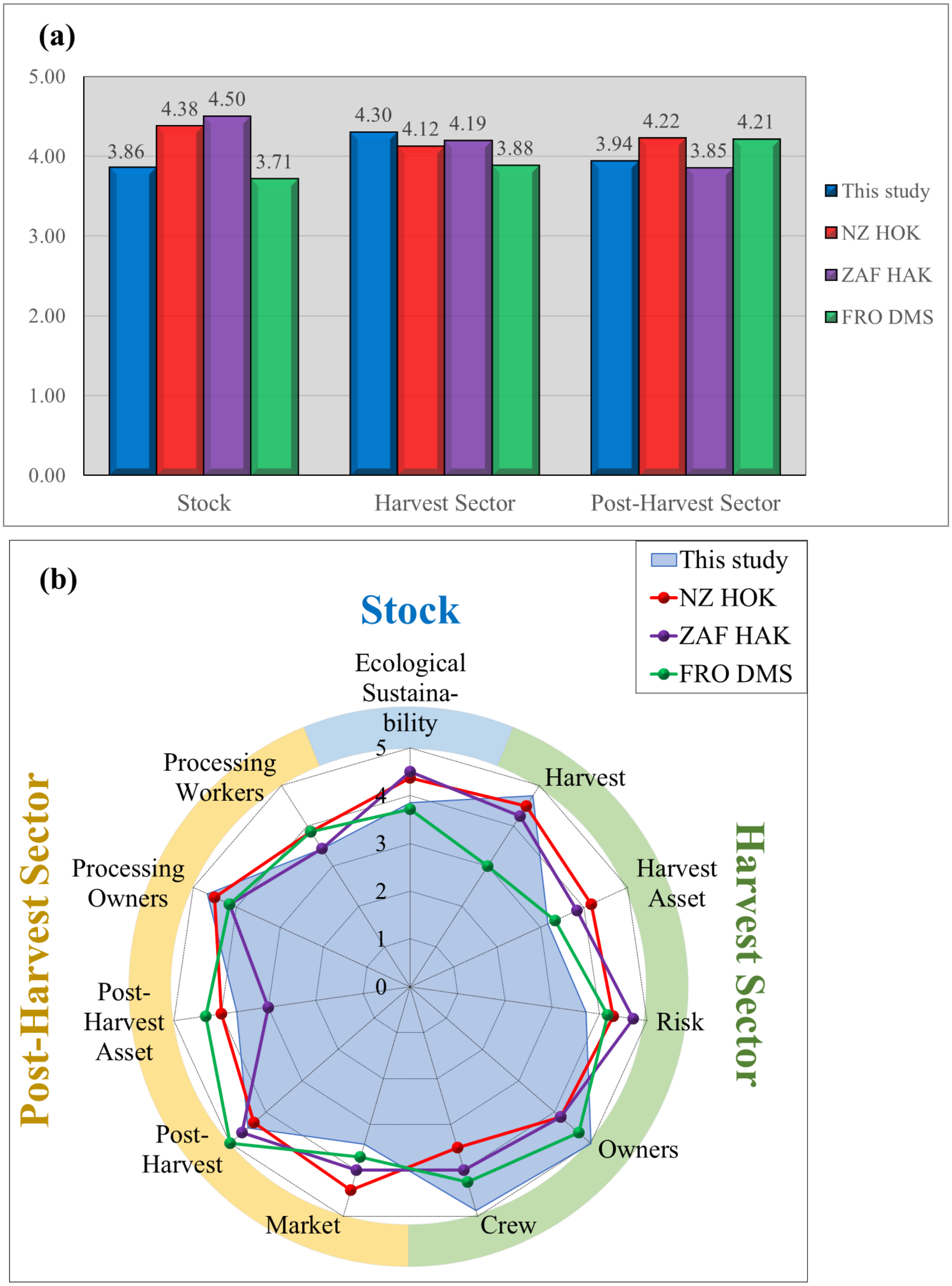


Figure 2.6: FPI output scores by sector indicator (a) and sector dimension (b). NZ HOK: New Zealand hoki trawl; ZAF HAK: South Africa hake deep-sea trawl; FRO DMS: Faroe Islands demersal trawl.

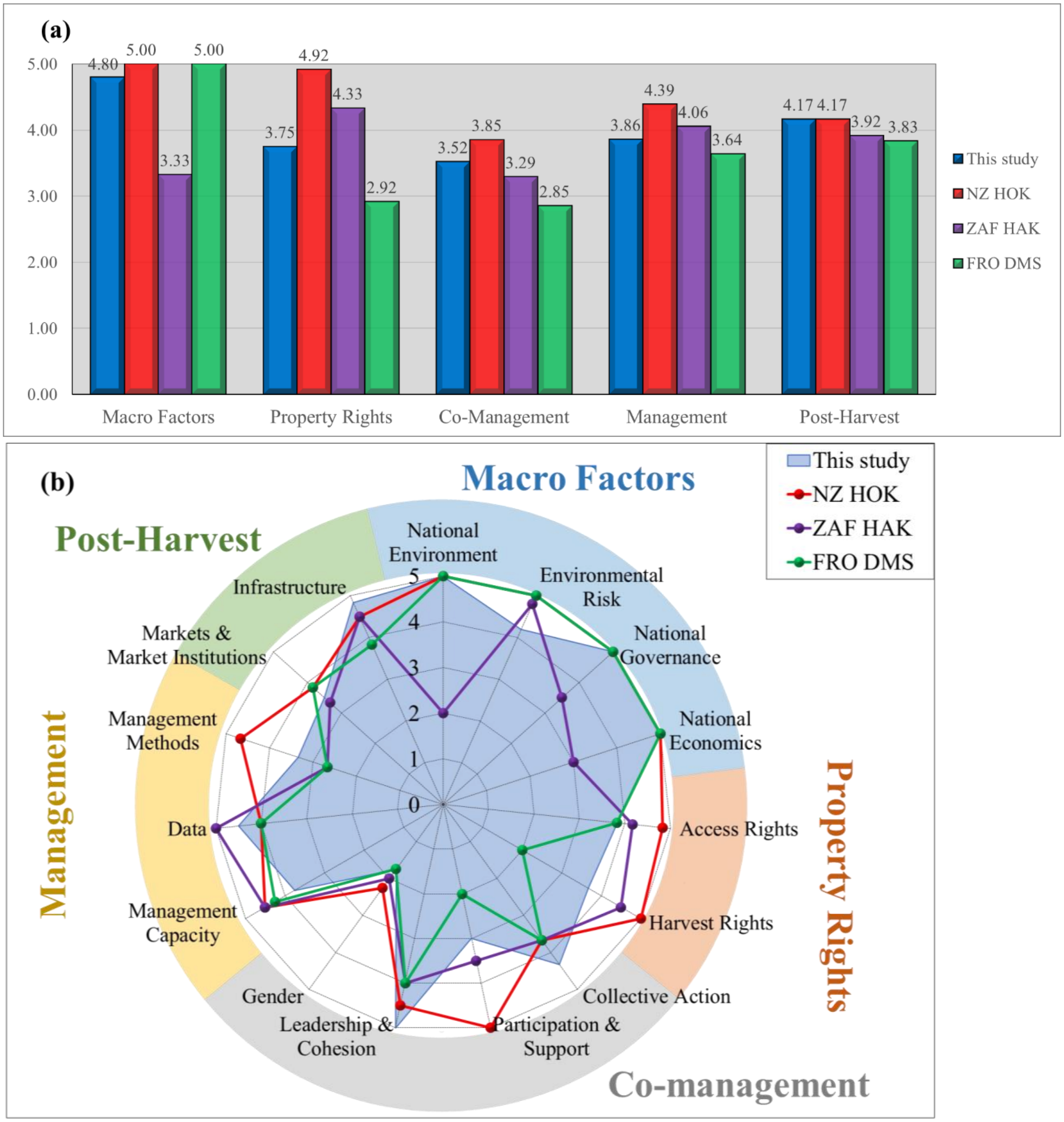


Figure 2.7: FPI input scores by component (a) and dimension (b). NZ HOK: New Zealand hoki trawl; ZAF HAK: South Africa hake deep-sea trawl; FRO DMS: Faroe Islands demersal trawl.

Chapter 3: A bioeconomic analysis of Japanese multispecies fishery under different harvest scenarios

3.1 Abstract

Under the new fisheries policy, Japan is expanding the use of Total Allowable Catch (TAC) to regulate its fisheries. TACs will be set based on species-specific Harvest Control Rules (HCRs), pre-determined through stakeholder dialogue. This study simulated multiple harvest scenarios with an age-structured multispecies bioeconomic model incorporating pollock, cod, and a species group of others, with a case study of the Hokkaido Pacific offshore trawl, where a TAC will be introduced for cod. Under the contrasting situations of abundant pollock and decreased cod, the results revealed a significant trade-off between cod recovery and socioeconomic benefits. A scenario introducing the basic HCRs for pollock and cod and nearly achieving the policy of recovering the decreased stock within ten years would have required a 47% reduction in effort for the Hokkaido Pacific offshore trawl on average over 20 years compared to a scenario with the basic HCR for pollock only, resulting in a 33% reduction in the catch, 61% reduction in profit, and 28% reduction in crew salary. Besides, the risk of in-season closure and significant yield loss was 100% and 98%, respectively. A harvest scenario introducing the basic HCR only for pollock would not collapse the cod stock and provide more favorable socioeconomic benefits but would be hampered by the policies of the stock recovery timeline and the expansion of TAC. To promote cooperative management under the new management system, it is necessary to explicitly show what will be improved and what the risks are involved in not acting, and to facilitate discussion with stakeholders.

3.2 Introduction

Japan's fisheries management is in the middle of implementing reform. The Fisheries Act passed by the Diet in 2018 stipulates that output control using Total Allowable Catch (TAC) is the principle to be applied fisheries resource management. This is a turning point for Japan, which has traditionally managed fish stocks primarily through input control and voluntary management by fishermen. The coverage of the TAC will be expanded from 60% of the marine capture fishery production by volume in 2018 to approximately 80% in 2023 (FAJ, 2023). Because the current TAC requirements are applied to the eight species with large catch volume, this 20% increase makes a big difference, and indeed, new TACs will be introduced for 15 species (or species groups) or 34 stocks (FAJ, 2023). The primary motivation for the reform is the declining catch in response to the low abundance in stocks. Some research indicates that roughly half of the stocks in Japan are below levels that would produce maximum sustainable yield (MSY) [Ichinokawa et al., 2017; Tokunaga et al., 2019a]. The Fisheries Agency of Japan (FAJ) states, "Although various factors could have contributed to the decline in the fish landings, many of them would have been prevented or mitigated if fish stocks had been maintained through appropriate management."(FAJ, 2023, p6).

Under the new fisheries policy, TACs will be set based on pre-determined Harvest Control Rules (HCRs). The structure of the basic HCR is shown in Figure 3.1. Mathematically, the basic HCR advises the fishing mortality F in year t for a stock as follows.

$$F_t = \begin{cases} 0 & \text{if } SSB_t < SSB_{ban} \\ \dfrac{SSB_t - SSB_{ban}}{SSB_{limit} - SSB_{ban}} \cdot \beta \cdot F_{MSY} & \text{if } SSB_{ban} < SSB_t < SSB_{limit} \\ \beta \cdot F_{MSY} & \text{if } SSB_{limit} < SSB_t \end{cases} \tag{1}$$

The basic HCR consists of two biological reference points (BRPs) regarding spawning biomass (SSB), a limit on fishing mortality (in principle, F_{MSY}), and a coefficient β on it. The first BRP, SSB_{limit}, is a threshold at which fishing mortality begins to be reduced, and the second BRP, SSB_{ban}, is a threshold at which fishing is closed to avoid potentially irreversible impacts such as the Allee effect (Kramer et al., 2009). Their defaults are the SSB levels which theoretically yields catches of 60% and 10% of MSY, respectively (FAJ, 2020; FRA, 2022a). Stocks below the SSB_{limit} are subject to a rebuilding plan (FAJ, 2020). A value of 0.8 is recommended for β, as lower fishing pressure leads to stock conservation, higher profits, and stable catches (Okamura et al., 2020). Although HCRs are commonly used around the world and have a variety of structures (Deroba & Bence, 2008; Froese et al., 2011; Thorson et al., 2015), Japan's basic HCR provides a stable catch near maximum while avoiding recruitment overfishing (Okamura et al., 2020). On the other hand, the basic HCR is one of the various options, and other HCRs could be used (Ichinokawa et al., 2022). For example, the HCR for pollock agreed in 2020 fixes the TAC at 170,000 mt until 2023, after which the basic HCR will be applied. Hereafter in this paper, a harvest strategy, including the structure of the HCR, the BRPs, and the timeline and probability to achieve it, will be referred to as a harvest scenario.

The key point of HCRs is to pre-determine how the fishery will change in response to stock status. This reduces the cost of consensus building, promotes decision-making, and ensures transparency (Ichinokawa et al., 2022). Additionally, simulating the performance of multiple HCRs can clarify tradeoffs and risks and provide a rationale for decision-making.

An important process introduced by the new fisheries policy to determine harvest scenarios is the stakeholder (SH) meeting (FAJ, 2023). The Japan Fisheries Research and Education Agency (FRA), a research agency, conducts a stock assessment of each stock and proposes several harvest scenarios to stakeholders. If the stakeholders accept a harvest scenario at the SH meeting, FAJ, a management agency, adopts the harvest scenarios after consulting with the Fisheries Policy Council, an advisory body to the Minister of Agriculture, Forestry, and Fisheries. The basic policy is that the HCR should allow a decreased stock to recover to the level of MSY within ten years with a 50% or greater probability (FAJ, 2020). However, it is up to the stakeholders to choose what harvest scenario they will take to achieve this goal. Indeed, stakeholders have made various proposals for harvest scenarios at SH meetings (Ichinokawa et al., 2022). In addition, stakeholders can also decide at what level to maintain stocks above the MSY level.

This process poses questions to stakeholders: What stock level do they want to have as a target, how do they want to achieve the target, and how much risk do they accept? On the other hand, in drafting harvest scenarios, the primary focus is on achieving stock recovery, and the socioeconomic benefits and tradeoffs are not sufficiently analyzed. Fishing is an economic activity, and proposals that focus solely on stock conservation will not only fail to gain the agreement of fishermen but may also cause them to distrust and oppose scientists (Makino, 2008). Moreover, no guidelines exist on how much biological, social, and economic risk is acceptable, except for the probability of achieving stock recovering to MSY levels (Ichinokawa et al., 2022).

The difficulties in developing harvest scenarios and expanding TACs is apparent for the management of multispecies fisheries. Although it has not occurred much in Japan, which traditionally has focused on input controls, species with low quotas can limit fishing opportunities for species with high quotas as choke species (Mortensen et al., 2018; Schrope, 2010). For example, in the U.S. West Coast groundfish fishery, overfishing was declared for 10 stocks between 1999 and 2010, resulting in significant reductions in quotas for several stocks, which became choke species. Even in recent years when some stocks have rebuilt, only 20-30% of the TAC is caught (McQuaw & Hilborn, 2020). Some species will be overfished when maximizing landings from multispecies fisheries (Worm et al., 2009). In Japan, the lack of multispecies consideration in the basic HCR has been recognized from the beginning (Okamura et al., 2020). Some experts have stated that harvest scenarios should be carefully designed in multispecies fisheries, including developing selective fishing techniques and compensation schemes (Fisheries Policy Council, 2022). Given that the stock status of non-TAC fish species is worse than that of TAC species (Ichinokawa et al., 2017), the expansion of TAC can be a significant constraint on fishing operations in multispecies fisheries.

Bioeconomic models are often used to analyze the performance of different harvest scenarios in multispecies fisheries. Many models have been developed in North America, Europe, Australia, and NZ (Nielsen et al., 2018). Bioeconomic modeling has been attempted in Japan for several decades (Tanaka, 1994) but has not reached a practical level of implementation. Recent studies are either holistic analyses focusing on all stocks or all benthic stocks in the country (Tanaka, 2018&2019; Tokunaga et al., 2019a) or single species analyses (Jang et al., 2019; Makino, 2011). Some studies have conducted production analyses without stock dynamics, looking at the short-term relationship between effort and profitability (Ishimura et al., 2022; Makino & Sakamoto, 2001). In Japan, where multiple fisheries catch diverse stocks, the limited data availability is likely the main limitation of the analysis. The new fisheries policy is expanding stock assessment species and data availability (e.g., Stock assessment data since 2020 are available on the FRA website (https://abchan.fra.go.jp/hyouka/).), and the development of multispecies bioeconomic models is becoming feasible.

This study uses a multispecies bioeconomic model to simulate biological, social, and economic performance under different harvest scenarios, with a case study of the Hokkaido Pacific offshore trawl, where TAC will be introduced for cod. The model includes three species (pollock, cod, and "others" species) and three fleets (the offshore trawl and two coastal fisheries). The study

i) identifies the performance and risks of multiple realistic scenarios and ii) presents a tool to visualize them clearly for stakeholders.

3.3 Methods

3.3.1 Model framework

An age-structured bioeconomic model was employed to simulate the outcome of different harvest scenarios on the Hokkaido Pacific offshore trawl. The model comprises two age-structured fish stocks, pollock, and cod, and includes "other" fish species for economic analysis. Although this research focused on the offshore trawl fishery, two coastal fisheries - targeting pollock or cod - were also incorporated into the model to capture the impact of all fishing on the fish stocks; namely, the model had three fleets. The catch shares of each fleet are in Table 3.1.

3.3.2 Population dynamics

An age-structured population dynamics model was used in this research to simulate the population dynamics for pollock and cod.

$$N_{a,t} = \begin{cases} R_t & \text{if } a = a_{\min} \\ \left(N_{a-1,t-1} \cdot \exp\left(-\frac{M_{a-1}}{2}\right) - C_{a-1,t-1}\right) \cdot \exp\left(-\frac{M_{a-1}}{2}\right) & \text{if } a_{\min} < a < a_{\max} \\ \left(N_{a-1,t-1} \cdot \exp\left(-\frac{M_{a-1}}{2}\right) - C_{a-1,t-1}\right) \cdot \exp\left(-\frac{M_{a-1}}{2}\right) + & \\ \left(N_{a,t-1} \cdot \exp\left(-\frac{M_{a}}{2}\right) - C_{a,t-1}\right) \cdot \exp\left(-\frac{M_{a}}{2}\right) & \text{if } a = a_{\max} \end{cases} \tag{2}$$

where $N_{a,t}$ is the number of individuals of age a at time t. M_a is the natural mortality at age a, assumed constant through time. $C_{a,t}$ is the catch-at-age at age a at time t. R_t is the number of recruitments arising from the spawning stock biomass SSB_t at time t under a stock-recruitment relationship.

$$SSB_t = \sum_a m_a \cdot N_{a,t} \cdot w_a \tag{3}$$

where m_a and w_a are the maturity (%) and the weight at age a, respectively, assumed constant over time.

3.3.3 Stock-recruitment relationship

For pollock, a Hockey-Stick model was used as the stock-recruitment relationship following the stock assessment in Japan (Ishino et al., 2021). However, this research also examined the difference in performance from using the Ricker model. This is because the Hockey-Stick model was adopted in the Japanese stock assessment to avoid predicting excess recruitment when SSB is low, but the Ricker model fits the data better (Sakai et al., 2019) [Figure 3.2]. This study relied on Japanese stock assessment data and could not provide further analysis of the plausibility of the stock-recruitment relationship. Hence, a bioeconomic analysis under two stock-recruitment relationships was explored.

A stock-recruitment relationship for cod has yet to be identified in Japan. Thus, the stock-recruitment relationship used in the simulation was selected from Beverton-Holt, Ricker, and Hockey-Stick by fitting the data to each model. The model fitting and parameter estimations were done by an R library *frasyr* v. 2.2.0.3, widely used in the Japanese stock assessment.

The recruitment predicted from each stock-recruit model deterministically, $\hat{R}_t$, is:

Beverton-Holt model

$$\hat{R}_t = \frac{a \cdot SSB_t}{1 + b \cdot SSB_t}$$

Ricker model

$\hat{R}_t = a \cdot SSB_t \cdot \exp(-b \cdot SSB_t)$

Hockey-Stick model

$$\hat{R}_t = \begin{cases} a \cdot SSB_t & \text{if } SSB_t < b \\ a \cdot b & \text{if } SSB_t \geq b \end{cases}$$

where a and b are parameters in each model.

In the simulation, the recruitment R_t was obtained from the following probability distribution:

$$R_t = \hat{R}_t \cdot \exp(\varepsilon_t - 0.5\sigma_R^2) \tag{4}$$

$$\varepsilon_t = \rho \cdot \varepsilon_{t-1} + \omega_t \cdot \sqrt{1-\rho^2},\ \omega_t \sim N(0,\ \sigma_R^2) \tag{5}$$

where ε_t is the recruitment deviation for year t, and ρ is a first-order autocorrelation coefficient and is zero when there is no autocorrelation. σ_R is the standard deviation of residuals. In this study, recruitment was assumed to follow a log-Normal distribution.

3.3.4 Fleet dynamics

Under each harvest scenario, an advised fishing mortality $Fadv_{s,t}$ for species s at time t is determined before each fishing season from the equation (1) following the basic HCR (Figure 3.1), which in turn provides an advised catch (in weight) $Cadv_{s,t}$ to be set as TAC.

$$Cadv_{s,t} = \sum_a \left(1 - \exp\left(-l_{a,s} \cdot Fadv_{s,t}\right)\right) \cdot \exp\left(-\frac{M_{a,s}}{2}\right) \cdot N_{a,s,t} \cdot w_{a,s} \tag{6}$$

$$TAC_{s,t} = Cadv_{s,t} \tag{7}$$

where l is the selectivity at age and is assumed to be constant at the average from 2016 to 2020 in the projection. Quota for a fleet f is given as a fraction of the TAC.

$$Q_{f,s,t} = \lambda_{f,s} \cdot TAC_{s,t} \tag{8}$$

where λ is the fleet's share of the TAC and was fixed to the 2016-2020 average catch share throughout the simulation to account for the difficulty of changing the allocation among fleets.

On the other hand, catch (in weight) by fleet f for species s in time t is given by:

$$C_{f,s,t} = \sum_a C_{a,s,f,t} = \sum_a q_{a,s,f} \cdot E_{f,t} \cdot N_{a,s,t} \cdot w_{a,s} \tag{9}$$

where q is the catchability considered constant over time and was fixed at the average from 2016 to 2020, and E is the fishing effort, expressed in terms of days at sea. An assumption here is that the catch is linear in effort and biomass $N*w$.

Under a harvest scenario, a fleet stops fishing when its catch of either pollock or cod reaches the quota or when its effort reaches the limit, *Elim*. The effort limit was introduced to avoid unrealistically high fishing efforts. The effort limit for offshore trawl was set at the maximum effort in the past ten years. For coastal fisheries, effort data were not available. Thus, it was assumed that they had a constant effort for the past five years, and this effort was used as the limit in the projection, given the downward trend in coastal fishing boats. Observation error was not included in the model because the offshore trawl and coastal fisheries land fish in local ex-vessel markets, which allows for accurate and timely catch monitoring. In addition, all fleets belong to local fishery cooperatives, and monitoring and enforcement work well within the cooperatives to ensure that fishing stops when quotas are reached.

The catch of “others” species by offshore trawl, needed to compute the total landings, was derived from a linear regression of the effort, as in Hoff et al. (2010).

$$C_{trawl,others,t} = \gamma \cdot E_{trawl,t} + \delta \quad (10)$$

where γ and δ are the parameters and constant over time.

3.3.5 Economic dynamics

For the Hokkaido Pacific offshore trawl, profit P_t is the difference between gross revenue GR_t and total cost TC_t at time t.

$$P_t = GR_t - TC_t \quad (11)$$

Gross revenue is the sum of landings value obtained by multiplying the ex-vessel price $p_{s,t}$ of species s, by the landings volume $C_{s,t}$.

$$GR_t = \sum_s p_{s,t} \cdot C_{s,t} \quad (12)$$

The price of pollock is highly dependent on international market conditions, which is an economic concern in the Hokkaido Pacific offshore trawl (Kushiro Fisheries Revitalization Committee. 2019; Stable Seafood Supply Organization, 2018). To account for this uncertainty, a stochastic price was introduced to pollock as:

$$p_{pollock,t} \sim N(\mu, \ \sigma_p^2) \quad (13)$$

where μ is the average ex-vessel price from 2016 to 2020 and σ_p is the standard deviation of pollock price. The prices for cod and "others" were fixed at the average of the past five years through the projection periods. The relationship between catch and price was not strong for all species (Figure 3.3).

The total cost TC_t consists of the fixed cost FC and the variable cost VC_t which is further composed of fuel cost FU_t, sales fee SF_t, and crew wage CW_t.

$$TC_t = FC + VC_t \tag{14}$$

$$VC_t = FU_t + SF_t + CW_t \tag{15}$$

FU_t varies with effort; SF_t is 5% of GR_t, which is a common rate at ex-vessel markets in Japan; CW_t is 50% of the amount of GR_t minus FU_t and SF_t, based on recent years' data (MAFF, n.d.).

Coastal fisheries were excluded from the economic analysis because their economic data were not available and because they are usually engaged in multiple fisheries and an economic analysis based on pollock and cod fishing alone would not represent their financial conditions.

3.3.6 Harvest scenarios

Given the current management situation of the Hokkaido Pacific offshore trawl, five harvest scenarios combining HCRs for pollock and cod were explored. The details of each scenario are below. A list of all scenarios is in Table 3.2. Each scenario was simulated 1,000 times over 20 years from 2021 to 2040, using a library *FLBEIA v*. 1.15.6.8 (Garcia et al., 2017) under the R language *v*. 4.1.1. To initiate the simulation, management advice was required for the first year, and the actual pollock catch for that year was given as the TAC.

Scenario 1

- The TAC for pollock is constant at 170,000 mt, which is the official HCR in Japan through 2023 (Ishino et al., 2021). This HCR was introduced due to strong request from local fishermen for stable pollock catches (FAJ, 2021).
- No HCR for cod, which means the effort for offshore trawl is associated with pollock, while the effort for coastal fisheries is constant.

Scenario 2

- Pollock has a basic HCR with $\beta = 0.9$, $SSB_{limit} = 151{,}000$ mt, and $SSB_{ban} = 60{,}000$ mt, which is the official HCR after 2024 (Ishino et al., 2021).
- No HCR for cod.

Scenario 3

- Pollock has the basic HCR above.
- Cod has a basic HCR with $\beta = 1.0$, the limit of β, $SSB_{limit} = SSB_{60\%MSY}$ and $SSB_{ban} = SSB_{10\%MSY}$, the default for BRPs (FRA, 2022a). $SSB_{x\%MSY}$ is the SSB that is expected to produce x% of MSY.

Scenario 4

- Pollock has the basic HCR above.
- Cod has a basic HCR with $\beta = 0.8$, the default of β, $SSB_{limit} = SSB_{60\%MSY}$, and $SSB_{ban} = SSB_{10\%MSY}$.

Scenario 5

- Pollock has the basic HCR above.
- Cod has a basic HCR with $\beta = 0.7$, $SSB_{limit} = SSB_{60\%MSY}$, and $SSB_{ban} = SSB_{10\%MSY}$. This conservative scenario was added because preliminary analysis found that the cod stock is decreased.

3.3.7 Performance and risk metrics

To assess the performance of each scenario, the following biological, economic, and social metrics for the Hokkaido Pacific offshore trawl were evaluated.

Biological performance

- *SSB*: Median SSB for each species over years and simulations

Economic performance

- *Catch*: Median total catch over years and simulations
- *Profit*: Median profit over years and simulations as defined in the model
- AAV_{profit}: Median of average annual variability (AAV) for profit defined as below. Stable profits contribute to the stabilization of the fishing business. In the display of results, "*Profit Stability*", which is the inverse of AAV, was used so that better performance would be scored higher.

$$\mathrm{AAV} = |P_t - P_{t-1}| / P_{t-1}$$

Social performance

- *Effort*: Median effort over years and simulations. The target of this study was the day-trip offshore trawl, and it was expected that higher effort (i.e., days at sea) would lead to more landings at local ports and more local employment.
- *Crew Salary*: Median crew salaries over years and simulations. This study adopted crew salary as a social metric, often used in other studies (e.g., Maynou, 2019), due to model limitations, but it should be noted that the contribution of a fishery to the community should be valued more broadly, including fishing gear, ice and boxes, vessel maintenance, fish processing, and tourism.
- AAV_{catch}: AAV for total catch. Stable landings are favorable for employment and operations in the fish processing and fishing supply industries. In the display of results, "*Catch Stability*", which is the inverse of AAV, was used.

The following risk metrics were also evaluated to fully capture the performance of each scenario.

Biological risk

- *"Un-recovery"*: Probability of SSB for cod being below SSB_{MSY} in the 10th year in the projection (i.e., $Pr(SSB_{cod,t=10} < SSBMSY_{cod})$). The preliminary research found that the cod stock was below SSB_{MSY}, the default target reference point for a stock (FRA, 2022a). The basic policy in Japan is for SSB to be above the target with a probability of more than 50% within ten years (FAJ, 2020).
- *"Rebuilding Plan"*: Probability of SSB for each species below SSB_{limit} (i.e., $Pr(SSB_{s,t} < SSBlimit_s)$) over years and simulations. When SSB falls below the limit reference point, the stock is subject to a rebuilding plan and the fishing mortality needs to be reduced (FAJ, 2020).

Economic risk

- *"Yield Loss"*: Probability of total catch less than 80% of multispecies MSY (MMSY) which is the maximum cumulative catch of all species, expected to be achieved when efforts are maintained at a certain level (i.e., $Pr(C_{all,t} < 80\%MMSY)$). Figure 3.4 shows the relationship between effort level and cumulative catch. Multispecies fisheries often entail a trade-off between stock conservation and yield loss (Hilborn et al., 2012). Fewer catches were assumed to be undesirable for the local economy, especially for the processing industry.

Social risk

- *"In-season Closure"*: Probability of effort being below the minimum of the past 10 years (i.e., $Pr(E_t < Emin)$). In the model, low effort means that the fishery was closed because the quota was reached. The Hokkaido Pacific offshore trawl has never ended a fishing season due to reaching the quota in the past, and it was assumed that an in-season closure would cause significant social disruption.

3.3.8 Input data

For pollock, the catch-at-age, the number-at-age from virtual population analysis (VPA), biological parameters (Table 3.3), and the stock-recruitment relationship (Table 3.4) were obtained from the Japanese stock assessment reports (Ishino et al., 2021; Sakai et al., 2019). The data covered the period from 1981 to 2020. The motivation for this study was to explore the performance of multiple harvest scenarios that could take place, and the parameter values in the projection were consistent with the stock assessment. Note that Russia catches the same pollock stock, yet its catch is unknown and excluded from the stock assessment in Japan (Ishino et al., 2021); therefore, the Russian fishery was not included in this study. The catch-at-age and number-at-age data are included in Appendix 3 and 4.

For cod, the catch-at-age from 2005 to 2020 and the number-at-age estimated by a pilot study of VPA were taken from the stock assessment reports (Chimura et al., 2019&2021). The biological parameters in Table 3.5 were also taken from the stock assessment reports. Recruitment and SSB, from which the stock-recruitment relationship models were fitted in this research, were based on the number-at-age data. Note that the catch-at-age and the biological parameters have high uncertainty, so the pilot VPA was not approved in Japan (Chimura et al., 2021). Nonetheless, this study adopted an age-structured model to simulate pollock stock dynamics accurately. The catch-at-age and number-at-age data are included in Appendix 5 and 6.

Table 3.6 shows the effort of each fleet in the last five years (the coastal fisheries were held constant at 100 for convenience), which was used to obtain the catchability by fleet by stock shown in Table 3.7. Catch-at-age by fleet, necessary to get the catchability, was not available and was estimated from the total catch-at-age in proportion to each fleet's catch share.

The economic parameter values of the Hokkaido Pacific offshore trawl are in Table 3.8. Landing volume and value by species, from which the ex-vessel price was calculated, were provided by the Hokkaido Trawl Fisheries Cooperative Federation (HTFCF). The number of offshore trawl vessels was 16 in 2020, which was assumed to be constant in the projection. The other parameters were fixed in the projection at the average from 2016 to 2020 except for effort, which depended on TAC, and the ex-vessel price for pollock, which varied stochastically.

The values of reference points for HCRs and the value of MMSY are in Table 3.9.

3.4 Results

3.4.1 Stock-recruitment relationship for cod

Figure 3.5 shows the fitting of the Beverton-Holt, Ricker, and Hockey-Stick stock-recruitment models to the stock-recruitment data of cod. Estimated parameter values and AICc for each model are in Table 3.10. The data covered the period from 2005 to 2019. Two types of optimization were used in model fitting: the least absolute value method (L1) and the least squares method (L2). As a result, the Hockey-Stick model using L1 had the smallest AICc (Table 3.10). No evidence of autocorrelation was found in this model (Figure 3.6). Although the difference in AICc with the Hockey-Stick model with L2 was small, it is known that L2 is sensitive to outliers, and L1 gives more robust reference points when the sample size is small (FRA, 2022b). The differences in AICc of the Beverton-Holt and Ricker models with L1 were also small. However, an unrealistic reference point was observed in the Beverton-Holt model (i.e., SSB_{MSY} = 119,000 mt). This stock has no record of density compensation, such as cannibalism, that would support the Ricker model (Chimura et al., 2021). Therefore, given that the Hockey-Stick model is recommended for stock assessment in Japan (FRA, 2022a), the Hockey-Stick model with L1 was used in the simulations in this study.

3.4.2 Time series of each harvest scenario

Figure 3.7 shows the time series of catch, fishing mortality, recruitment, and SSB for pollock (Figure 3.7a) and cod (Figure 3.7b) under the five harvest scenarios. For pollock, the catch has declined substantially since 1980, and in 2020, the year before the simulation, the fishing mortality was 0.16, less than half of FMSY (=0.43), and the SSB was 277,767 mt, above SSB_{MSY} (=228,000 mt). For cod, however, the fishing mortality has been consistently above FMSY (=0.35) since 2005, when the data were available, and the SSB was below SSB_{MSY} (=49,000 mt) in 2020. As such, the two species' stock status and fishing status were contrasting.

In Scenarios 1 and 2, which have no HCR for cod, the fishing mortalities for both species were generally constant throughout the simulations. This is because, given the abundant pollock stock, the pollock HCR always advised a higher effort than the effort limit for each fleet, and the effort for each fleet stayed at the limit. The main difference between the two scenarios is that in Scenario 1, with the constant catch HCR, fishing was sometimes halted by reaching the TAC before the effort limit was met, whereas in Scenario 2, with a basic HCR for pollock, the effort was always constant. The effort limit maintained low fishing mortality for pollock (Figure 3.7a, upper right), and the SSB remained healthy, although it declined slightly right after the HCRs began (Figure 3.7a, lower right). The total pollock catch for all fleets stabilized around 150,000 to 170,000 mt after 2030 (Figure 3.7a, upper left), the latter half of the simulation. On the other hand, for cod, these two scenarios sustained excessive fishing mortality (Figure 3.7b, upper right) and did not allow stock recovery (Figure 3.7b, lower right). Nevertheless, the SSB did not fall below SSB_{limit}, and the catch (Figure 3.7b, upper left) remained stable at current levels over the simulation period.

In Scenarios 3 to 5 with an HCR for cod, the stock severely constrained fishing operations, that is it became a choke species. The fishing mortality was capped and significantly reduced according to the HCR for cod (Figure 3.7b, upper right). Scenario 5 (β=0.7), Scenario 4 (β=0.8), and Scenario 3 (β=1.0), in that order, are more conservative because they have lower limits on fishing mortality. In all three scenarios, cod stocks increased after the introduction of HCR (Figure 3.7b, lower right), but the stock recovery to SSB_{MSY} did not occur in Scenario 3 and was limited in Scenario 4. Only Scenario 5 generally achieved recovery. Although the catch declined after the start of the HCR, it began to rise within a few years, and after the late 2020s, the three scenarios generally outperformed Scenarios 1 and 2 (Figure 3.7b, upper left). Meanwhile, these restrictions on fishing operations resulted in lower pollock catches than in Scenarios 1 and 2 (Figure 3.7a, upper left). Although the pollock stock became more abundant (Figure 3.7a, lower right), too little fishing mortality (Figure 3.7a, upper right) led to smaller catches.

Figure 3.8 presents the catch, effort, profit, and crew salary for the Hokkaido Pacific offshore trawl during the simulation period under each harvest scenario. As noted above, Scenario 1 generally kept constant effort, but the fishing sometimes ended during the fishing season when pollock stock was highly abundant (Figure 3.8, upper right). Scenario 2 maintained the effort at the limit, and Scenarios 3 through 5 led to less effort. Median catch, profit, and crew salary were similar in Scenarios 1 and 2, but those benefits were capped in Scenario 1, whereas Scenario 2 occasionally yielded more (Figure 3.8, upper left & lower panels). Although Scenarios 3 to 5 provided more catch for cod in the later part of the simulation (Figure 3.7b, upper left), the total catch with pollock and other species was not as large as in Scenarios 1 and 2

(Figure 3.8, upper left). Besides, those scenarios were also below Scenarios 1 and 2 regarding profit and crew salary. In particular, profits were negative right after the introduction of the cod HCR, with a probability of only 0.7% in Scenario 3 but 14% in Scenario 4 and 36% in Scenario 5 over the first five years of the simulation.

In summary, Scenarios 3 and 4, which introduce a basic HCR for cod, did not provide sufficient stock recovery with the threat of adverse socioeconomic impacts. Scenario 5, with the most conservative basic HCR, generally achieved the stock recovery policy. However, it led to the lowest catch, effort, profits, and crew salary for the Hokkaido Pacific offshore trawl, and in particular, there is a risk of negative profit in the short term. Scenarios 1 and 2, which did not involve any consideration for cod, kept the cod stock at a low level but did not drop it below the limit and could produce higher socioeconomic benefits.

3.4.3 Performance and risk metrics

The results of the performance and risk metrics for the Hokkaido Pacific offshore trawl are shown in Figure 3.9a. The value of each metric is normalized so that the best scenario is 1. This type of radar chart is a tool to visualize the performance and trade-offs of each scenario clearly to stakeholders.

Scenarios 1 and 2 showed similar performance. They were almost tied for first place in Catch, Profit, Profit Stability, Effort, and Crew Salary and were nearly equal in biological metrics, with only Catch Stability being won by Scenario 1 by 26%. However, compared to the best scenario, Scenario 1 (2) was less favorable for pollock SSB by 15% (15%), for cod SSB by 62% (63%).Scenario 3 (4) was less than the best scenario by 7% (4%) for pollock (cod) SSB, 38% (16%) for cod SSB, 17% (28%) for Catch, 33% (50%) for Profit, 21% (33%) for Profit Stability, 37% (40%) for Effort, 15% (23%) for Crew Salary, and 27% (27%) for Catch Stability.

The most conservative Scenario 5, naturally, provided the best results for pollock and cod SSB. On the other hand, the scenario was worse than the best scenario by 33% in Catch, 61% in Profit, 33% in Profit Stability, 47% in Effort, 28% in Crew Salary, and 27% in Catch Stability.

Figure 3.9b shows the results of the risk metrics for the Hokkaido Pacific offshore trawl under each harvest scenario. The value of each metric indicates the probability of each incident, i.e., a high value is undesirable. In all scenarios, the SSB for pollock and cod stayed above the limit, and the risk that either species would be subject to a rebuilding plan was zero. However, only Scenario 5 (Pr("Un-recovery") = 52%) almost met Japan's basic policy to recover the cod stock with a probability of 50% or more within ten years from the start of the HCR (i.e., reduce the probability of "un-recovery" to less than 50%). Additional analysis showed a basic HCR with $\beta = 0.69$ achieved the policy with Pr("Un-recovery") = 42%. The un-recovery risk was 100% for Scenario 3 with $\beta = 1$ and 90% for Scenario 4 with $\beta = 0.8$. At the same time, the socioeconomic risk of introducing a basic HCR for cod was considerable, with a 98% (100%, 100%) probability of In-season Closure in Scenarios 3 (4, 5) and 75% (90%, 95%) probability of Yield Loss in Scenarios 3 (4, 5). Scenarios 1 and 2 had almost the same risk for Yield Loss of 40% and 41%, but the risk of In-season Closure was slightly higher in Scenario 1 (12%) than in Scenario 2 (5%).

3.4.4 Hockey-Stick vs. Ricker stock-recruitment model for pollock

To investigate the impact of two stock-recruitment relationships on the performance of the Hokkaido Pacific offshore trawl, scenarios 2 and 4 with two stock-recruitment models for pollock were tested. Figure 3.10 displays the time series of catch, fishing mortality, recruitment, and SSB for pollock under each scenario. The average recruitment during the simulation period was 9% lower for Scenario 2 and 17% lower for Scenario 4 under the Ricker model than the

Hockey-Stick model. This was because i) the Ricker model leads to less recruitment when the SSB is abundant above about 340,000 mt due to density compensation (Figure 3.2), and ii) the Ricker model has less variance and is less likely to produce a strong year class. As a result, the average catch (SSB) was 7% (6%) lower in Scenario 2 and 13% (12%) lower in Scenario 4 with the Ricker model than with the Hockey-Stick model. However, even under Scenario 2, with the highest fishing mortality, there was a 0% probability that the SSB would fall below the limit of 151,000 t, which was set assuming the Hockey-Stick model, even if the stock-recruitment relationship was the Ricker model.

Figure 3.11 shows the time series of catch, effort, profit, and crew salary for the Hokkaido Pacific offshore trawl under each scenario. Over the simulation period, the average catch (profit, crew salary) was 6% (9%, 4%) lower for Scenario 2 and 10% (23%, 7%) lower for Scenario 4 with the Ricker model than with the Hockey-Stick model.

Overall, the simulations assuming the Ricker model showed less favorable results on all metrics than those with the Hockey-Stick model.

3.5 Discussion

These analyses revealed a dilemma for fisheries managers, with significant tradeoffs between cod stock recovery and socioeconomic benefits. In Scenarios 3 through 5, where cod was subject to TAC under a basic HCR, not only did nearly all performance metrics for the Hokkaido Pacific offshore trawl decline in exchange for increased stock abundance and catch of cod, but the risk of in-season closure and yield loss increased significantly. It would be difficult for fishermen to agree to such harvest scenarios. Worse, Scenario 3 ($\beta = 1$), the most non-regulatory scenario of these, and Scenario 4 ($\beta = 0.8$), with a default basic HCR, were insufficient to achieve the policy of restoring decreased cod abundance to MSY levels. Only the most conservative Scenario 5 ($\beta = 0.7$) almost achieved cod recovery. To implement this scenario, the Hokkaido Pacific offshore trawl would need to reduce effort by 47% compared to Scenario 2, averaged over the next 20 years, resulting in a 33% reduction in catch, 61% in profit, and 28% in crew salary. The loss of profit was significant, with a 36% probability of negative profit in the first five years after the introduction of cod HCR. Also, such a significant effort reduction may require strong fishing capacity limitation, such as a vessel reduction program.

It is worth pointing out that although the cod SSB increases as fishing mortality is reduced, the catch would be flat over a wide range of fishing mortality. Average cod SSB in the last ten years of the simulations for Scenarios 3, 4, and 5 would increase by 1.8, 2.4, and 2.9 times from Scenario 2, but the cod catches are only 1.1 times higher in either case. At the same time, Scenario 3 performed better than Scenario 5 on all performance and risk metrics. If a biological target lower than the MSY level is acceptable, the less restrictive Scenario 3 could be an option.

For fishermen (and possibly fisheries managers as well), the "comfortable" option among these harvest scenarios may be Scenario 1 or 2, which is close to the status quo. In particular, the constant TAC strategy (Scenario 1), which is currently implemented by strong requests from fishermen, has, expectedly, performed the best in terms of catch stability. Although the risk of in-season closure is slightly higher in this scenario than in Scenario 2 with a basic HCR, it should not be a serious concern, as such situations occur when the pollock stock is highly abundant, and the catch limit could increase easily. One piece of good news is that even under these two scenarios, the cod stock is not estimated to collapse to the point subject to a rebuilding plan. Furthermore, the recent downward trend in the number of fishing boats may also contribute to cod recovery. In these scenarios, the issue is the balance with the policies of the stock recovery and the expansion of TAC.

When the Ricker model was applied to the stock-recruitment relationship for pollock, the performance of all metrics was lower compared to the Hockey-Stick model. The Hockey-Stick model was identified in 2019 using data up to 2014 (Sakai et al., 2019). However, recent recruitment data (Sakai et al., 2022a) are relatively supportive of the Ricker model with density compensation. Unexpectedly low recruitment at high stock abundance can lead to low catches and distrust among fishermen toward stock assessments. At a time when the new fisheries policy calls for science-based fishery management, it is essential to build trust between scientists and stakeholders. Therefore, even a stock-recruitment relationship, once identified, should be reviewed and updated as needed and be adaptive.

The incompleteness of data posed a limitation to this study. Because effort, economic data, and operational information for the coastal fisheries were unavailable, economic analyses could not be performed on them. One crucial issue that this study could not explore is how to promote consensus when different harvest scenarios create tradeoffs not only between the triple bottom line but also between the offshore and coastal fisheries. To avoid conflicts among stakeholders, one option may be to conduct a socioeconomic analysis that integrates all involved fisheries, as in Tanaka (2019).

Data uncertainty is also an issue. This study assessed the cod stock as decreased based on Japanese pilot VPA data covering from 2005 onward. However, the stock assessment adopted in Japan determined the cod stock to be high, based primarily on an abundance index using CPUE data since 1985 (Figure 3.12). The Japanese stock assessment did not endorse the pilot VPA due to the high uncertainty in catch-at-age and biological parameters (Chimura et al., 2021). The cod stock could be more optimistic than in this study. Another serious uncertainty is the potential change in selectivity when a TAC covers cod. Although this study assumed constant selectivity over the simulation period, it is natural to assume that the solid constraining effects of a cod TAC would result in changes in target species, operating season, and area. Potential future research would incorporate changes in fishing operations into the model in collaboration with local fishermen and researchers.

Given these data incompleteness and uncertainties, the results of this study cannot be used immediately in practice. However, this research is pioneering in analyzing the biological, social, and economic aspects of multispecies fisheries management, which are not fully incorporated in the current fisheries management process, and further development is expected, such as, i) development of more complex and sophisticated models, ii) developing fisheries business plans that take into account long-term stock dynamics and business risks, iii) policy making by fisheries managers that balances triple bottom line, and iv) designing tools to facilitate communication between scientists and stakeholders.

A challenge then is the data availability. Presently, access to stock assessment data is limited to researchers from government agencies directly involved in the process. Although outputs from the stock assessment after 2020 are open on the FRA website (https://abchan.fra.go.jp/hyouka/), some data, such as abundance indices, are not available. With the rapid expansion of stock assessment species, it will be necessary to fully utilize scientific resources throughout Japan, including universities, NGOs, and think tanks, as well as government research institutions. As Tokunaga et al. (2019a) pointed out, it is necessary to establish data disclosure procedures to support scientific analysis.

This study presented a radar chart of performance and risk for each harvest scenario. While the Japanese stock assessment has yet to use such an approach (in the first place, no socioeconomic analysis has been conducted), it is common in academia (e.g., Garcia et al., 2020;

Okamura et al., 2020). Such a method expectedly provides an intuitive display of each harvest scenario's results and contributes to smoother communication between scientists and stakeholders. Furthermore, the metrics are adjustable according to individual cases. In particular, there are no guidelines for risk tolerance, which is up to social choice. Visualizing risks and discussing them with stakeholders may increase stakeholders' awareness of fisheries management and secure their right to self-determination.

Enhancing science-based fisheries management is urgently needed in Japan, where about half the stocks are in low abundance. The critical issue is how to facilitate discussions with stakeholders and build consensus. A policy that emphasizes only stock conservation may not only fail to gain the agreement of fishermen but may also provoke distrust and opposition from fishermen toward fisheries managers and scientists (Makino, 2008). To promote cooperative, rather than confrontational, management, it is necessary to explicitly show what will be improved by the new management system and what risks are involved in not acting. Beyond that, it is important for the stakeholders themselves to choose a desirable fishery, or desirable future, without deviating from the bounds legally allowed, just as the fishermen themselves have played a leading role in Japan's traditional fishery management.

3.6 Tables

Table 3.1: The catch shares of each fleet. The catch is the average from 2016 to 2020. Note that "others" species was used only for the economic analysis of the Hokkaido Pacific offshore trawl.

	Alaska pollock (mt)	Pacific cod (mt)	Others (mt)
Hokkaido Pacific Offshore trawl	61,096 (59.5%)	8,057 (47.1%)	5,631
Coastal fisheries (pollock)	30,349 (40.5%)	-	-
Coastal fisheries (cod)	-	9,115 (52.9%)	-
Total	91,445 (100.0%)	91,445 (100.0%)	-

Table 3.2: A list of harvest scenarios simulated in this study

	Alaska pollock	Pacific cod
Scenario 1	Constant TAC (170,000 mt)	No HCR*
Scenario 2	Basic HCR (β = 0.9)	No HCR*
Scenario 3	Basic HCR (β = 0.9)	Basic HCR (β = 1.0)
Scenario 4	Basic HCR (β = 0.9)	Basic HCR (β = 0.8)
Scenario 5	Basic HCR (β = 0.9)	Basic HCR (β = 0.7)

* The effort for the Hokkaido Pacific offshore trawl is associated with pollock. The efforts for the coastal fisheries are constant at the average over the last 5 years.

Table 3.3: Biological parameters for Alaska pollock in the simulation. Selectivity was determined in this study from the catch-at-age, number-at-age, and natural mortality.

Age	0	1	2	3	4	5	6	7	8	9	10+	Reference
Natural mortality	0.40	0.35	0.30	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	Ishino et al., 2021
Maturity (%)	0.00	0.00	0.00	0.00	0.20	0.80	0.90	1.00	1.00	1.00	1.00	Ishino et al., 2021
Weight (kg)	0.04	0.13	0.22	0.35	0.46	0.56	0.65	0.71	0.76	0.78	0.83	Ishino et al., 2021
Selevtivity (2016-2020 ave. F)	0.00	0.01	0.02	0.05	0.17	0.28	0.34	0.30	0.25	0.30	0.30	This research

Table 3.4: Stock-recruitment relationship and the parameter values for Alaska pollock. The Hockey-Stick model with underline was used in the projection of this research, while the Ricker model was also tested in the section 3.4.4. L1: Least absolute value method, L2: Least squares method.

	Optimization	Autocorrelation	*a*	*b*	S.D.	Reference
Hockey-Stick	**L2**	**No**	**11.795**	**150,944**	**0.580**	**Ishino et al., 2021**
Ricker	L2	No	29.001	5.00E-06	0.472	Sakai et al., 2019

Table 3.5: Biological parameters for Pacific cod in the simulation. Selectivity was determined in this study from the catch-at-age, number-at-age, and natural mortality.

Age	1	2	3	4	5	6	7	8+	Reference
Natural mortality	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	Chimura et al., 2021
Maturity (%)	0.00	0.00	0.00	0.50	1.00	1.00	1.00	1.00	Chimura et al., 2021
Weight (kg)	0.48	1.56	3.11	5.01	6.84	8.44	10.19	10.19	Chimura et al., 2019
Selevtivity (2016-2020 ave. F)	0.39	0.40	0.31	0.50	0.75	0.93	1.02	1.07	This research

Table 3.6: Effort data for each fleet

Age	2016	2017	2018	2019	2020	Reference
Hokkaido Pacific offshore trawl	2682	2700	2718	2556	2208	MAFF, n.d.
Coastal fisheries (pollock)	100	100	100	100	100	This research
Coastal fisheries (cod)	100	100	100	100	100	This research

Table 3.7: Catchability by fleet for Alaska pollock (upper) and Pacific cod (lower)

Age	0	1	2	3	4	5	6	7	8	9	10+	Reference
Hokkaido Pacific offshore trawl	4.60.E-07	2.37.E-06	4.48.E-06	1.21.E-05	3.71.E-05	5.71.E-05	6.52.E-05	5.98.E-05	4.98.E-05	6.11.E-05	6.11.E-05	This research
Coastal fisheries (pollock)	1.00.E-05	4.00.E-05	8.00.E-05	2.10.E-04	6.40.E-04	9.90.E-04	1.16.E-03	1.06.E-03	8.80.E-04	1.06.E-03	1.06.E-03	This research

Age	1	2	3	4	5	6	7	8+	Reference
Hokkaido Pacific offshore trawl	6.05.E-05	6.06.E-05	4.96.E-05	7.13.E-05	9.48.E-05	1.08.E-04	1.18.E-04	1.22.E-04	This research
Coastal fisheries (cod)	1.69.E-03	1.73.E-03	1.43.E-03	2.10.E-03	2.76.E-03	3.17.E-03	3.44.E-03	3.53.E-03	This research

Table 3.8: Economic parameter values of the Hokkaido Pacific offshore trawl. The values are the average from 2016 to 2020 except for the number of vessels, which is the number in 2020, and effort, which indicates the minimum and maximum values in the last 10 years. The parameters for the “Others” catch function was estimated in this research.

	Symbol	Value	S.D.	Reference
Number of vessels	$N_{vessels}$	16		HRO, 2022
Catch share (%)	$\lambda_{pollock}$	59.5		Ishino et al., 2021
	λ_{cod}	47.1		Chimura et al., 2021
Ex-vessel fish price (¥/kg)	$p_{pollock}$	65.3	10.0	HTFCF
	p_{cod}	223.5		HTFCF
	p_{others}	308.3		HTFCF
Fixed cost (¥1000/yr/vessel)	FC	136,763		MAFF, n.d.
Fuel cost (¥1000/day/vessel)	FU	246		MAFF, n.d.
Effort (days/yr/vessel)	E	138-169		MAFF, n.d.
"Others" catch parameter	γ	2.2		This research
	δ	171.2		This research

Table 3.9: The values of reference points for HCRs and the value of MMSY. The reference points for Pacific cod are derived from the stock-recruitment relationship identified in the section 3.4.1.

	Alaska pollock		Pacific cod	
		(Reference)		(Reference)
SSB_{MSY} (mt)	228,000	(Ishino et al., 2021)	49,000	(This research)
SSBlimit (mt)	151,000	(Ishino et al., 2021)	9,000	(This research)
SSBban (mt)	60,000	(Ishino et al., 2021)	1,000	(This research)
F_{MSY}	0.43	(This research)	0.35	(This research)
MMSY for the Hokkaido Pacific offshore trawl (mt)	113,000			(This research)

Table 3.10: Estimated parameter values and AICc of the stock-recruitment relationship models for Pacific cod. The Hockey-Stick model with underline was used in the projection of this research. L1: Least absolute value method, L2: Least squares method.

	Optimization	Autocorrelation	*a*	*b*	S.D.	AICc	Reference
Beverton-Holt	L1	No	2.064	5.45E-05	0.240	4.184	This research
Beverton-Holt	L2	No	4.247	1.97E-04	0.230	6.656	This research
Ricker	L1	No	1.857	3.25E-05	0.238	4.006	This research
Ricker	L2	No	2.684	6.22E-05	0.227	6.218	This research
Hockey-Stick	**L1**	**No**	**1.388**	**12,894**	**0.230**	**3.003**	**This research**
Hockey-Stick	L2	No	1.436	10,932	0.214	4.484	This research

3.7 Figures

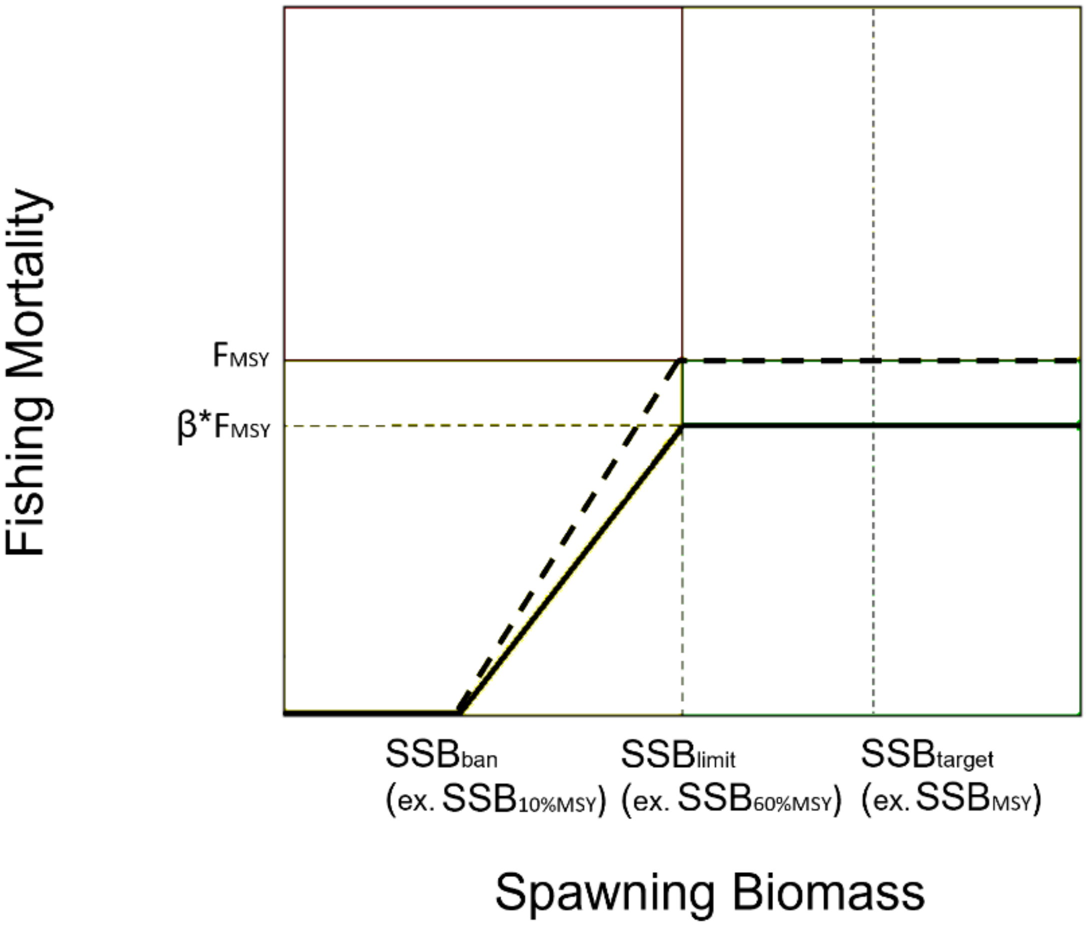


Figure 3.1: The basic HCR in Japan. β is a coefficient multiplied. $SSB_{x\%MSY}$ is the SSB that is expected to produce x% of MSY.

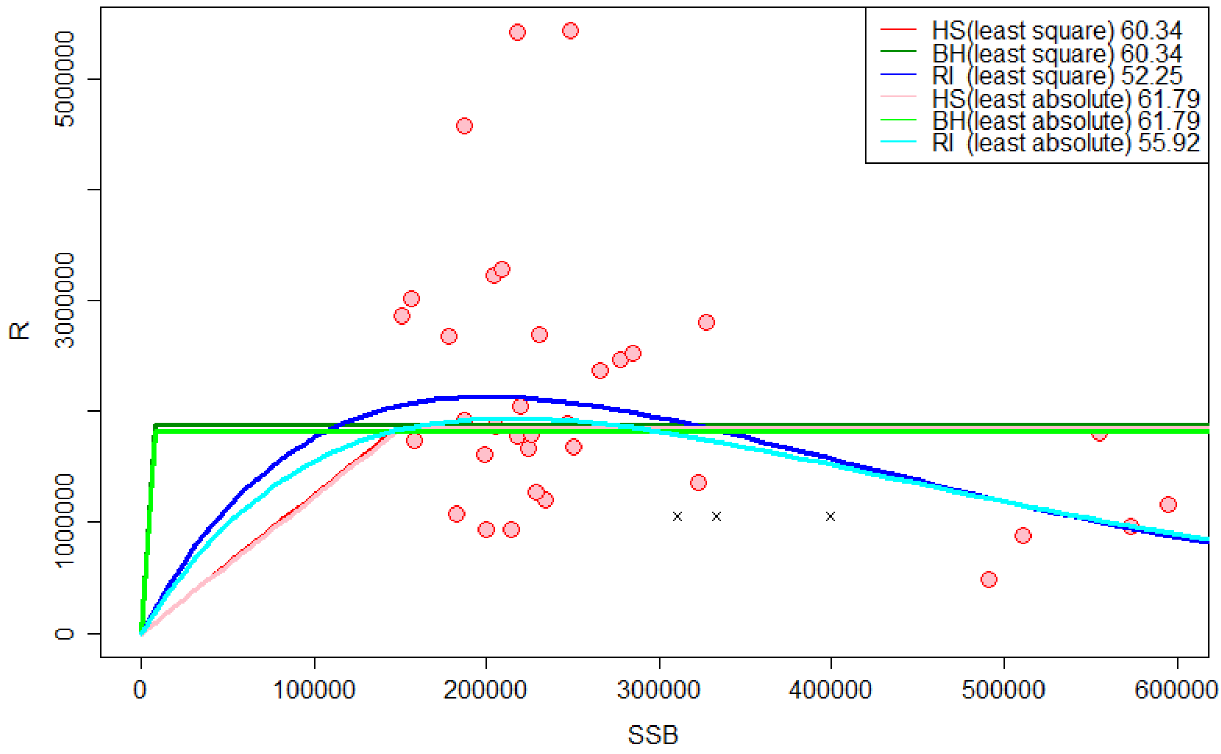


Figure 3.2: Fitting of stock-recruitment models to the recruitment data for Alaska pollock from Sakai et al. (2019). X marks are the data excluded from the fitting. HS: Hockey-Stick model, BH: Beverton-Holt model, RI: Ricker model. The values in the legend indicate the AICc for each model. The Hockey-Stick model with least square optimization (dark red line) was used in this study, while the Ricker model with least square optimization (dark blue line) was also explored in the section 3.4.4.

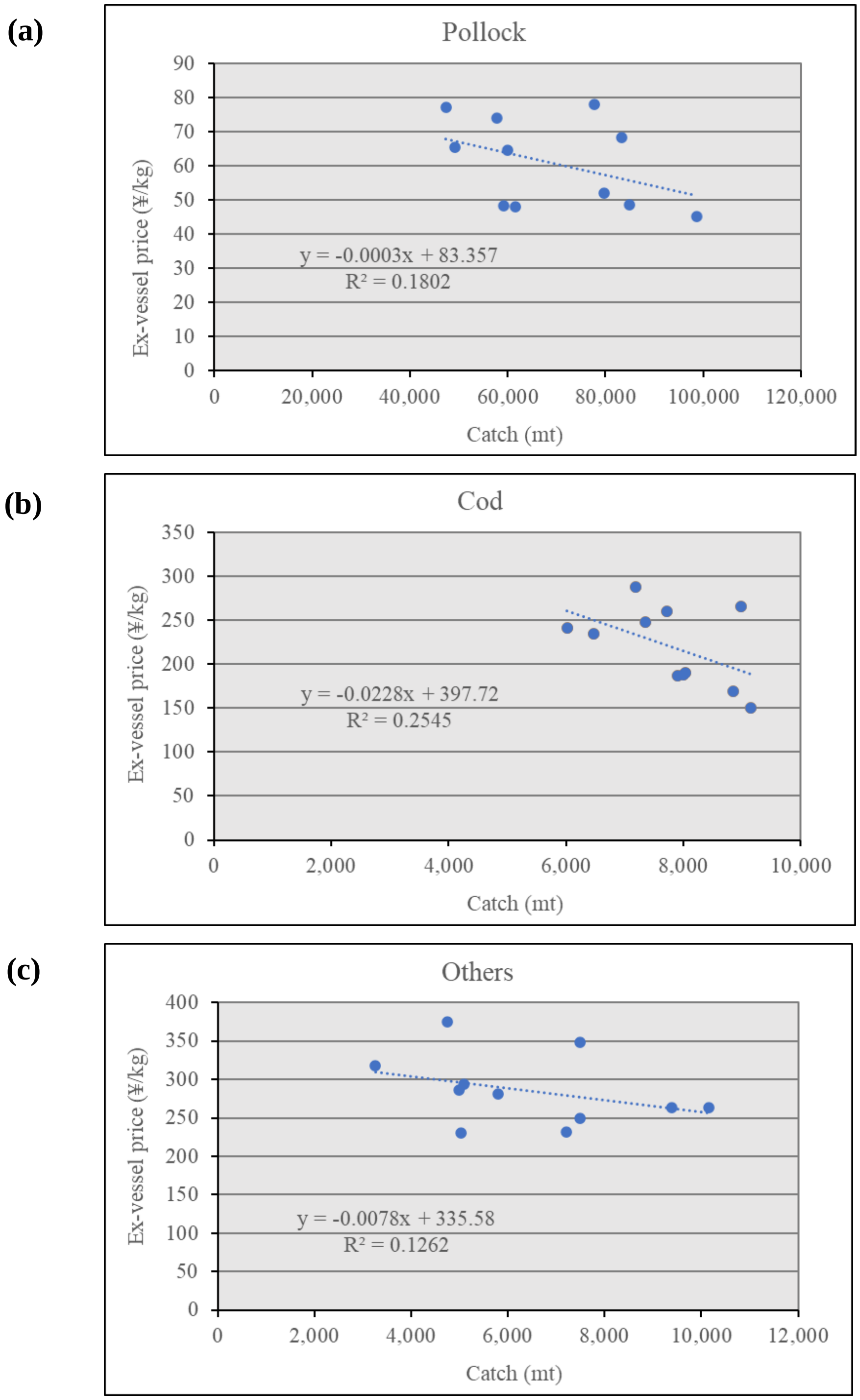


Figure 3.3: The relationship between catch volume and ex-vessel price for pollock (a), cod (b), and other species (c) with regression lines on an annual basis for the past 10 years

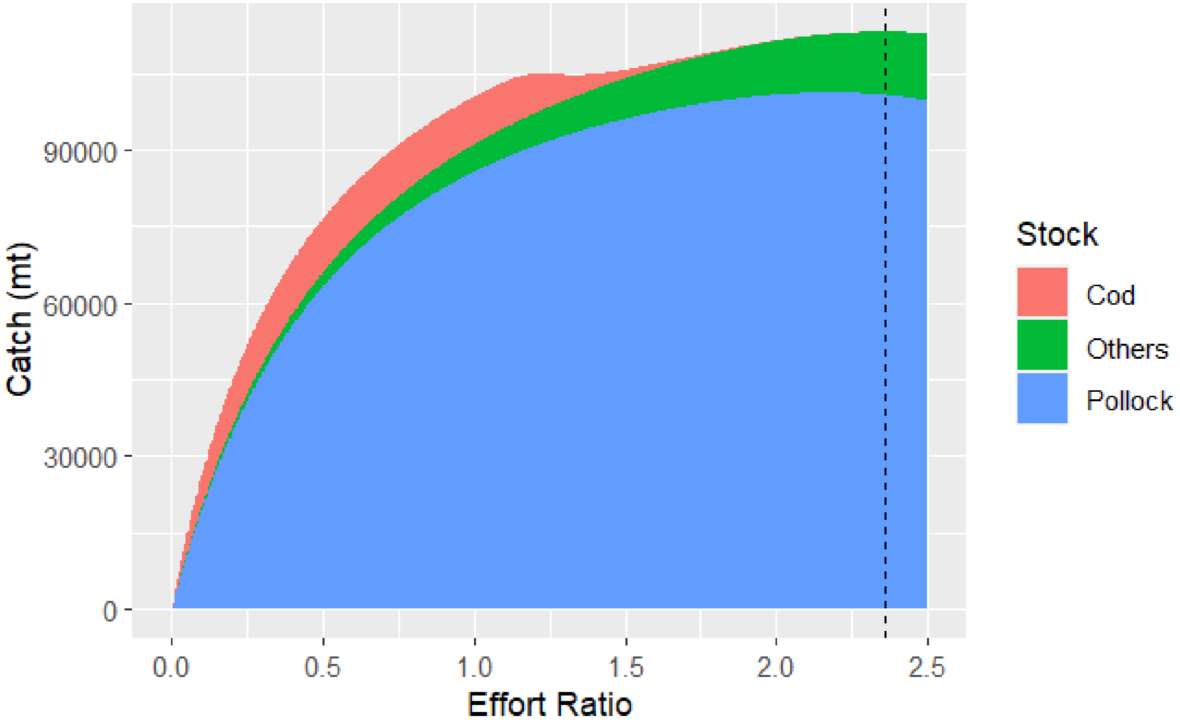


Figure 3.4: Cumulative catch by species for the Hokkaido Pacific offshore trawl for varying effort ratios to current level. The catch is the average in the terminal year of a 20-year simulation, with 1000 iterations. The black dotted line represents the effort level that maximizes the total cumulative catch, at which the catch is defined as MMSY in this study.

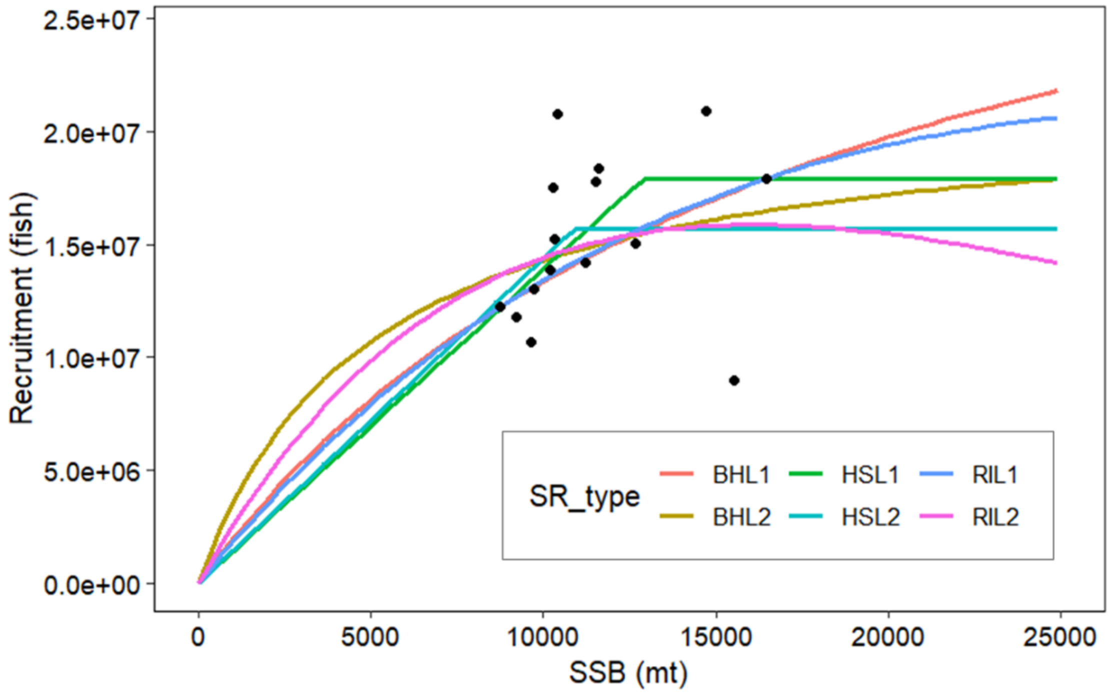


Figure 3.5: Fitting of the Beverton-Holt (BH), Ricker (RI), and Hockey-Stick (HS) models to the stock-recruitment data (black dots) for Pacific cod. L1: Least absolute value method, L2: Least squares method.

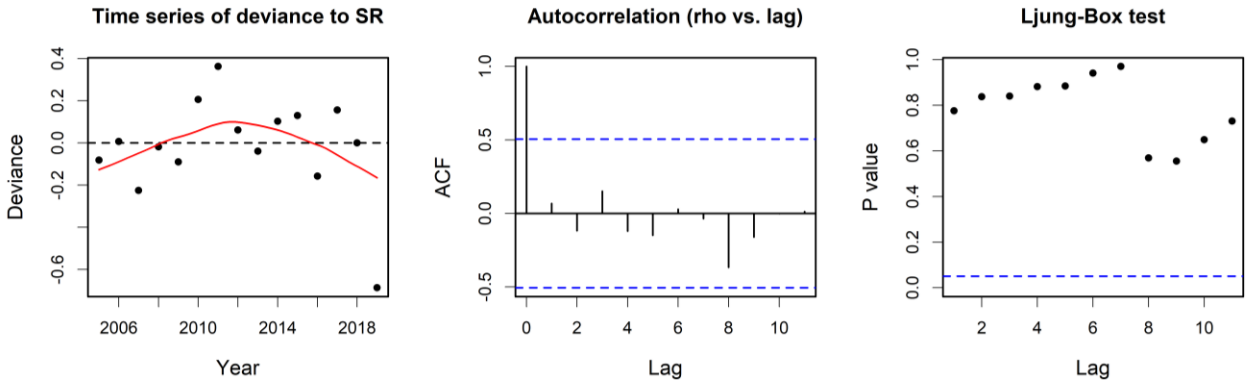


Figure 3.6: Figures to check autocorrelation for Pacific cod; (Left panel) Time series of deviance of the recruitment data to the Hockey-Stick model with L1. When autocorrelation exists, a trend is observed in the red line; (Middle panel) Autocorrelation coefficient ρ for lags from 1 to 11 years. The blue line is 95% confidence interval, and ρ=0 for all lag years falls within this interval.; (Right panel) P-value in the Ljung-Box test. The null hypothesis was "the autocorrelation at lag year n is 0." and was not rejected for all years.

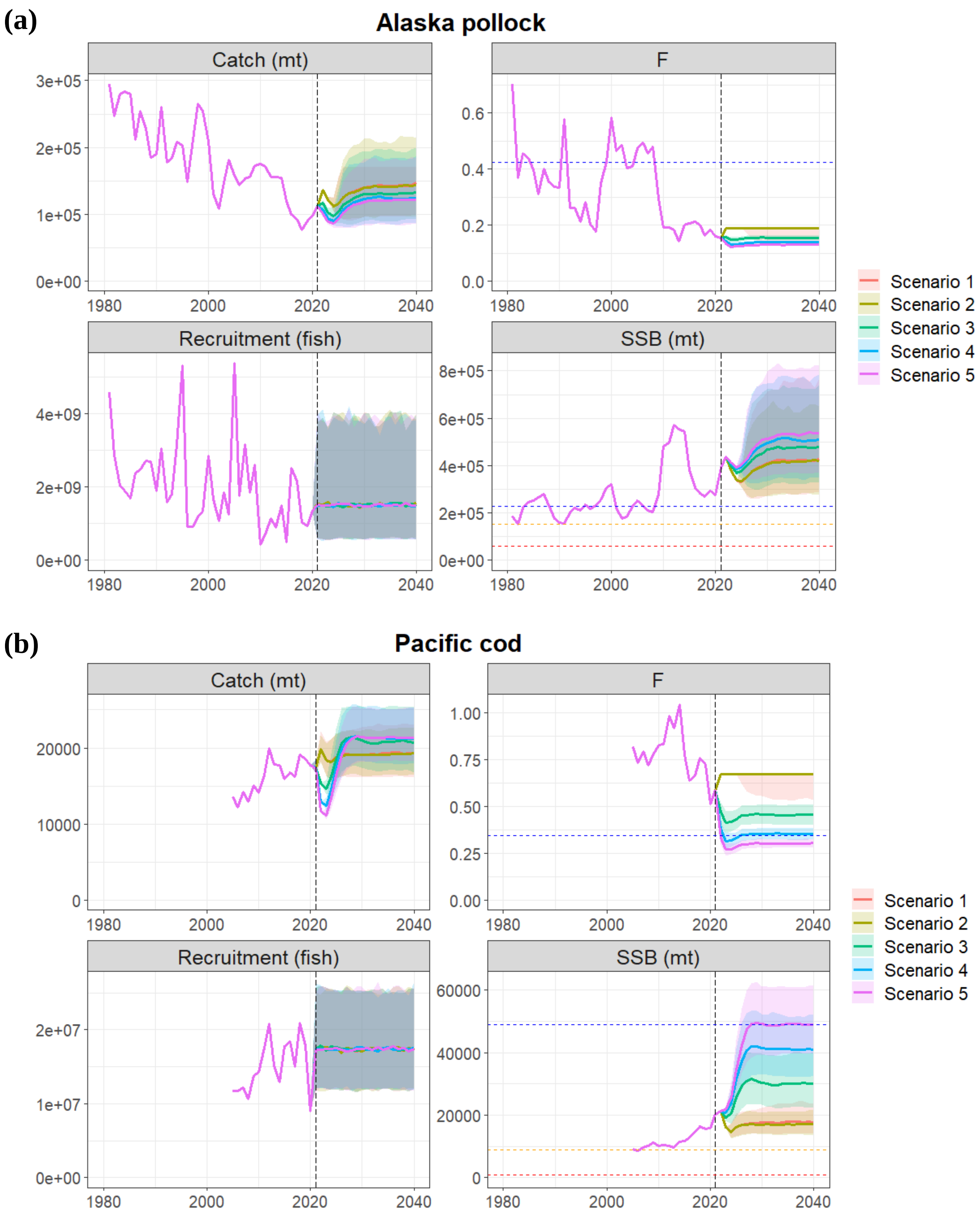


Figure 3.7: Time series of catch, fishing mortality, recruitment, and SSB for Alaska pollock (a) and Pacific cod (b) under each harvest scenario. The solid line for each scenario is the median for

all simulations, and the shaded area shows the 95%-tile of simulations. The black dotted vertical line indicates the simulation start year, and the horizontal dotted lines are F_{MSY} and SSB_{MSY} in blue, SSB_{limit} in yellow, and SSB_{ban} in red. Note that the input data covered from 1980 to 2020 for pollock, while it covered from 2005 to 2020 for cod.

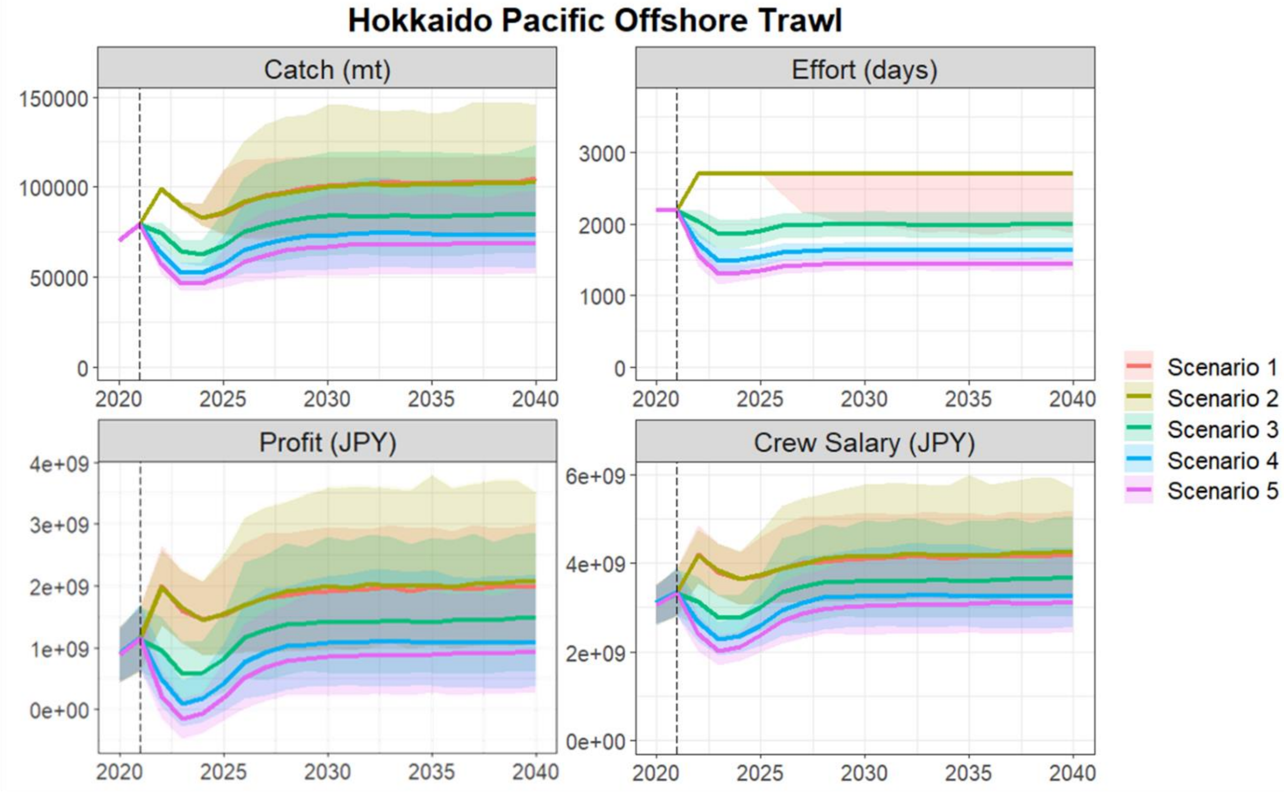
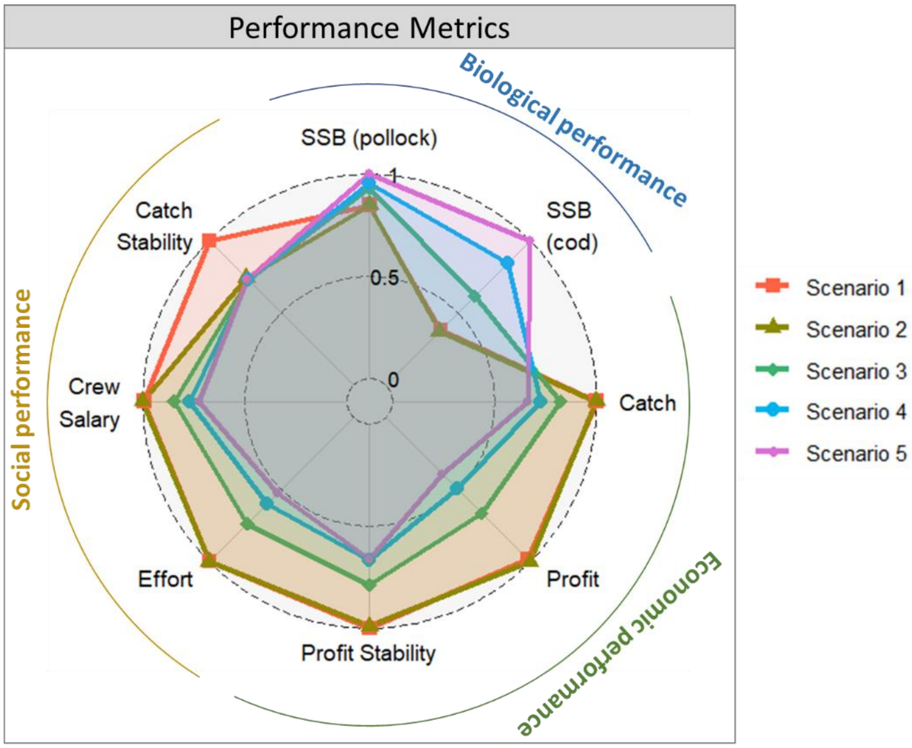


Figure 3.8: Catch, effort, profit, and crew salary for the Hokkaido Pacific offshore trawl during the simulation period under each harvest scenario. The solid line for each scenario is the median for all simulations, and the shaded area shows the 95%-tile of simulations. The black dotted vertical line indicates the simulation start year. Note that the catch is cumulative for pollock, cod, and "others". The black dotted vertical line indicates the simulation start year.

(a)



(b)

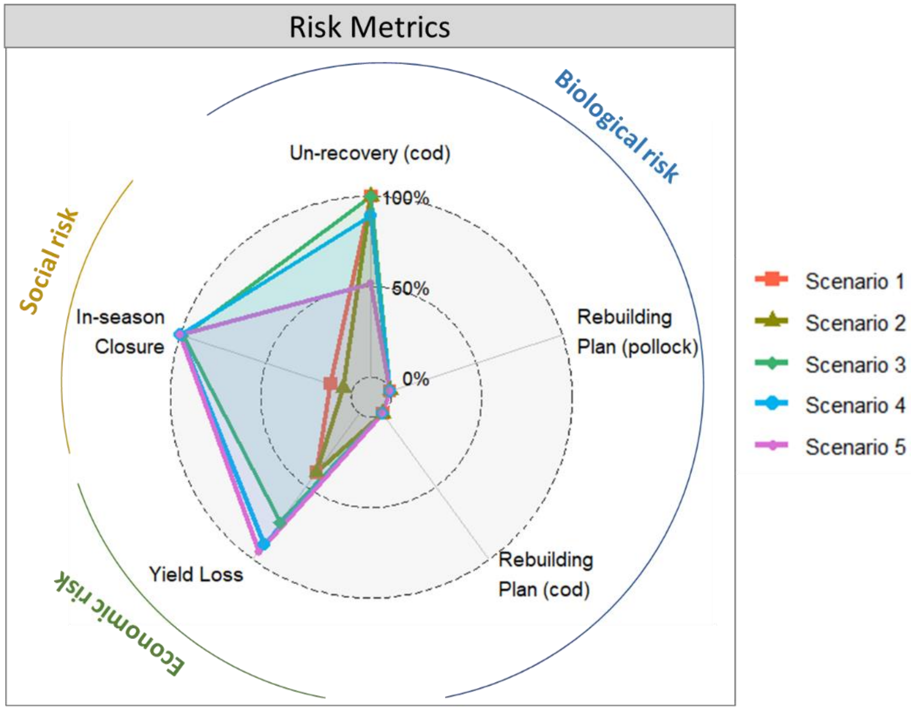


Figure 3.9: The results of performance metrics (a) and risk metrics (b) for the Hokkaido Pacific offshore trawl under each harvest scenario. The value of performance metrics is normalized so that the best scenario is 1. The value of risk metrics indicates the probability that each incident will occur.

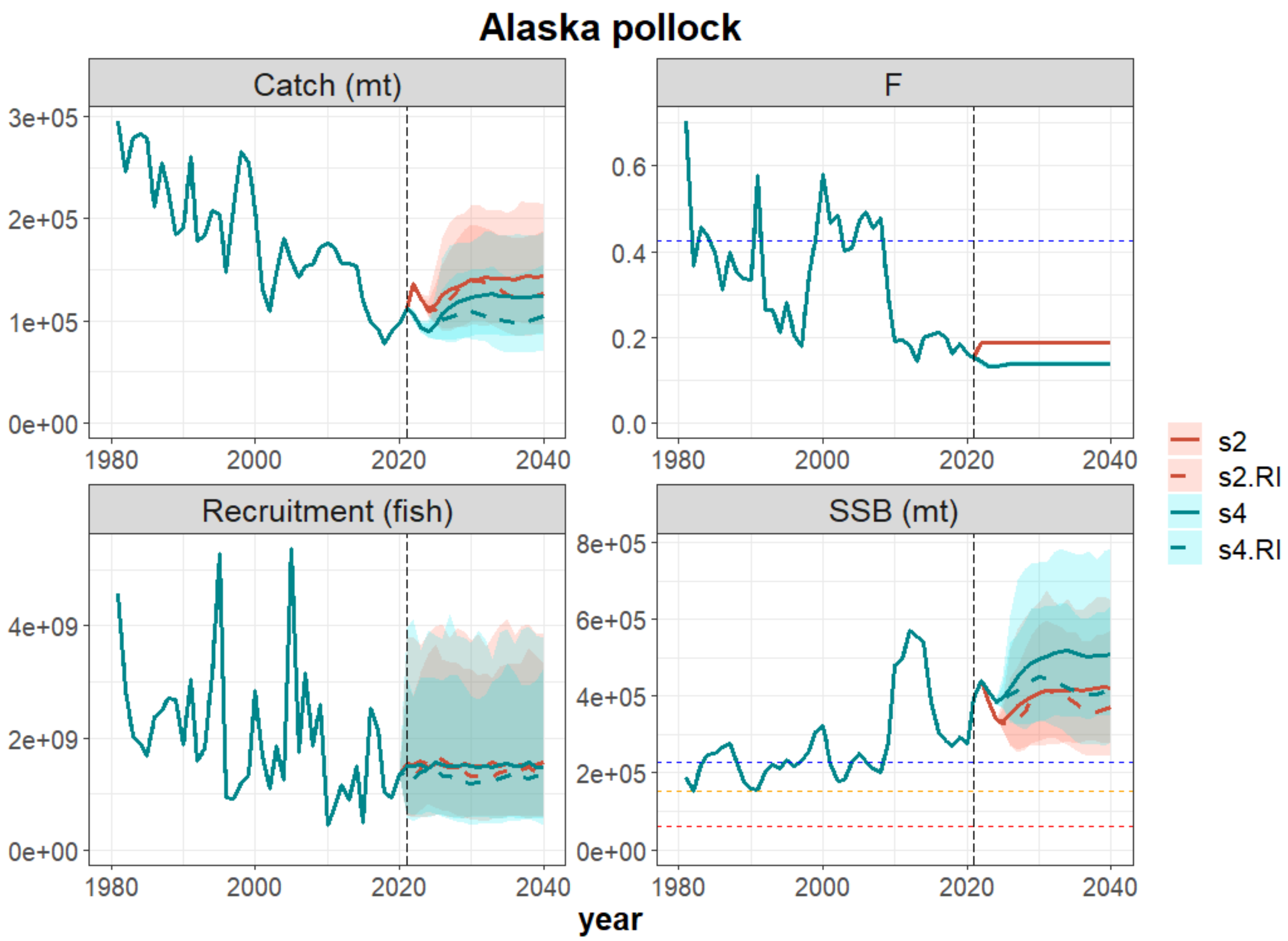


Figure 3.10: Time series of catch, fishing mortality, recruitment, and SSB for Alaska pollock under harvest scenario 2 (red line) and 4 (blue line) with the Hockey-Stick (solid line) or Ricker (dotted line) stock-recruitment model. The thick line for each scenario is the median for all simulations, and the shaded area shows the 95%-tile of simulations. The black dotted vertical line indicates the simulation start year, and the horizontal dotted lines are F_{MSY} and SSB_{MSY} in blue, SSB_{limit} in yellow, and SSB_{ban} in red.

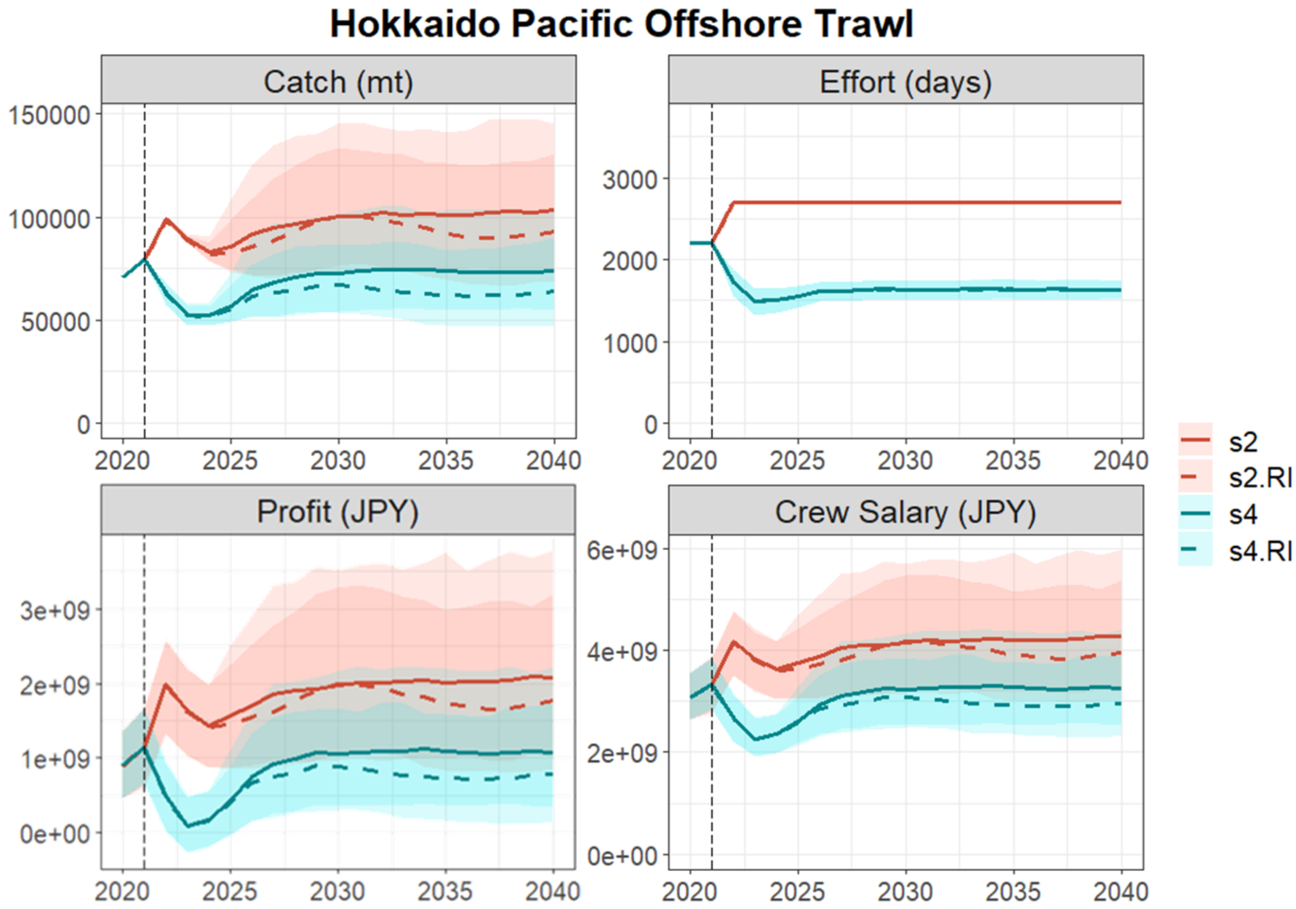


Figure 3.11: Time series of catch, effort, profit, and crew salary for the Hokkaido Pacific offshore trawl under harvest scenario 2 (red line) and 4 (blue line) with the Hockey-Stick (solid line) or Ricker (dotted line) stock-recruit model. The thick line for each scenario is the median for all simulations, and the shaded area shows the 95%-tile of simulations. The black dotted vertical line indicates the simulation start year. Note that the catch is cumulative for pollock, cod, and “other”. The black dotted vertical line indicates the simulation start year.

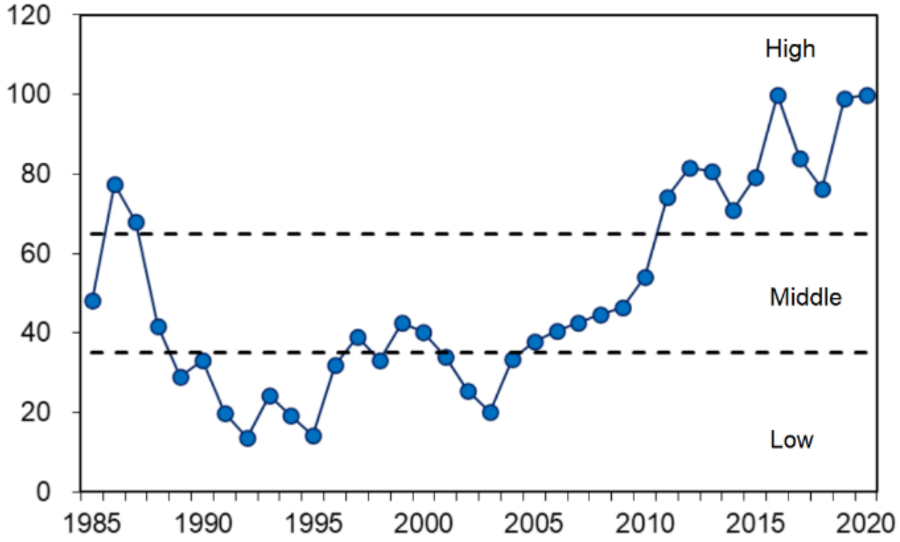


Figure 3.12: Abundance index for Pacific cod from Chimura et al. (2021).

APPENDIX

Appendix 1: FPI output scores for the Hokkaido Pacific offshore trawl

Component	Dimension	Sust. Category	Measure	Score	Summary
Ecologically Sustainable Fisheries	Fish Stock Health & Environmental Performance	Ecology	Proportion of Harvest with a 3rd Party Certification	1	3.86
		Ecology	Percentage of Stocks Overfished	3	
		Ecology	Overfishing or Rebuilding	5	
		Ecology	Regulatory Mortality	5	
		Ecology	Selectivity	4	
		Ecology	Illegal, Unregulated or Unreported Landings	5	
		Ecology	Status of Critical Habitat	4	
Harvest Sector Performance	Harvest Performance	Economics	Landings Level	4	4.75
		Economics	Excess Capacity	5	
		Economics	Season Length	5	
		Community	Harvest Safety	5	
	Harvest Asset Performance	Economics	Ratio of Asset Value to Gross Earnings	1	3.17
		Economics	Total Revenue versus Historic High	2	
		Economics	Asset (Permit, Quota) Value versus Historic High	4	
		Economics	Borrowing Rate Relative to Risk-free Rate	5	
		Economics	Source of Capital	3	
		Economics	Functionality of Harvest Capital	4	
	Risk	Economics	Annual Total Revenue Volatility	4	3.71
		Economics	Annual Landings Volatility	5	
		Economics	Intra-annual Landings Volatility	2	
		Economics	Annual Price Volatility	4	
		Economics	Intra-annual Price Volatility	3	
		Economics	Spatial Price Volatility	3	
		Community	Contestability & Legal Challenges	5	
	Owners, Permit Holders & Captains (Those holding the right or ability to access)	Community	Earnings Compared to Regional Average Earnings	5	5.00
		Community	Fishery Wages Compared to Non-fishery Wages	5	
		Community	Education Access	5	
		Community	Access to Health Care	5	
		Community	Social Standing of Boat Owners and Permit Holders	5	
		Community	Proportion of Nonresident Employment	5	
	Crew (Those depending on others for access)	Community	Earnings Compared to Regional Average Earnings	5	4.88
		Community	Fishery Wages Compared to Non-fishery Wages	5	
		Community	Education Access	5	
		Community	Access to Health Care	5	
		Community	Social Standing of Crew	4	
		Community	Proportion of Nonresident Employment	5	
		Community	Crew Experience	5	
		Community	Age Structure of Harvesters	5	

Post Harvest Performance	Market Performance	Economics	Ex-vessel Price versus Historic High	**3**	**3.43**
		Economics	Final Market Use	**3**	
		Economics	International Trade	**2**	
		Economics	Final Market Wealth	**5**	
		Economics	Wholesale Price Relative to Similar Products	**3**	
		Economics	Capacity of Firms to Export to the US & EU	**3**	
		Economics	Ex-vessel to Wholesale Marketing Margins	**5**	
	Post-harvest, Processing & Support Industry Performance	Economics	Processing Yield	**5**	**4.50**
		Economics	Shrink	**5**	
		Economics	Capacity Utilization Rate	**5**	
		Economics	Product Improvement	**2**	
		Community	Sanitation	**5**	
		Community	Regional Support Businesses	**5**	
	Post-Harvest Asset Performance	Economics	Borrowing Rate Relative to Risk-free Rate	**5**	**3.67**
		Economics	Source of Capital	**3**	
		Economics	Age of Facilities	**3**	
	Processing Owners & Managers	Community	Earnings Compared to Regional Average Earnings	**5**	**4.67**
		Community	Manager Wages Compared to Non-fishery Wages	**4**	
		Community	Education Access	**5**	
		Community	Access to Health Care	**5**	
		Community	Social Standing of Processing Managers	**4**	
		Community	Nonresident Ownership of Processing Capacity	**5**	
	Processing Workers	Community	Earnings Compared to Regional Average Earnings	**2**	**3.43**
		Community	Worker Wages Compared to Non-fishery Wages	**3**	
		Community	Social Standing of Processing Workers	**2**	
		Community	Education Access	**4**	
		Community	Access to Health Care	**5**	
		Community	Proportion of Nonresident Employment	**4**	
		Community	Worker Experience	**4**	

Appendix 2: FPI input scores for the Hokkaido Pacific offshore trawl

Component	Dimension	Measure	Fishery	Summary
Macro Factors	General Environmental Performance	Environmental Performance Index (EPI)	**5**	**5.00**
	Exogenous Environmental Factors	Disease and Pathogens	**5**	**4.20**
		Natural Disasters and Catastrophes	**3**	
		Pollution Shocks and Accidents	**3**	
		Level of Chronic Pollution (Stock effects)	**5**	
		Level of Chronic Pollution (Consumption effects)	**5**	
	Governance	Governance Quality	**5**	**5.00**
		Governance Responsiveness	**5**	
	Economic Condition	Index of Economic Freedom	**5**	**5.00**
		Gross Domestic Product (GDP) Per Capita	**5**	
Property Rights & Responsibility	Fishing Access	Proportion of Harvest Managed Under Limited Access	**5**	**3.83**
		Transferability Index	**2**	
		Security Index	**5**	
		Durability Index	**5**	
		Flexibility Index	**3**	
		Exclusivity Index	**3**	
	Harvest Rights	Proportion of Harvest Managed with Rights-based Management	**3**	**3.67**
		Transferability Index	**3**	
		Security Index	**5**	
		Durability Index	**5**	
		Flexibility Index	**3**	
		Exclusivity Index	**3**	
Co-Management	Collective Action	Proportion of Harvesters in Industry Organizations	**5**	**4.33**
		Harvester Organization Influence on Fishery Management & Access	**4**	
		Harvester Organization Influence on Business & Marketing	**4**	
	Participation	Days in Stakeholder Meetings	**5**	**3.00**
		Industry Financial Support for Management	**1**	
	Community	Leadership	**5**	**5.00**
		Social Cohesion	**5**	
	Gender	Business Management Influence	**1**	**1.75**
		Resource Management Influence	**1**	
		Labor Participation in Harvest Sector	**1**	
		Labor Participation in Post-Harvest Sector	**4**	
Management	Management Inputs	Management Expenditure to Value of Harvest	**4**	**3.75**
		Enforcement Capability	**5**	
		Management Jurisdiction	**3**	
		Level of Subsidies	**3**	
	Data	Data Availability	**5**	**4.50**
		Data Analysis	**4**	
	Management Methods	MPAs and Sanctuaries	**1**	**3.33**
		Spatial Management	**5**	
		Fishing Mortality Limits	**4**	

Post-harvest	Markets & Market Institutions	Landings Pricing System	**5**	**3.50**
		Availability of Ex-vessel Price & Quantity Information	**5**	
		Number of Buyers	**5**	
		Degree of Vertical Integration	**2**	
		Level of Tariffs	**1**	
		Level of Non-tariff Barriers	**3**	
	Infrastructure	International Shipping Service	**4**	**4.83**
		Road Quality Index	**5**	
		Technology Adoption	**5**	
		Extension Service	**5**	
		Reliability of Utilities/Electricity	**5**	
		Access to Ice & Refrigeration	**5**	

Appendix 3: Catch-at-age for Alaska pollock from Ishino et al., 2021 (unit: 1000 fish).

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Age 0	594,529	366,429	30,115	5,007	176,725	513,309	518,240	457,112	366,705	174,167
Age 1	341,925	639,149	49,009	24,655	164,059	24,071	186,800	125,630	114,936	181,518
Age 2	37,002	106,635	238,807	73,472	148,636	40,474	29,863	52,302	46,816	155,443
Age 3	101,209	19,775	93,260	120,398	129,027	59,792	83,425	80,606	69,665	43,217
Age 4	135,940	166,383	133,364	188,057	103,686	112,225	108,326	127,396	111,782	42,289
Age 5	124,604	54,898	131,058	130,792	125,754	102,104	119,575	99,969	77,036	63,600
Age 6	46,630	19,352	36,268	56,894	49,512	51,509	66,731	58,726	38,124	24,802
Age 7	26,641	5,801	8,542	9,838	11,485	11,949	23,329	21,777	13,346	13,702
Age 8+	1,829	1,508	3,175	2,374	2,827	3,665	7,600	9,066	7,484	11,176
Total	1,410,308	1,379,930	723,597	611,486	911,711	919,098	1,143,891	1,032,586	845,893	709,915

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Age 0	66,851	19,430	28,650	55,572	70,418	7,993	6,569	61,599	5,958	27,594
Age 1	106,516	95,215	37,837	36,319	76,250	115,758	20,345	29,459	34,815	12,005
Age 2	210,041	65,450	253,570	148,305	100,255	170,534	399,891	36,850	41,164	37,096
Age 3	80,385	91,002	42,652	209,139	48,542	30,280	157,997	282,344	24,353	36,070
Age 4	58,173	80,832	47,709	76,429	134,986	48,312	57,979	172,858	264,805	53,201
Age 5	67,524	91,496	63,610	64,709	62,083	58,855	33,454	69,918	106,187	181,795
Age 6	26,906	38,974	48,231	29,972	39,503	20,748	20,780	31,671	45,545	49,360
Age 7	5,987	4,388	12,808	7,177	21,240	13,680	11,173	36,853	25,119	24,351
Age 8(+)	2,850	2,820	4,130	3,508	14,132	14,146	11,787	11,873	7,222	6,798
Age 9(+)								4,791	5,238	4,126
Age 10(+)									3,921	6,314
Total	625,232	489,608	539,198	631,129	567,408	480,307	719,974	738,215	564,328	438,710

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Age 0	6,056	5,744	114,337	2,780	42,282	28,337	6,045	23,733	106,104	35,453
Age 1	16,029	25,435	2,874	10,256	11,400	38,510	10,602	4,092	28,654	24,789
Age 2	24,826	98,938	14,412	26,745	36,457	15,736	86,920	7,312	19,908	26,866
Age 3	20,019	22,838	163,587	81,749	31,267	69,567	25,017	118,764	26,208	34,131
Age 4	21,992	14,399	52,560	160,240	78,735	46,107	88,392	43,795	192,822	55,943
Age 5	37,473	15,359	34,983	60,826	92,555	57,224	56,202	81,685	61,453	197,168
Age 6	75,129	16,893	19,479	42,433	43,241	52,472	48,918	38,650	43,000	28,608
Age 7	23,950	33,630	11,363	16,781	21,206	25,145	26,290	24,471	6,367	9,816
Age 8	11,916	9,457	13,908	3,648	9,222	10,382	6,937	12,951	3,763	1,305
Age 9	3,756	4,608	1,687	2,573	1,551	3,021	1,658	1,185	2,899	1,310
Age 10+	1,106	1,592	882	1,057	1,636	789	1,078	1,035	461	995
Total	242,252	248,893	430,072	409,089	369,553	347,291	358,060	357,671	491,637	416,385

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Age 0	39,169	30,360	5,983	11,325	3,979	6,177	7,012	158	2,323	102
Age 1	1,810	10,115	1,198	6,114	4,664	5,988	5,897	4,265	2,424	8,125
Age 2	18,367	12,865	5,172	19,759	28,019	10,295	6,242	5,972	19,862	7,633
Age 3	37,725	28,163	9,471	16,239	18,946	10,099	28,682	8,107	46,045	26,332
Age 4	93,150	58,028	97,712	13,366	19,752	37,272	29,555	34,307	18,281	107,969
Age 5	78,636	91,388	61,399	90,110	12,066	29,090	34,999	30,031	40,608	18,032
Age 6	98,311	38,778	61,438	43,699	55,641	8,916	18,703	23,399	26,982	20,601
Age 7	10,681	52,755	17,421	51,820	23,217	29,736	5,308	6,907	10,965	8,584
Age 8	4,085	5,628	35,931	13,845	35,626	11,006	18,461	1,752	2,956	5,707
Age 9	1,421	2,766	1,964	21,618	6,997	18,942	6,237	8,632	1,455	2,205
Age 10+	1,741	1,830	1,054	4,497	17,138	16,171	12,679	11,195	14,551	7,956
Total	385,095	332,676	298,744	292,393	226,046	183,690	173,776	134,724	186,451	213,248

Appendix 4: Number-at-age for Alaska pollock from Ishino et al., 2021 (unit: 1000 fish).

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Age 0	4,578,178	2,864,137	2,043,096	1,888,943	1,685,414	2,374,249	2,477,575	2,708,200	2,691,020	1,882,832
Age 1	2,216,568	2,582,086	1,619,882	1,344,873	1,262,097	985,077	1,171,245	1,236,469	1,441,109	1,503,612
Age 2	924,684	1,274,958	1,283,027	1,100,371	927,019	751,664	673,965	668,551	765,864	919,049
Age 3	796,741	653,174	852,730	744,947	751,937	558,821	522,010	473,583	450,258	527,071
Age 4	336,899	531,186	491,241	581,806	473,914	471,743	382,444	332,920	297,692	289,182
Age 5	191,508	142,411	266,856	264,886	287,151	277,582	268,356	202,250	146,852	133,195
Age 6	67,814	39,184	62,463	92,169	90,869	112,656	126,075	103,471	69,290	46,384
Age 7	33,831	11,663	13,438	16,640	21,573	27,075	42,280	39,297	28,757	20,319
Age 8+	2,323	3,032	4,994	4,015	5,309	8,306	13,775	16,360	16,126	16,573
Total	9,148,546	8,101,831	6,637,727	6,038,648	5,505,284	5,567,171	5,677,724	5,781,101	5,906,967	5,338,217

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Age 0	3,048,396	1,593,251	1,811,022	3,125,009	5,299,772	928,182	910,459	1,178,934	1,332,746	2,847,798
Age 1	1,119,504	1,988,668	1,052,080	1,190,507	2,049,258	3,494,890	615,635	604,921	739,830	888,488
Age 2	907,201	699,486	1,321,461	709,626	808,448	1,380,079	2,365,633	416,752	401,551	492,124
Age 3	547,057	491,287	461,858	760,713	398,057	512,623	875,607	1,408,315	277,020	262,046
Age 4	372,344	355,108	302,305	322,055	407,880	267,169	372,509	542,492	847,630	194,252
Age 5	187,895	238,645	205,224	193,333	183,368	198,532	165,436	238,944	269,947	426,445
Age 6	47,606	86,743	105,111	103,693	93,462	88,020	102,677	99,318	124,388	116,525
Age 7	14,237	13,331	33,161	39,297	54,306	37,927	50,239	61,626	49,399	56,680
Age 8(+)	6,777	8,567	10,693	19,205	36,132	39,219	35,524	29,266	15,472	16,304
Age 9(+)								17,264	12,315	5,676
Age 10(+)									9,217	8,687
Total	6,251,015	5,475,085	5,302,917	6,463,439	9,330,683	6,946,640	5,493,721	4,597,834	4,079,516	5,315,026

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Age 0	1,665,161	1,081,873	1,846,854	1,255,434	5,380,913	1,749,253	3,157,956	1,858,792	2,600,588	432,705
Age 1	1,886,344	1,111,232	720,498	1,144,372	839,266	3,572,316	1,149,359	2,111,892	1,226,555	1,656,356
Age 2	616,030	1,315,829	761,721	505,314	797,816	581,851	2,485,041	801,039	1,484,790	840,284
Age 3	332,646	434,998	889,633	551,892	351,326	559,657	417,501	1,766,151	587,131	1,082,825
Age 4	172,250	241,398	318,622	548,482	357,671	246,020	374,468	303,073	1,270,671	434,130
Age 5	104,334	114,741	175,294	201,760	285,747	209,071	150,911	213,631	197,385	819,435
Age 6	171,682	48,186	75,806	105,646	103,451	140,861	112,324	67,931	94,289	99,492
Age 7	47,190	67,405	22,619	41,847	44,830	42,408	63,396	44,308	18,796	35,485
Age 8	22,653	15,616	22,817	7,588	17,781	16,199	10,837	26,172	12,912	9,020
Age 9	6,698	7,126	3,816	5,496	2,690	5,710	3,454	2,318	8,954	6,735
Age 10+	1,972	2,462	1,996	2,259	2,836	1,491	2,246	2,024	1,423	5,117
Total	5,026,960	4,440,865	4,839,676	4,370,090	8,184,328	7,124,836	7,927,494	7,197,332	7,503,495	5,421,585

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Age 0	721,829	1,149,596	889,285	1,501,655	487,553	2,518,585	2,150,551	1,018,958	943,421	1,339,215
Age 1	261,025	451,788	745,741	591,207	997,317	323,559	1,683,200	1,435,817	682,898	630,492
Age 2	1,146,405	182,422	309,879	524,509	411,484	698,882	222,982	1,181,181	1,008,223	479,196
Age 3	599,374	833,469	124,069	225,112	371,559	280,719	508,884	159,816	869,900	729,814
Age 4	813,184	433,500	624,252	88,266	160,986	272,651	209,712	371,007	117,311	636,844
Age 5	288,731	551,104	286,401	399,937	56,946	107,945	179,448	137,242	258,665	75,229
Age 6	464,177	155,469	348,550	168,865	231,950	33,701	58,395	108,868	80,381	165,613
Age 7	52,237	274,742	86,858	217,232	92,949	131,540	18,378	28,973	64,137	38,790
Age 8	18,973	31,257	167,413	52,271	123,449	51,899	76,202	9,628	16,469	40,273
Age 9	5,874	11,172	19,376	98,672	28,490	64,703	30,707	43,054	5,953	10,217
Age 10+	7,195	7,388	10,399	20,525	69,784	55,237	62,423	55,836	59,519	36,863
Total	4,379,005	4,081,906	3,612,221	3,888,252	3,032,468	4,539,420	5,200,881	4,550,379	4,106,877	4,182,547

Appendix 5: Catch-at-age for Pacific cod from Chimura et al., 2021 (unit: 1000 fish).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Age 1	2,097	1,976	2,663	1,954	3,351	2,573	3,465	6,487	4,443	2,235	4,504	6,244	3,991	4,437	5,025	2,653
Age 2	1,635	1,897	2,074	1,900	1,577	2,218	2,779	3,431	3,151	2,076	2,112	2,863	2,245	2,068	2,975	2,754
Age 3	1,182	942	1,164	1,004	1,145	1,001	1,216	1,362	1,520	1,604	1,051	925	894	973	891	1,567
Age 4	687	544	644	597	737	591	646	744	658	915	786	569	715	1,005	713	691
Age 5	254	225	252	260	329	281	292	307	237	344	309	356	385	487	487	361
Age 6	104	93	102	102	133	121	128	127	101	126	104	113	149	198	155	123
Age 7	29	27	28	28	33	35	33	32	28	35	26	20	50	53	46	28
Age 8+	4	5	6	5	6	8	6	6	4	5	3	3	8	15	13	8
Total	5,992	5,709	6,932	5,850	7,311	6,827	8,565	12,496	10,143	7,340	8,895	11,094	8,436	9,236	10,305	8,185

Appendix 6: Number-at-age for Pacific cod from Chimura et al., 2021 (unit: 1000 fish).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Age 1	11,767	11,790	12,217	10,696	13,869	14,215	17,540	20,778	15,223	12,986	17,741	18,362	15,038	20,921	17,898	9,012
Age 2	6,222	6,912	7,034	6,758	6,242	7,390	8,316	10,012	9,810	7,453	7,697	9,267	8,229	7,705	11,680	8,935
Age 3	3,221	3,202	3,488	3,426	3,372	3,267	3,566	3,769	4,464	4,555	3,734	3,885	4,400	4,164	3,929	6,092
Age 4	1,474	1,369	1,562	1,582	1,673	1,512	1,559	1,595	1,620	1,998	1,993	1,862	2,081	2,491	2,247	2,143
Age 5	517	500	545	602	659	605	612	599	541	634	693	800	889	927	980	1,051
Age 6	176	165	177	187	223	205	207	202	179	197	173	248	286	328	267	307
Age 7	43	41	42	43	51	51	48	43	40	46	37	39	86	84	73	64
Age 8+	6	8	9	8	10	11	9	8	5	6	5	5	13	24	21	19
Total	23,426	23,987	25,073	23,304	26,098	27,256	31,856	37,005	31,882	27,875	32,074	34,467	31,024	36,643	37,095	27,623

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