# Effectiveness of Sustainability Indicators in Shrimp Fisheries with Bycatch and in Aquaculture

混獲のあるエビ漁業と養殖業における持続可能性指数の有効性

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

By

**Umme Kaniz Fatema**

ウメ カニズ ファテマ

Presented to

Department of Natural Environment
Graduate School of Environment and Information Sciences
Yokohama National University

**September 2022**

2022年9月

YNU 横浜国立大学
YOKOHAMA National University

# Declaration

I hereby declare that this study is original and was carried out by me, Umme Kaniz Fatema, under the active supervision of Professor Hiroyuki Matsuda. I have duly acknowledged other's works with references.

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**Umme Kaniz Fatema** Date

(PhD Candidate)

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**Professor Hiroyuki Matsuda** Date

(Academic Supervisor)

## Acknowledgements

All commends are due to Almighty Allah, the most gracious and most merciful, has enabled me to complete the dissertation for the degree of Doctor of Philosophy (PhD).

I would like to express my sincere gratitude to my respected supervisor, Professor Hiroyuki Matsuda, Department of Natural Environment, Graduate School of Environment and Information Sciences, Yokohama National University (YNU), Japan, for his scholastic guidance, insightful suggestions, worthy inspirations, and generous support in carrying out of the research work and writing up to the dissertation.

I would like to convey my cordial thanks to my respected co-supervisor, Professor Fumito Koike and Professor Maiko Kagami, Department of Natural Environment, Graduate School of Environment and Information Sciences, YNU, Japan for their valuable suggestions to improve my research work. I am also indebted to Professor Shinji Shimode and Professor Takehiro Sasaki for their kind cooperation as my research evaluation committee members.

I would like to express my heartfelt thanks to Professor Daisuke Kitazawa, Institute of Industrial Science, University of Tokyo (UTokyo), Japan for his kind cooperation, and valuable suggestions on my research work.

I am grateful to the authority of YNU for awarding me Global Doctoral Program for Academic Career Support (GDACS) scholarship for my studies in Japan, also thankful to the Graduate School of Environment and Information Sciences, YNU for the financial support through Yokohama Industry Association and Joint Research Promotion Program (Grant Number: 65A0519b) for carrying out my research smoothly.

I am indebted to the authority of Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU) for granting my study leave. I am thankful to my respected colleagues in Faculty of Fisheries, BSMRAU, Bangladesh, for their kind cooperation.

I am also grateful to the lab members of Matsuken for sharing valuable information, insightful comments, and kind support to carry out my research. My heartfelt thanks to Ms.

Satoko Nakata for her cordial cooperation, and inspirations.

I am thankful to the Marine Fisheries Office, Bangladesh and Fisheries Cooperatives, Japan for sharing informative statistics and cordial cooperation to conduct my study.

I would like to express my heartfelt respects to my beloved family members for their blessings, inspirations, support, forbearance, and endless love to me during this journey.

Author

# List of Abbreviation and Acronyms

| | |
|---|---|
| $A$ | Area of aquaculture farm |
| AO | Areal overlap |
| BC | Breeding cycle |
| BS | Breeding strategy |
| $C$ | Degree of closure |
| $CC$ | Carbon content |
| CR | Critically endangered |
| CTC | Catch trend category |
| $D$ | Distance from farm's to bay mouth |
| DD | Data deficient |
| DoF | Department of Fisheries |
| DQ | Data quality |
| $DW_C$ | Dry weight of carbon |
| EN | Endangered |
| $E$ | Exploitation rate |
| ESI | Environmental Sensitivity Index |
| $F$ | Fishing mortality |
| FAO | United Nations Food and Agriculture Organization |
| $FCR$ | Feed Conversion Ratio |
| FGD | Focus group discussion |
| $H$ | Mean depth of aquaculture farm |
| ha | Hectare |
| IOTC | Indian Ocean Tuna Commission |
| IUCN | The International Union for Conservation of Nature |
| $k$ | Von Bertalanffy growth coefficient |
| $L\infty$ | Asymptotic maximum length |
| LC | Least concerned |
| $L_{mat}$ | Size at first maturity |
| $L_{max}$ | Maximum size |
| $M$ | Natural mortality |
| MAFF | Ministry of Agriculture, Forestry and Fisheries |
| MCAC | Morphological characteristics affecting capture |

| | |
|---|---|
| MF | Measured fecundity |
| MTL | Mean trophic level |
| MSt | Management strategy |
| MDA | Maritime Domain Awareness |
| NE | Not evaluated |
| NT | Near threatened |
| ODQ | Overall data quality score |
| OF | Overfishing |
| $P$ | Productivity attribute/ weighted average score |
| $P_s$ | Total fish production of aquaculture farm |
| $p$ | Annual fish production of aquaculture farm |
| PDQ | Weighted average of data quality scores of productivity attributes |
| PSA | Productivity susceptibility analysis |
| $R_s$ | Stock rate of species $s$ |
| $S$ | Susceptibility attribute/ weighted average score |
| SABR | Schooling, aggregation, and other behavioral responses |
| SCR | Survival after capture and release |
| SDQ | Weighted average of data quality scores of susceptibility attributes |
| SM | Seasonal migrations |
| SMD | Species market demand |
| SMV | Species market value |
| $T$ | Temperature (Celsius) |
| $T_C$ | Total carbon |
| $T_N$ | Total nitrogen |
| $T_s$ | Time for aquaculture of species $s$ |
| TF Faster R-CNN | Tensorflow Faster Region based Convolutional Neural Networks |
| $t_{mat}$ | Age at first maturity |
| $t_{max}$ | Maximum age |
| UF | Underfishing |
| USD | US dollar |
| $V$ | Vulnerability |
| $Vi$ | Volume of fish cage $i$ |
| $V$eMSt | Vulnerability scores excluded management strategy |
| VO | Vertical overlap |
| VU | Vulnerable |

| | |
|---|---|
| $WC_F$ | Water content of feed |
| $WC_f$ | Water content of fish |
| $y$ | Economic yield |

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## General Abstract

Fisheries and aquaculture production are key sources of nutritious food and livelihoods around the world. Marine fisheries, and aquaculture contribute significantly to the development of seafood production and security for food, and nutrition. Conversely, the sector is under risk and the resiliency of those who depend on it is undermined in many locations due to overfishing, illicit fishing, and the combined effects of ocean-based activities on resources and ecosystems. To ensure that future generations continue to benefit from ocean resources and ecosystem services, fisheries and aquaculture management must be improved. Increased yield from marine aquaculture has enormous potential for future food, but since it typically focuses on a few selected organisms, it may result in a decrease in biological diversity. Intensification of marine fisheries and aquaculture is thus likely to be necessary, but it must be done in a sustainable way to avoid negative environmental consequences that jeopardize the prospect of food production.

We conducted the study focuses on the effectiveness of sustainability indicators in both marine fisheries such as shrimp fisheries with its bycatch and in marine aquaculture such as Coho Salmon, Red Sea Bream, Yellowtail, and Bluefin Tuna aquaculture. To determine the sustainability of marine fisheries, we used productivity susceptibility analysis, which is widely applicable semi-quantitative ecological risk assessment tool for data-limited fisheries based on the available species-specific biological, and fishery-specific characteristics (Chapter 3). Concurrently, we used simple indicators to the evaluation of sustainability in data-limited marine aquaculture based on the aquaculture production, nutrient load produced in aquaculture farms, and location of the farms in enclosed bays (Chapter 4).

By using productivity susceptibility analysis (PSA), we were able to evaluate the relative risk of the 60 species belonging to 32 families and four classes, namely Malacostraca, Cephalopoda, Elasmobranchii, and Actinopterygii, those interacted with the shrimp trawl fishery in the Bay of Bengal, Bangladesh, based on the information that was available about species-specific life histories and fishery-specific attributes. The high risk group had seven non-target bycatch species, while the moderate risk contained 17 species including 2 target shrimp species with commercial importance. The PSA results were additionally confirmed by the IUCN Red List extinction risk categories, the exploitation rate of the stocks as determined by the FAO-ICLARM stock assessment tools, and the catch trends of the stock as perceived by the skippers and crew of the shrimp trawlers. According to the overall productivity and

susceptibility scores, 37% and 46% of all the identified species respectively scored higher productivity and higher susceptibility, while 36% and 27% respectively scored moderate and lower productivity, and 44% and 11% respectively scored moderate and lower susceptibility. The IUCN Red List extinction risk categories showed 2 species were in the global threatened list. The shrimp trawl fishery overfished all of the moderately and highly vulnerable species in accordance with the vulnerability scores ($V \geq 1.8$). The majority of the species with $V \geq 1.8$ displayed a decreasing catch trend, whereas species with $V \leq 1.72$ displayed a constant or growing catch trend. The degree of conformity between $V$ and exploitation rates ($E$) among the 20 stocks was 80% when comparing $V$ with the data on $E$, which revealed that $V \geq 1.8$ matched with the $E > 0.5$ (9 species), $V < 1.8$ matched with the $E < 0.5$ (7 species), with some exceptions (4 species). The overall data quality (DQ) scores for the vulnerability of target stocks varied from 2.64–2.93, indicating moderate data quality, while for the bycatch species ranged from 2.49–3.36 indicating 43.4% moderate and 56.6% low data quality. The majority of species were found to be data-limited, according to data quality analysis of productivity and susceptibility attributes, which emphasizes the acquisition of spatio-temporal abundance, catch, and effort data as well as biological information of age, growth, and reproduction of the identified species.

In marine aquaculture, by applying simple indicators assessment of sustainability of Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna aquaculture were observed in the enclosed bays and open water areas of Miyagi, Mie, and Kagoshima prefectures based on the estimation of annual aquaculture production, annual nutrient load and farms' location in the enclosed bays. The degree of the sustainability indictors, $I_1$, $I_2$, and $I_3$ were varied significantly among the marine aquaculture in different enclosed bays and open water areas. In enclosed bays, higher values of the sustainability indictors, $\Sigma I_2$, and $\Sigma I_3$ indicated higher effects on the aquatic environment and in consequence, lower sustainability of marine aquaculture. The log $\Sigma I_1$, log $\Sigma I_2$, and log $\Sigma I_3$ values were further verified with red tides occurrences and the degree of closure ($C$) in the enclosed bays. The correlation analysis indicated that, positive correlation between log $\Sigma I_3$ and red tides in FY 2018 and statistically significant correlation between log $\Sigma I_3$ and $C$. According to the study, the impact of marine aquaculture on the aquatic environment increased with the annual nutrient load and distance of aquaculture farms from the mouth of the enclosed bay. Feed conversion ratio (*FCR*) regarded as the significant factor of marine aquaculture. The species with higher *FCR*, such as Bluefin Tuna had a high environmental impact, the nutrient load per unit production weight was also higher than other fish species. Alternatively, *FCR* of Coho Salmon was low, and the nutrient load per production was also low. In the case of Red Seabream and Yellowtail, the nutrient load per production was not much different. Moreover, the nutrient load per economic yield was found to be rather low for Bluefin Tuna due to the high fish price.

The baseline findings of our research can assist fishery administrators to implement of ecosystem approach for future sustainability and conservation of marine biodiversity in the Bay of Bengal, Bangladesh. In addition, can assist aquaculture administrators to estimate annual fish production and nutrient load associated with marine aquaculture in Miyagi, Mie, and Kagoshima prefectures, Japan and to implement ecosystem approach for ensuring long-term viability of marine aquaculture. Maintaining ecosystem approach in fisheries and aquaculture are the appropriate alternatives for the sustainability of the both sectors.

# Chapter 1

## General Introduction

# 1. General Introduction

## 1.1 Background

Global fish production is estimated to have reached about 179 million tonnes in 2018, of which capture fisheries, and aquaculture production have reached a record of 96.4 million tonnes, and 82.1 million tonnes respectively (FAO, 2020). About 88% of world fish production was utilized for direct human consumption in 2018 and fish consumption accounted for 17% of the global population's intake of animal proteins in 2017 (FAO, 2020). The global demand for fish and fishery products is gradually expanding in tandem with the world's growing population (Clavelle et al., 2019; Costello et al., 2020; Naylor et al., 2021). The proportion of fish stocks that are within biologically sustainable levels decreased from 90% in 1974 to 66% in 2017, with 60% classified as being maximally sustainably fished stocks and 6% underfished stocks (FAO, 2020). Alternatively, the percentage of stocks fished at biologically unsustainable levels increased from 10% in 1974 to 34% in 2017 (FAO, 2020). In consequence, wild fish stocks have decreased and most of the stocks are deemed fully exploited or overexploited, while aquaculture is considered as a promising alternative to fisheries has grown for ensuring food security (FAO, 2020; Naylor et al., 2021; Troell et al., 2014). Global aquaculture production of farmed aquatic animals grew on average at 5.3% per year in the period of 2001–2018, whereas the farming of aquatic animals in 2018 was dominated by finfish (54.3 million tonnes) (FAO, 2020). Since the 1950s, global aquaculture production has risen dramatically, but global catch fisheries productivity has remained flat. (Figure 1.1). In terms of regional contribution to world fisheries and aquaculture production, Asia has dominated fish farming over the past 20 years (Figure 1.2), which has produced 89% of the global total fish production (FAO, 2022).

Capture fisheries are closely linked to ocean seafood exploitation focusing on the target fish stocks, but many other non-target (bycatch) species are seriously affected by multi-species fishery (Finkelstein et al., 2008; Soykan et al., 2008). Habitat loss is frequently caused by destructive fishing practices, which have negative consequences for vulnerable marine ecosystems (Issifu et al., 2022). Although, the potential for enhanced output from marine aquaculture to meet world seafood consumption is significant (Costello et al., 2020), however, various studies have shown that aquaculture production has negative consequences, particularly in terms of environmental and ecological repercussions (Alleway et al., 2019; Rosa et al., 2020; Howarth et al., 2011).

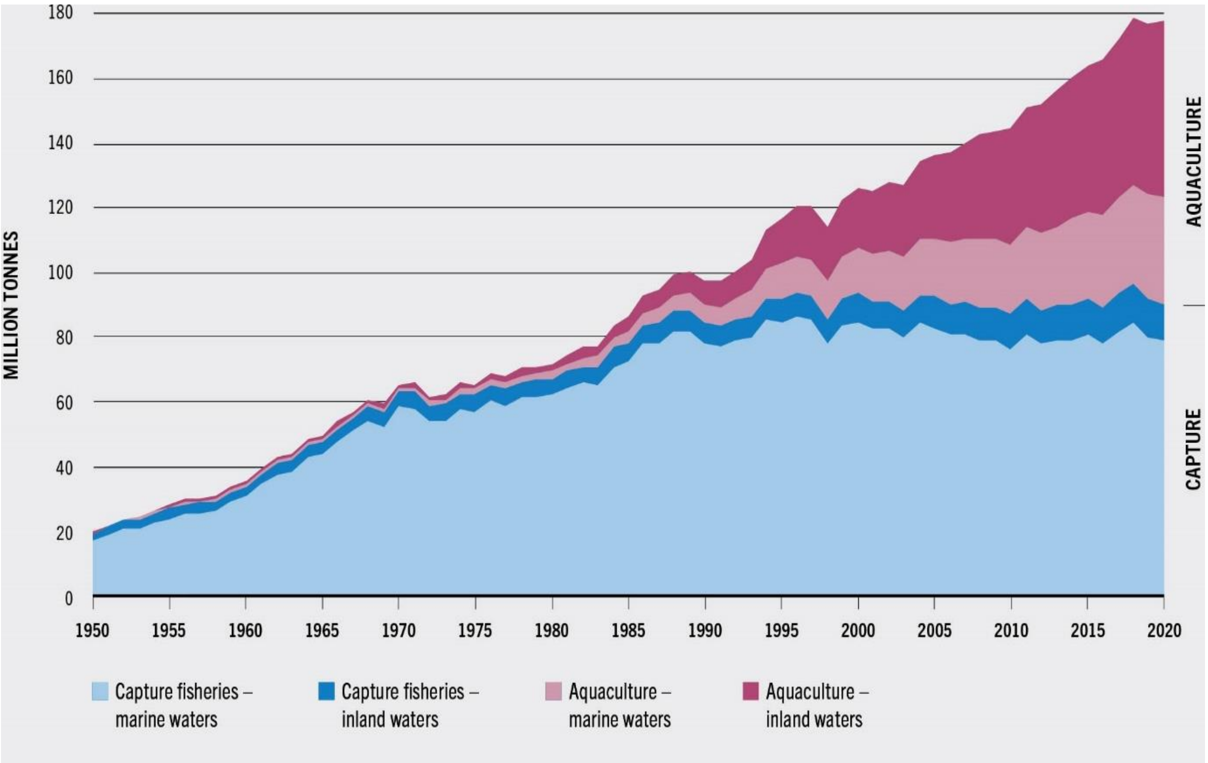

**Figure 1.1** World capture fisheries and aquaculture production, 1950–2020 (FAO, 2022).

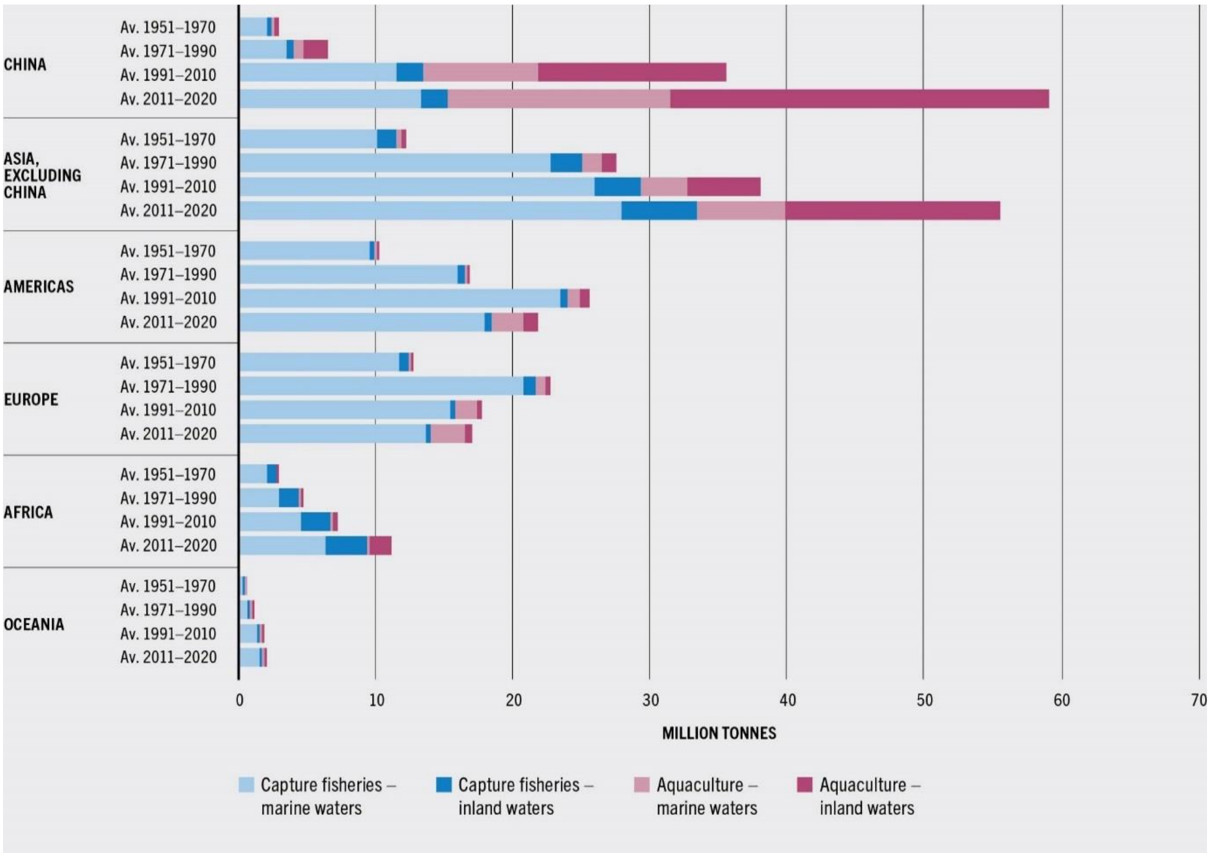

**Figure 1.2** Regional contribution to world fisheries and aquaculture production (FAO, 2022).

Aquaculture production, which often focuses on a few selected species, may result in a reduction in biodiversity (Sampantamit et al., 2020). Therefore, intensification of marine fisheries and aquaculture is required, but it must be accomplished in a sustainable way for optimum natural resources utilization and aquaculture production (Aivaz, 2021; Little et al., 2018). Moreover, marine capture fisheries and aquaculture are linked directly and indirectly through numerous ecological interactions and these connections occur primarily at local and regional levels (Clavelle et al., 2019). In consequence, scientific research on the sustainability assessment is essential to evaluate fisheries and aquaculture impacts from fishing activates, environmental pollution, and ecosystem alteration for ensuring conservation of the species biodiversity.

### 1.2 Marine capture fisheries: Insight from shrimp fishery in Bangladesh

Bangladesh, which has sovereign rights over nearly 118,813 km$^2$ in the Bay of Bengal (BoB), the northeastern part of the Indian Ocean, possesses vast marine water resources (DoF, 2019). BoB is enriched with coastal and marine ecosystems and is regarded as a potential breeding ground for marine species diversity (Islam, 2003; Shamsuzzaman et al., 2017). Industrial shrimp and fish trawlers have been actively engaged in carrying out commercial fishing on a large-scale beyond 40 m water depth in the fishing areas of Swatch of No-Ground, Middle Ground, South Patches and South of South Patches within the Exclusive Economic Zone (EEZ) (MFO, 2019). With changes in fleet design and fishing technique, shrimp trawlers caught both target shrimps and non-target bycatch species as a multi-species tropical fishery (Barua et al., 2018). Giant Tiger Prawn, *Penaeus monodon*, is recognized as the most important target species of shrimp trawl fishery of Bangladesh because of its high market demand and export value (Fanning et al., 2019; Hossain, 2004), and Bangladesh has obtained a Geographical Indication (GI) registration certificate for Giant Tiger Prawn in May, 2022 (DPDT, 2022). The Speckled Shrimp, *Metapenaeus monoceros* contributed about 42.8% of the total shrimp capture (DoF, 2019).

Marine fishing sector provides about 15% of national fisheries production, and large industrial fishery contributes 16% of total marine production of in 2018–19 (DoF, 2019). Since 1983–84, the total marine catch of 165,000 MT has increased to 659,900 MT in FY 2018–19 (DoF, 2019), but, the overall shrimp biomass trend has been consistently downward over the last 30 years (Fanning et al., 2019). Catch rates of large size and commercially valued shrimp species have declined, while increased for the smaller and less valuable species (Fanning et al., 2019). The government of Bangladesh has given much priority for the sustainable management of marine fisheries resources and undertaken various measures, i.e., monitoring, controlling and surveillance (MCS), catch monitoring, declaration and surveillance of 698 $km^2$ marine reserve and marine protected area of 1738 $km^2$ in the Bay of Bengal to protect and conserve the breeding grounds of marine flora and fauna and for efficient use of natural resources (DoF, 2019; MFO, 2019).

## 1.3 Marine aquaculture: Insight from Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna aquaculture in Japan

Japan is an island nation with many coastal areas suitable for marine aquaculture, and has a diverse food culture based on marine fish (Matsuura et al., 2019). Since the 1960s, marine aquaculture in Japan has developed steadily and many novel aquaculture techniques have been invented (Takeda, 2010; Watanabe and Sakami, 2021). The aquaculture industry includes marine finfish species that are predominantly produced in Japan, including Coho Salmon (*Oncorhynchus kisutch*), Red Seabream (*Pagrus major*), Yellowtail (*Seriola quinqueradiata*, *S. dumerili*, and *S. lalandi*), and Bluefin Tuna (*Thunnus orientalis*) (Abo et al., 2013; Matsuura et al., 2019; Watanabe and Sakami, 2021). Coho salmon is the first registered geographical indication (GI) product in Miyagi prefecture in Japan and named as “Miyagi Salmon” (Tashiro et al., 2018). National and international demands for Yellowtail fulfilled by the aquaculture productions, and export is expanding, therefore Yellowtail considered as one of the most economically important fish in Japan (Matsuura et al., 2019; Watanabe and Sakami, 2021).

Marine finfish aquaculture accounts for approximately 90% of total finfish production and Yellowtail is the predominant aquaculture fish, accounting for more than 50% of total production of finfish by aquaculture (Matsuura et al., 2019). The production of Coho Salmon, Red Seabream, and Bluefin Tuna corresponds to around 6%, 25%, and 8% respectively of the total marine finfish aquaculture production in Japan in FY 2019 (MAFF, 2021). Coho Salmon aquaculture production have increased from steadily FY 2012 to FY 2018, and decreased in FY 2019 (MAFF, 2021). Productions of Red Seabream have declined markedly, whereas Yellowtail rather stable in terms of volume and value (Watanabe and Sakami, 2021). Alternatively, productions of Bluefin Tuna, which has been included in the statistics since FY

2012, is increasing remarkably due to the strong affinity of Japanese consumers and the declining wild population (Watanabe and Sakami, 2021).

### 1.4 Justification of this study

In marine fisheries in Bangladesh, shrimp trawl fishery catches many different non-target (bycatch) species of fishes, and crustaceans with target species (Fanning et al., 2019; Uddin et al., 2012). Destructive fishing practices, including bottom trawling (i.e., shrimp fishery) has negative consequences for vulnerable marine ecosystems (Clarke et al., 2018; Morishita, 2008). Therefore, conservation and management measures are essential for species belonging to the same ecosystem, or associated with or dependent on the target stocks, in order to maintain or restore species diversity (Fanning et al., 2019; Morishita, 2008). However, due to lack of biological productivity data and species-specific fishery statistics for a given species, improvement of ecosystem sustainability through considerable management efforts for tropical fisheries may be hampered (Bornatowski et al., 2014). Data-limited techniques can be useful tools for assessing ecological risk and guiding management and conservation of vulnerable marine species when there is a lack of information (Clarke et al., 2018). Productivity susceptibility analysis (PSA) is a widely used example of a semi-quantitative ecological risk assessment method in data-limited multi-species and multi-gear fisheries (Clarke et al., 2018; Duffy et al., 2019). This is also being investigated as an alternate strategy for assessing the vulnerability of extremely diversified, target and non-target assemblages influenced by fisheries in order to ensure ecological sustainability using the ecosystem approach (Duffy et al., 2019). Moreover, for identifying species with similar risk categories, as well as providing qualitative management information for highly vulnerable species, PSA tool is a rapid and cost-effective approach (Hobday et al., 2011; Patrick et al., 2010).

We assessed vulnerability of the target shrimp stocks, with other non-target species interacted to shrimp trawl fishery using PSA. Results of PSA analysis further verified with the different risk categories of the IUCN Red List, exploitation rate of the stocks estimated by FAO-ICLARM stock assessment tools, and catch trends of the stocks based on the perceptions of skippers and crew of the shrimp trawlers. The outcomes of our study revealed the species identification with similar vulnerability level, and the species with higher risk of vulnerability. Besides, our findings can assist fishery administrators to implement ecosystem approach for future sustainability and conservation of marine biodiversity in the Bay of Bengal in Bangladesh.

In marine aquaculture in Japan, the achievement of sustainable marine aquaculture is one of the important issues when considering Japanese fisheries policy (Takeda, 2010). In FY 2019, marine aquaculture accounted for 22% of the total fisheries and aquaculture production in Japan in terms of volume and 34% of the total production in terms of values (MAFF, 2021). Marine aquaculture is an essential industry in Japan, however, marine fed aquaculture (finfish farming) generates, and discharges a large amounts of organic wastes and nutrients in and around aquaculture facilities, and it may have large impacts on the benthic environment (Abo et al., 2013; Takeda, 2010). Organic wastes, i.e., feces and uneaten feed that produced from fish farming facilities deposit on the bottom substrate. In consequence, due to excrement and associated residues, intensive and long-term culture activity causes eutrophication and hypoxia, which may affect benthic ecosystems in aquaculture areas (Abo et al., 2013; Imai et al., 2006). Fish farming in Japan is often conducted intensively in enclosed bays and large amounts of sludge accumulate on the seafloor (Abo et al., 2013; International EMECS Center, n.d.). As a result of organic matter loading from fish cages and lower seawater exchange capacity, harmful algal blooms frequently occur around the fish farming area in enclosed bays (International EMECS Center, n.d.). Since the 1970s, the occurrence of harmful algal blooms around fish farm areas has increased, frequently resulting in mass mortality of aquaculture fish (Imai et al., 2006; Makino, 2017). Therefore, sustainability assessment of marine aquaculture is necessary focusing on the factors, i.e., annual production, nutrient load, and location of aquaculture farms, which may have an impact on the environmental capacity of the aquaculture area (Gao et al., 2022).

We also assessed sustainability of marine aquaculture of majorly produced finfish species, i.e., Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna in Japan using simple indicators related to aquaculture and surrounding environments. Results of indicators analysis further verified with red tides occurrences and the degree of closure. Our findings revealed that the degree of sustainability indicators varied considerably in one species to another species marine aquaculture in Miyagi, Mie, and Kagoshima prefectures. We identified the enclosed bays in different prefectures which have a higher risk of environmental consequences. The outcomes of the study can help to estimate annual yields and nutrient load from marine aquaculture that can further assist aquaculture managers to practice an ecosystem approach to ensure the long-term viability of marine aquaculture in Miyagi, Mie, and Kagoshima prefectures in Japan.

## 1.5 Study objectives

This study was designed to evaluate shrimp trawl net fishing impacts on marine capture fisheries in the Bay of Bengal, Bangladesh, and marine aquaculture impacts on surrounding environmental consequences in Miyagi, Mie, and Kagoshima prefectures, Japan. Therefore, the study assessed the relative risk of the species to shrimp trawl fishery using semi-quantitative PSA approach (Chapter 3). The environmental impact of marine aquaculture was also assessed (Chapter 4). The findings of this study revealed the baseline information that could assist to maintain sustainability in both marine fisheries and aquaculture in the applicable area.

The specific objectives of the present study were as follows:

a) To identify the non-target bycatch species interacted with shrimp trawl fishery in the Bay of Bengal, Bangladesh.

b) To assess the relative vulnerability level of the identified species from shrimp trawl fishery by PSA tool.

c) To estimate the annual fish production, and nutrient load from marine aquaculture of Coho Salmon in Miyagi prefecture, Red Seabream, and Bluefin Tuna in Mie prefecture, and Yellowtail, and Bluefin Tuna in Kagoshima prefecture, Japan.

d) To assess sustainability of marine aquaculture applying simple indicators focusing on aquaculture production, nutrient load, and location of aquaculture farms.

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# Chapter 2

# Literature Review

## 2. Literature review

### 2.1 Background

The future sustainability of sea fisheries and aquaculture faces significant challenges. These include generally declining fish stocks, biodiversity threats, environmental impacts, and climate change (Ahmed et al., 2019; Blanchard et al., 2017). Overfishing has been going on for several decades, have resulted in seriously low stock sizes for many of the world's wild commercial fish species, that has partly driven the rise in demand for marine aquaculture (Paramor and Frid, 2015). Aquaculture accounts for more than 40% of all fish consumed currently, and this figure is expected to rise in the future (Beveridge et al., 2013). Both capture fisheries and aquaculture have significant environmental impacts on marine systems, particularly in coastal areas, and this has led to demands for better protection of these systems (Paramor and Frid, 2015).

One of the main threats to biodiversity on the seas is unsustainable fishing. Bottom trawling, has led to considerable declines in species diversity (Clarke et al., 2018; Morishita, 2008), in particular for seamounts and deep-coral ecosystems, as these are composed of extremely slow-growing and long-lived organisms which makes them predominantly vulnerable to fishing impacts (Althaus et al., 2009; Parker et al., 2009). The consequences of catching bottom-dwelling fish, which reduces benthic species' biomass and production while also harming corals, oysters, and sponges that make up productive marine environments, can be far-reaching. (Clarke et al., 2018; Althaus et al., 2009). Many commercial fishing operations, in addition to catch a growing number of fish from the ocean, also degrade aquatic habitat, which has been ravaged in many locations due to trawling (Thrush and Dayton, 2002). Burrowing worms and filter feeders, which are important because their burrows promote interaction between sediments and water, can also be declined from the sediment by this approach (Coleman and Williams, 2002). These occurrences restore nutrients to the water, where they are utilized by microorganisms in nutrient cycling, and without these burrowing animals, the waters along the seafloor might become oxygen-depleted and inhospitable (Coleman and Williams, 2002; Middelburg and Levin, 2009). It also substantially contributed to the overexploitation of a number of targeted commercially important stocks and there are declines in a number of bycatch species also (Gilman, 2011; Lobo et al., 2010). Overfishing results ecosystem collapse in many aquatic systems by diminishing large predators, which causes population explosions of their prey (Coleman and Williams, 2002). This is known as a trophic cascade and is a consequence of overfishing (Daskalov, 2002).

Despite the fact that aquaculture is one of the fastest expanding food production sectors, it has negative environmental repercussions, including as chemical and biological pollution, disease outbreaks, unsustainable feeds, and competition for coastal area (Carballeira Braña et al., 2021; Hossain et al., 2013). The environmental impact of marine fish farming is determined by the type of fish farmed, the technique of culture, the stocking density, the feed type, the hydrography of the site, and farming practices (Cao et al., 2007; Tovar et al., 2000). As the aquaculture industry grows and expands, one significant indirect effect of the production process is the high impact on aquatic ecosystems caused by the need to feed carnivorous species of farmed fish with wild fish (Little et al., 2016). However, a significant portion of the organic carbon and nutrient input into a marine fish culture system as feed may be lost to the environment through feed wastage, fish excretion, faecal production, and respiration in all cultured systems (Tovar et al., 2000; Wu, 1995). High-density farming and excessive feeding, both of which are aimed at increasing productivity, are the primary causes of excessive organic loading in the sediments (Takeda, 2010). The high pollutant loading has caused significant environmental concern, particularly in waters with limited carrying capacity (Camargo and Alonso, 2006; Cao et al., 2007; Wu, 1995). Untreated effluent from fish farms contains high quantities of nutrients as well as water contaminant agents, and in the case of open net cages, the capacity to keep these contaminants from entering the surrounding water is severely limited (Carballeira Braña et al., 2021). Environmental impacts of a single farm may not be significant when considered individually but may be relevant if other farms, fishing grounds, or activities are located in the same area (Carballeira Braña et al., 2021). Aquaculture farms in unsuitable location, administrative challenges, and excessive production may impact on the benthos and overlying water column surrounding aqua-environment (Chopin et al., 2012). Therefore, environmental concern about marine finfish aquaculture and its interactions with the environment grows due to insufficient environmental monitoring in farm site, as well as excessive waste decomposition, which affects aquaculture output growth and continuity (Carballeira Braña et al., 2021; Chopin et al., 2012).

Much of the effects of fishing and aquaculture is due to the demise of commercially valuable fisheries, as well as the threat of environmental consequences (FAO, 2020; Pauly et al., 2002). Many fisheries throughout the world have no regulations or standards in place to protect the oceans and marine life and the fishing practices and activities are either barely or not at all monitored (Browman et al., 2004). Fishing techniques may be able to progress in the future in a more environmentally friendly manner due to the practices with which the detrimental environmental impacts of fishing may be identified (Garcia et al., 2003). Environmental monitoring strategies that are optimized can help to understand the effects of fishing and aquaculture in marine environment (FAO, 2020). In addition, higher fishing revenues and reduced pollution in the environment may benefit both the fisheries and aquaculture industries, and are crucial for long-term viability (Carballeira Braña et al., 2021; FAO, 2020). Sustainable fisheries and aquaculture practices are challenging to emphasize the proper ecological balance in water bodies. Therefore, scientific research are essential to identify the fishing and aquaculture impact to the related biodiversity stocks and the factors that influences environmental consequences.

### 2.2 Assessment indicators

Appropriate indicators are often developed for the use of analysts and decision makers who assess the sustainability performance of an entity (Zhou and Ang, 2008). The indicator approach to sustainability evaluation has been extensively researched for decision-making and policy-making and the role of sustainability indicators as an evaluation method for sustainability within the emerging context of governance focusing on policy processes (Hezri and Dovers, 2006). To choose the relevant indicators for decision support, it is necessary to understand the context of the indicators and the decision problem that is to be addressed (Dong and Hauschild, 2017). The concept of sustainability has a variety of origins, including ecological carrying capacity, resource reserve, and technological critique (Dong and Hauschild, 2017). Each of these research areas has its own roots and thus unique targets, e.g., staying below ecological carrying capacity, not deplete resource reserves and minimize impacts from technology development and to observe how well those targets are met, relevant indicators and corresponding assessment methods have been developed (Dong and Hauschild, 2017). The present study aims to examine the sustainability indicators and evaluate the effectiveness of the indicators to assess sustainability of target shrimp species with non-target bycatch in industrial shrimp trawl fishery using productivity susceptibility analysis (PSA) and sustainability of marine finfish aquaculture specifically Coho Salmon, Red Seabream, Yellowtail and Bluefin Tuna aquaculture using simple indicators in relation to the impacts of aquatic environmental consequences.

### 2.2.1 Application of PSA in marine capture fisheries

Target stocks (fish species that are directly pursued by commercial fisheries) and non-target stocks (fish species that are not directly pursued by commercial fisheries but are caught incidentally in target fisheries) are the two types of stocks in the fishery, and stocks can be managed as single species or as stock complexes (Patrick et al., 2009). Stocks in the marine fisheries are overfished, or are on the verge of becoming overfished, or are likely to become so in the future (FAO, 2020). It is necessary to take management measures for the conservation of stocks and to implement proper management measures it is mandatory to analyze which stocks are subjected to be overexploited. As a result of their life cycle, ecology, and socioeconomic factors, marine fish populations can be vulnerable to overfishing (Pontón-Cevallos et al., 2020). In this case, vulnerability assessments can help with fisheries decision-making by assisting with species prioritization and evaluation. For example, PSA is ideally suited for multispecies fisheries with low gear selectivity and limited fishery-independent and dependent data (Pontón-Cevallos et al., 2020). The PSA can be used as a flexible tool that can incorporate regional-specific information on fishery and management activity (Patrick et al., 2010).

Determining vulnerability for target stocks with generally available data on stock status and fishing impacts can be relatively simple; however, determining vulnerability for non-target species with limited data might be more complex (Ormseth and Spencer, 2011). In such circumstances, several risk assessment approaches were examined to determine which one would be the most flexible and adaptable across fisheries and regions (Patrick et al., 2009) and developed a method for determining the vulnerability of marine fish stocks (Patrick et al., 2010). To estimate the relative sustainability of particular species impacted by fishing, a semi-quantitative attribute-based ecological risk assessment method has been developed (Griffiths et al., 2017). The method uses a semi-quantitative approach termed as PSA, which was developed to address bycatch difficulties in the Australian prawn fisheries (Milton, 2001; Stobutzki et al., 2001), because many fisheries lack the data needed to conduct completely quantitative analysis (Dulvy et al., 2003).

The modified version of the PSA was deemed the most effective method for assessing stocks' vulnerability (Patrick et al., 2009, 2010), because of its previous use in other fisheries (Milton 2001; Stobutzki et al., 2001; Griffiths et al., 2006) and as a reasonable approach for determining risk, recommended by various organizations and work groups (Hobday et al., 2007; Rosenberg et al., 2007). The PSA, on the other hand, varies from previous approaches in that it considers not only the biological productivity of the stock, but also the degree to which fisheries can impose mortality on the stock when assessing vulnerability to overfishing (Ormseth and Spencer, 2011). Although multiple versions of PSAs exist, they always evaluate aspects of productivity ($P$), such as natural mortality and age at maturity, with attributes of susceptibility to fishing impacts ($S$), such as spatial overlap with fisheries and fishing gear selectivity (Ormseth and Spencer, 2011). The potential for a stock's productivity to be diminished by direct and indirect fishing pressure is characterized as its vulnerability to becoming overfished and vulnerability is expected to vary among stocks depending on their life history traits and susceptibility to the fishery (Patrick et al., 2009, 2010). Most PSAs also contain some assessment of uncertainty or data quality, and the mean $P$ and $S$ scores are used to determine a vulnerability ($V$) score that indicates the likelihood that a stock would be overfished in the absence of conservation measures (Ormseth and Spencer, 2011).

PSA has been widely used in data-poor fisheries because of its flexibility to rapidly produce a relative measure of vulnerability for a large number of species that can be easily interpreted by fishery managers, policymakers, and laypeople using a variety of data formats (Griffiths et al., 2017). The PSA has been utilized for a wide range of species and taxa, including marine mammals, sea birds, sea turtles, sharks, skates and rays, and teleosts, as well as over 1000 targeted and by-catch fish populations and other stocks (Hordyk and Carruthers, 2018). A number of productivity and susceptibility attributes for a stock are utilized in a PSA to aid regional fishery management, and index scores and measures of uncertainty are computed and graphically displayed from these attributes (Patrick et al., 2010). The overall vulnerability score of a stock is calculated as the following formula of Patrick et al., 2010.

$$V = \sqrt{(P-3)^2 + (S-1)^2}$$

Stocks with varying degrees of productivity and susceptibility, as well as varying data quality, were used to illustrate the utility of the resulting vulnerability assessment (Patrick et al., 2010). Although fixed thresholds separating low, moderate, and highly vulnerable species were not observed, the PSA was capable of differentiating stock vulnerability along a gradient of productivity and susceptibility indices (Patrick et al., 2010). The x-axis of the biplot graph showed the stocks' weighted average $P$ scores on a range of high (3) to low (1), while the y-axis represented the stocks' weighted average $S$ scores on a scale of low (1) to high (3).

The stock's productivity or biological sensitivity (related to its biological characteristics) and its fisheries susceptibility (related to the likely impact of the specific fishery/gear on the stock) were assumed to influence vulnerability, and each of these components was comprised of a number of different traits or factors (McCully et al., 2013). Stocks with a low productivity score but a high susceptibility score are the most sensitive to overfishing, while stocks with a high productivity score but low susceptibility score are the least vulnerable (Patrick et al., 2010).

The number of both productivity and susceptibility attributes considered for PSA can be varied by researchers (Hobday et al., 2011). The productivity (*P*) attributes, i.e., maximum age, maximum size, measured fecundity, breeding strategy, age at maturity, and mean trophic level (see Duffy et al., 2019; Hobday et al., 2007; Zhou et al., 2016), von Bertalanffy growth coefficient, and natural mortality (see Duffy et al., 2019; McCully Phillips et al., 2015; Mejía-Falla et al., 2019; Osio et al., 2015) of a species are frequently used in PSA (Ormseth and Spencer, 2011; Patrick et al., 2010). In addition, intrinsic growth (see Clarke et al., 2018; Duffy et al., 2019; McCully Phillips et al., 2015; Osio et al., 2015; Patrick et al., 2010), breeding cycle, and maturity size ratio (see McCully Phillips et al., 2015; Mejía-Falla et al., 2019), size at maturity (see Clarke et al., 2018; Hobday et al., 2011; Zhou et al., 2016), and maturity age ratio (see Mejía-Falla et al., 2019) are also considered in the PSA study.

The susceptibility (*S*) attributes, i.e., areal overlap, and vertical overlap (see Clarke et al., 2018; Duffy et al., 2019; Hobday et al., 2007; McCully Phillips et al., 2015; Mejía-Falla et al., 2019; Osio et al., 2015; Patrick et al., 2010; Zhou et al., 2016), seasonal migrations, schooling, aggregation, and other behavioral responses, and management strategy (see Clarke et al., 2018; Duffy et al., 2019; McCully Phillips et al., 2015; Patrick et al., 2010), morphological characteristics affecting capture, and survival after capture and release (see Clarke et al., 2018; Hobday et al., 2007; McCully Phillips et al., 2015; Osio et al., 2015; Patrick et al., 2010; Zhou et al., 2016), fishing rate relative to natural mortality (see Osio et al., 2015; Patrick et al., 2010), desirability or value of the fishery (see Clarke et al., 2018; Duffy et al., 2019; McCully Phillips et al., 2015; Mejía-Falla et al., 2019; Osio et al., 2015; Patrick et al., 2010), and geographic concentration (see Clarke et al., 2018; Hobday et al., 2007; McCully Phillips et al., 2015; Patrick et al., 2010) are commonly used in PSA.

According to Patrick et al., 2009, 2010, not all productivity and susceptibility attributes are equally significant in determining a stock's vulnerability, and a weighting scheme in which all attributes were given a default weight of 2 and weights for specific attributes could be adjusted with each application to reflect their perceived significance within a fishery (Hordyk and Carruthers, 2018). A significant outcome of the PSA analysis is data quality scoring. This might be used to find species with insufficient data and suggest ways to improve data collection for those species (Osio et al., 2015). The data quality of specific *V* scores was defined by a data quality table based on five tiers on the scale of 1–5, with best data (1), adequate (2), limited (3), very limited (4), and no data (5) (Patrick et al., 2010). As a result, instead of reflecting the specific data type utilized in the PSA analysis, the weighted average data quality scores for productivity and susceptibility reflected the overall quality of the data.

### 2.2.2 Application of simple indicators in marine aquaculture

Aquaculture intensification has emerged as a feasible option for expanding aquaculture productivity, however it demands greater inputs such as fish and feed per unit culture area, as well as increased waste generation from aquaculture production systems (Dauda et al., 2019). The impact of aquaculture waste products has raised concerns about aquaculture's long-term viability (Akinwole et al., 2016; Dauda et al., 2019). Through feed wastage, fish excretion, feces generation, and respiration, a significant amount of organic carbon and food input into a marine fish culture system as feed may be lost to the environment (Wu, 1995). Intensive finfish farming produces a lot of organic waste and nutrients, which causes environmental degradation in and around aquaculture operations (Yokoyama, 2010). Due to organic matter loading from fish cages, harmful algal blooms frequently develop around the fish farming area (Abo et al., 2013). In terms of frequency, magnitude, duration, geographic ranges, and species composition, harmful algal blooms are becoming more common around the world, and their consequences on productivity vary greatly depending on species-specific effects (Matsuyama and Shumway, 2009; Naylor et al., 2021; Shumway et al., 2018).

Recycling or remediation of fish production wastes is the key to inexpensive and sustainable aquaculture methods and the long-term viability, and the reduction of ecological impacts are dependent on the environmental legislation and regulations (Carballeira Braña et al., 2021). The best tools for preventing or minimizing the negative environmental effects of farming are environmentally sound sites away from ecologically important habitats, as well as adequate management (Porporato et al., 2020). To accomplish sustainable aquaculture, measures for environmental conservation and the use of low-emission feeds are strongly suggested with the aim of maintaining an acceptable environment and avoid red tide from forming around the culture cages (Okuzawa et al., 2015). Several research have sought to analyze material flows in fish farms, estimate potential environmental implications, formulate criteria for optimizing farm site and production levels, and develop ways for improving aquaculture habitats (Yokoyama, 2010). In consequences, sustainability assessment of marine aquaculture is necessary to predict optimal aquaculture production to minimize environmental consequences for addressing global food demand and sustainability challenges (Bohnes et al., 2022).

Many coupled numerical models of hydrodynamics and ecosystems in coastal waters have been developed to make estimates, and in general, using a sophisticated simulation for data preparation is time consuming and tedious, and it is still difficult to make a regional evaluation for collections of fisheries farms based on limited data (Gao et al., 2019). To assess sustainability in the marine aquaculture using simple indicators can be significant in determining impacts on the aquaculture area's environmental capacity (Gao et al., 2022).

## 2.3 Conclusions

Assessing sustainability of the marine fisheries stocks and aquaculture is the most challenging issues nowadays considering overexploitation of the stocks and environmental impacts on long term aquaculture. This chapter focuses on the application sustainability indicators in marine fisheries and aquaculture. Chapter 3 focuses on the results of applying sustainability indicator in marine capture fisheries, and chapter 4 focuses on the results of applying sustainability indicators in marine aquaculture with the aim to the comprehensive overall and species objectives of the present study.

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# Chapter 3

# Vulnerability Assessment of Target Shrimps and Bycatch Species from Industrial Shrimp Trawl Fishery in the Bay of Bengal, Bangladesh

*Publication based on this chapter*

**Umme Kaniz Fatema**, Hasan Faruque, Md. Abdus Salam, **Hiroyuki Matsuda**. 2022. Vulnerability assessment of target shrimps and bycatch species from industrial shrimp trawl fishery in the Bay of Bengal, Bangladesh. *Sustainability*, 14, 1691.

## Abstract

Productivity susceptibility analysis (PSA) is a semi-quantitative ecological risk assessment tool, widely used to determine the relative vulnerability of target and non-target species to fishing impacts. Based on the available information of species-specific life-history and fishery-specific attributes, we used PSA to assess relative risk of the 60 species interacted with the shrimp trawl fishery in the Bay of Bengal, Bangladesh. *Penaeus monodon*, the most important target and *Metapenaeus monoceros*, the highest catch contributor, along with other 15 species were found in the moderate risk, while seven non-target bycatch species were found in the high risk category. PSA derived vulnerability results were validated with two previously assessed analytical approaches, i.e., IUCN extinction risk and exploitation rate, and also with the stocks' catch trend. Majority of the identified species showed higher productivity (37%) and higher susceptibility (46%), and all the moderately and highly vulnerable species were subjected to overfishing condition by shrimp trawl fishery coincide with the vulnerability scores ($V \geq 1.8$). Species with $V \geq 1.8$ mostly showed the decreasing catch trend, while the species of stable or increasing catch trend had the $V \leq 1.72$. Data quality analysis of productivity and susceptibility attributes indicated that the majority of species were considered data-limited that emphasizes the acquisition of spatio-temporal abundance, catch and effort data as well as biological information specifically relating to species age, growth, and reproduction. However, our findings can assist fishery administrators to implement of ecosystem approach for future sustainability and conservation of marine biodiversity in the Bay of Bengal.

**Keywords:** shrimp fishery; non-target species; multi-species fisheries; productivity susceptibility analysis; risk assessment; over-fishing; Bay of Bengal

### 3.1 Introduction

The Bay of Bengal, the northeastern part of the Indian ocean, is enriched with coastal and marine ecosystems, and considered as a potential ground for marine species diversity together with shrimps to flourish naturally (Islam, 2003; Shamsuzzaman et al., 2017). Industrial trawlers (i.e., shrimp and fish trawlers), the most significant component of commercial fisheries in the Bay of Bengal, have been engaged in carrying out fishing on a large scale in the EEZ (Exclusive Economic Zone) of Bangladesh (Kumar et al., 2019). Being multi-species tropical fishery, shrimp trawlers caught both target shrimps and non-target bycatch species significantly with changing the fleet configuration and fishing technique (Barua et al., 2018). Catch per unit fishing effort has been declining and some species of marine shrimps and fish stocks are depleting (Fanning et al., 2019; Hussain and Hoq, 2010; Uddin et al., 2012). In consequence, natural harmony of the aquatic ecosystems is being disrupted by the over-exploitation of marine resources (Haque et al., 2021; Murshed-e-Jahan et al., 2014).

Shrimp and demersal trawl surveys in the Bay of Bengal by the research vessel "RV Meen Shandhani" indicated, larger, slower growing, and slower reproducing species are being replaced by small-sized, fast-growing, and fast reproducing species (Fanning et al., 2019). In marine ecosystems, small, lower trophic level forage species are key prey to large, higher trophic level predatory species (Hilborn et al., 2017). Increasing small species reflects a significant alteration to the ecosystem structure, and the ability to rebuild the stocks of larger, and high-valued stocks can be impaired consequentially (Fanning et al., 2019). For the conservation of marine ecosystems, species' habitats protection, appropriate practice of fisheries resources utilization, and improvement of gear specification to minimize bycatch in a specific fishery, the ecosystem approach can be practiced in fisheries resource management (Gaichas et al., 2018; Townsend et al., 2019). In order to put the ecosystem approach into practice, Bangladesh government has completely prohibited the introduction of new shrimp trawler to recover and protect seabed habitat and biodiversity, as shrimp trawlers haul on the seabed, causing destruction of marine flora and fauna (Uddin et al., 2012). Considering the breeding of sea species populations and their conservation, Bangladesh government has also introduced a monsoonal fishery closure (65-day fishing ban) between May and July in the Bay of Bengal, which promotes the ecological restoration of depleted fisheries resources (Islam et al., 2021).

The multi-gear and multi-species fisheries exploit the traditional fishing grounds in the Bay of Bengal. Therefore, scientific research on species-specific fishery and stock status is required for effective management strategy (Uddin et al., 2012). A high diversity of non-target bycatch species tend to be highly susceptible to shrimp trawl fishery due to areal and vertical overlap in the shrimp fishing ground. Relative vulnerability analysis of these species along with target shrimp stocks have a significant impact on the species conservation. However, improvement of the ecosystem sustainability through significant management efforts for the tropical fisheries could be hindered due to lack of biological productivity data, and the species-specific fishery statistics for a particular species (Bornatowski et al., 2014). In the case of information inadequacy, data-limited approaches can be valuable tools for ecological risk assessment and to guide the management and conservation of vulnerable marine species (Clarke et al., 2018).

Productivity susceptibility analysis (PSA) is a widely applicable example of semi-quantitative ecological risk assessment tool in data-limited multi-species and multi-gear fisheries (Clarke et al., 2018; Duffy et al., 2019; Ormseth and Spencer, 2011). The PSA approach was originally developed in Australia to analyze bycatch sustainability in prawn trawl fisheries (Stobutzki et al., 2001). The method addresses species' vulnerability by considering both the productivity attributes, e.g., life-history traits, and susceptibility attributes, e.g., fishery-specific activities (Ormseth and Spencer, 2011; Patrick et al., 2010). Attributes selection and multiplicative models for calculating vulnerability can be varied in PSAs (Osio et al., 2015; Patrick et al., 2010), depending on the evaluation of fishery management measures (Hobday et al., 2011; Rosenberg et al., 2007). This is also considered as an alternative method to assess the vulnerability of highly diverse, target and non-target assemblages impacted by fisheries in order to maintain ecological sustainability through the practice of ecosystem approach (Duffy et al., 2019), furthermore for identifying species with similar risk categories, and providing qualitative management information for highly vulnerable species (Hobday et al., 2011; Patrick et al., 2010).

We used the PSA approach to evaluate the relative vulnerability of the species identified from shrimp trawl fishery for understanding the effect of fishing on shrimp, and associated other stocks in the Bay of Bengal. The PSA outcomes further verified with the different risk categories of the IUCN Red List, exploitation rate of the stocks estimated by FAO-ICLARM stock assessment tools, and catch trends of the stock perceived by skippers and crew of the shrimp trawlers. We observed the impact of existing management strategy on the stock interacted with shrimp trawl net and also emphasized the improvement of research design for further analysis to recommend additional fishery management strategy.

## 3.2 Materials and methods

### 3.2.1 Study areas

In Bangladesh's Exclusive Economic Zone (EEZ, 200 nautical miles) in the Bay of Bengal, there are four important fishing areas (i.e., Swatch of No-Ground, Middle Ground, South Patches and South of South Patches) (MFO, 2019) (Figure 3.1). Within these grounds, 32 industrial shrimp trawlers operated by 15 different companies or organizations (Table A.1) and approved by the Board of Investment (BOI), the Ministry of Fisheries and Livestock (MOFL), Bangladesh are now actively engaged in catching target stocks shrimps, and many other species as bycatch including some non-target shrimp, finfishes, squids, crabs, etc. (MFO, 2019). These trawlers generally navigated for 30 days' time period intended for each voyage by completing five to six hauls every day for a period of three to four hours depending on weather and sea environments, as well as the fishing vessels' efficacy (Uddin et al., 2012).

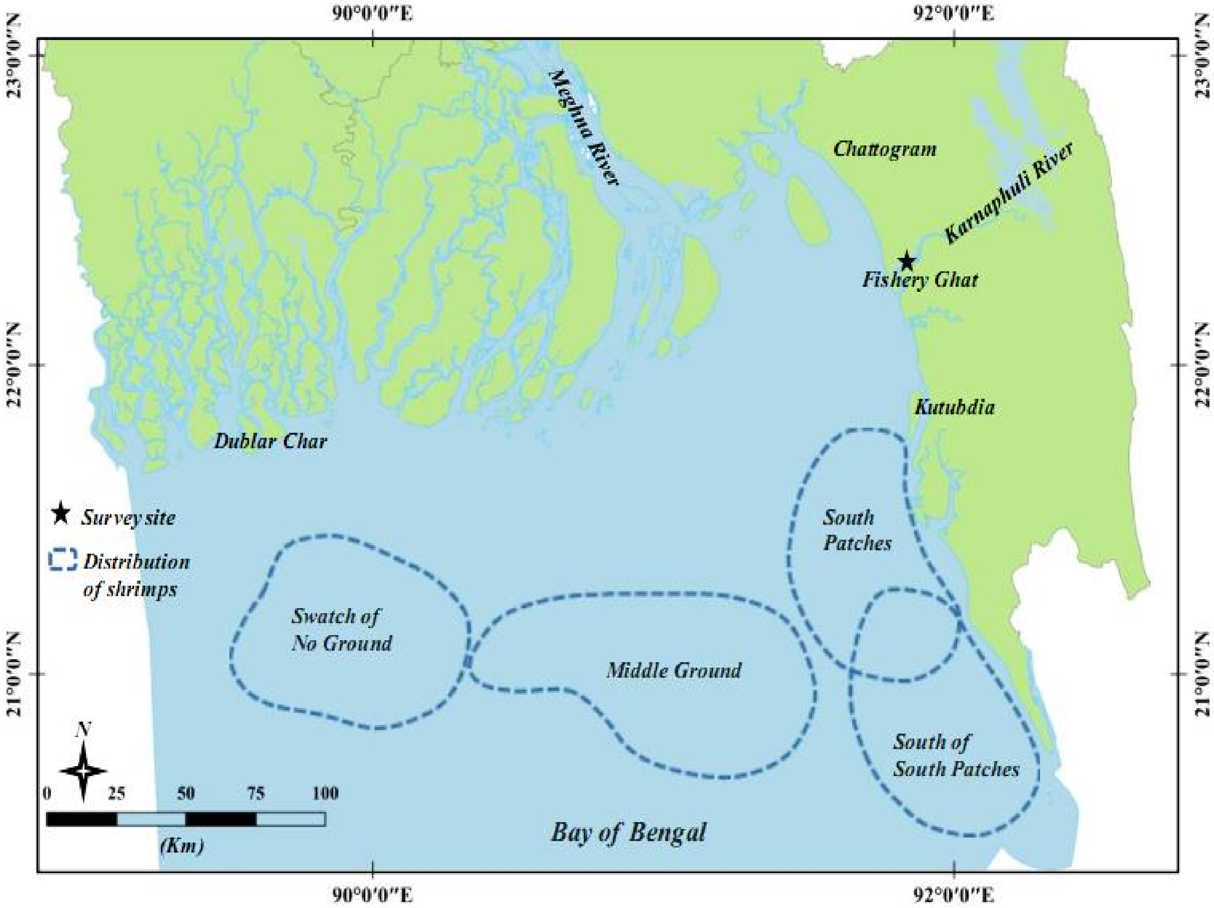

**Figure 3.1** Map showing the distribution of shrimp in exclusive economic zone (EEZ) in the Bay of Bengal, and the survey site for identifying the industrial shrimp trawlers' catch compositions.

Trawler companies are provided a catch log sheet to report their catch before getting sailing permission for the next fishing voyage. After each haul, the skippers of these fishing vessels fill out the provided catch log sheet. The skippers submit these log sheets to the Marine Fisheries Office in Chattogram when they return from their sea voyages, and the authorized person, i.e., inspector, cross-check the number and quantity of species landed in the shrimp trawlers' specific jetties with the species-specific quantity reported on the catch log sheet by the skippers. These jetties are located near the "Fishery Ghat", which is one of Bangladesh's largest fish landing and berthing facilities in the Chattogram fishing harbor beside the Karnaphuli river (Figure 3.1). Therefore, we considered the "Fishery Ghat" as our study site for conducting necessary interview survey.

*Penaeus* and *Metapenaeus* are the target genera of the industrial shrimp trawling of Bangladesh. Giant Tiger Prawn, *Penaeus monodon*, is recognized as the most important target species of shrimp trawl fishery of Bangladesh because of its high market demand and export value (Fanning et al., 2019; Hossain, 2004). However, the Speckled Shrimp, *Metapenaeus monoceros* contributed about 42.8% of the total shrimp capture (DoF, 2019). Adults *P. monodon* are habitually found in deeper water in the sea, while juveniles inhabit in seagrass beds, mangrove swamps, and estuaries. They are trawled over sandy bottoms to a depth of 40–100 m (Hossain, 2004; IOTC, 2018; MFO, 2019). Adult spawning takes place in offshore seas, where the larval stages are successively found. This omnivorous and demersal species contributes to the maintenance of the aquatic ecosystem by scavenging and predating aquatic species (Ahmed et al., 2008; IUCN, 2015b).

The length of the shrimp trawlers varies from 20 to 30 m and have a capacity of gross tonnage of 115–300 MT and engine power of 249.8–820.3 kW (MFO, 2019). Generally, the shrimp trawlers operated two to four nets at a time using outriggers and fishing beyond 40 m in depth. These trawlers used shrimp trawl nets attached with Turtle Excluder Device (TED) and the cod end having a mesh size of 45 mm (MFO, 2019). The head rope length of the shrimp trawl net ranges from 15–35 m and tickler chains are used in the bottom line to increase shrimps catch compositions (MFO, 2019).

### 3.2.2 Species identification

For the identification of bycatch species from shrimp trawl fishery, primarily, we prepared a list of common and commercially important marine species found in the Bay of

Bengal from the relevant literatures due to limited data on shrimp trawl fishery specific species. Of the 32 industrial shrimp trawlers, we compiled landings data of 20 trawlers' catch log sheets, and catch reports, collected from the Marine Fisheries Office and shrimp trawlers companies during surveys conducted from November 2020 to April 2021. We drafted another list of species in combination of literature and catch data. Based on these data, we prepared a species photos scrapbook including the regional, common and scientific names of the species as well as their general identification characteristics. We also observed the landed catch of ten shrimp trawlers, which have higher catch quantity and species variation in the catch log sheets and catch reports using the taxonomic key suggested by Ahmed et al. (2008), Quddus and Shafi (1983), Rahman et al. (2009), and Siddiqui et al. (2007).

A total of hundred skippers and crew (one skipper and four crew from each of the 20 trawlers, who have at least ten years of voyages experiences) (Table A.1) of the trawlers were requested to identify the species caught in their shrimp trawl nets throughout the entire fishing seasons in the Bay of Bengal from the species photos scrapbook. The skippers and crew reported a very few species that are commonly captured at alternative fishing times of the year but were not found in the landed catch during the survey period. Therefore, we cross-checked those species at the time of discussion with the key informant, i.e., fisheries officers, fishery experts, and enlisted as bycatch species of shrimp trawl fishery. After that, we completed a final list of 53 bycatch species and seven target stocks of shrimp trawl fishery in the Bay of Bengal and validated the scientific names of the bycatch species based on SeaLifeBase (Palomares and Pauly, 2021) and FishBase (Froese and Pauly, 2021).

### 3.2.3 Focus Group Discussions (FGDs)

We conducted one focus group discussion (FGD) from each of the ten shrimp trawlers where catch composition landings were observed. A total of 50 skippers and crew (one skipper and four crew members from each of ten shrimp trawler with at least ten years of voyages experience) were selected for the FGD, and the discussions lasted two to three hours (Table A.1). FGDs are appropriate for identifying suspected and subtle issues as well as for understanding stakeholders' perspective on a specific topic of interest (Kumer and Urbanc, 2020). At the beginning of each FGD, we provided the list of shrimp trawl net specific target and bycatch species, including their photographs and local names of species, to the skippers and crew. We asked them about the seasonal species abundance, catch frequencies and tendencies, catchabilities, catch trends, etc. These factors are greatly influenced by the horizontal and vertical distributions of stocks, species selectivity to trawl net, in addition to environmental variables (Maynou and Sardà, 2001; McAllister et al., 2010).

We also asked about the area of shrimp fishing ground, depth of fishing, trawl net selectivity, species survivability, bycatch discard tendency, the degree to which existing fisheries regulations are enforced and followed, market prices and demand for each species of shrimp trawl fishery. These data were emphasized for scoring the susceptibility attributes, leading towards the vulnerability analysis of the stocks (Tables A.2 and A.4). For understanding the relative stock status of the target and bycatch species, we qualitatively obtained the catch trends data. We asked the skippers and crew to score the bycatch species on a scale of 1–3, indicating the decreasing (1), stable (2), and increasing (3) trends of the stocks, and we compared this catch trend data with the vulnerability scores for bycatch species (Faruque and Matsuda, 2021a) (Table A.2).

### 3.2.4 Productivity susceptibility analysis (PSA)

#### 3.2.4.1 Selection of productivity and susceptibility attributes; and related data collection

The number of attributes that can be examined in PSA has grown significantly as the PSA has been expanded to evaluate other management factors (e.g., habitat impacts, ecosystem concerns, management efficacy) (Hobday et al., 2011; Rosenberg et al., 2007). However, the choice of attributes was mostly determined by the availability of data and its applicability to vulnerability analysis (Patrick et al., 2010). For PSA of the target and bycatch species of shrimp trawl fishery, we considered 12 productivity (e.g., species biological characteristics) and ten susceptibility (e.g., impacts from fishery-specific activities) attributes (Table 3.1).

The productivity of a species is significantly influenced by their inherent traits (Hobday et al., 2011). In our research, we consider the productivity attributes ($P$), i.e., maximum age, maximum size, von Bertalanffy growth coefficient, natural mortality, measured fecundity, breeding strategy, age at maturity, and mean trophic level of a species from the study of Patrick et al. (2010); and due to the strong correlation with the productivity of the stocks, these attributes are frequently used in PSA (Ormseth and Spencer, 2011). Species with protracted breeding season or multiple broods per year, annual cycle with a seasonal peak and then species with bi/triennial breeding cycle are considered to be more productive, in that order (McCully Phillips et al., 2015). Size at maturity and maximum size of a species also correlated with productivity, i.e., species that mature quickly in relation to their maximum size have a high productivity probability than species that mature slowly in relation to maximum size (Hobday et al., 2011). These phenomena are directly associated with the productivity of a species. Therefore, breeding cycle and size at maturity were also considered respectively from the study of McCully Phillips et al. (2015) and Hobday et al. (2011), as well as the maturity size ratio and maturity age ratio were taken from Mejía-Falla et al. (2019) (Table 3.1).

**Table 3.1** Productivity (*P*), and susceptibility (*S*) attributes and scoring thresholds used to assess vulnerability (*V*) of the stocks caught from shrimp trawl fishery.

| **Productivity attributes** | **Low risk (3)** | **Moderate risk (2)** | **High risk (1)** |
|---|---|---|---|
| Maximum age ($t_{max}$, year) | < 3 | 3–7 | > 7 |
| Maximum size ($L_{max}$, cm) | < 26 | 26–42 | > 42 |
| Von Bertalanffy growth coefficient ($K$, year$^{-1}$) | > 0.90 | 0.38–0.90 | < 0.38 |
| Estimated natural mortality ($M$, year$^{-1}$) | > 1.61 | 0.92–1.61 | < 0.92 |
| Measured fecundity (MF) | > 73854 | 13182–73854 | < 13182 |
| Breeding strategy (BS) | Broadcast spawners | External brooders/ demersal egg layer/ guarders | Live bearers/ mouth brooders |
| Age at first maturity ($t_{mat}$, year) | < 1 | 1–2 | > 2 |
| Size at first maturity ($L_{mat}$, cm) | < 13 | 13–25 | > 25 |
| Mean trophic level (MTL) | < 3.4 | 3.4–3.9 | > 3.9 |
| Breeding cycle (BC) | Annual cycle with protracted breeding season | Annual cycle with a seasonal peak | Bi/Triennial |
| Age at first maturity/ Maximum age ($t_{mat}/t_{max}$) | < 0.20 | 0.20–0.29 | > 0.29 |
| Size at first maturity/ Maximum size ($L_{mat}/L_{max}$) | < 0.51 | 0.51–0.59 | > 0.59 |

| **Susceptibility attributes** | **High risk (3)** | **Moderate risk (2)** | **Low risk (1)** |
|---|---|---|---|
| Areal overlap (AO) | > 50% of stock present in the area fished | Between 25% and 50% of the stock present in the area fished | < 25% of stock present in the area fished |

| | | | |
|---|---|---|---|
| Vertical overlap (VO) | > 50% of stock present in the depths fished | Between 25% and 50% of the stock present in the depths fished | < 25% of stock present in the depths fished |
| Seasonal migrations (SM) | Seasonal migrations increase overlap with the fishery | Seasonal migrations do not substantially affect the overlap with the fishery | Seasonal migrations decrease overlap with the fishery |
| Schooling, aggregation, and other behavioral responses (SABR) | Behavioral responses of species increase the catchability of the gear | Behavioral responses of species do not substantially affect the catchability of the gear | Behavioral responses of species decrease the catchability of the gear |
| Morphological characteristics affecting capture (MCAC) | Species shows high selectivity to the fishing gear | Species shows moderate selectivity to the fishing gear | Species shows low selectivity to the fishing gear |
| Management strategy (MSt) | Stocks do not have catch limits or accountability measures, and are not closely monitored | Stocks have catch limits, reactive accountability measures, and are occasionally monitored | Stocks have catch limits, proactive accountability measures, and are closely monitored |
| Survival after capture and release (SCR) | Probability of survival < 33% | 33% < probability of survival < 67% | Probability of survival > 67% |
| Species market value (SMV, USD/kg) | > 4 | 2–4 | < 2 |
| Species market demand (SMD) | High | Moderate | Low |
| Fishing rate relative to $M$ ($F/M$) | > 1 | 0.5–1 | < 0.5 |

We considered the available species-specific information to compile the productivity attributes data. However, data of the species of similar genus or taxa from the waterbodies of Bangladesh or the Indian subcontinent, or outside of these regions are also considered in the case of species-specific data unavailability. All these data were gathered from the relevant literatures and web-based global species databases, i.e., SeaLifeBase (Palomares and Pauly, 2021) and FishBase (Froese and Pauly, 2021). When data are not available, using an empirical equation to calculate productivity values for specified attributes can be a viable option (Faruque and Matsuda, 2021b; Lin et al., 2020). Therefore, based on the empirical equations suggested by Froese and Binohlan (2000) and Pauly (1980), we calculated some correlated life-history traits for fish species, i.e., maximum age ($t_{max}$) = $3/K$, length at maturity ($L_{mat}$) = $L_\infty 10^{(0.8979 - 0.07827T)}$, age at maturity ($t_{mat}$) = $-\mathrm{Log}_e(1 - L_{mat}/L_\infty)/K$ and natural mortality ($M$) = $0.985\, L_\infty^{-0.279} K^{0.6543} T^{0.4634}$, where, $K$, $L_\infty$ and $T$ are denoting the von Bertalanffy growth coefficient, asymptotic maximum length and water temperature (28 °C), respectively. However, we did not apply any empirical equations and instead, sorted the data from the relevant literatures for crustaceans and cephalopods.

A set of attributes with a correlation coefficient greater than 0.9 might be excluded to avoid double-counting of the correlated life-history traits (Hobday et al., 2011). We found correlation coefficient greater than 0.9 for the sets of productivity attributes, i.e., von Bertalanffy growth coefficient and natural mortality, and maximum size and size at first maturity. For the rest of the attributes, we did not find any strong correlation. We considered all the productivity attributes, because the exclusion of the correlated attributes did not significantly changed either the overall vulnerability score or category for a specific species.

The susceptibility attributes ($S$), i.e., areal overlap, vertical overlap, seasonal migrations, schooling, aggregation, and other behavioral responses, morphological characteristics affecting capture, management strategy, survival after capture and release, and fishing rate relative to $M$ (natural mortality) were considered directly, as well as, species market value and species market demand were partially modified from the susceptibility attribute “desirability or value of the fishery” from the study of Patrick et al. (2010). We considered the attribute “fishing rate relative to $M$” for the stocks with available data, because data on this attribute was unavailable for most of the assessed stocks in our PSA.

### 3.2.4.2 Data scoring and weighing

We used scoring scale of 1–3, for the data of each of the productivity and susceptibility attributes (Tables A.3 and A.4). Productivity attributes scoring scale 1–3, indicating high (1), moderate (2), and low (3) risk corresponding to low, moderate, and high productivity of the stock, respectively. The quantitative values of the productivity attributes were split into 33rd and 67th percentiles to determine scoring threshold of equal probabilities for each of the risk categories as adopted by Clarke et al. (2018) and Duffy et al. (2019). For example, we found von Bertalanffy growth coefficient ($K$) values for all stocks within 0.11 to 1.7, therefore we scored value, > 0.90 (low risk), 0.38–0.90 (moderate risk) and < 0.38 (high risk) as 3, 2, and 1 respectively (Table 3.1 and Table A.3). We modified the scoring categories for “breeding strategy" attribute based on the work of Monterey Bay Aquarium (2018) and Patrick et al. (2010). We considered score 3 for broadcast spawners, generally, that leave eggs in the water column, score 2 for external brooders or demersal egg layers or guarders, and score 1 for mouth brooders or live bearers. Scoring categories for the attributes "breeding cycle", we considered score 3 for species that have annual cycle with protracted breeding season, generally breed thorough the year or have extended breeding season, score 2 for species that have annual cycle with a seasonal peak and score 1 for species that have bi/triennial breeding cycle (McCully Phillips et al., 2015).

Susceptibility attributes were scored on a scales of 1–3, indicating low (1), moderate (2) and high (3) risk, was used for each attribute of the susceptibility of the stock, respectively (Table 3.1 and Table A.4). We considered similar scoring criteria for most of the susceptibility attributes from Patrick et al. (2010). However, we modified the scoring criterion for "morphological characteristics affecting capture" from Monterey Bay Aquarium (2018) and FGDs' data. Therefore, we assigned score 3 for species that shows high selectivity to trawl net, i.e., species enter and cannot escape easily from the gear, score 2 for species those can enter into the gear and escape but have moderate possibility to be caught, i.e., generally large size fast swimming species have tendency to escape from the trawl net (Killen et al., 2015), and score 1 for the irregularly caught species. For the attributes "species market value" and "species market demand", we assigned score 3 for high, 2 for moderate and 1 for low market valued and demanded species. Due to high fishing effort considering high market demand, the desire to catch huge quantities of high-valued species that have the potential to produce substantial revenues for fishers, has a negative impact on fisheries resources (Funge-Smith and Bennett, 2019). In our study, we considered species market value > 4 USD/kg as score 3 (high risk), 2–4 USD/kg as score 2 (moderate risk), and < 2 USD/kg as score 1 (low risk).

After scoring both the productivity and susceptibility attributes, an equal weight score of 2 was assigned to each attribute value (Patrick et al., 2010). The scores assigned to each attributes were averaged, and we used the weighted average scores of the overall productivity and susceptibility because it is more commonly used than the multiplicative method and avoids the tendency to underestimate vulnerability (Osio et al., 2015).

### 3.2.4.3 Vulnerability analysis of the identified species

The calculation of an overall vulnerability score ($V$) of a species depends on the two-dimensional nature of the PSA, defined as the Euclidean distance of overall productivity ($P$) and susceptibility ($S$) scores, and graphically displayed on an x–y scatter plot (Osio et al., 2015; Patrick et al., 2010). The overall vulnerability score of a stock is calculated as, $V = \sqrt{(P-3)^2 + (S-1)^2}$ (Patrick et al., 2010). In the biplot graph, the x-axis represented the weighted average $P$ scores of the stocks on a scale of high (3) to low (1), while the y-axis represented the weighted average $S$ scores of the stocks on a scale of low (1) to high (3) (Figure 3.4). Low $P$ and high $S$ score of the stocks signified the most vulnerable condition to be overfished, while high $P$ and low $S$ score of the stocks indicated the least vulnerable condition (Patrick et al., 2010). The vulnerability scores of the stocks were categorized as on the scale of low ($V < 1.8$), moderate ($1.8 \leq V < 2$), and high ($V \geq 2$) for further analysis (Faruque and Matsuda, 2021a).

### 3.2.4.4 Data quality (DQ) score and category

The scoring of data quality is a key outcome of the PSA analysis. This could be used to identify species with limited data and recommend ways to improve data gathering for those species (Osio et al., 2015). The data quality of specific $V$ scores was defined by a data quality table based on five tiers on the scale of 1–5, ranging from best data (1) to no data (5) (Patrick et al., 2010) (Table 3.2 and Figure 3.3b). Therefore, the weighted average data quality scores for the productivity and susceptibility reflected the overall quality of the data, instead of the specific data type used in the PSA analysis (Table 3.3). We considered the data quality and categorized as on the scale of high ($DQ < 2.0$), moderate ($2.0 \leq DQ < 3.0$), and low ($DQ \geq 3.0$) (Ormseth and Spencer, 2011). In our study, we assigned data quality score based on the availability of the data and the definition of the data quality. However, the data on life-history traits resulting from the empirical equations, were considered as very limited data (4).

**Table 3.2** Data quality scoring tiers used in the Productivity Susceptibility Analysis (PSA) for the stocks of shrimp trawl fishery (Patrick et al., 2010).

| Data Quality Scores | Data Quality | Description | Example |
|---|---|---|---|
| 1 | Best | Information is based on collected data for the stock and area of interest that is established and substantial | Data rich stock assessment; published literature for which multiple methods are used, etc. |
| 2 | Adequate | Information is based on limited coverage and corroboration, or for some other reason is deemed not as reliable as tier-1 data | Limited temporal or spatial data, relatively old information, etc. |
| 3 | Limited | Estimates with high variation and limited confidence, and may be based on studies of similar taxa or life-history strategies | Similar genus or family, etc. |
| 4 | Very limited | Information based on expert opinion or general literature reviews from a wide range of species, or from outside of region, or data derived by equation using the correlated life-history parameter | General data not referenced |
| 5 | No data | No information | |

### 3.2.5 Species' vulnerability in comparison with IUCN extinction risk, exploitation rate, and catch trend status

Outcomes of the PSA were compared with the further three analytical approaches, i.e., IUCN extinction risk, exploitation rate ($E$), and catch trend status of the stocks, to acquire an in-depth understanding of relative status of the stocks identified in the shrimp trawl fishery. We verified the different risk categories of the stocks in the previously assessed IUCN Red List of Bangladesh (IUCN, 2015a, 2015b), and global (IUCN, 2021) according to IUCN Red List categories, i.e., critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), data deficient (DD), and not evaluated (NE) (Table 3.3 and Figure 3.5).

Gulland (1971) obtained the exploitation rate ($E$) of a specific stock as $E = F / (F + M)$, where $M$ and $F$ respectively denoting the natural mortality and fishing mortality coefficients. For most of the stocks, data of $E$ were not available, and we found $E$ of only 20 stocks to identify the stock status from the Bay of Bengal, which have been assessed by FAO-ICLARM stock assessment tools previously. When fishing mortality is equal to natural mortality, it indicates the stocks are optimally exploited ($E = 0.5$) (Gulland, 1971); thus, it is over-exploited if $E > 0.5$ and under-exploited if $E < 0.5$ (Table 3.3 and Table A.2). The $V$ score resulting from PSA with the $E$ were compared. We found a substantial relationship between the $V$ score ($V \geq 1.8$) and the exploitation rate ($E > 0.5$) (Figure 3.6).

The vulnerability scores were also compared with the identified stocks' catch trend status, obtained during FGDs with 50 participants from ten shrimp trawlers. We considered their perceptions about the stock status of the species depending upon the catch frequencies and catchabilities by the shrimp trawl fishery. If there were more than total 30 participants perceived the same category, which means < 5% statistically significant ($\sum_{x=31}^{50} {}_{50}C_x 0.5^x 0.5^{50-x} < 5\%$), we evaluated the catch trend of a specific stock to be increasing (2), increasing or stable (1), or decreasing (-1) and if not, we considered as not significant (0) (Faruque and Matsuda, 2021a) (Table 3.3 and Table A.2).

## 3.3 Results

### 3.3.1 Composition of the identified species

We identified 60 species including target and bycatch shellfish and finfish from the shrimp trawl fishery in the Bay of Bengal, Bangladesh belonging to 32 families and four classes, namely Malacostraca, Cephalopoda, Elasmobranchii, and Actinopterygii (Table 3.3 and Figure 3.2). Species of the family Penaeidae are the most prominent, followed by Carangidae, Ariidae, Engraulidae, Nemipteridae, Polynemidae, and the remaining families. Eels (Congridae, Muraenesocidae), catfishes (Ariidae, Plotosidae), ponyfishes (Leiognathidae), croakers (Sciaenidae), tongue soles (Cynoglossidae), pomfrets (Stromateidae, Carangidae), groupers (Serranidae), and ribbonfishes (Trichiuridae) are significantly caught as finfish bycatch from shrimp trawl fishery.

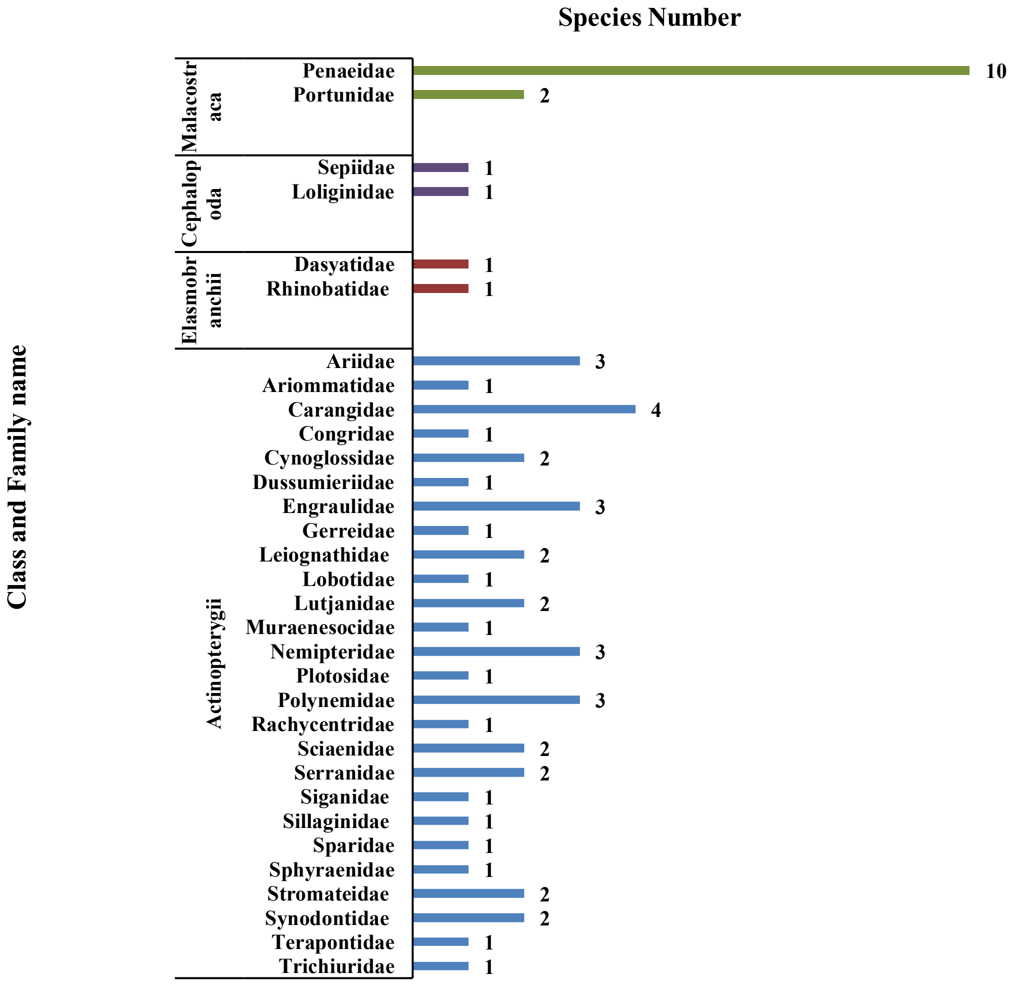

**Figure 3.2** Composition of the species identified from shrimp trawl fishery. Numbers in the bars indicate the number of species belonging to the corresponding family.

### 3.3.2 Vulnerability assessment by productivity susceptibility analysis (PSA)

All the identified species from shrimp trawl fishery were evaluated by PSA. The weighted average productivity scores ranged from 1.25 (*Arius maculatus*, *Plicofollis layardi*) to 2.83 (*Gerres filamentosus*) and susceptibility scores ranged from 1.44 (*Himantura uarnak*) to 2.90 (*Parastromateus niger*) (Table 3.3). Overall productivity and susceptibility scores showed that, 37% and 46% of all the identified species respectively scored higher productivity and higher susceptibility, while 36% and 27% respectively scored moderate and lower productivity, and 44% and 11% respectively scored moderate and lower susceptibility (Figure 3.3a).

**Table 3.3** Results of the Productivity Susceptibility Analysis (PSA) for the species caught from shrimp trawl fishery are provided with their common and family name, as well as 3-alpha FAO codes. Target stocks species scientific name and FAO code are listed as bold. Productivity attributes' weighted average scores (*P*), with weighted average of data quality scores (*PDQ*), whereas, susceptibility attributes' weighted average scores (*S*), with weighted average of data quality scores (*SDQ*) are shown. Vulnerability scores (*V*) of the species with vulnerability scores excluded management strategy (*V*eMSt), overall data quality scores (*ODQ*) averaged from *PDQ* and *SDQ* are also displayed. IUCN Red List of the species are categorized as in Bangladesh (BD$^*$) and global (G) extinction risk, i.e., vulnerable (VU), near threatened (NT), least concerned (LC), data deficient (DD), and not evaluated (NE). Catch trend categories (CTC) indicates, decreasing (D), not significant (NS), stable (S) and increasing (I) status of the stocks. Exploitation rate (*E*) of the assessed stocks are also included.

| **Scientific Name** | **Common Name** | **Family** | **FAO Code** | ***P*** | ***PDQ*** | ***S*** | ***SDQ*** | ***V*** | ***V*eMSt** | ***ODQ*** | **IUCN (BD$^*$/G)** | **CTC** | ***E*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Penaeus monodon*** | Giant Tiger Prawn | Penaeidae | **GIT** | 2.58 | 3.33 | 2.80 | 2.20 | 1.85 | 1.93 | 2.77 | LC$^*$ | D | 0.65 |
| ***Penaeus indicus*** | Indian White Prawn | Penaeidae | **PNI** | 2.42 | 3.33 | 2.80 | 2.50 | 1.89 | 1.98 | 2.92 | LC$^*$ | D | 0.74 |
| ***Penaeus merguiensis*** | Banana Prawn | Penaeidae | **PBA** | 2.42 | 3.33 | 2.60 | 2.20 | 1.70 | 1.77 | 2.77 | LC$^*$ | S | 0.68 |
| ***Penaeus semisulcatus*** | Green Tiger Prawn | Penaeidae | **TIP** | 2.42 | 3.33 | 2.70 | 2.30 | 1.80 | 1.87 | 2.82 | LC$^*$ | D | 0.60 |
| ***Metapenaeus monoceros*** | Speckled Shrimp | Penaeidae | **MPN** | 2.58 | 3.33 | 2.80 | 2.20 | 1.85 | 1.93 | 2.77 | LC$^*$ | D | 0.62 |
| ***Metapenaeus affinis*** | Jinga Shrimp | Penaeidae | **MTJ** | 2.67 | 3.42 | 2.67 | 2.44 | 1.70 | 1.78 | 2.93 | DD$^*$ | S | |
| ***Metapenaeus brevicornis*** | Yellow Shrimp | Penaeidae | **MPB** | 2.25 | 3.08 | 2.70 | 2.20 | 1.86 | 1.93 | 2.64 | LC$^*$ | D | 0.81 |
| *Mierspenaeopsis sculptilis* | Rainbow Shrimp | Penaeidae | NAP | 2.75 | 3.33 | 2.60 | 2.40 | 1.62 | 1.69 | 2.87 | LC$^*$ | S | 0.55 |
| *Parapenaeopsis hardwickii* | Spear Shrimp | Penaeidae | NAW | 2.67 | 3.67 | 2.22 | 2.56 | 1.27 | 1.29 | 3.11 | DD$^*$ | S | |
| *Parapenaeopsis stylifera* | Kiddi Shrimp | Penaeidae | NAY | 2.67 | 3.33 | 2.22 | 2.56 | 1.27 | 1.29 | 2.94 | LC$^*$ | S | |
| *Portunus pelagicus* | Blue Swimming Crab | Portunidae | SCD | 2.33 | 3.67 | 2.11 | 2.56 | 1.30 | 1.31 | 3.11 | LC$^*$ | S | |
| *Scylla serrata* | Indo-Pacific Swamp Crab | Portunidae | MUD | 2.08 | 3.17 | 2.10 | 2.40 | 1.43 | 1.44 | 2.78 | LC$^*$ | S | 0.39 |
| *Sepia aculeata* | Needle Cuttlefish | Sepiidae | EJA | 2.25 | 3.67 | 2.33 | 2.89 | 1.53 | 1.57 | 3.28 | DD | S | |
| *Uroteuthis duvaucelii* | Indian Squid | Loliginidae | OJD | 2.08 | 3.67 | 2.44 | 2.89 | 1.71 | 1.76 | 3.28 | DD | S | |
| *Himantura uarnak* | Honeycomb Stingray | Dasyatidae | DHV | 1.50 | 3.25 | 1.44 | 2.89 | 1.56 | 1.55 | 3.07 | VU | S | |
| *Rhinobatos annandalei* | Annandale's Guitarfish | Rhinobatidae | RHD | 1.58 | 3.58 | 1.67 | 2.89 | 1.57 | 1.55 | 3.24 | DD | S | |
| *Arius arius* | Threadfin Sea Catfish | Ariidae | AUI | 1.33 | 3.50 | 2.33 | 2.56 | 2.13 | 2.16 | 3.03 | LC | D | |
| *Arius maculatus* | Spotted Catfish | Ariidae | CAO | 1.25 | 3.50 | 2.11 | 2.33 | 2.07 | 2.08 | 2.92 | NE | D | |
| *Plicofollis layardi* | Thinspine Sea Catfish | Ariidae | UKY | 1.25 | 3.58 | 2.33 | 2.67 | 2.20 | 2.23 | 3.13 | NE | D | |
| *Ariomma indicum* | Indian Driftfish | Ariommatidae | DRI | 2.50 | 3.17 | 2.80 | 2.50 | 1.87 | 1.95 | 2.83 | NE | D | 0.62 |
| *Alepes djedaba* | Shrimp Scad | Carangidae | LSJ | 2.33 | 3.42 | 2.56 | 2.56 | 1.69 | 1.76 | 2.99 | LC | S | |
| *Atropus atropos* | Cleftbelly Trevally | Carangidae | TUP | 2.58 | 3.67 | 2.56 | 2.44 | 1.61 | 1.68 | 3.06 | LC | S | |
| *Parastromateus niger* | Black Pomfret | Carangidae | POB | 2.08 | 2.58 | 2.90 | 2.40 | 2.11 | 2.20 | 2.49 | LC | D | 0.52 |
| *Selar crumenophthalmus* | Bigeye Scad | Carangidae | BIS | 2.58 | 3.50 | 2.78 | 2.56 | 1.83 | 1.92 | 3.03 | LC | D | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Conger cinereus* | Conger Eel | Congridae | COI | 1.42 | 3.67 | 2.67 | 2.89 | 2.30 | 2.36 | 3.28 | LC | D | |
| *Cynoglossus bilineatus* | Fourlined Tongue Sole | Cynoglossidae | YOB | 1.67 | 3.50 | 2.22 | 2.78 | 1.81 | 1.83 | 3.14 | NE | D | |
| *Cynoglossus lingua* | Long Tongue Sole | Cynoglossidae | YOG | 1.67 | 3.50 | 2.33 | 2.44 | 1.89 | 1.92 | 2.97 | LC[*] | D | |
| *Dussumieria acuta* | Rainbow Sardine | Dussumieriidae | RAS | 2.00 | 3.67 | 1.89 | 2.89 | 1.34 | 1.33 | 3.28 | LC | S | |
| *Coilia dussumieri* | Goldspotted Grenadier Anchovy | Engraulidae | ECD | 2.42 | 2.92 | 2.30 | 2.40 | 1.42 | 1.46 | 2.66 | LC[*] | S | 0.48 |
| *Stolephorus tri* | Spined Anchovy | Engraulidae | ESJ | 2.25 | 3.17 | 2.10 | 2.30 | 1.33 | 1.34 | 2.73 | NE | S | 0.85 |
| *Thryssa mystax* | Moustached Thryssa | Engraulidae | EYY | 2.33 | 3.67 | 2.22 | 2.56 | 1.39 | 1.42 | 3.11 | LC | S | |
| *Gerres filamentosus* | Whipfin Silver-biddy | Gerreidae | GEF | 2.83 | 3.67 | 2.67 | 2.56 | 1.67 | 1.76 | 3.11 | LC | S | |
| *Aurigequula fasciata* | Striped Ponyfish | Leiognathidae | LGS | 2.08 | 3.67 | 2.33 | 2.56 | 1.62 | 1.65 | 3.11 | LC | S | |
| *Eubleekeria splendens* | Splendid Ponyfish | Leiognathidae | LGP | 2.42 | 3.42 | 2.33 | 2.56 | 1.46 | 1.49 | 2.99 | LC | I | |
| *Lobotes surinamensis* | Tripletail | Lobotidae | LOB | 2.08 | 3.67 | 2.00 | 2.67 | 1.36 | 1.36 | 3.17 | LC | S | |
| *Lutjanus johnii* | John's Snapper | Lutjanidae | LJH | 1.67 | 3.00 | 2.60 | 2.50 | 2.08 | 2.13 | 2.75 | LC | D | 0.78 |
| *Lutjanus lutjanus* | Bigeye Snapper | Lutjanidae | LJL | 2.00 | 3.67 | 2.56 | 2.44 | 1.85 | 1.91 | 3.06 | LC | D | |
| *Congresox talabonoides* | Indian Pike Conger | Muraenesocidae | MCG | 1.42 | 3.33 | 2.44 | 2.67 | 2.14 | 2.18 | 3.00 | NE | D | |
| *Nemipterus japonicus* | Japanese Threadfin Bream | Nemipteridae | NNJ | 2.33 | 3.17 | 2.70 | 2.50 | 1.83 | 1.90 | 2.83 | LC | NS | 0.59 |
| *Nemipterus randalli* | Randall's Threadfin Bream | Nemipteridae | NNZ | 2.00 | 3.67 | 2.56 | 2.89 | 1.85 | 1.91 | 3.28 | LC | NS | |
| *Parascolopsis aspinosa* | Smooth Dwarf Monocle Bream | Nemipteridae | NPS | 2.50 | 3.83 | 2.56 | 2.89 | 1.63 | 1.70 | 3.36 | LC | S | |
| *Plotosus lineatus* | Striped Eel Catfish | Plotosidae | PII | 2.08 | 3.42 | 2.00 | 2.44 | 1.36 | 1.36 | 2.93 | NE | S | |
| *Eleutheronema tetradactylum* | Fourfinger Threadfin | Polynemidae | FOT | 1.83 | 3.00 | 2.44 | 2.44 | 1.86 | 1.90 | 2.72 | NE | D | |
| *Leptomelanosoma indicum* | Indian Threadfin | Polynemidae | OYD | 1.75 | 3.67 | 2.33 | 2.67 | 1.83 | 1.86 | 3.17 | NE | D | |
| *Polydactylus sextarius* | Blackspot Threadfin | Polynemidae | OAX | 1.83 | 3.50 | 2.44 | 2.67 | 1.86 | 1.90 | 3.08 | NE | D | |
| *Rachycentron canadum* | Cobia | Rachycentridae | CBA | 1.92 | 3.42 | 2.22 | 2.56 | 1.63 | 1.65 | 2.99 | LC | S | |
| *Johnius dussumieri* | Sin Croaker | Sciaenidae | JOU | 2.42 | 3.67 | 2.00 | 2.56 | 1.16 | 1.16 | 3.11 | LC | S | |
| *Otolithoides biauritus* | Bronze Croaker | Sciaenidae | OTB | 1.83 | 3.83 | 1.78 | 2.56 | 1.40 | 1.39 | 3.19 | DD | S | |
| *Epinephelus lanceolatus* | Giant Grouper | Serranidae | EEN | 1.75 | 3.42 | 2.00 | 2.78 | 1.60 | 1.60 | 3.10 | DD | S | |
| *Epinephelus malabaricus* | Malabar Grouper | Serranidae | MAR | 2.00 | 3.50 | 2.22 | 2.67 | 1.58 | 1.60 | 3.08 | LC | S | |
| *Siganus canaliculatus* | White-spotted Spinefoot | Siganidae | SCN | 2.42 | 3.67 | 2.00 | 2.56 | 1.16 | 1.16 | 3.11 | LC | S | |
| *Sillago sihama* | Silver Sillago | Sillaginidae | ILS | 2.17 | 3.33 | 2.10 | 2.70 | 1.38 | 1.39 | 3.02 | LC | S | 0.75 |
| *Argyrops spinifer* | King Soldier Bream | Sparidae | KBR | 1.50 | 3.67 | 2.00 | 2.44 | 1.80 | 1.80 | 3.06 | LC | D | |
| *Sphyraena obtusata* | Obtuse Barracuda | Sphyraenidae | YRB | 1.92 | 3.25 | 2.44 | 2.67 | 1.81 | 1.85 | 2.96 | NE | NS | |
| *Pampus argenteus* | Silver Pomfret | Stromateidae | SIP | 2.17 | 2.83 | 2.40 | 2.30 | 1.63 | 1.67 | 2.57 | NE | S | 0.40 |
| *Pampus chinensis* | Chinese Silver Pomfret | Stromateidae | CPO | 1.92 | 3.00 | 2.30 | 2.30 | 1.69 | 1.72 | 2.65 | NE | S | 0.39 |
| *Harpadon nehereus* | Bombay-duck | Synodontidae | BUC | 2.25 | 3.17 | 2.00 | 2.30 | 1.25 | 1.25 | 2.73 | NT | S | 0.38 |
| *Saurida tumbil* | Greater Lizardfish | Synodontidae | LIG | 2.00 | 3.17 | 2.40 | 2.70 | 1.72 | 1.76 | 2.93 | LC | I | 0.35 |
| *Terapon jarbua* | Jarbua Terapon | Terapontidae | TJB | 1.83 | 3.33 | 2.22 | 2.33 | 1.69 | 1.71 | 2.83 | LC | S | |
| *Lepturacanthus savala* | Savalai Hairtail | Trichiuridae | SVH | 2.08 | 2.67 | 2.30 | 2.40 | 1.59 | 1.62 | 2.53 | NE | S | 0.43 |

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[*] IUCN Red List of Bangladesh (IUCN, 2015a, 2015b).

PSA derived vulnerability scores of the identified species ranged from 1.16–2.30. The most important target stock, Giant Tiger Prawn, *Penaeus monodon,* was considered moderately vulnerable ($V$ =1.85), resulting from its $P$ and $S$ scores of 2.58 and 2.80, respectively. We obtained the vulnerability scores of other target species, i.e., *P. indicus* (1.89), *P. merguiensis* (1.70), *P. semisulcatus* (1.80), *M. monoceros* (1.85), *M. affinis* (1.70), and *M. brevicornis* (1.86), indicating $V < 1.8$ (low vulnerability), $1.8 \leq V < 2.0$ (moderate vulnerability). The vulnerability scores of the bycatch species showed that, seven species (*Arius arius*, *Arius maculatus*, *Conger cinereus*, *Congresox talabonoides*, *Lutjanus johnii*, *Parastromateus niger*, *Plicofollis layardi*) from the Bay of Bengal were highly vulnerable to shrimp trawl fishery, $V$ scores ranged between 2.07 to 2.30, while 12 stocks obtained the moderate vulnerability scores ($1.80 \leq V \geq 1.89$) and the remaining 34 species scored the low vulnerability, ranged from 1.16 to 1.72 (Table 3.3 and Figure 3.4).

69.9% of data for the assessed stocks obtained "very limited" data quality category for the overall productivity attributes, followed by, "limited" (10.6%), "best" (10.1%) and "adequate" (9.4%). For susceptibility attributes, 39.3% of data for the for the assessed stocks obtained "very limited" data quality category, followed by, "best" (38.0%), "limited" (13.2%), and "adequate" (9.5%) (Figure 3.3b). The weighted average data quality ($DQ$) scores for the productivity attributes ranged from 2.58–3.83, indicating 6.7% moderate and 93.3% low data quality, while the $DQ$ scores for susceptibility ranged from 2.20–2.89, indicating moderate data quality for all susceptibility scores (Table 3.3). The overall $DQ$ scores for the vulnerability of target stocks were 2.64–2.93, indicating moderate data quality, while for the bycatch species ranged from 2.49–3.36 indicating 43.4% moderate and 56.6% low data quality (Table 3.3).

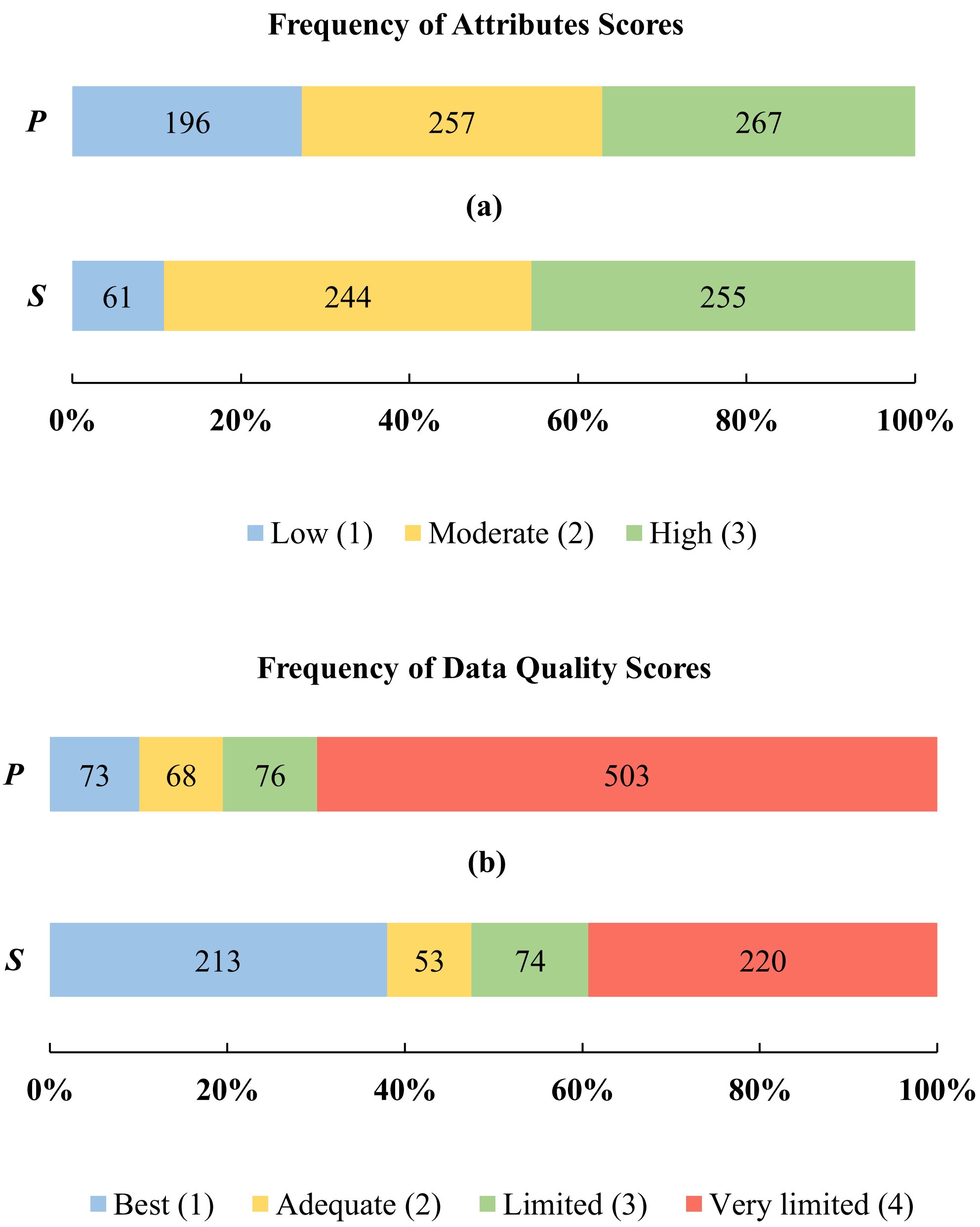

**Figure 3.3** (a) Attributes scoring categories and (b) data quality scoring categories of overall productivity (*P*) and susceptibility (*S*). Data labels indicate the frequencies of both categories.

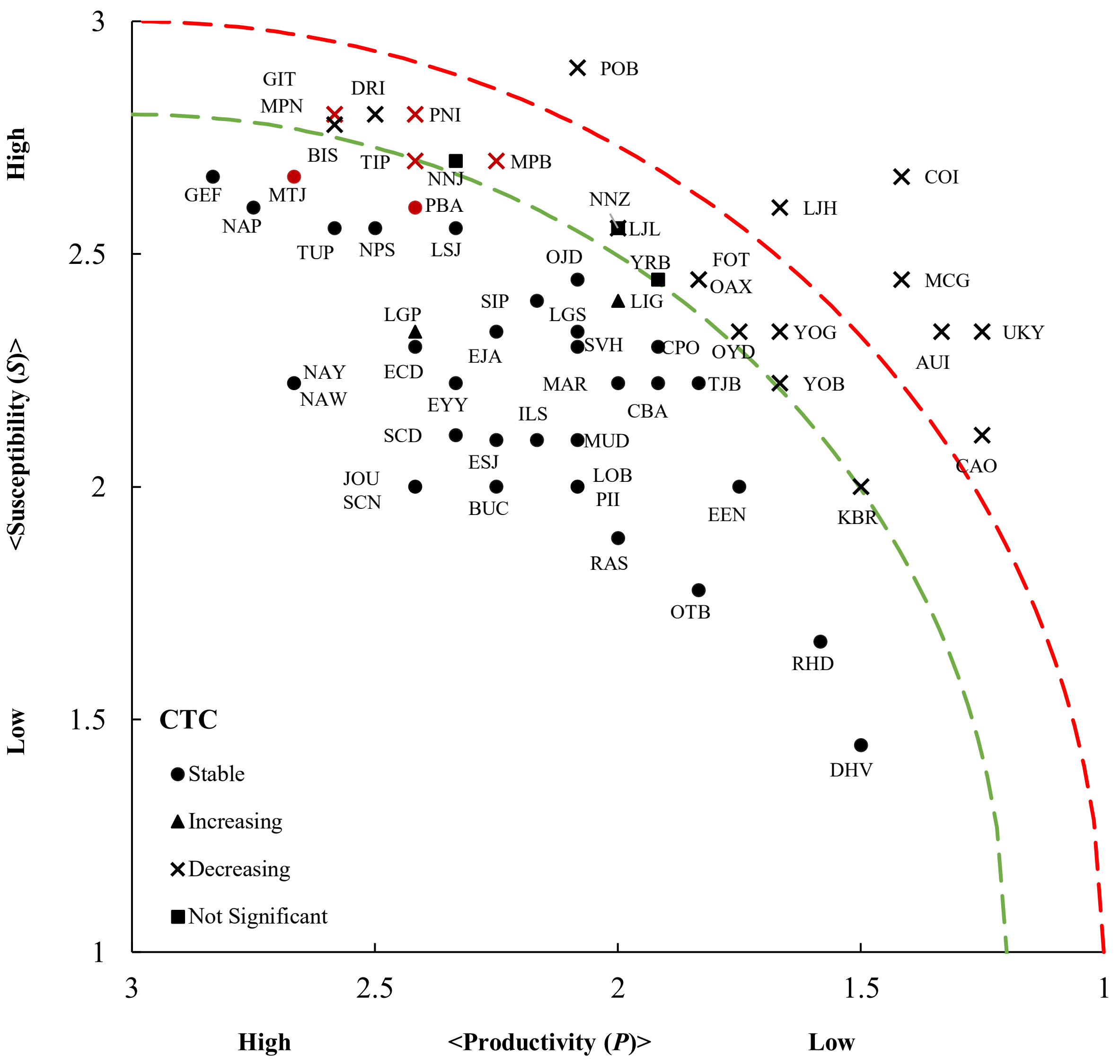

**Figure 3.4** Productivity (*P*) and susceptibility (*S*) scores are displayed in two-dimensional (x–y scatter) plot to indicate the vulnerability (*V*) of identified species labeled by 3-alpha FAO codes from shrimp trawl fishery. *V* scores of 1.8 and 2.0 are shown by contour lines, along with "low" ($V < 1.8$), "moderate" ($1.8 \leq V < 2.0$), and "high" ($V \geq 2.0$) vulnerability categories. *V* of target and bycatch stocks are marked by red and black, respectively. Catch trend categories (CTC) of the overall stocks are also expressed in the legend.

### 3.3.3. Species' vulnerability in comparison with IUCN extinction risk, exploitation rate, and catch trend status

We categorized the identified species based on the Bangladesh and global IUCN Red Lists. In most cases, our identified species were unavailable in the IUCN Red List of

Bangladesh, therefore we considered the global IUCN Red List for the species that were not included in the Bangladesh IUCN Red List. We found only one bycatch species from globally vulnerable (VU, *Himantura uarnak*) and near threatened (NT, *Harpadon nehereus*) categories. 12 species from least concern (LC) and 2 species from data deficient (DD) categories were found in the IUCN Red Lists of Bangladesh. Alternatively, 25 species from LC, followed by 14 species from not evaluated (NE) and 5 species from DD categories were found in the global IUCN Red List. However, we did not find any species from critically endangered (CR) or endangered (EN) categories (Figure 3.5 and Table 3.3).

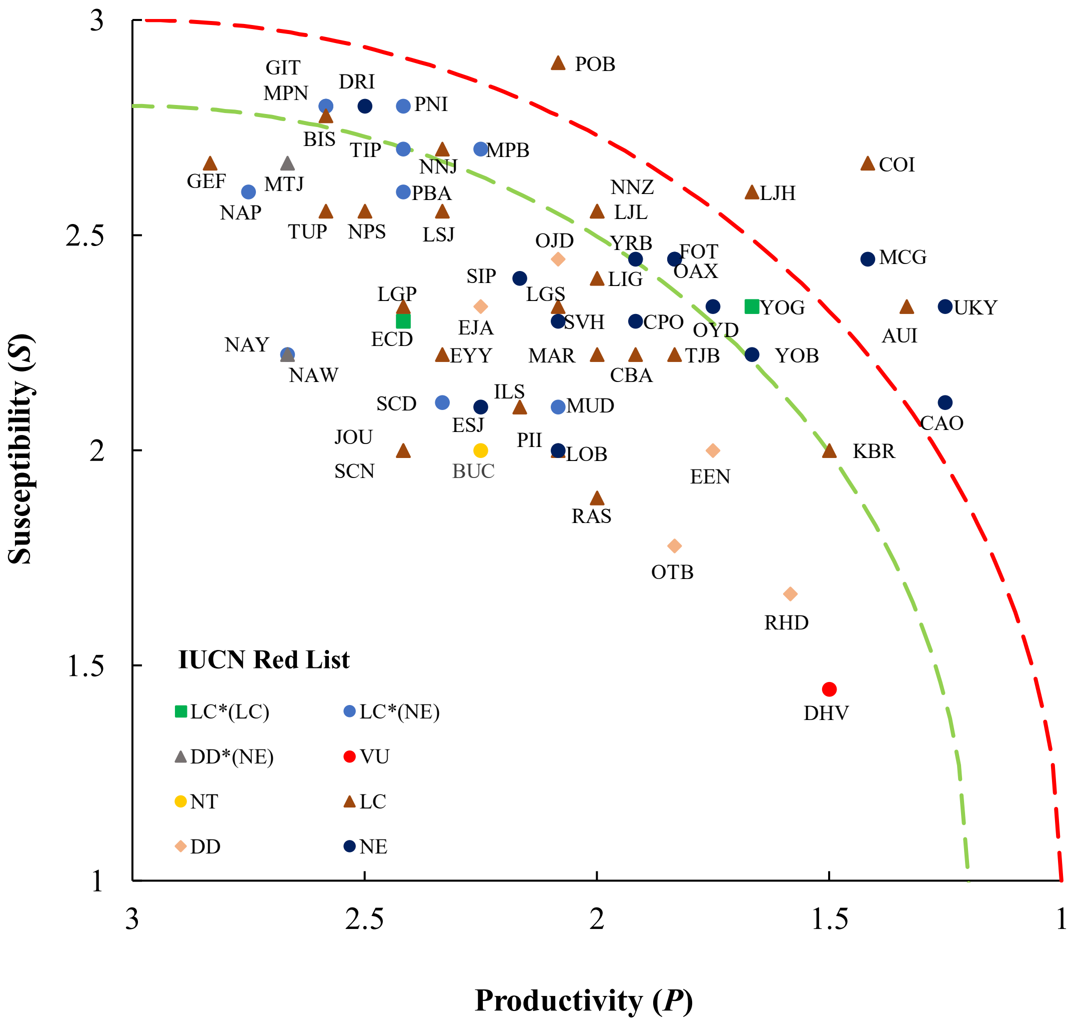

**Figure 3.5** Species vulnerability labelled by 3-alpha FAO codes from shrimp trawl fishery are categorized by the IUCN Red List of Bangladesh* and global, i.e., vulnerable (VU), near threatened (NT), least concerned (LC), data deficient (DD), and not evaluated (NE). Species categorized by Bangladesh* IUCN Red List are further categorized by global IUCN Red List as expressed in parenthesis.

When comparing PSA derived vulnerability scores with the IUCN extinction risk, we found both the VU and NT listed species obtained lower vulnerability to shrimp trawl fishery, i.e. *H. uarnak* ($V = 1.56$) and *H. nehereus* ($V = 1.25$). The most important target, *P. monodon,* was categorized as LC in the IUCN Red Lists of Bangladesh and moderately vulnerable ($V = 1.85$) to shrimp trawl fishery. Except, *P. merguiensis* (low vulnerability, LC) and *M. affinis* (low vulnerability, DD), other four moderately vulnerable target stocks were considered as LC in the IUCN Red Lists of Bangladesh. *Cynoglossus lingua* is ranked as LC and a moderately vulnerable bycatch species, while all the other five low vulnerable bycatch species were ranked in the LC category and *P. hardwickii* was DD in the IUCN Red List of Bangladesh. Among the seven bycatch species with highly vulnerable, four species (i.e., *A. arius*, *C. cinereus*, *L. johnii*, and *P. niger*) were ranked as LC, and three species (i.e., *A. maculatus*, *C. talabonoides*, and *P. layardi*) were ranked as NE in the global IUCN Red List. For the remaining 37 bycatch species from global IUCN Red List, 11 species were moderately vulnerable (13.51% for LC and 16.22% for NE) and 26 species were low vulnerable (43.24% for LC, 18.92% for DD, and 8.11% for NE) to shrimp trawl fishery (Figure 3.5 and Table 3.3).

We also compared the vulnerability scores ($V$) with the available data of exploitation rates ($E$) for 20 species to determine if the stocks were over-exploited ($E > 0.5$) or under-exploited ($E < 0.5$). When comparing with the $V$ scores, we observed that, $V \geq 1.8$ matched with the $E > 0.5$ (nine stocks), while $V < 1.8$ matched with the $E < 0.5$ (seven stocks), in some exceptions (four stocks), indicated that, the degree of conformity was 80% between $V$ and $E$ among the 20 stocks (Figure 3.6). Therefore, we considered $V \geq 1.8$ for over-fishing and $V < 1.8$ for under-fishing status, and our analysis suggested that 24 (40%) of the stocks including target (except, *P. merguiensis* and *M. affinis*) and bycatch stocks were in over-fishing category and 36 (60%) were in under-fishing category (Table 3.3).

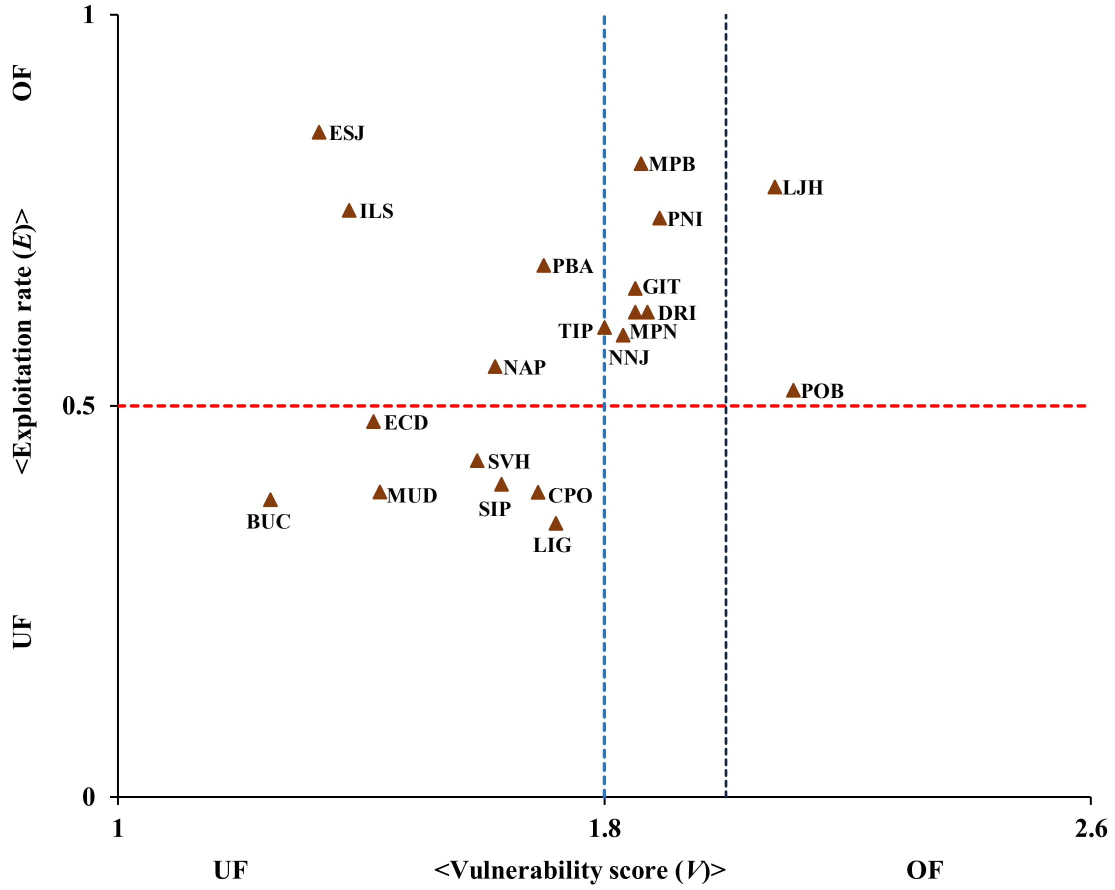

**Figure 3.6** Exploitation rate (*E*) and vulnerability (*V*) scores of the species labeled by 3-alpha FAO codes are compared. $V \geq 1.8$ and $E > 0.5$ signifies over-fishing status (OF), while, $V < 1.8$ and $E < 0.5$ signifies under-fishing (UF) status of the stocks.

There was a high correlation between the catch trend and the vulnerability score by the PSA. The vulnerability ($V$) scores of 21 (35%) species with "declining" catch trends and three (5.0%) species, i.e., *Sphyraena obtusata*, *Nemipterus japonicas*, and *Nemipterus randalli* with "not significant" catch trends were ≥ 1.8, while the vulnerability scores of 34 (56.7%) species with "stable" catch trends and two (3.3%) species, i.e., *Eubleekeria splendens* and *Saurida tumbil* with "increasing" catch trends were ≤ 1.72 (Table 3.3 and Table A.2). Therefore, $V \geq 1.8$, indicated the substantial relationship not only with exploitation status and but also with catch trends of the stocks identified from shrimp trawl fishery in the Bay of Bengal.

## 3.4 Discussion

### 3.4.1 Composition of the identified species

Of the 60 identified species, shrimps from family Penaeidae (class Malacostraca) was the family with the highest number of species from shrimp trawl fishery. Non-target finfish species from the shrimp trawl fishery were comprised approximately 35–40% of total catch (Hoq et al., 2013), and only a small percentage (0.47%) of sharks and rays are reported in industrial catch (IOTC, 2018). In our study we identified 44 fin fish species from the class Actinopterygii, belongs to 26 different families. Species from class Malacostraca, i.e., crabs belonging to family Portunidae, as well as, species from Cephalopoda and Elasmobranchii were also interacted with shrimp trawl fishery (Figure 3.2). Impacts on the dynamics of marine ecosystems depend upon the types of fishing gear used, affecting not only the target species populations but also the diversity of non-target species, as well as changing the ecosystems' total biomass and species composition (Bastardie et al., 2021). According to Marine Fisheries Ordinance, 1983 (Rule 7) of Bangladesh, discarding trash fish/bycatch at sea is prohibited (IOTC, 2018). Therefore, almost all fish caught are brought ashore as alternate use of fishes, i.e., as a reasonable protein source, dried low priced trash fish have high market value for aquaculture and livestock industry (Fanning et al., 2019; IOTC, 2018). However, relative distribution of stock biomass, functioning of trawl net at fishing areas and the degree of species sensitivity to each gear have influence on the catchabilities and catch ratios of specific stocks (McAllister et al., 2010).

### 3.4.2 Vulnerability assessment by productivity susceptibility analysis (PSA)

All the productivity and susceptibility attributes are not equally significant to figure out if a stock is vulnerable to a particular fishery (Patrick et al., 2009, 2010), and susceptibility attribute score has a greater impact on calculating vulnerability than productivity attribute score (Hordyk and Carruthers, 2018). The impacts from fishery-specific activities showed that, a majority of moderate to higher scores of susceptibility attributes among the identified species, whereas the scores of productivity attributes signified the varying degrees of species' biological characteristics (Figures 3.3a and 3.4). The phenomenon emphasized on the size and/or age groups of species, reproductive and migratory behavior, swimming capacity, interaction between species morphology and gear characteristics (i.e., cod-end selection, mesh size regulations, towing speed) during fishing operation and fleet dynamics of trawler in fishing grounds (Fauconnet et al., 2016; Stepputtis et al., 2016).

*P. monodon* (GIT), *P. indicus* (PNI), and *M. monoceros* (MPN) were more susceptible to shrimp trawl fishery than the other four target stocks. The bycatch species *P. niger* (POB) had the highest susceptibility score (2.90) among all species. Depending on the magnitude of fishing vessel and gear operation, bycatch species could have higher susceptibility to a specific fishery than target species (Duffy et al., 2019). Alternatively, productivity scores (2.42–2.58) of *P. monodon*, *P. indicus*, and *M. monoceros* were higher than the productivity scores (2.08) of bycatch *P. niger*. However, *P. monodon*, *P. indicus*, and *M. monoceros* were moderately vulnerable ($V = 1.85$–$1.89$) and *P. niger* was highly vulnerable ($V = 2.11$).

PSA derived vulnerability scores of the other bycatch species showed that, i.e., eels (MCG, COI) and Ariidae catfish (AUI, CAO, UKY) were highly vulnerable to shrimp trawl fishery. Extended life cycle and large body size, while slower growth rates and late maturity, resulted in lower behavioral responses, inevitable overlap in vertical distribution in the fishing region, reducing relative stock abundance, and led to higher vulnerability scores. Majority of catfish and eel also showed high and moderate vulnerability to Hilsa gillnet fishery, respectively (Faruque and Matsuda, 2021a). Alternatively, the target shrimp stocks received moderate to low vulnerability scores, due to their short life cycle and body size, fast maturity, high growth, as well as areal and vertical overlaps with some other fishing gears. However, the overall abundance of shrimp and catfish biomass, as well as their catch amount in Bangladesh, has been consistently downward over the last three decades (Fanning et al., 2019; Roy et al., 2019).

The weighted average data quality scores of productivity attributes for the identified species obtained moderate to low category, and moderate data quality category for susceptibility attributes. Data on life-history traits and stock assessment of the identified species from the Bay of Bengal as well as adjacent waterbodies of Bangladesh have not been adequately analyzed (Alam et al., 2021; Haque et al., 2021). The majority of overall productivity attributes' data categorized as "very limited", and for susceptibility attributes, "best data" scored significantly (Figure 3.3b) due to fishery-specific information collected from the relevant sources of shrimp trawl fishery by the current comprehensive state of the stocks in the Bay of Bengal, which had impact on species' vulnerability analysis through semi-quantitative approach (Griffiths et al., 2019; Liu et al., 2021).

### 3.4.3 Species' vulnerability in comparison with IUCN extinction risk, exploitation rate, and catch trend status

Concerns about reliability sometimes be raised on the scoring of productivity and susceptibility attributes, which signified the vulnerability of a species (Hobday et al., 2011). Faruque and Matsuda (2021a) and Osio et al. (2015) suggested the results of species' vulnerability by PSA can be compared with IUCN Red List. *C. cinereus* scored highly vulnerable ($V = 2.30$), while it is listed globally as Least Concern (IUCN, 2021). We found only *H. uarnak* in the Vulnerable category of global Red List (IUCN, 2021), and in our PSA study the species scored low vulnerability ($V = 1.56$) in shrimp trawl fishery. The species is mainly exploited by artisanal fishing gears, i.e., modified drift gill nets, set bag nets, hooks and long lines (Roy et al., 2015; Haque et al., 2021). *H. nehereus*, as a single species listed as Near Threatened in the global Red List (IUCN, 2021), whereas it scored low vulnerability ($V = 1.25$) and largely caught by set bag nets, seine nets and gill nets (Sarker et al., 2017).

According to the exploitation rate ($E$) of the species previously assessed by FAO-ICLARM stock assessment tools in Figure 3.6, *M. sculptilis* (NAP), *P. merguiensis* (PBA), *S. sihama* (ILS), and *S. tri* (ESJ), which were categorized as low vulnerability ($V < 1.8$) in the PSA, had $E > 0.5$, indicating the over-fishing status of the stocks (Table 3.3 and Table A.2). *M. sculptilis* and *P. merguiensis* are majorly caught and exploited by set bag nets, drift nets and seine nets (Ahmed et al., 2008), whereas, *S. sihama* and *S. tri* are significantly captured by estuarine set bag nets, purse seines and beach seines (Rahman et al., 2009). Exploitation rate and vulnerability scores of the remaining species (Figure 3.6), were matched with each other and majority of those species are commonly caught by trawl nets (Fanning et al., 2019; Mustafa et al., 2006; Rahman et al., 2009). This is probably because the magnitude of stocks' exploitation rate can be fluctuated depending on spatio-temporal distribution of the stocks in fishing area, species sensitivity to different gears, fishing effort, and fishing pressure (Hilborn et al., 2020; Tu et al., 2018).

The species scored $V \geq 1.8$ had "decreasing" or "not significant" catch trend, whereas the species scored $V < 1.8$ had "stable" or "increasing" catch trend. Catch trends were determined by stakeholders' perceptions on the relative abundance of shrimp trawl fishery specific species. For instances, *N. japonicas* is ranked as "not significant" trend in the shrimp trawl fishery (Table 3.3), but was considered "stable" in the Hilsa gillnet fishery (Faruque and Matsuda, 2021a). Majority of larger and more valuable species were in the decreasing catch trend (Table 3.3 and Tables A.3 and A.4). Thus, the marine fisheries resources in the Bay of

Bengal are being exploited and depleted with declining trends in more valuable stocks (Fanning et al., 2019).

### 3.4.4 Impact of management strategy over the species' vulnerability caught from shrimp trawl fishery

In Bangladesh, a number of laws and regulations have been enacted to ensure the optimal resources utilization, conservation, and enhancement of fishery production, but conflicts frequently arise with the implementation of these laws and rules (Islam et al., 2017). Thereafter new policies and action plans have been implemented in order to sustain the potential of blue economy in the Bay of Bengal (Rahman, 2017). As a result, regulations have been framed, i.e., prohibiting discarded bycatch at sea, use of prescribed mesh size in gear, and specified fishing zones in continental shelf (IOTC, 2018). Though, noncompliance with these regulations, such as, use of small meshed net, failure of TED (Turtle Excluder Device) installation, fishing at a depth of less than 40 m, have been reported in some extent (MFO, 2019). It is expected that the present management strategy decreased the vulnerability scores for the majority of species from shrimp trawl fishery. However, we did not find any changes in the vulnerability categories, considering the $V < 1.8$ (low), $1.8 \leq V < 2.0$ (moderate), and $V \geq 2.0$ (high) scale (see column $V$ and $V$eMSt in Table 3.3), where $V$eMSt is the vulnerability scores obtained by excluding scores of category "Management Strategy" shown in Table 3.1. It is suggested that the present management strategy is not significantly effective to improve sustainable fisheries in the Bay of Bengal (Fanning et al., 2019). However, the future management planned by DoF (2020) may improve the sustainability of the industrial shrimp trawl fisheries. Stakeholders' compliance with the fishery regulations, and proper understanding of how the fishery laws are being enforced are also essential for sustainable resource management (Catedrilla et al., 2012).

## 3.5 Conclusions

Species vulnerability to shrimp trawl fisheries through PSA validated with the previously assessed IUCN extinction risk and exploitation rate, and also significantly with catch trend. We identified large information gaps in the species-specific life-history attributes that emphasized the need of species stock assessment in the Bay of Bengal. As in the case of data-limited multi-species fishery, our findings from such semi-quantitative ecological risk assessment tool may aid in the implementation of ecosystem approach to the conservation of the species at higher risk category.

## Acknowledgments

We are grateful to the officers and staffs of the Marine Fisheries Office, Chattogram, Bangladesh and management authorities of shrimp trawlers for their cordial supports during conducting surveys. We are also thankful to the skippers and crews of the shrimp trawlers for participating in interviews, and FGDs, and sharing valuable information about shrimp trawl fishery specific species. The authors would like to acknowledge the financial supports by the "Yokohama Industry Association Fellowship 2020-2021" through the Graduate School of Environment and Information Sciences, Yokohama National University, Japan.

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# Chapter 4

# Simple Indicators for Assessing Sustainability of Marine Aquaculture in Miyagi, Mie, and Kagoshima Prefectures, Japan

## Abstract

Assessment of aquaculture sustainability is a process to enhance optimal aquaculture production by minimizing environmental impacts such as eutrophication. In the present study, simple indicators are applied for sustainability assessment of Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna aquaculture in the enclosed bays and open water areas of Miyagi, Mie, and Kagoshima prefectures based on the estimation of annual aquaculture production, nutrient load and farms' location. The magnitude of sustainability indictors are varied significantly among the marine aquaculture in different enclosed bays and further verified with red tides occurrences and the degree of closure. Higher values of the sustainability indictors, $\Sigma I_2$, and $\Sigma I_3$ in enclosed bays indicated higher aquatic environmental consequences, and thus lower marine aquaculture sustainability. The study showed that the nutrient load with aquaculture farms' distance from bay mouth are related to higher impacts of marine aquaculture in aquatic environment. Bluefin Tuna farming have been considered to have a high feed conversion ratio and a high environmental impact, the nutrient load per unit production weight is also higher than other fish species. The nutrient load per production is lower in Coho Salmon and not much different between Red Seabream and Yellowtail. Furthermore, the nutrient load per economic yield was found to be rather low in Bluefin Tuna due to the high fish price. The findings of our research can assist aquaculture administrators to estimate annual fish production and nutrient load associated with marine aquaculture and to implement ecosystem approach for ensuring long-term viability of marine aquaculture.

**Keywords:** marine finfish; assessment indicators; sustainable aquaculture; annual fish production; nutrient load; red tides

## 4.1 Introduction

Aquaculture as a promising alternative to fisheries has grown while wild fish stocks have decreased (Naylor et al., 2021; Troell et al., 2014). Increased production from marine aquaculture has enormous potential to meet global seafood demand (Costello et al., 2020) and has contributed to bringing previously high-priced species within reach of the average consumer (De Silva, 2001). The expansion of aquaculture raises a number of issues directly related to its sustainable development (Lazard et al., 2011). For example, in intensive marine finfish aquaculture, excessively generated sediments and nutrients are mixed with the marine aquatic environment (Alleway et al., 2019; Rosa et al., 2020), that are linked to potentially causing environmental degradation such as eutrophication in aquatic ecosystems (Howarth et al., 2011).

Majority of the aquaculture farms are located in enclosed bay areas along the coast of Japan where the seawater exchange rate is comparatively low that leads to frequent occurrences of eutrophication (International EMECS Center, n.d.). Enclosed bay means where the cross-sectional area of the bay mouth is small compared to the maximum cross-sectional area of the bay, resulting in poor seawater exchange and making them prone to water pollution and eutrophication, and 88 enclosed bay areas are designated in Japan (International EMECS Center, n.d.). Despite such problems, enclosed bay areas are blessed with a calm natural environment and have been used as fishing grounds for a long time (International EMECS Center, n.d.). Microflora of an aquatic ecosystem can be impacted by an accumulation of organic enrichment of sediments underlying fish farms through discharges and waste products (Holmer et al., 2005). It affects the overlying water column of aquatic environment causing significant changes in sediment chemistry (Terlizzi et al., 2010), and seafood production through marine aquaculture might be disrupted (Fitridge et al., 2012).

Estimation of annual aquaculture production from the identified farms are essential to calculate aquaculture intensity. As marine aquaculture production grows, the intensity is anticipated to increase (Oddsson, 2020). Nutrient load that are associated with the productions of aquaculture are calculated by residual feeds and wastes from aquaculture (Bueno et al, 2017; Gao et al., 2022). The ability to exchange nutrients from the bay to the open ocean depends on the width of the bay mouth and the distance from farms to the bay mouth (Yokoyama, 2010). Nutrient load generated eutrophication such as red tides that severely affected marine aquaculture production in enclosed bays (International EMECS Center, n.d.).

The ratio of nutrient load to the farm volume is an important indicator of the environmental impact of aquaculture farms. Identification of aquaculture cages in a fish farm from satellite images by object detection can be possible through the application of deep learning (Ren et al., 2015, Gao et al., 2019). The rapid adoption of deep learning technology in a variety of fields, including aquaculture, has created both new opportunities and challenges for information and data processing (Zhao et al., 2021).

Sustainability assessment of marine aquaculture is necessary focusing on the factors, i.e., annual production, nutrient load estimation, location of aquaculture farms, which may have an impact on the environmental capacity of the aquaculture area (Gao et al., 2022). We used simple indictors to assess sustainability of marine aquaculture of majorly produced finfish species, i.e., Coho Salmon in Miyagi prefecture, Red Seabream, and Bluefin Tuna in Mie prefecture and Yellowtail, and Bluefin Tuna aquaculture in Kagoshima prefecture. Outcomes of the sustainability indictors' analysis further verified with red tides occurrences and the degree of closure of the enclosed bay. We observed the effect of aquatic environmental issues on marine finfish aquaculture to promote sustainable development of marine aquaculture in different enclosed bays in Japan.

## 4.2 Materials and methods

### 4.2.1 Study areas

Marine aquaculture is an important food producing industry in Japan, produced approximately 249,491 tons (25%) and 248,137 tons (27%) fishes from overall marine aquaculture production in fiscal year (FY) 2018 and FY 2019 respectively according to Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan (MAFF, 2021). The aquaculture industry includes marine finfish species that are predominantly produced in Japan, including Coho Salmon (*Oncorhynchus kisutch*), Red Seabream (*Pagrus major*), Yellowtail (*Seriola quinqueradiata*, *S. dumerili*, and *S. lalandi*), and Bluefin Tuna (*Thunnus orientalis*) (Abo et al., 2013; Matsuura et al., 2019; Watanabe and Sakami, 2021). Based on the majority of aquaculture species and their production in the study areas, aquaculture farms of Coho Salmon in Miyagi prefecture, Red Seabream and Bluefin Tuna in Mie prefecture, and Yellowtail and Bluefin Tuna in Kagoshima prefecture are selected for sustainability assessment. Marine aquaculture of Coho Salmon in Miyagi contributed approximately 88% of total Coho Salmon production in Japan (MAFF, 2021). Both Red Seabream and Bluefin Tuna of Mie contributed on an average 6%, whereas from Kagoshima, Yellowtail and Bluefin Tuna contributed on an average 32% and 17% of total production during FY 2018 to FY 2019, respectively (MAFF, 2021). There are 3 enclosed bays in Miyagi, whereas 5 in Mie and 4 in Kagoshima prefecture where different farms produced aquaculture species. Along with the farms in enclosed bays, several marine aquaculture farms are also identified outside of the studied 12 enclosed bays are considered as open water areas (Figure 4.1). Coloured triangles denote the fish farms with multiple cages where single to multi-species aquaculture exist. Enclosed bays and their areas are listed in the International EMECS Center, n.d.

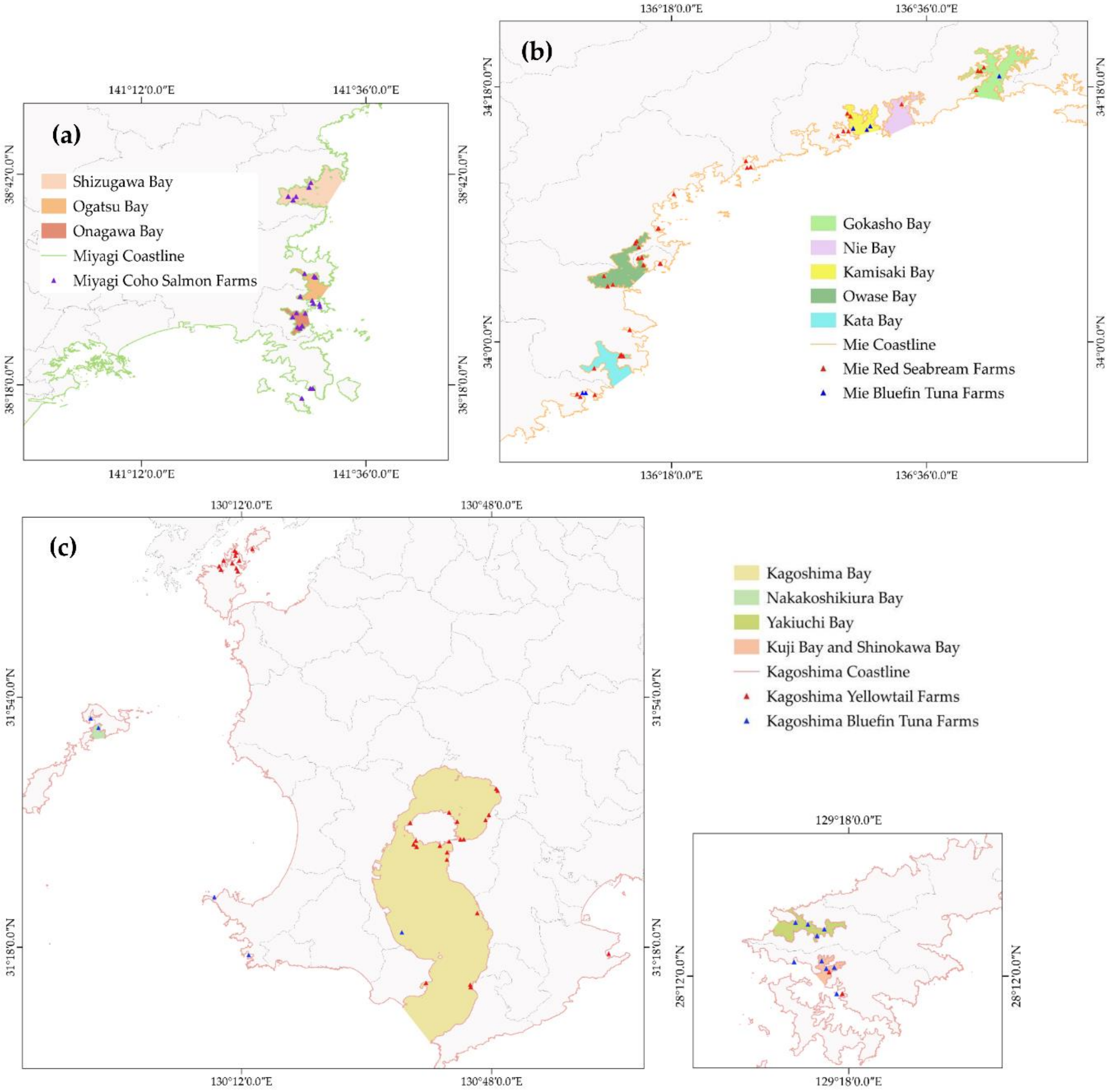


**Figure 4.1** Maps showing 111 marine aquaculture farms and 12 enclosed bays in (a) Miyagi, (b) Mie, and (c) Kagoshima prefectures in Japan. Coloured triangles indicate aquaculture farms and coloured filled areas indicate enclosed bays analyzed.

### 4.2.2 Aquaculture farms, annual fish production and nutrient load estimation

#### 4.2.2.1 Aquaculture cage detection and area calculation

Aquaculture farms location and area are obtained from the MDA Situational Indication Linkages and the Aquaculture Ground Database. Aquaculture Ground Database includes a map of aquaculture fishing grounds focusing on the Coho Salmon, Red Seabream, Bluefin Tuna and Yellowtail. Mean depth of aquaculture farms is estimated from the new pec smart (an application program made by mapple-on). The area and number of the aquaculture cages are identified and calculated manually based on historical satellite images of the aquaculture farms during FY 2018 to FY 2019 from Google Earth Pro software. However, some farms are also analyzed by object detection in Tensorflow Faster Region based Convolutional Neural Networks (TF Faster R-CNN), where the aquaculture cage is displayed in a bounding box with level of confidence.

#### 4.2.2.2 Estimation of annual fish production

The annual fish production is defined as the total farm production divided by the number of years between stocking and final harvesting (Gao et al., 2019). The estimated annual fish production for each farm is calculated using the following formula as taken from Gao et al. (2022),

$$p = \sum_{s=1}^{m} \left(\frac{P_s}{T_s}\right) \qquad (1)$$

where $p$ (kg/year) is the estimated annual fish production of each farm. Variable $m$ is the number of species reared in a farm and $s$ indicates fish species. $P_s$ (kg) is the estimated total production of each farm in $T_s$ (year) of species $s$. $T_s$ is the period between stocking and harvesting of species $s$. $P_s$ is estimated in the following Equation (Gao et al., 2022),

$$P_s = R_s \times \sum_{i=1}^{n} \rho V_i, \qquad (2)$$

where $n$ is the number of aquaculture cages in each farm;. $V_i$ ($m^3$) is the volume of fish cage $i$, and $V = (a \times d)$, $a$ = cage area ($m^2$) and $d$ = cage mean depth (m); $\rho$ (1025 kg/m$^3$) is the density of seawater; $R_s$ is the “species stock rate” of species $s$, which means weight ratio of stocked fish and seawater inside the cage when the fish are available for final harvest; $n$ denotes the number of cages used for species $s$ in a farm (Gao et al., 2022).

The statistical production for each farm in each year is not disclosed, while the prefecture-wide production $\Sigma_s P_s$ by year by fish species is disclosed. From Equation 2, we assume that each cage production is in proportion to its volume. For multi-species aquaculture and the fish species that take two years or more to final harvest, the number of cages in farms used for final harvest in a particular year is unknown, but we assume that the same volume of cages in farms is produced each year. From Equation 2, $\Sigma_{\mathrm{pref}} P_s = R_s(\Sigma_{\mathrm{pref}}\,\rho V)/T_s$, so $R_s = \Sigma_{\mathrm{pref}}\, P_s T_s\,/(\Sigma_{\mathrm{pref}}\,\rho V)$, where the sum "$\Sigma_{\mathrm{pref}}$" is taken for the entire prefecture. The production $P_s$ for each farm is calculated using Equation 2 with $R_s$. The production per year of farm is given by $p = \Sigma_{\mathrm{farm}} P_s/T_s = (\Sigma_{\mathrm{farm}}\rho V)\Sigma_{\mathrm{pref}} P_s/(\Sigma_{\mathrm{pref}}\,\rho V)$, in which $T_s$ is cancelled.

Average depth of each aquaculture cage is assumed as shown in Table 4.1, by interviewing some prefectural fish farmers. The statistical production $\Sigma P_s$ for each fish species in each prefecture is known. We estimated the total volume $\Sigma V_i$ of all farms by $\Sigma(a\times d)$. The mean value of $R_s$ can be estimated from $\Sigma P_s/\Sigma\rho V_s$. However, the stock rate is subjected to change due to the natural mortality of fish caused by typhoon and other natural disasters.

**Table 4.1** Aquaculture period, mean depth of cages and statistical marine aquaculture production in FY 2018 and FY 2019.

| **Prefectures** | **Aquaculture Species** | **Culture Period (years)** | **Cages Mean Depth (m)** | **Estimated Stock Rate (%)** | | **Statistical Production ($\Sigma P_s$, tons)** | |
|---|---|---|---|---|---|---|---|
| | | | | **2018** | **2019** | **2018** | **2019** |
| Miyagi | Coho Salmon | 1 | 10 | 2.25 | 2.01 | 15867 | 14179 |
| Mie | Red Seabream | 2 | 8 | 0.27 | 0.26 | 3824 | 3809 |
| | Bluefin Tuna | 3 | 10 | 0.09 | 0.13 | 950 | 1390 |
| Kagoshima | Yellowtail | 2 | 8 | 1.40 | 1.30 | 46277 | 43039 |
| | Bluefin Tuna | 3 | 10 | 0.16 | 0.17 | 3083 | 3362 |

#### 4.2.2.3 Estimation of annual nutrient load

The nutrient component ratios released from aquaculture farms depend on the content of nitrogen and phosphorus in the feed. Although these ratios vary among fish species and aquaculture sites, on average they are close to the Redfield ratios; $T_C$ (total carbon): $T_N$ (total nitrogen): $T_P$ (total phosphorus) = 1: 0.2: 0.03 (Gao et al., 2022).

The dry weight of carbon ($DW_C$) from aquaculture farms is estimated from feed conversion ratio ($FCR$), water content of feed ($WC_F$) and water content of fish ($WC_f$), which depends on species (Gao et al., 2022),

$$DW_C = WW_f \times \left[FCR \times (1 - WC_F) - \left(1 - WC_f\right)\right] \times CC, \tag{3}$$

where $CC$ is the carbon content (40%) in the discharged wastes from aquaculture farms. The first term in the Equation 3, $WW_f \times FCR \times (1-WC_F) \times CC$, is the dry weight of carbon of the feed and the second term $WW_f \times (1-WC_f) \times CC$, is the dry weight of carbon of the fish. Therefore,

$$T_C = p \times \left[FCR \times (1 - WC_F) - \left(1 - WC_f\right)\right] \times CC, \tag{4}$$

where $p$ is the annual production of the aquaculture farm. We use $WC_F$, and $WC_f$ for Red Seabream, and Yellowtail as given by Gao et al. (2022). Since compound feed is used for Coho Salmon aquaculture, $WC_F$ and $WC_f$ of Coho Salmon are similar with Red Seabream and Yellowtail. $WC_f$ for Bluefin Tuna is 75% and $WC_F$ is 60% as we assumed Bluefin Tuna required feed composed of both raw fish and fish meal in their diet from expert opinion (I Nagano, pers. comm.). We considered $FCR$ for Coho Salmon, Red Seabream, and Yellowtail from JFA (2014) and for Bluefin Tuna from the study of Ono and Nakahara (2009) as shown in Table 4.2. $T_N$ and $T_P$ are calculated from $T_C$ according to the Redfield ratio: *e.g.*, $T_N = 0.2\ T_C$. These fish species also differ in fish price (denoted by $q$). The economic yield per production $y$ is expressed by $qp$. As well as the nutrient load per production, the nutrient load per economic yield is also shown in Table 4.2. We use the fish price of each species as shown in Minato Shimbun.

**Table 4.2** Parameters for calculating nutrient load in marine aquaculture farm.

| **Parameters** | **Aquaculture Species** | | | |
|---|---|---|---|---|
| | **Coho Salmon** | **Red Seabream** | **Yellowtail** | **Bluefin Tuna** |
| $FCR$ | 1.3–1.5 | 2.5–2.7 | 2.3–2.8 | 13–15 |
| $WC_F$ (%) | 10 | 10 | 10 | 60 |
| $WC_f$ (%) | 75 | 75 | 75 | 75 |
| $T_N/p$ | 0.07–0.09 | 0.16–0.17 | 0.15–0.18 | 0.40–0.46 |
| Price $q$ (JPY/kg) | 500 | 600 | 1000 | 2500 |
| $T_N/y$ (kg/1000JPY) | 0.15–0.18 | 0.27–0.29 | 0.15–0.18 | 0.16–0.18 |

From the above Equation, a relationship between production weight ($p$) and nitrogen load ($T_N$) can be derived. It can be seen that the nutrient load of Bluefin Tuna is higher and the load of Coho Salmon is lower, mainly according to the $FCR$. However, as Bluefin Tuna has a higher fish price, the nitrogen load per economic yield ($y$) of Bluefin Tuna is considered to be low. Therefore, comparisons are made not only for production weight $p$, but also for production price $y$. Values for $FCR$ and nutrient load are given as intervals in Table 4.2, but the underlined values will be used in subsequent calculations.

### 4.2.3 Calculation of sustainability indicators

We conducted the present study to understand the practicability of the sustainability indicators in marine aquaculture on the basis of different parameters. Based on the annual fish production from each aquaculture farm, the sustainability of aquaculture can be evaluated through the following indicator, $I_1$ as taken from Gao et al. (2020). Aquaculture production per farm also termed as aquaculture intensity index by Gao et al. (2019) and aquaculture intensity has been used for years as a means to gauge how much production a site makes (Oddsson, 2020).

$$I_1 = \frac{p}{A \times H} = \frac{R_S \times \rho \times (a \times d)}{T_S \times A \times H} \qquad (5)$$

where $p$ (kg) is farm's annual fish production that derived from the Equation 1; $A$ ($m^2$) is surface area and $H$ (m) is mean depth of the farm site.

To consider the environmental impact, the nitrogen load per farm (kg/year) can be an important indicator. This is based on total nitrogen ($T_N$) instead of $p$ in $I_1$. We define the nitrogen load per farm, $I_2$, as:

$$I_2 = \frac{T_N}{A \times H}. \qquad (6)$$

However, the distance of the aquaculture farm from the bay mouth, denoted by $D$ (m), is significant for exchanging nutrient load. To this end, Gao et al. (2022) defined the following indicator.

$$I_3 = \frac{T_N \times D}{A \times H}. \qquad (7)$$

Gao et al. (2022) calculated indicator $I_4$ using $T_P$ instead of $T_N$ in $I_3$ and compared them with the nutrient loads from land inflow. Since the Redfield ratio was assumed, however, the ratio of $I_3$ and $I_4$ for each farm corresponds exactly to the Redfield ratio of $T_N$ and $T_P$. Therefore, we do not use $I_4$ for the phosphorus load.

Compared to $I_1$, the higher the $FCR$, the lower the water content $WC_F$ of the aquaculture species and the longer the distance ($D$) from the bay mouth, the higher the value of $I_3$ and the higher the environmental impact.

### 4.2.4 Red tides, the degree of closure and correlation analysis of the indictors

Duration of red tides information in the enclosed bays of studied prefectures during FY 2018 and FY 2019 are collected from the website of the prefectural government (Table B.1). Regulations of wastewater in enclosed bays depends on the degree of closure, which is defined as,

$$C = \frac{\sqrt{S} \times D_1}{W \times D_2}$$

where $S$ and $W$ are the area of enclosed bay and the width of bay mouth, respectively, and $D_1$ and $D_2$ are the maximum water depth in the bay and the maximum water depth along the bay mouth (International EMECS Center, n.d.) (Table B.2).

Once we found $I_1$, $I_2$, and $I_3$ of each aquaculture in an enclosed bay, we calculated $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ of all the studied aquaculture in each enclosed bay during FY 2018 and FY 2019. The total number of aquaculture farms varied among the enclosed bays, therefore, cumulative values for the sustainability indicator, $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ in each enclosed bay are also considered. We calculated the correlation coefficient for each enclosed bay's $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ with red tides occurrences in each enclosed bay during FY 2018 and FY 2019 and the degree of closure ($C$) to evaluate the validity of the indicators for aquaculture sustainability assessment.

## 4.3 Results

### 4.3.1 Aquaculture cage detection and area calculation

Aquaculture farms among the three prefectures varied in numbers and areas. Total 5918 aquaculture cages of 943272 m$^2$ area were identified (Table 4.3). Shape of aquaculture cages varied depending on the species cultured. Coho Salmon is majorly cultured in octagonal shaped cages, while Red Seabream, and Yellowtail in square and Bluefin Tuna in circular, and rectangular shaped cages.

**Table 4.3** Estimation of aquaculture area and cages information identified from satellite images analysis.

| Prefectures | Aquaculture Species | Farms Number | Total Farms Area (ha) | Total Cages Number | Total Cages Area ($m^2$) |
|---|---|---|---|---|---|
| Miyagi | Coho Salmon | 22 | 121 | 292 | 68701 |
| Mie | Red Seabream | 35 | 246 | 1632 | 175645 |
|  | Bluefin Tuna | 6 | 64 | 48 | 102460 |
| Kagoshima | Yellowtail | 34 | 1786 | 3833 | 404210 |
|  | Bluefin Tuna | 14 | 184 | 113 | 192256 |

### 4.3.2 Estimation of annual aquaculture production

We obtained the total production ($P_s$) of each farm using the $R_s$ for the entire prefecture and by the Equation 2. Therefore, by the Equation 1, we estimated annual production (*p/year*). The estimated aquaculture productions of Coho Salmon, Red Seabream, Bluefin Tuna and Yellowtail from the farms of the 12 enclosed bays account for more than half of the aquaculture production in Miyagi, Mie, and Kagoshima prefectures (Figure 4.1). Total 15 of 22 Coho Salmon aquaculture farms located in enclosed bay areas in Miyagi, whereas 20 of 35 Red Seabream farms and 4 of 6 Bluefin Tuna farms in Mie, and 21 of 34 Yellowtail farms, and 9 of 14 Bluefin Tuna farms in Kagoshima prefecture. In FY 2018, estimated Coho Salmon aquaculture production from enclosed bays in Miyagi was 9004 tons, and 8046 tons in FY 2019, which contributed around 57% of estimated annual Coho Salmon production in Miyagi (Figure 4.2). Estimated annual production from Red Seabream in combination with Bluefin Tuna from enclosed bays in Mie was 1635 tons and 1725 tons in FY 2018 and FY 2019 respectively, which shared around 73% of estimated annual production. In Kagoshima, estimated annual production form Yellowtail in combination with Bluefin Tuna from enclosed bays was 13753 tons in FY 2018 and 12900 tons in FY 2019, which shared around 57% of estimated annual production in Kagoshima respectively (Figure 4.2).

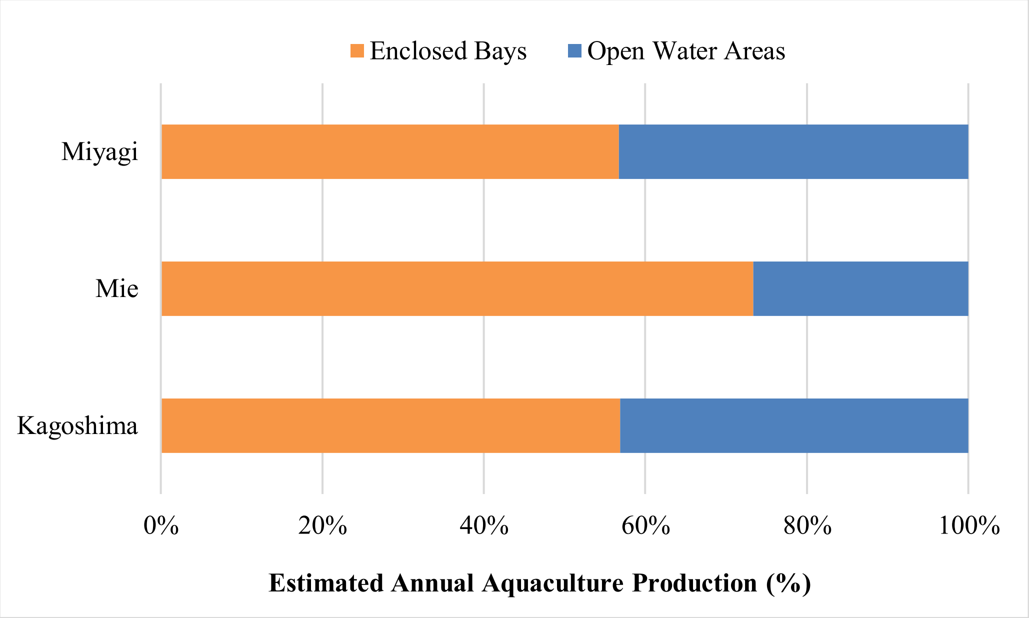


**Figure 4.2** Estimated annual aquaculture production (%) from enclosed bays and open water areas in Miyagi, Mie, and Kagoshima prefectures in FY 2018.

### 4.3.3 Estimation of annual nutrient load

Nutrient load estimated from aquaculture productions of Coho Salmon, Red Seabream, Bluefin Tuna, and Yellowtail are varied among 3 prefectures during FY 2018 and FY 2019 (Table 4.4). Feed conversion ratio (*FCR*) of different aquaculture species have great significance for the estimation of nutrient load. Production of nutrient load depend on the number of cages and annual production from each cage. In FY 2018, estimated annual total nitrogen ($T_N$) from Coho Salmon aquaculture farms in enclosed bays in Miyagi prefecture was 792 tons, whereas 708 tons in FY 2019 (Table 4.4). Around 57% annual nutrient load produced from different enclosed bays' Coho Salmon farms in Miyagi (Figure 4.3). In Mie prefecture, estimated annual $T_N$ from Red Seabream was 249 tons in FY 2018 and 248 tons in FY 2019, and from Bluefin Tuna was 95 tons, and 139 tons in FY 2018, and FY 2019 respectively (Table 4.4). Annual nutrient load from Red Seabream and Bluefin Tuna in enclosed bays shared around 75% and 65% respectively in Mie (Figure 4.3). Estimated annual $T_N$ from the enclosed bays in Kagoshima prefecture from Yellowtail aquaculture was 2374 tons in FY 2018 and 2208 tons in FY 2019, while from Bluefin Tuna was 312 tons and 340 tons in FY 2018, and FY 2019 respectively (Table 4.4). Enclosed bays in Kagoshima prefectures shared around 57% of Yellowtail and 66% of Bluefin Tuna estimated nutrient load (Figure 4.3).

**Table 4.4** Estimated nutrient load in the 12 enclosed bays and open water areas during FY 2018 and FY 2019.

| **Prefectures** | **Areas** | **Farm IDs** | **Aquaculture Species*** | **Total Nitrogen (tons/year)** | |
|---|---|---|---|---|---|
| | | | | **FY 2018** | **FY 2019** |
| Miyagi | **Enclosed Bays** | | | | |
| | Shizugawa | 1-5 | C | 399 | 356 |
| | Ogatsu | 6-9 | C | 164 | 147 |
| | Onagawa | 10-15 | C | 230 | 205 |
| | **Open Water** | | | | |
| | Izushima | 16-19 | C | 356 | 318 |
| | Ayukawa | 20-21 | C | 183 | 163 |
| | Ajishima | 22 | C | 65 | 58 |
| Mie | **Enclosed Bays** | | | | |
| | Gokasho | 1-5 | S, T | 63 | 74 |
| | Nie | 6 | S | 16 | 16 |
| | Kamisaki | 7-11 | S, T | 79 | 112 |
| | Owase | 12-20 | S | 158 | 157 |
| | Kata | 21-24 | S | 28 | 28 |
| | **Open Water** | | | | |
| | Minamiise | 25-27 | S | 18 | 18 |
| | Taiki | 28-30 | S | 18 | 18 |
| | Kihoku | 31-33 | S | 15 | 15 |
| | Sugari | 34-35 | S | 12 | 12 |
| | Kuki | 36 | S | 2 | 2 |
| | Kumano | 37-41 | S, T | 70 | 94 |
| Kagoshima | **Enclosed Bays** | | | | |
| | Kagoshima | 1-21 | Y, T | 2335 | 2173 |
| | Nakakoshikiura | 22 | T | 4 | 4 |
| | Yakiuchi | 23-26 | T | 181 | 198 |
| | Kuji and Shinokawa | 27-30 | Y, T | 166 | 173 |
| | **Open Water** | | | | |
| | Kimotsuki | 31 | Y | 105 | 98 |
| | Minami Satsuma | 32-33 | T | 23 | 25 |
| | Kuwanoura | 34 | T | 64 | 70 |
| | Nagashima | 35-45 | Y | 1560 | 1451 |
| | Setouchi | 46-48 | Y, T | 236 | 232 |

*C= Coho Salmon, S= Red Seabream, T= Bluefin Tuna, and Y= Yellowtail.

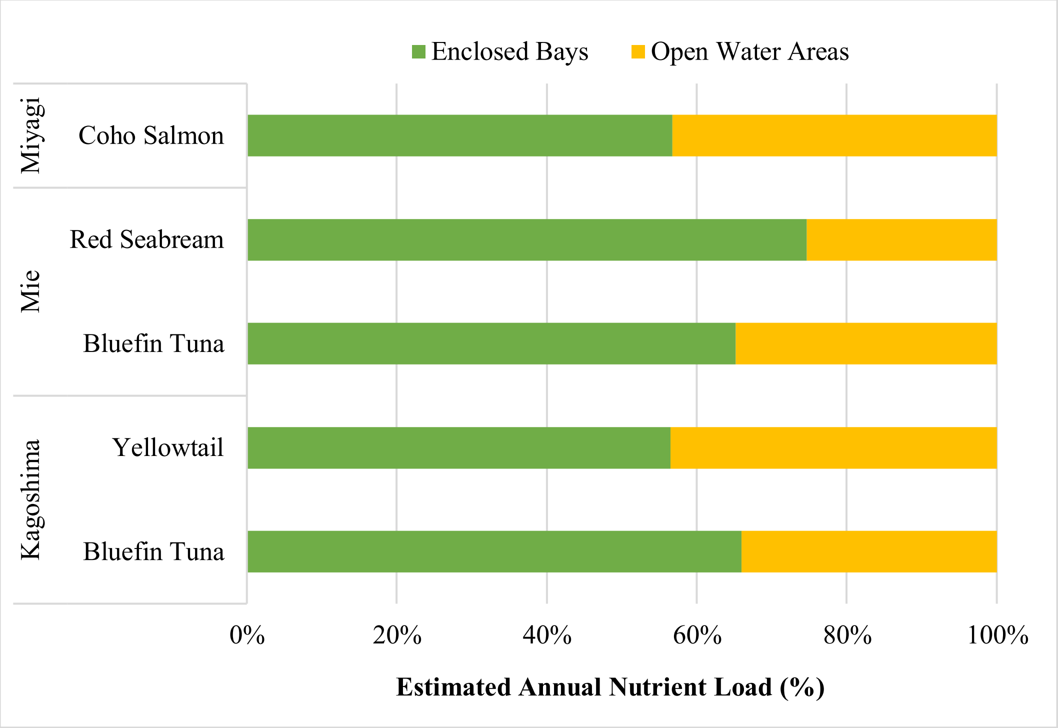


**Figure 4.3** Estimated annual nutrient load (%) from enclosed bays and open water areas in Miyagi, Mie, and Kagoshima prefectures in FY 2018.

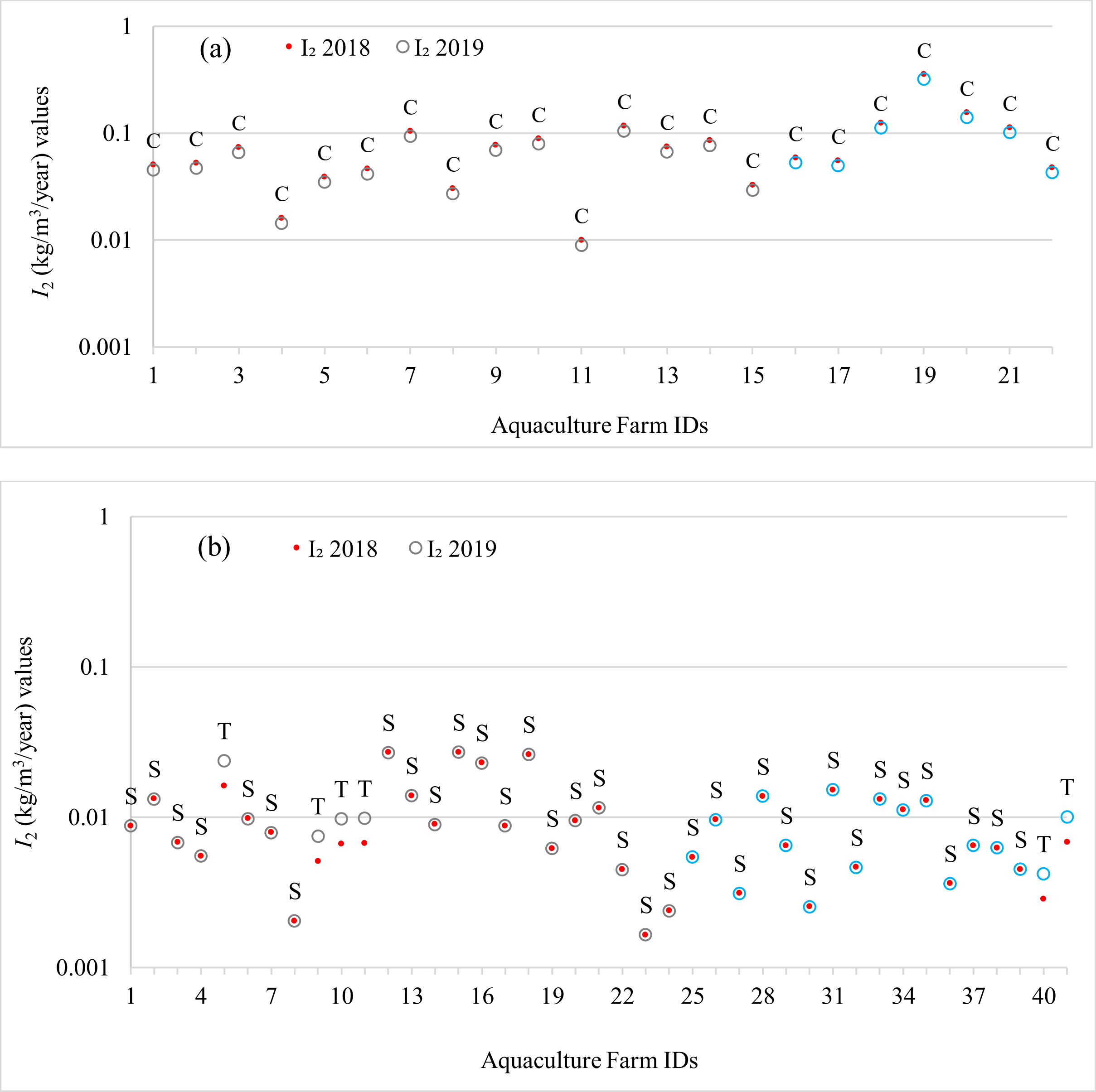
### 4.3.4 Calculation of sustainability indicators

#### 4.3.4.1 $I_1$ and $I_2$ index of all aquaculture farms

The $I_1$ values among 22 Coho Salmon aquaculture farms in Miyagi prefecture varied significantly. $I_1$ values ranged from 0.12 to 4.06 in FY 2018 and 0.10 to 3.63 in FY 2019 in Miyagi. In Mie prefecture, 35 Red Seabream farms, and 6 Bluefin Tuna aquaculture farms were identified. The $I_1$ values of Red Seabream farms in Mie ranged from 0.01 to 0.16 in both FY 2018 and FY 2019, whereas in Bluefin Tuna farms' $I_1$ values ranged from 0.01 to 0.04 and 0.01 to 0.05 in FY 2018 and FY 2019 respectively. In total, 34 Yellowtail farms were identified in Kagoshima prefecture and $I_1$ values were ranged from 0.003 to 0.73 in FY 2018, whereas in FY 2019, $I_1$ values of Yellowtail farms ranged from 0.003 to 0.68. Among 14 identified Bluefin Tuna farms in Kagoshima, $I_1$ values ranged from 0.003 to 0.04 in both FY 2018 and FY 2019.

We calculated $I_2$ values for the aquaculture farms located in both enclosed bays and open water areas. $I_2$ values ranged from 0.01 to 0.36 in FY 2018, whereas 0.01 to 0.32 in FY 2019 for Coho Salmon aquaculture in Miyagi (Figure 4.4). The deviation in $I_2$ from FY 2018 to FY 2019 were 0.1% to 3.8% among 22 Coho Salmon aquaculture farms. For Red Seabream aquaculture, we found $I_2$ values of 0.002 to 0.03 in both FY 2018 and FY 2019, whereas for

Bluefin Tuna farms 0.003 to 0.02 in FY 2018 and 0.04 to 0.02 in FY 2019 in Mie (Figure 4.4). The deviation of $I_2$ between FY 2018 and FY 2019 ranged 0–0.01% in Red Seabream farms and 0.1–0.8% in Bluefin Tuna farms in Mie. In Kagoshima, $I_2$ values ranged from 0.001 to 0.13 in FY 2018 and 0.0005 to 0.12 in FY 2019 for Yellowtail farms, whereas for Bluefin Tuna farms 0.001 to 0.02 in FY 2018 and 0.002 to 0.02 in FY 2019 (Figure 4.4). Deviation of $I_2$ in Yellowtail aquaculture ranged 0–0.9%, whereas 0.01–0.2% for Bluefin Tuna from FY 2018 to FY 2019 in Kagoshima. As the nutrient load was estimated from aquaculture fish production using the Redfield ratio, $I_2$ tended to be similar to $I_1$ in enclosed bays and open water areas in the studied prefectures. The phenomenon indicated that $I_2$ values of the marine aquaculture vary considerably in terms of annual nutrient load production.



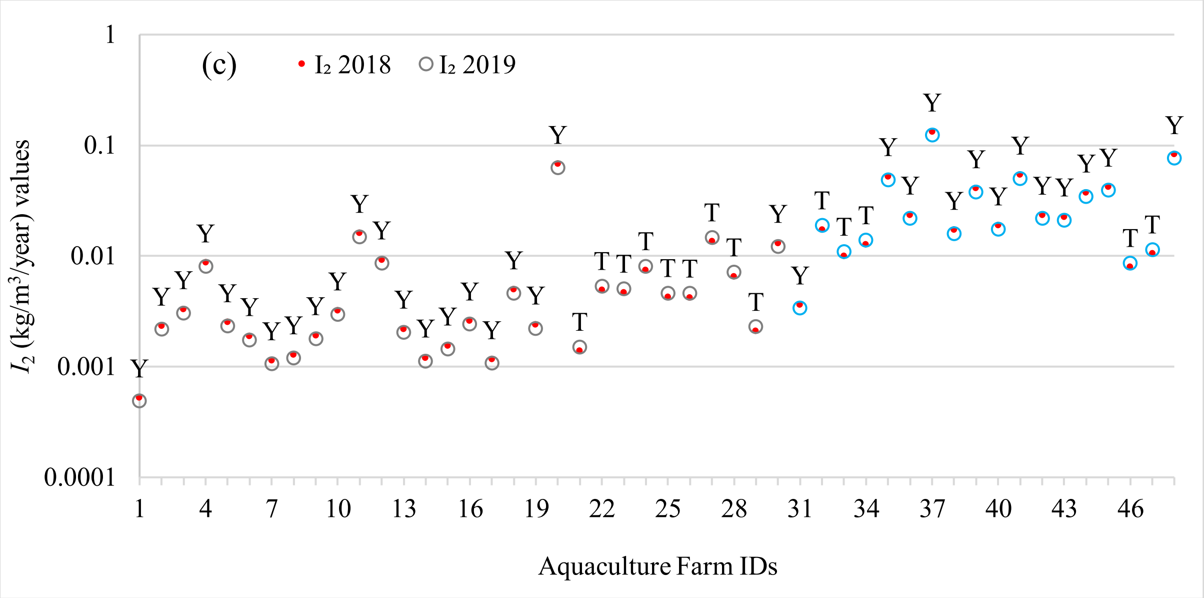


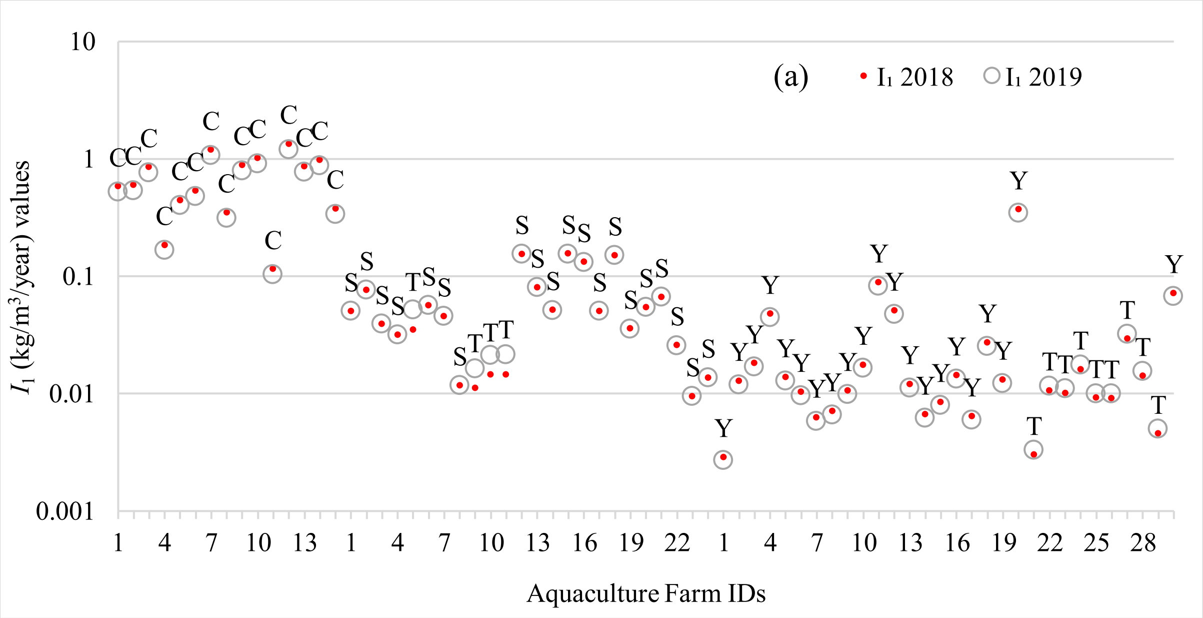
**Figure 4.4** Graphs showing $I_2$ values of different (a) Coho Salmon (labeled "C") farms in Miyagi prefecture, (b) Red Seabream ("S") and Bluefin Tuna farms ("T") in Mie prefecture, (c) Yellowtail ("Y") and Bluefin Tuna farms in Kagoshima prefecture. Red dots, and open circles indicate $I_2$ in FY 2018, and FY2019, respectively. Grey and Blue circles indicate aquaculture farms in enclosed bays, and open water, respectively. Numbers in horizontal axis indicate farm IDs shown in Table 4.4.

Variation in $I_1$ and $I_2$ values between years was small for all farms. This suggests that $I_1$ values and annual production, $I_2$ values and annual nutrient load varied between farms rather than between years. The area and mean depth of each farm were the same in both years, it suggests that the variation in annual production is reflected in the variation in $I_1$, and variation in annual nutrient load is reflected in the variation in $I_2$. The $I_1$ and $I_2$ were slightly higher in FY 2018 for Coho Salmon in Miyagi and Yellowtail in Kagoshima, whereas it were slightly higher in FY 2019 for Bluefin Tuna in Mie, and it were little difference between Red Seabream in Mie and Bluefin Tuna in Kagoshima prefecture. For Coho Salmon, $I_1$ and $I_2$ values tended to be higher in open water farms than in enclosed bay farms. In Mie Prefecture, $I_1$ and $I_2$ values tended to be higher in Red Seabream farms in enclosed bays. In Kagoshima Prefecture, disparities by region and by farm were observed, such as higher $I_1$ and $I_2$ for Yellowtail farms in Nagashima and lower $I_1$ and $I_2$ for one Bluefin Tuna farm in Kagoshima Bay.

### 4.3.4.2 Comparison between $I_1$, $I_2$ and $I_3$ indices in enclosed bays

The values of $I_1$, $I_2$ and $I_3$ are compared for aquaculture farms in enclosed bays (Figure 4.5). Coho Salmon had lower $I_3$ for higher $I_1$, mainly because farms for Coho Salmon are located at the shorter distance (*D)* from the bay mouth. Farms for Bluefin Tuna also have shorter *D*, but due to their high *FCR*, they have a high nutrient load per production. Around 62% (69) of the total 111 studied aquaculture farms are located in enclosed bay areas in the 3 prefectures. Therefore, distance from the aquaculture farms to bay mouth is another important factor along with the nutrient load for aquaculture sustainability.

Nutrient load, i.e., total nitrogen ($T_N$) estimated from different aquaculture farms are associated with distance from the aquaculture farms to bay mouth. $I_3$ values varied significantly among the aquaculture farms in the studied enclosed bays. In enclosed bays, $I_3$ values ranged from 5 to 387 in FY 2018, whereas 4 to 346 in FY 2019 for Coho Salmon farms in Miyagi (Figure 4.5). In the enclosed bay areas in Mie, $I_3$ values ranged from 1 to 138 in FY 2018 and 1 to 137 in FY 2019 for Red Seabream farms, whereas 4 to 47 in FY 2018, and 6 to 69 in FY 2019 for Bluefin Tuna farms (Figure 4.5). For Yellowtail aquaculture, $I_3$ values ranged from 23 to 1095 in FY 2018, and 22 to 1019 in FY 2019, whereas 5 to 46 in FY 2018, and 6 to 50 in FY 2019 for Bluefin Tuna aquaculture in enclosed bays in Kagoshima (Figure 4.5).



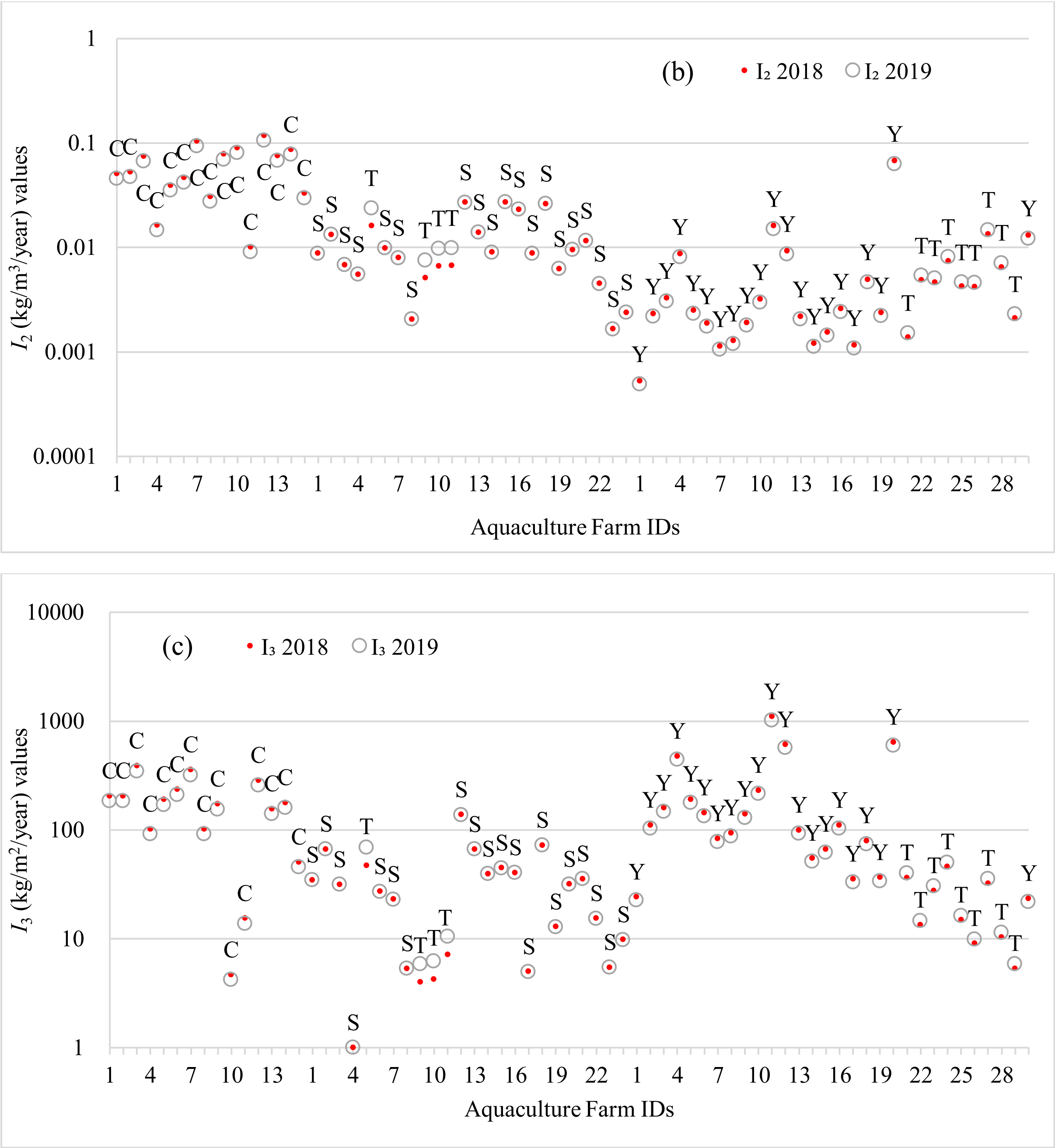


**Figure 4.5** Graphs showing (a) $I_1$, (b) $I_2$ and (c) $I_3$ values of aquaculture farms in enclosed bays. Red dots and open circles indicate values in FY2018 and FY2019, respectively. Labels “C”, “S”, “Y” and “T” indicates species as shown in Figure 4.4. Numbers in horizontal axis indicates farm IDs (from left to right: Miyagi, Mie, Kagoshima) shown in Table 4.4.

A comparison of the $\Sigma I_2$, and $\Sigma I_3$ of all the studied aquaculture farms in each bay showed variation among the bays in each year (Table 4.5). Higher $\Sigma I_2$ value was found in Onagawa Bay followed by Ogatsu Bay, whereas higher $\Sigma I_3$ value was found in Kagoshima Bay followed by Shizugawa Bay in both FY 2018 and FY 2019. The values of $\Sigma I_2$, and $\Sigma I_3$ in enclosed bays were comparatively higher in FY 2018 than FY 2019 (Table 4.5). Duration of red tides also higher in FY 2018 than FY 2019 in different enclosed bays. The degree of closure ($C$) values among all the studied bays were more than 1 and higher $C$ value was found in Kagoshima Bay (6.26) followed by Yakiuchi Bay (2.01).

**Table 4.5** $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ in the enclosed bays with the degree of closure ($C$) and duration of red tides occurrence.

| **Enclosed Bays** | **FY 2018** | | | **FY 2019** | | | **Red Tides* (days)** | | **$C$**** |
|---|---|---|---|---|---|---|---|---|---|
| | **$\Sigma I_1$** | **$\Sigma I_2$** | **$\Sigma I_3$** | **$\Sigma I_1$** | **$\Sigma I_2$** | **$\Sigma I_3$** | **FY 2018** | **FY 2019** | |
| Shizugawa | 2.67 | 0.23 | 1089 | 2.39 | 0.21 | 973 | 0 | 0 | 1.04 |
| Ogatsu | 2.97 | 0.26 | 866 | 2.65 | 0.23 | 774 | 0 | 0 | 1.48 |
| Onagawa | 4.71 | 0.41 | 691 | 4.21 | 0.37 | 618 | 1 | 0 | 1.39 |
| Gokasho | 0.23 | 0.05 | 181 | 0.25 | 0.06 | 202 | 36 | 1 | 1.81 |
| Nie | 0.06 | 0.01 | 27 | 0.06 | 0.01 | 27 | 0 | 1 | 1.08 |
| Kamisaki | 0.10 | 0.03 | 44 | 0.12 | 0.04 | 51 | 0 | 0 | 1.17 |
| Owase | 0.87 | 0.15 | 450 | 0.86 | 0.15 | 449 | 22 | 11 | 1.70 |
| Kata | 0.12 | 0.02 | 66 | 0.12 | 0.02 | 66 | 0 | 0 | 1.26 |
| Kagoshima | 0.75 | 0.14 | 4510 | 0.70 | 0.13 | 4200 | 50 | 11 | 6.26 |
| Nakakoshikiura | 0.01 | 0.005 | 13 | 0.01 | 0.01 | 15 | 0 | 15 | 1.20 |
| Yakiuchi | 0.04 | 0.02 | 97 | 0.05 | 0.02 | 106 | 0 | 0 | 2.01 |
| Kuji and Shinokawa | 0.12 | 0.04 | 72 | 0.12 | 0.04 | 74 | 0 | 0 | 1.20 |

*Table B.1

**Table B.2

### 4.3.5 Correlation of the indictors with red tides and the degree of closure

There were positive significant correlations among the $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ for logarithmic scales in the aquaculture farms located in different enclosed bays (Table 4.6). The logarithm was taken because there was a very large variation, especially for $\Sigma I_3$ values. Correlation coefficient ($r$) values found positive (0.541) between log $\Sigma I_3$ values in FY 2018 and red tides during FY 2018 (P=8.8%), and $r$ (0.561) found between log $\Sigma I_3$ values in FY 2019 and red tides during FY 2018 (P=7.6%), whereas the red tide occurrence in FY 2019 is not significantly correlated with log $\Sigma I_3$ values in FY 2018 (P=92.6%) and log $\Sigma I_3$ values in FY 2019 (P=91.3%). We also found statistically significant correlations of log $\Sigma I_3$ in FY 2018 and FY 2019 with the degree of closure (*C*) (P=5.3% and 4.8%, respectively). These results remain qualitatively the same with the other *FCR* values shown in Table 4.2.

**Table 4.6** Correlation among the $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ in enclosed bays with the degree of closure (*C*) and red tides occurrences during FY 2018 and FY 2019 according to Table 4.5.

| | **Parameters** | **FY 2018** | | | **FY 2019** | | | **FY 2018** | **FY 2019** |
|---|---|---|---|---|---|---|---|---|---|
| **FY 2018** | | $\log \Sigma I_1$ | | | | | | | |
| | $\log \Sigma I_2$ | $0.983^{**}$ | $\log \Sigma I_2$ | | | | | | |
| | $\log \Sigma I_3$ | $0.864^{**}$ | $0.895^{**}$ | $\log \Sigma I_3$ | | | | | |
| **FY 2019** | $\log \Sigma I_1$ | $1^{**}$ | $0.985^{**}$ | $0.862^{**}$ | $\log \Sigma I_1$ | | | | |
| | $\log \Sigma I_2$ | $0.974^{**}$ | $0.998^{**}$ | $0.885^{**}$ | $0.978^{**}$ | $\log \Sigma I_2$ | | | |
| | $\log \Sigma I_3$ | $0.854^{**}$ | $0.890^{**}$ | $0.999^{**}$ | $0.853^{**}$ | $0.882^{**}$ | $\log \Sigma I_3$ | | |
| **FY 2018** | Red tides | 0.197 | 0.262 | 0.541 | 0.201 | 0.273 | 0.561 | Red tides | |
| **FY 2019** | Red tides | -0.231 | -0.181 | 0.031 | -0.235 | -0.190 | 0.036 | 0.446 | Red tides |
| | *C* | 0.167 | 0.235 | 0.605 | 0.163 | 0.231 | $0.617^{*}$ | $0.807^{**}$ | 0.434 |

‘*’ and ‘**’ denote significance levels of 5% and 1%, respectively

## 4.4 Discussion

### 4.4.1 Aquaculture production and nutrient load

Aquaculture production and nutrient load varied significantly among all farms of the Coho Salmon in Miyagi, Red Seabream, and Bluefin Tuna in Mie, Yellowtail, and Bluefin Tuna in Kagoshima prefecture. Large farm area and low stocking density creates less chance of environmental pollution. As aquaculture production involve with the addition of solids and nutrients to the marine environment, and these inputs lead to potential environmental degradation (Gentry et al., 2016). The average water depths of aquaculture farms ranged from approximately 12 to 27 m in Miyagi, 8 to 41 m in Mie, and 8 to 156 m in Kagoshima prefecture. Greater water depth reduces the buildup of organic material beneath fish aquaculture area. Alternatively, smaller water depth increases impact on the flora and fauna of aquaculture area that causes major changes in sediment chemistry and thus affecting the overlying water column (Terlizzi et al., 2010). Aquaculture farms with species that are tolerable for highly intensive aquaculture are often subject to high nutrient loads. Conversely, in farms with species vulnerable to highly intensive aquaculture, nutrient load is mitigated for stable production.

Some farms of Coho Salmon and Yellowtail are the former and farms of Bluefin Tuna are the latter.

The distance from 15 aquaculture farms to the bay mouth ranged from approximately 52 to 6240 m in Miyagi, whereas 131 to 5092 m for 24 farms in Mie, and 1591 to 76266 m for 30 farms in Kagoshima prefecture. Greater distances between aquaculture farms and the bay's mouth point toward a lower chance of nutrients spreading from the farms to outside the bay (Gao et al., 2020), which might be cause environmental contamination and reduce aquaculture productivity (Olsen et al., 2008). Residual feed and metabolic waste of fish release nitrogen and phosphorus into the water of aquaculture farms may create a significant source of nutrients within the coastal areas (Carballeira Braña et al., 2021). Nitrogen and phosphorus are two important components of aquaculture wastes, both of which are regarded as potential water contaminants with significant environmental consequences (Dauda et al., 2019; Piedrahita, 2003), which may result toxic algal blooms by the proliferation of primary producers in aquatic environment (Paerl et al., 2018; Wang et al., 2018). Nutrient load per unit production weight from Bluefin Tuna aquaculture is higher due to higher *FCR*, but nutrient load per economic yield is lower as the price of Bluefin Tuna is likewise higher. Conversely, nutrient load per unit production weight is lower for Coho Salmon with lower *FCR*, while nutrient load per economic yield is higher for Coho Salmon with lower price.

Higher amount of nutrient load from Coho Salmon aquaculture were found in Shizugawa Bay, whereas in Owase Bay from Red Seabream aquaculture and in Kagoshima Bay from Yellowtail, and Bluefin Tuna aquaculture during FY 2018 to FY 2019. If farms have lower distance with bay mouth, nutrient load are easily circulated and exchanged from enclosed bay to open sea that reduce chances of bottom pollution. Therefore, aquaculture environment will be managed sustainably by utilizing aquatic resources (Frankic and Hershner, 2003).

### 4.4.2 Red tides and the degree of closure

In enclosed bay areas, water contamination and eutrophication are more likely to occur due to inadequate seawater exchange because the cross-sectional area at the bay's mouth is smaller than the bay's maximum cross-sectional area (International EMECS Center, n.d.). Therefore, the width of bay mouth is a significant feature for the viability of nutrient circulation produced from aquaculture farms. In recent years, overcrowded fish farms and excessive feeding have led to environmental deterioration of coastal areas, thought to be a major cause of eutrophication, red tides and fish diseases (Makino, 2017). During FY 2018 to FY 2019, red tides affected 6 of the 12 studied enclosed bays in Miyagi, Mie, and Kagoshima prefectures, whereas duration of red tides was higher in Owase and Kagoshima Bays. The phenomenon algal bloom, i.e., red tides was most likely driven by eutrophication of coastal areas caused by effluent loading and aquaculture expansion (Zohdi and Abbaspour, 2019). Noxious red tides are harmful to fish and invertebrates causing mass mortalities, particularly in intensive aquaculture in coastal area and increasing the negative impact on the aquaculture industry (Imai et al., 2006).

Wastewater regulations are applied to areas where the degree of closure ($C$), is 1 or higher according to the Water Pollution Control Law, Japan (International EMECS Center, n.d.). Among the 12 studied enclosed bays, higher $C$ value (6.26) was found in Kagoshima Bay, which has a relatively small bay mouth width of 11 km for a bay surface area of 1040 km$^2$. On the contrary, lower $C$ value (1.04) was found in Shizugawa Bay, which has a relatively large bay mouth width of 6.6 km for a bay surface area of 46.8 km$^2$. However, $C$ also depends on the maximum water depth both in the bay and bay mouth. $C$ values among the enclosed bays are ranged from 1.04 to 1.48 in Miyagi, 1.08 to 1.81 in Mie and 1.2 to 6.26 in Kagoshima. National government has specifically established an environmental standard type in consideration of the situation of water area (International EMECS Center, n.d.). Our studied bays are designated as “sea areas” and the environmental standard values, i.e., chemical oxygen demand ($COD$), total nitrogen ($TN$), and total phosphorus ($TP$) are assigned from 2 ≥ to 3 ≥ (mg/L), 0.2 ≥ to 0.3 ≥ (mg/L), and 0.02 ≥ to 0.03 ≥ (mg/L), respectively in order to prevent water pollution and water quality management for aquatic environment conservation in “sea areas” (International EMECS Center, n.d.).

### 4.4.3 Sustainability indicators and correlation analysis

Higher number of Coho Salmon aquaculture farms in Miyagi prefecture were found in Onagawa Bay compared to the area of bay, and width of bay mouth of Onagawa Bay was also smaller. Alternatively, surface area and width of bay mouth of Shizugawa Bay were larger compared to number of aquaculture farms. We found that, $\Sigma I_2$ value was higher in Onagawa Bay followed by Ogatsu and Shizugawa Bays, and $\Sigma I_3$ value was higher in Shizugawa Bay followed by Ogatsu and Onagawa Bays during FY 2018 and FY 2019 that suggested lower aquaculture sustainability, whereas $C$ value of Ogatsu Bay (1.48) was comparatively higher than other 2 bays. Red tides occurrence was observed once (1 day) in Onagawa Bay during FY 2018, whereas no record of red tides in Shizugawa and Ogatsu Bays. In FY 2019, red tides did not occur in the enclosed bays in Miyagi. The $\Sigma I_2$, and $\Sigma I_3$ values in 3 enclosed bays in Miyagi were decreased from FY 2018 to FY 2019 and red tides occurrences also decreased. Apart from 3 bays in Miyagi, 1 farm in Izushima area beside Ogatsu Bay had maximum $I_2$ values and most of the farms outside of the bay had comparatively higher $I_2$ values. In majority of aquaculture farms, $I_2$ of Coho Salmon aquaculture in Miyagi were decreased from FY 2018 to FY 2019. Therefore, nutrient load production from aquaculture should be considered for future sustainability and marine aquaculture development.

In Mie prefecture, $I_2$ values in the aquaculture farms located in bay areas were comparatively higher than open water areas. The width of bay mouth of Gokasho and Owase Bays were smaller in compared to the surface area than other 3 bays. Conversely, the number of aquaculture farms in Owase Bay was comparatively higher. The $\Sigma I_2$ value was also higher in Owase Bay followed by Gokasho, Kamisaki, Kata, and Nie Bays, whereas $\Sigma I_3$ value was higher in Owase Bay followed by Gokasho, Kata, Kamisaki, and Nie Bays. $C$ value in Gokasho Bay (1.81) was higher followed by Owase Bay (1.70). Red tides occurred thrice (total 22 days) and twice (total 36 days) in Owase and Gokasho Bays respectively during FY 2018, whereas once in Owase (11 days), Gokasho (1 day) and Nie (1 day) Bays during FY 2019. However, in Kamisaki and Kata Bays, red tides did not occur. In Owase Bay, $\Sigma I_2$ value was stable, but $\Sigma I_3$ value was slightly decreased from FY 2018 to FY 2019, and $\Sigma I_2$, and $\Sigma I_3$ values were increased in Gokasho and Kamisaki Bays, while stable in Nie and Kata Bays. Duration of red tides occurrences in Mie also decreased in Owase and Gokasho Bays, whereas increased in Nie Bay from FY 2018 to FY 2019.

Study in Kagoshima prefecture showed that, $I_2$ values in the farms of Nagashima area were comparatively higher than other Yellowtail aquaculture. Although the Kagoshima Bay had larger area, but width of bay mouth was smaller. In addition, number of farms were higher in Kagoshima Bay in comparison with Nakakoshikiura, Yakiuchi, Kuji and Shinokawa Bays. The $\Sigma I_2$ value was maximum in Kagoshima Bay followed by Kuji and Shinokawa, Yakiuchi, and Nakakoshikiura Bays, while $\Sigma I_3$ value was higher in Kagoshima Bay followed by Yakiuchi, Kuji and Shinokawa, and Nakakoshikiura Bays. $C$ value was also higher in Kagoshima Bay (6.26). Red tides occurred thrice (total 50 days) in Kagoshima Bay during FY 2018 and no record of red tides in other bays. In FY 2019, red tides occurred once in both Kagoshima (11 days) and Nakakoshikiura (15 days) Bays, whereas did not occur in Yakiuchi, Kuji and

Shinokawa Bays. The $\Sigma I_2$, and $\Sigma I_3$ values were decreased in Kagoshima Bay, while slightly increased in Nakakoshikiura Bay, and $\Sigma I_2$ value was stable, whereas $\Sigma I_3$ value was increased in Yakiuchi, Kuji and Shinokawa Bays from FY 2018 to FY 2019. Duration of red tides also decreased in Kagoshima Bay, whereas increased in Nakakoshikiura Bay.

Correlation analysis indicated a statistically significant correlation between log $\Sigma I_3$ values and the degree of closure ($C$) across the bay, although $I_3$ does not directly take the degree of closure into account. It suggests that enclosed bays with higher $C$ have consequently more aquaculture impacts at longer distances from the bay mouth. This suggests that a simple indicator, $I_3$, can be a useful indicator for assessing aquaculture sustainability. The fact that there was also a positive correlation between log $\Sigma I_3$ values and the red tides occurrence in FY 2018 indicates that nutrient load and farms' location in enclosed bay may have an impact on red tide occurrence. However, in FY 2019, the frequency of red tide outbreaks was lower than in FY 2018, except in Nakakoshikiura Bay, and no correlation with log $\Sigma I_3$ values was observed. If nutrient load and farms' location affects the frequency of red tide occurrence in enclosed bay, it may be limited to years when red tide is more likely to occur due to other factors.

Considering nutrient load per aquaculture farm, $I_2$ values could be indicators for assessing sustainability of Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna aquaculture outside of the enclosed bays as nutrient load production significantly related with environmental consequences. Alternatively, $\Sigma I_2$ and $\Sigma I_3$ values could be indicators for long-term sustainability assessment of marine aquaculture in enclosed bays. Higher values for $\Sigma I_2$, and $\Sigma I_3$ in enclosed bays suggested lower aquaculture sustainability and higher possibility of red tides occurrences. Therefore, Shizugawa and Onagawa Bays in Miyagi prefecture, Owase, and Gokasho Bays in Mie prefecture and Kagoshima Bay in Kagoshima prefecture may have the possibility to be affected by the risk of environmental consequences in marine aquaculture.

## 4.5 Conclusions

Increasing aquaculture productivity is one of the biggest challenges in terms of aquatic environmental sustainability. Duration of red tides occurrence in enclosed bays signified that the numerous issues to be addressed and accomplished for aquaculture sustainability. We emphasized on the improvement of research design by more thorough field work to recommend optimum aquaculture production. Baseline findings of this research on marine aquaculture can be helpful for estimating farms' level aquaculture production and associated nutrient load to predict future optimum seafood production from ecologically balanced aquatic environment.

## Acknowledgments

We are grateful to the staffs of the Japan Fisheries Cooperatives in Miyagi, Mie and Kagoshima prefectures for their cordial supports by sharing information related to marine aquaculture. We would like to thank Dr. Ichiro Nagano from the Central Research Laboratory, Tokyo Innovation Center, Nippon Suisan Kaisha, Ltd., Japan, for his insightful comments and suggestions about $FCR$, $WC_F$ and $WC_f$. The authors would like to acknowledge the financial support given by the Joint Research Promotion Program (Grant Number: 65A0519b), Graduate School of Environment and Information Sciences, Yokohama National University, Japan and JST SPRING (Grant Number: JPMJSP2108).

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# Chapter 5

# Study Limitations, Future Directions, and Conclusions

### 5.1 Study limitations and future directions

In shrimp trawl fishery, we did not accomplish molecular techniques, which are considered as the potential analytical approaches for the identification of highly diverse and morphologically flexible species (Zhang and Hanner, 2012).

We exclude, intrinsic rate of population increase, the most significant productivity attributes, while, susceptibility attribute, i.e., selectivity (size of capture relative to the size of maturity) is the strongest predictor of risk for a specific stock (Hordyk and Carruthers, 2018), from our PSA analysis due to lack of relevant data. A detailed study could be conducted later on to comprehend the impact of both attributes on the species' vulnerability from shrimp trawl fishery.

There are 9 species of CR and 30 of EN listed for freshwater fishes, and 2 species of EN listed for Crustacean in Bangladesh water (IUCN, 2015a, 2015b). It may be necessary to pay attention to the possibility of bycatch of species that were not included in this bycatch species list.

Commercially important Penaeidae shrimp species are currently exploited by both artisanal and industrial fisheries depending on different stages of life, i.e., juveniles and pre-adult by artisanal fishery, whereas adult by industrial fishery (Fanning et al., 2019). The majority of bycatch finfish and shellfish species are also caught by set bag nets, gillnets, seine nets, drift nets, hooks and long lines (Ahmed et al., 2008; Rahman et al., 2009). We did not combine species sensitivity to other gear types in our study because of insufficient data. However, inclusion of all types of gear sensitivity are effective for understanding the actual fishing status in the Bay of Bengal.

Moreover, we did not determine the over-exploited stocks' status in relation to overall multi-species fisheries in the Bay of Bengal to predict outcomes of management alternatives. Therefore, a convenient framework through harvest control rules based on the quantitative stock assessment, input control rules based on co-management, could be incorporated for further analysis to conduct sustainable management evaluations (Carruthers et al., 2014; de Bruyn et al., 2013; DoF, 2020). In addition, to determine the amount (number, weight) of species caught as bycatch, how that changes through time, and how that compares to the distribution/abundance of these species (also the distribution and intensity of fishing effort) would be significant to further guide management (Gallaway et al., 2020; Putman and Gallaway, 2020; Scott-Denton et al., 2016).

In marine aquaculture, we conducted the study focusing on the 4 major aquaculture species of 12 enclosed bays in 3 different prefectures based on the available data. Other fed and non-fed aquaculture species should be considered for overall sustainability analysis. Non-fed aquaculture species, i.e., oyster, scallop etc. are known to have a much lower nutrient load than fed aquaculture (Oita et al., 2015). Absorption of phytoplankton that uses nutrients excreted from cages in integrated multi-trophic aquaculture (IMTA) can further reduce the load from cultured fish to surrounding water (Abo et al., 2013). In addition, nutrient inputs from rivers, such as domestic wastewater, should also be considered.

Number of identified aquaculture cages from satellite images can be varied because some cages are kept bellow in water and not all the cages are used for aquaculture purposes at final harvest. Mean depth of cages and aquaculture farms can be varied also. Therefore, actual $I_1$, $I_2$, and $I_3$ values can be varied from farms to farms. In this regard, detailed field study of the aquaculture farms should be needed for the improved applicability of the indicators.

Red tides have significance on the sustainability of marine aquaculture, but the other parameters such as nutrients and oxygen concentrations may be the alternatives of the index. The nutrient load from aquaculture production that has an impact on red tides was taken into account, but red tides also influenced by other environmental parameters, i.e. light intensity, temperature, salinity etc. in marine environment (Genitsaris et al., 2019; Wells et al., 2020). Sustainability indicators including all the relevant environmental factors for red tides occurrences should be included for predicting effectiveness of the indicators in long-term sustainability analysis.

We did not suggest any threshold values of the sustainability indicators. However, threshold values of these indicators could be useful for proper resources utilization. Therefore, further analysis in overall aquaculture areas and longer term analysis could be included later on for the feasibility of the sustainability indicators that we proposed.

## 5.2 Conclusions

This study assessed the effects of shrimp trawl net fishing on marine capture fisheries in Bangladesh's Bay of Bengal using semi-quantitative ecological risk assessment PSA tool. We used PSA to evaluate the relative risk of the 60 species that interacted with the shrimp trawl fishery in the Bay of Bengal, Bangladesh, based on the information that was available regarding species-specific life histories and fishery-specific features. Seven (12%) of the non-target bycatch species were identified in the high risk category, whereas 17 (28%) of the species were found into the moderate risk category. The majority of the identified species showed higher productivity (37%) and susceptibility (46%). Considering previously assessed exploitation rate ($E$), 80% conformity degree was found between vulnerability ($V$) and $E$ among the identified 20 stocks. We also found significant relationship of the $V$ and catch trends. According to the vulnerability scores ($V \geq 1.8$), species were overfished by shrimp trawl fisheries and were categorized as moderate and high vulnerable with majority of decreasing catch trends and $V \leq 1.72$ showed the species of stable or increasing catch trends.

The study also assessed the marine aquaculture effects on the surrounding ecosystem in Japan's Miyagi, Mie, and Kagoshima prefectures using simple indicators for Coho Salmon, Red Seabream, Yellowtail, and Bluefin Tuna aquaculture in the enclosed bays and open water areas based on the aquaculture production per farm ($I_1$), nutrient load per farm ($I_2$), and nutrient load per farm with farms' location ($I_3$). The degree of the sustainability indictors, $\Sigma I_1$, $\Sigma I_2$, and $\Sigma I_3$ were notably different among the enclosed bays' marine aquaculture. The sustainability indicators that showed higher $\Sigma I_2$, and $\Sigma I_3$ values in the enclosed bays, had an adverse effect on the aquatic ecosystem and lower sustainability of marine aquaculture. The log $\Sigma I_3$ values in the enclosed bays showed positive correlation with the red tides duration in FY 2018 and statistically significant correlation with the degree of closure ($C$). Indicators analysis showed that marine aquaculture in Shizugawa and Onagawa Bays in Miyagi prefecture, Owase and Gokasho Bays in Mie prefecture, and Kagoshima Bay in Kagoshima prefecture had a greater impact on the aquatic ecosystem.

The findings of the study revealed the baseline information that assist to the fishery and aquaculture managers for maintaining future sustainability in both marine fisheries and marine aquaculture and effectiveness of the sustainability indicators was deemed to be appropriate considering the application in marine fisheries in Bangladesh and marine aquaculture in Japan.

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# Appendix

# Appendix A

**Table A.1** The following is a summary of the total shrimp trawlers (MFO, 2019*). Number of interviews and participants, as well as in parenthesis, Focus Group Discussions (FGDs) are shown.

| Sl. No. | Name of Trawler | Gross Tonnage (MT) | Capacity (BHP) | Interviews (FGDs) No. | Participants No. in Interview (FGDs) | Key Informants Interview (KII) |
|---|---|---|---|---|---|---|
| 1 | FT SRL–6 (Heartford–6) | 155 | 500 | 1 (1) | 5 (5) | 5 |
| 2 | FT SRL–3 (Heartford–10) | 230 | 960 | 1 | 5 | |
| 3 | FV Fisher–1 | 250 | 960 | 1 (1) | 5 (5) | |
| 4 | FV Fisher–2 | 239 | 960 | 1 (1) | 5 (5) | |
| 5 | FV Fisher–3 | 250 | 960 | 1 (1) | 5 (5) | |
| 6 | FV Deep Sea–4 (Fisher–4) | 239 | 960 | 1 | 5 | |
| 7 | FV Fisher–4 (Deep Sea-1) | 155 | 500 | 1 (1) | 5 (5) | |
| 8 | FV Deep Sea–3 | 230 | 960 | 1 | 5 | |
| 9 | F.V. Zanjabil | 127 | 520 | | | |
| 10 | F. V. Imam–1 | 185 | 410 | | | |
| 11 | F. V. Imam–2 | 185 | 410 | 1 | 5 | |
| 12 | F. V. Imam–3 | 195 | 720 | 1 | 5 | |
| 13 | F. V. RSR–1 (Meenhar–1) | 200 | 900 | | | |
| 14 | F. V. Meenhar–2 | 193 | 660 | 1 | 5 | |
| 15 | F. V. Mita | 193 | 560 | | | |
| 16 | F. V. Joutha Jatra | 193 | 750 | | | |
| 17 | F. V. Joutha Udyam | 193 | 560 | | | |
| 18 | F. V. Shah Jalal–1 | 115 | 400 | | | |
| 19 | F. V. Hasikin–10 | 152 | 335 | 1 | 5 | |
| 20 | F. V. Nabi | 128 | 800 | 1 | 5 | |
| 21 | F. V. Moin | 125 | 700 | 1 | 5 | |
| 22 | F. V. Mahishowar–1 | 160 | 410 | | | |
| 23 | F. V. Mahishowar–2 | 160 | 410 | | | |
| 24 | F. V. Moitri–S | 148 | 700 | 1 (1) | 5 (5) | |
| 25 | F. V. Moitri–T | 273 | 1100 | 1 (1) | 5 (5) | |
| 26 | F. V. Rupchanda | 181 | 840 | | | |
| 27 | F. V. Seyam | 226 | 520 | 1 | 5 | |
| 28 | F. V. Najat | 223 | 480 | 1 (1) | 5 (5) | |
| 29 | F. V. Rahmat | 234 | 900 | 1 (1) | 5 (5) | |
| 30 | F. V. Magferat | 220 | 520 | 1 (1) | 5 (5) | |
| 31 | F. V. Katla | 211 | 660 | | | |
| 32 | F. V. Datina | 214 | 660 | | | |

* MFO, 2019. Progress report on different activities of Marine Fisheries Office. Marine Fisheries Office, Department of Fisheries, Bangladesh, pp. 139.

**Table A.2** Species market value (SMV), species market demand (SMD), selectivity to Shrimp trawl net (SSTN), exploitation rate (*E*) data are shown. Catch trend (CT), catch trend score (CTS) and catch trend categories (CTC) of the listed species are also displayed.

| **Species FAO Code** | **SMV* (USD/kg)** 1 USD = 85 BDT | **SMD** * | **SSTN** | **Ref.** | ***E*** | **Ref.** | **CT* (N*=50)** | | | **CTS** ** | **CTC** ** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Increasing (1)** | **Stable (2)** | **Decreasing (3)** | | |
| GIT | 9.41 | High | High | 3; FGD | 0.65 | 6 | 7 | 9 | 34 | -1 | D |
| PNI | 7.65 | High | High | 3; FGD | 0.74 | 7 | 10 | 8 | 32 | -1 | D |
| PBA | 7.06 | High | High | 3; FGD | 0.68 | 8 | 16 | 19 | 15 | 1 | S |
| TIP | 7.65 | High | High | 3; FGD | 0.6 | 6 | 10 | 9 | 31 | -1 | D |
| MPN | 6.47 | High | High | 3; 4; FGD | 0.62 | 6 | 6 | 8 | 36 | -1 | D |
| MTJ | 5.88 | High | High | 3; FGD | | | 12 | 24 | 14 | 1 | S |
| MPB | 5.88 | High | High | 3; FGD | 0.81 | 7 | 7 | 12 | 31 | -1 | D |
| NAP | 4.12 | Moderate | High | 3; FGD | 0.55 | 9 | 17 | 25 | 8 | 1 | S |
| NAW | 4.12 | Moderate | High | 3; FGD | | | 14 | 24 | 12 | 1 | S |
| NAY | 4.12 | Moderate | High | 3; FGD | | | 17 | 23 | 10 | 1 | S |
| SCD | 2.06 | Low | High | 3; FGD | | | 16 | 23 | 11 | 1 | S |
| MUD | 2.35 | Low | High | 3; FGD | 0.39 | 10 | 15 | 21 | 14 | 1 | S |
| EJA | 2.94 | Low | High | 5; FGD | | | 15 | 28 | 7 | 1 | S |
| OJD | 2.59 | Low | High | 5; FGD | | | 14 | 21 | 15 | 1 | S |
| DHV | 2.35 | Low | Low | 1; 2; FGD | | | 15 | 23 | 12 | 1 | S |
| RHD | 2.12 | Low | Low | 1; 2; FGD | | | 11 | 24 | 15 | 1 | S |
| AUI | 2.47 | Moderate | High | 1; 2; FGD | | | 5 | 10 | 35 | -1 | D |
| CAO | 2.47 | Moderate | High | 1; 2; FGD | | | 8 | 9 | 33 | -1 | D |
| UKY | 2.35 | Moderate | High | 1; 2; FGD | | | 5 | 8 | 37 | -1 | D |
| DRI | 4.47 | High | High | 2; FGD | 0.62 | 11 | 7 | 11 | 32 | -1 | D |
| LSJ | 2.94 | Moderate | High | 2; FGD | | | 13 | 22 | 15 | 1 | S |
| TUP | 2.76 | Moderate | High | 2; FGD | | | 14 | 25 | 11 | 1 | S |
| POB | 4.71 | High | High | 1; 2; FGD | 0.52 | 15 | 7 | 6 | 37 | -1 | D |
| BIS | 3.18 | High | High | 2; FGD | | | 4 | 5 | 41 | -1 | D |
| COI | 4.12 | High | High | 2; FGD | | | 6 | 8 | 36 | -1 | D |
| YOB | 1.41 | Low | High | 1; 2; FGD | | | 8 | 8 | 34 | -1 | D |
| YOG | 1.53 | Low | High | 1; FGD | | | 7 | 10 | 33 | -1 | D |
| RAS | 2.94 | Moderate | High | 1; 2; FGD | | | 15 | 24 | 11 | 1 | S |
| ECD | 1.47 | Low | High | 1; 2; FGD | 0.48 | 12 | 15 | 22 | 13 | 1 | S |
| ESJ | 1.53 | Moderate | High | 1; 2; FGD | 0.85 | 7 | 17 | 20 | 13 | 1 | S |
| EYY | 1.65 | Moderate | High | 1; 2; FGD | | | 25 | 17 | 8 | 1 | S |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GEF | 3.71 | High | High | 2; FGD | | | 16 | 20 | 14 | 1 | S |
| LGS | 3.53 | High | High | 2; FGD | | | 16 | 27 | 7 | 1 | S |
| LGP | 3.53 | High | High | 2; FGD | | | 33 | 12 | 5 | 2 | I |
| LOB | 3.65 | High | Moderate | 1; FGD | | | 18 | 24 | 8 | 1 | S |
| LJH | 4.94 | High | High | 2; FGD | 0.78 | 14 | 6 | 9 | 35 | -1 | D |
| LJL | 4.94 | High | High | 2; FGD | | | 8 | 10 | 32 | -1 | D |
| MCG | 3.76 | High | High | 1; FGD | | | 5 | 7 | 38 | -1 | D |
| NNJ | 2.35 | Moderate | High | 1; 2; FGD | 0.59 | 15 | 17 | 8 | 25 | 0 | NS |
| NNZ | 2.47 | Moderate | High | 1; 2; FGD | | | 10 | 14 | 26 | 0 | NS |
| NPS | 2.47 | Moderate | High | 1; 2; FGD | | | 21 | 22 | 7 | 1 | S |
| PII | 3.18 | Moderate | High | 1; 2; FGD | | | 15 | 28 | 7 | 1 | S |
| FOT | 5.88 | High | High | 1; 2; FGD | | | 5 | 6 | 39 | -1 | D |
| OYD | 6.47 | High | Moderate | 1; 2; FGD | | | 3 | 6 | 41 | -1 | D |
| OAX | 5.53 | High | High | 1; 2; FGD | | | 9 | 8 | 33 | -1 | D |
| CBA | 3.65 | Moderate | Moderate | 1; 2; FGD | | | 23 | 18 | 9 | 1 | S |
| JOU | 3.59 | Moderate | High | 1; 2; FGD | | | 16 | 27 | 7 | 1 | S |
| OTB | 3.59 | Moderate | Moderate | 1; 2; FGD | | | 18 | 20 | 12 | 1 | S |
| EEN | 3.29 | High | Moderate | 2; FGD | | | 17 | 25 | 8 | 1 | S |
| MAR | 3.12 | High | Moderate | 2; FGD | | | 14 | 26 | 10 | 1 | S |
| SCN | 2.35 | Moderate | High | 2; FGD | | | 20 | 19 | 11 | 1 | S |
| ILS | 3.29 | High | High | 2; FGD | 0.75 | 7 | 16 | 25 | 9 | 1 | S |
| KBR | 2.71 | Moderate | High | 1; 2; FGD | | | 8 | 8 | 34 | -1 | D |
| YRB | 4.00 | High | High | 2; FGD | | | 13 | 9 | 28 | 0 | NS |
| SIP | 7.65 | High | High | 1; 2; FGD | 0.4 | 15 | 15 | 22 | 13 | 1 | S |
| CPO | 7.06 | High | High | 1; 2; FGD | 0.39 | 15 | 21 | 19 | 10 | 1 | S |
| BUC | 1.29 | High | High | 1; 2; FGD | 0.38 | 7 | 19 | 22 | 9 | 1 | S |
| LIG | 1.53 | Moderate | High | 1; 2; FGD | 0.35 | 16 | 32 | 10 | 8 | 2 | I |
| TJB | 2.59 | Moderate | High | 2; FGD | | | 22 | 18 | 10 | 1 | S |
| SVH | 1.76 | High | High | 1; 2; FGD | 0.43 | 13 | 16 | 23 | 11 | 1 | S |

[*] Data for SMV, SMD and CT are collected from Focus Group Discussions (FGDs). N represents number of participants.

[**] CTS and CTC represents, D = decreasing (-1); S = stable (1); NS = not significant (0); and I = increasing (2).

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**Table A.3** Twelve productivity (P) attributes of the listed species, i.e., maximum age ($t_{max}$), maximum size ($L_{max}$), von Bertalanffy growth coefficient ($K$), estimated natural mortality ($M$), measured fecundity (MF), breeding strategy (BS), age at first maturity ($t_{mat}$), size at first maturity ($L_{mat}$), mean trophic level (MTL), breeding cycle (BC), age at first maturity/maximum age ($t_{mat}/t_{max}$), size at first maturity/maximum size ($L_{mat}/L_{max}$) are shown in below with 3–alpha FAO codes, scores (P score), data quality (DQ) and references (Ref.).

| Species FAO Code | $t_{max}$ (yr$^*$) | P score | DQ | Ref. | $L_{max}$ (cm$^*$) | P score | DQ | Ref. | $K$ (yr$^{-1}$) | P score | DQ | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GIT | 2 | 3 | 4 | 153 | 35 | 2 | 4 | 154 | 0.97 | 3 | 2 | 155 |
| PNI | 2 | 3 | 4 | 163 | 23 | 3 | 4 | 154 | 0.55 | 2 | 2 | 27 |
| PBA | 2 | 3 | 4 | 167 | 25 | 3 | 4 | 154 | 1.235 | 3 | 2 | 168 |
| TIP | 1.8 | 3 | 4 | 160 | 23 | 3 | 4 | 154 | 0.9 | 2 | 2 | 155 |
| MPN | 2.5 | 3 | 4 | 171 | 11 | 3 | 4 | 154 | 1.52 | 3 | 2 | 155 |
| MTJ | 3 | 2 | 4 | 180 | 19 | 3 | 1 | 177 | 1.7 | 3 | 4 | 181 |
| MPB | 3 | 2 | 4 | 176 | 15.2 | 3 | 1 | 177 | 0.31 | 1 | 2 | 27 |
| NAP | 3 | 2 | 4 | 184 | 17 | 3 | 4 | 154 | 1.25 | 3 | 2 | 185 |
| NAW | 3 | 2 | 4 | 184 | 13.5 | 3 | 4 | 154 | 1.1 | 3 | 4 | 189 |
| NAY | 2.5 | 3 | 4 | 188 | 14.5 | 3 | 4 | 154 | 1.66 | 3 | 2 | 27 |
| SCD | 3 | 2 | 4 | 191 | 20 | 3 | 4 | 192 | 1.4 | 3 | 4 | 193 |
| MUD | 4 | 2 | 4 | 196 | 28 | 2 | 4 | 192 | 0.36 | 1 | 2 | 197 |
| EJA | 2 | 3 | 4 | 201 | 23 | 3 | 4 | 202 | 0.67 | 2 | 4 | 203 |
| OJD | 3 | 2 | 4 | 202 | 40 | 2 | 4 | 206 | 0.9 | 2 | 4 | 203 |
| DHV | 25 | 1 | 4 | 1 | 450 | 1 | 1 | 2 | 0.12 | 1 | 4 | 1 |
| RHD | 24 | 1 | 4 | 11 | 270 | 1 | 3 | 2 | 0.29 | 1 | 4 | 12 |
| AUI | 6 | 2 | 4 | 36 | 60 | 1 | 4 | 37 | 0.33 | 1 | 3 | 38 |
| CAO | 8 | 1 | 4 | 40 | 80 | 1 | 4 | 41 | 0.28 | 1 | 4 | 42 |
| UKY | 8.48 | 1 | 4 | 44 | 45 | 1 | 4 | 45 | 0.35 | 1 | 4 | 44 |
| DRI | 2.68 | 3 | 4 | 3 | 23 | 3 | 2 | 5 | 1.12 | 3 | 2 | 80 |
| LSJ | 10.2 | 1 | 4 | 67 | 29 | 2 | 1 | 4 | 1 | 3 | 4 | 68 |
| TUP | 3 | 2 | 4 | 71 | 26.5 | 2 | 4 | 72 | 1.4 | 3 | 4 | 73 |
| POB | 6 | 2 | 4 | 84 | 54 | 1 | 1 | 85 | 0.59 | 2 | 2 | 86 |
| BIS | 4 | 2 | 4 | 75 | 30 | 2 | 2 | 5 | 1.4 | 3 | 4 | 76 |
| COI | 20 | 1 | 4 | 15 | 140 | 1 | 4 | 16 | 0.11 | 1 | 4 | 17 |
| YOB | 12.5 | 1 | 4 | 3 | 35 | 2 | 2 | 5 | 0.24 | 1 | 4 | 133 |
| YOG | 9.38 | 1 | 4 | 3 | 40 | 2 | 2 | 5 | 0.32 | 1 | 4 | 8 |
| RAS | 4.11 | 2 | 4 | 3 | 20 | 3 | 2 | 5 | 0.73 | 2 | 4 | 142 |
| ECD | 1.5 | 3 | 1 | 21 | 20 | 3 | 2 | 5 | 1.3 | 3 | 2 | 21 |
| ESJ | 3.06 | 2 | 4 | 26 | 12 | 3 | 2 | 5 | 0.65 | 2 | 2 | 27 |
| EYY | 4 | 2 | 4 | 30 | 24.8 | 3 | 4 | 31 | 1 | 3 | 4 | 32 |
| GEF | 2 | 3 | 4 | 3 | 30 | 2 | 4 | 4 | 1.5 | 3 | 4 | 94 |
| LGS | 2.3 | 3 | 4 | 89 | 21 | 3 | 4 | 4 | 0.72 | 2 | 4 | 8 |
| LGP | 2.3 | 3 | 4 | 89 | 17 | 3 | 1 | 4 | 0.52 | 2 | 4 | 91 |
| LOB | 7 | 2 | 4 | 134 | 110 | 1 | 4 | 135 | 0.42 | 2 | 4 | 136 |
| LJH | 10 | 1 | 2 | 97 | 40 | 2 | 2 | 5 | 0.28 | 1 | 2 | 97 |
| LJL | 11 | 1 | 4 | 99 | 35 | 2 | 4 | 100 | 0.15 | 1 | 4 | 98 |
| MCG | 15.79 | 1 | 4 | 3 | 200 | 1 | 2 | 5 | 0.19 | 1 | 4 | 8 |
| NNJ | 8 | 1 | 4 | 104 | 32 | 2 | 2 | 5 | 0.94 | 3 | 2 | 86 |
| NNZ | 3 | 2 | 4 | 106 | 25 | 3 | 4 | 107 | 0.32 | 1 | 4 | 107 |
| NPS | 4.48 | 2 | 4 | 3 | 30.8 | 2 | 4 | 111 | 0.67 | 2 | 4 | 112 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PII | 2.19 | 3 | 4 | 47 | 30 | 2 | 1 | 4 | 1.37 | 3 | 4 | 47 |
| FOT | 20 | 1 | 4 | 3 | 90 | 1 | 2 | 4 | 0.15 | 1 | 4 | 120 |
| OYD | 15.78 | 1 | 4 | 3 | 142 | 1 | 4 | 123 | 0.19 | 1 | 4 | 8 |
| OAX | 8.11 | 1 | 4 | 3 | 30 | 2 | 1 | 4 | 0.37 | 1 | 4 | 8 |
| CBA | 12.48 | 1 | 4 | 145 | 200 | 1 | 1 | 4 | 0.24 | 1 | 4 | 145 |
| JOU | 3.13 | 2 | 4 | 3 | 18 | 3 | 2 | 5 | 0.96 | 3 | 4 | 113 |
| OTB | 6 | 2 | 4 | 117 | 151.9 | 1 | 4 | 118 | 0.19 | 1 | 4 | 118 |
| EEN | 5 | 2 | 4 | 3 | 106 | 1 | 1 | 4 | 0.6 | 2 | 4 | 56 |
| MAR | 3.75 | 2 | 4 | 3 | 150 | 1 | 2 | 4 | 0.8 | 2 | 4 | 60 |
| SCN | 7.8 | 1 | 4 | 148 | 40 | 2 | 4 | 149 | 1.6 | 3 | 4 | 150 |
| ILS | 7 | 2 | 4 | 34 | 30 | 2 | 4 | 4 | 0.39 | 2 | 2 | 27 |
| KBR | 25 | 1 | 4 | 101 | 70 | 1 | 4 | 4 | 0.22 | 1 | 4 | 102 |
| YRB | 4.23 | 2 | 4 | 3 | 35 | 2 | 1 | 4 | 0.71 | 2 | 4 | 144 |
| SIP | 7 | 2 | 4 | 131 | 52 | 1 | 1 | 85 | 0.53 | 2 | 2 | 86 |
| CPO | 4.5 | 2 | 4 | 3 | 50 | 1 | 1 | 85 | 0.67 | 2 | 2 | 86 |
| BUC | 2.6 | 3 | 4 | 52 | 40 | 2 | 2 | 5 | 0.42 | 2 | 2 | 27 |
| LIG | 7 | 2 | 4 | 49 | 45 | 1 | 2 | 5 | 0.64 | 2 | 2 | 50 |
| TJB | 4 | 2 | 4 | 61 | 30 | 2 | 2 | 5 | 0.62 | 2 | 4 | 62 |
| SVH | 3.3 | 2 | 4 | 125 | 104 | 1 | 1 | 126 | 0.8 | 2 | 2 | 126 |

[*] yr = year and cm = centimeter

**Table A.3 (continued)**

| Species FAO Code | $M$ (yr$^{-1}$) | P score | D Q | Ref. | MF | P score | D Q | Ref. | BS (P score) | D Q | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GIT | 1.72 | 3 | 2 | 155 | 120155 | 3 | 4 | 156 | 2 | 1 | 157 |
| PNI | 1.303 | 2 | 2 | 27 | 40000 | 2 | 4 | 164 | 2 | 1 | 157 |
| PBA | 2.37 | 3 | 2 | 168 | 59449 | 2 | 4 | 169 | 2 | 1 | 157 |
| TIP | 1.72 | 3 | 2 | 155 | 51605 | 2 | 4 | 161 | 2 | 1 | 161 |
| MPN | 2.65 | 3 | 2 | 155 | 47930 | 2 | 4 | 172 | 2 | 1 | 173 |
| MTJ | 2.61 | 3 | 4 | 181 | 88000 | 3 | 4 | 182 | 2 | 1 | 157 |
| MPB | 0.997 | 2 | 2 | 27 | 47930 | 2 | 4 | 172 | 2 | 1 | 157 |
| NAP | 2.43 | 3 | 2 | 185 | 39500 | 2 | 4 | 186 | 2 | 1 | 187 |
| NAW | 2.07 | 3 | 4 | 189 | 17250 | 2 | 4 | 190 | 2 | 1 | 157 |
| NAY | 3.062 | 3 | 2 | 27 | 39500 | 2 | 4 | 186 | 2 | 1 | 186 |
| SCD | 2.2 | 3 | 4 | 193 | 60000 | 2 | 4 | 194 | 2 | 1 | 157 |
| MUD | 0.58 | 1 | 2 | 197 | 2000000 | 3 | 2 | 154 | 2 | 1 | 198 |
| EJA | 1.33 | 2 | 4 | 203 | 214 | 1 | 4 | 204 | 2 | 1 | 157 |
| OJD | 1.41 | 2 | 4 | 203 | 1500 | 1 | 4 | 207 | 2 | 1 | 157 |
| DHV | 0.2 | 1 | 4 | 3 | 5 | 1 | 2 | 4 | 1 | 1 | 4, 5, 6 |
| RHD | 0.2 | 1 | 4 | 3 | 6 | 1 | 4 | 13 | 1 | 1 | 4, 6 |
| AUI | 0.7 | 1 | 4 | 3 | 66 | 1 | 4 | 39 | 1 | 1 | 4 |
| CAO | 0.86 | 1 | 4 | 42 | 47 | 1 | 4 | 43 | 1 | 1 | 4 |
| UKY | 0.54 | 1 | 4 | 44 | 29 | 1 | 4 | 46 | 1 | 1 | 4 |
| DRI | 2.1 | 3 | 2 | 80 | 18234 | 2 | 4 | 81 | 3 | 1 | 82 |
| LSJ | 1.8 | 3 | 4 | 68 | 59744 | 2 | 4 | 69 | 3 | 1 | 70 |
| TUP | 2.34 | 3 | 4 | 73 | 33298 | 2 | 4 | 74 | 3 | 1 | 70 |
| POB | 1.16 | 2 | 2 | 86 | 112170 | 3 | 1 | 87 | 3 | 1 | 88 |
| BIS | 2.21 | 3 | 4 | 76 | 86760 | 3 | 4 | 77 | 3 | 1 | 4, 24 |
| COI | 0.25 | 1 | 4 | 18 | 3000000 | 3 | 4 | 19 | 3 | 1 | 20 |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| YOB | 0.49 | 1 | 4 | 133 | 360 | 1 | 4 | 33 | 3 | 1 | 24 |
| YOG | 0.64 | 1 | 4 | 8 | 360 | 1 | 4 | 33 | 3 | 1 | 24 |
| RAS | 1.59 | 2 | 4 | 142 | 12642 | 1 | 4 | 143 | 3 | 3 | 24 |
| ECD | 2.49 | 3 | 2 | 22 | 1000 | 1 | 4 | 23 | 3 | 1 | 24 |
| ESJ | 1.59 | 2 | 2 | 27 | 2055 | 1 | 4 | 28 | 3 | 1 | 29 |
| EYY | 1.03 | 2 | 4 | 32 | 1920 | 1 | 4 | 33 | 3 | 1 | 34 |
| GEF | 2.47 | 3 | 4 | 94 | 121700 | 3 | 4 | 95 | 3 | 1 | 96 |
| LGS | 1.4 | 2 | 4 | 3 | 5397 | 1 | 4 | 90 | 3 | 1 | 24 |
| LGP | 1.38 | 2 | 4 | 91 | 5715 | 1 | 4 | 92 | 3 | 1 | 93 |
| LOB | 0.97 | 2 | 4 | 137 | 66843 | 2 | 4 | 138 | 3 | 1 | 139 |
| LJH | 0.59 | 1 | 2 | 97 | 149223 | 3 | 4 | 98 | 3 | 1 | 99 |
| LJL | 0.48 | 1 | 4 | 98 | 143264 | 3 | 4 | 98 | 3 | 1 | 99 |
| MCG | 0.3 | 1 | 4 | 3 | 306573 | 3 | 2 | 5 | 3 | 3 | 20 |
| NNJ | 1.79 | 3 | 2 | 86 | 14212 | 2 | 4 | 105 | 3 | 1 | 4 |
| NNZ | 0.86 | 1 | 4 | 107 | 12548 | 1 | 4 | 108 | 3 | 1 | 109 |
| NPS | 1.4 | 2 | 4 | 112 | 45823 | 2 | 4 | 111 | 3 | 3 | 109 |
| PII | 1.66 | 3 | 4 | 47 | 913 | 1 | 4 | 47 | 2 | 1 | 48 |
| FOT | 0.5 | 1 | 4 | 3 | 1005219 | 3 | 1 | 121 | 3 | 1 | 122 |
| OYD | 0.4 | 1 | 4 | 3 | 1005219 | 3 | 3 | 121 | 3 | 3 | 122 |
| OAX | 0.89 | 1 | 4 | 8 | 150000 | 3 | 3 | 124 | 3 | 3 | 122 |
| CBA | 0.42 | 1 | 4 | 145 | 1231630 | 3 | 4 | 146 | 3 | 1 | 4 |
| JOU | 2.02 | 3 | 4 | 113 | 93679 | 3 | 4 | 114 | 3 | 3 | 115 |
| OTB | 0.37 | 1 | 4 | 118 | 182020 | 3 | 4 | 119 | 3 | 3 | 24 |
| EEN | 0.5 | 1 | 4 | 3 | 51087 | 2 | 4 | 57 | 3 | 1 | 58 |
| MAR | 1.05 | 2 | 4 | 60 | 99000 | 3 | 4 | 59 | 3 | 1 | 58 |
| SCN | 2.37 | 3 | 4 | 151 | 242000 | 3 | 4 | 152 | 3 | 1 | 24 |
| ILS | 0.99 | 2 | 2 | 27 | 12023 | 1 | 4 | 66 | 3 | 1 | 24 |
| KBR | 0.26 | 1 | 4 | 102 | 47000 | 2 | 4 | 103 | 3 | 1 | 103 |
| YRB | 1.35 | 2 | 4 | 144 | 30175 | 2 | 4 | 4 | 3 | 1 | 4 |
| SIP | 1.18 | 2 | 2 | 86 | 26109 | 2 | 1 | 129 | 3 | 1 | 24 |
| CPO | 1.29 | 2 | 2 | 86 | 26109 | 2 | 3 | 129 | 3 | 1 | 24 |
| BUC | 0.94 | 2 | 2 | 27 | 89600 | 3 | 4 | 53 | 3 | 1 | 48 |
| LIG | 1.66 | 3 | 2 | 50 | 24160 | 2 | 4 | 51 | 3 | 1 | 24 |
| TJB | 1.23 | 2 | 4 | 62 | 13475 | 2 | 4 | 63 | 2 | 1 | 64 |
| SVH | 1.08 | 2 | 2 | 126 | 10435 | 1 | 2 | 127 | 3 | 3 | 128 |

**Table A.3 (continued)**

| Species FAO Code | $t_{mat}$ (yr$^*$) | P score | D Q | Ref. | $L_{mat}$ (cm$^*$) | P score | D Q | Ref. | MTL | P score | D Q | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GIT | 0.67 | 3 | 4 | 158 | 16.35 | 2 | 4 | 156 | 3.36 | 3 | 3 | 159 |
| PNI | 0.372 | 3 | 4 | 165 | 14.86 | 2 | 4 | 166 | 3.32 | 3 | 3 | 159 |
| PBA | 0.416 | 3 | 4 | 169 | 16 | 2 | 4 | 169 | 3.77 | 2 | 3 | 159 |
| TIP | 0.5 | 3 | 4 | 162 | 15.7 | 2 | 4 | 162 | 2.92 | 3 | 3 | 159 |
| MPN | 0.58 | 3 | 4 | 174 | 7.4 | 3 | 4 | 175 | 3.35 | 3 | 3 | 159 |
| MTJ | 0.5 | 3 | 4 | 181 | 8.86 | 3 | 4 | 182 | 3.93 | 1 | 3 | 159 |
| MPB | 0.5 | 2 | 4 | 178 | 10 | 3 | 4 | 176 | 3.35 | 3 | 3 | 159 |
| NAP | 0.5 | 3 | 4 | 178 | 7.8 | 3 | 4 | 187 | 3.1 | 3 | 3 | 159 |
| NAW | 0.5 | 3 | 4 | 178 | 7.3 | 3 | 4 | 190 | 3.1 | 3 | 3 | 159 |
| NAY | 0.5 | 3 | 4 | 188 | 7.5 | 3 | 4 | 188 | 2.66 | 3 | 3 | 159 |
| SCD | 1 | 2 | 4 | 154 | 10.5 | 3 | 4 | 195 | 3.54 | 2 | 3 | 159 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MUD | 1.5 | 2 | 4 | 154 | 10.98 | 3 | 4 | 199 | 3.5 | 2 | 3 | 159 |
| EJA | 0.75 | 1 | 4 | 205 | 9.9 | 3 | 4 | 204 | 3.39 | 3 | 3 | 159 |
| OJD | 1 | 2 | 4 | 208 | 10.25 | 3 | 4 | 208 | 3.77 | 2 | 3 | 159 |
| DHV | 4 | 1 | 4 | 7 | 202.2 | 1 | 4 | 3 | 3.6 | 2 | 3 | 8 |
| RHD | 2 | 2 | 4 | 12 | 128.7 | 1 | 4 | 3 | 3.8 | 2 | 3 | 8 |
| AUI | 2.41 | 1 | 4 | 3 | 34.1 | 1 | 4 | 3 | 3.5 | 2 | 3 | 8 |
| CAO | 3 | 1 | 4 | 40 | 44 | 1 | 4 | 3 | 3.4 | 2 | 3 | 8 |
| UKY | 2.1 | 1 | 4 | 44 | 26.4 | 1 | 4 | 3 | 4 | 1 | 3 | 8 |
| DRI | 0.73 | 3 | 4 | 3 | 13.5 | 2 | 4 | 83 | 3.6 | 2 | 3 | 8 |
| LSJ | 0.85 | 3 | 4 | 3 | 17.4 | 2 | 4 | 69 | 3.3 | 3 | 3 | 8 |
| TUP | 0.65 | 3 | 4 | 71 | 8 | 3 | 4 | 4 | 3.6 | 2 | 3 | 8 |
| POB | 1.3 | 2 | 4 | 3 | 30 | 1 | 4 | 5 | 2.9 | 3 | 3 | 8 |
| BIS | 0.55 | 3 | 4 | 3 | 17 | 2 | 4 | 78 | 3.8 | 2 | 3 | 8 |
| COI | 6.35 | 1 | 4 | 3 | 72 | 1 | 4 | 3 | 4.3 | 1 | 3 | 8 |
| YOB | 3.61 | 1 | 4 | 3 | 21.2 | 2 | 4 | 3 | 3.5 | 2 | 3 | 8 |
| YOG | 2.64 | 1 | 4 | 3 | 23.8 | 2 | 4 | 3 | 3.5 | 2 | 3 | 8 |
| RAS | 1.3 | 2 | 4 | 3 | 12.9 | 3 | 4 | 3 | 3.4 | 2 | 3 | 8 |
| ECD | 0.75 | 3 | 4 | 3 | 13.1 | 2 | 4 | 25 | 3.3 | 3 | 3 | 8 |
| ESJ | 1.25 | 2 | 4 | 3 | 7.1 | 3 | 4 | 26 | 3.3 | 3 | 3 | 8 |
| EYY | 0.69 | 3 | 4 | 3 | 13 | 2 | 4 | 35 | 3.6 | 2 | 3 | 8 |
| GEF | 0.38 | 3 | 4 | 3 | 13.7 | 2 | 4 | 95 | 3.3 | 3 | 3 | 8 |
| LGS | 1.31 | 2 | 4 | 3 | 13.5 | 2 | 4 | 3 | 3.3 | 3 | 3 | 8 |
| LGP | 1.04 | 2 | 4 | 3 | 7.5 | 3 | 4 | 92 | 2.9 | 3 | 3 | 8 |
| LOB | 1 | 2 | 4 | 140 | 46.3 | 1 | 4 | 141 | 4 | 1 | 3 | 8 |
| LJH | 3.02 | 1 | 4 | 3 | 23.8 | 2 | 4 | 3 | 4.2 | 1 | 3 | 8 |
| LJL | 2.65 | 1 | 4 | 3 | 12 | 3 | 4 | 4 | 4.1 | 1 | 3 | 8 |
| MCG | 5.02 | 1 | 4 | 3 | 125 | 1 | 4 | 5 | 4.3 | 1 | 3 | 8 |
| NNJ | 0.84 | 3 | 4 | 3 | 18.3 | 2 | 4 | 105 | 4.1 | 1 | 3 | 8 |
| NNZ | 1.7 | 2 | 4 | 3 | 11.02 | 3 | 4 | 110 | 3.8 | 2 | 3 | 8 |
| NPS | 0.66 | 3 | 4 | 3 | 11.5 | 3 | 4 | 111 | 3.5 | 2 | 3 | 8 |
| PII | 0.65 | 3 | 4 | 3 | 18.5 | 2 | 4 | 3 | 3.6 | 2 | 3 | 8 |
| FOT | 2.77 | 1 | 4 | 3 | 31.5 | 1 | 4 | 120 | 4.1 | 1 | 3 | 8 |
| OYD | 3.68 | 1 | 4 | 3 | 73 | 1 | 4 | 3 | 3.9 | 2 | 3 | 8 |
| OAX | 2.39 | 1 | 4 | 3 | 18.5 | 2 | 4 | 3 | 3.8 | 2 | 3 | 8 |
| CBA | 1.77 | 2 | 4 | 147 | 72 | 1 | 4 | 147 | 4 | 1 | 3 | 8 |
| JOU | 0.901 | 3 | 4 | 3 | 11 | 3 | 4 | 116 | 4.1 | 1 | 3 | 8 |
| OTB | 1.1 | 2 | 4 | 8 | 110.1 | 1 | 4 | 119 | 4.1 | 1 | 3 | 8 |
| EEN | 1.21 | 2 | 4 | 3 | 56.3 | 1 | 4 | 3 | 4 | 1 | 3 | 8 |
| MAR | 0.87 | 3 | 4 | 3 | 76.6 | 1 | 4 | 3 | 4.2 | 1 | 3 | 8 |
| SCN | 1.9 | 2 | 4 | 148 | 22.6 | 2 | 4 | 152 | 2.8 | 3 | 3 | 8 |
| ILS | 1.94 | 2 | 4 | 3 | 16.7 | 2 | 4 | 66 | 3.3 | 3 | 3 | 8 |
| KBR | 5.6 | 1 | 4 | 101 | 37.2 | 1 | 4 | 101 | 4.5 | 1 | 3 | 8 |
| YRB | 1.22 | 2 | 4 | 3 | 21.2 | 2 | 4 | 3 | 4.5 | 1 | 3 | 8 |
| SIP | 1.34 | 2 | 4 | 3 | 27.5 | 1 | 4 | 132 | 3.3 | 3 | 3 | 8 |
| CPO | 1.22 | 2 | 4 | 3 | 29 | 1 | 4 | 3 | 3.6 | 2 | 3 | 8 |
| BUC | 0.96 | 3 | 4 | 54 | 23.8 | 2 | 4 | 52 | 4.2 | 1 | 3 | 8 |
| LIG | 0.93 | 3 | 4 | 51 | 29.6 | 1 | 4 | 51 | 4.4 | 1 | 3 | 8 |
| TJB | 1.74 | 2 | 4 | 3 | 20.8 | 2 | 4 | 65 | 3.9 | 2 | 3 | 8 |
| SVH | 0.45 | 3 | 4 | 3 | 32.5 | 1 | 2 | 127 | 4.3 | 1 | 3 | 8 |

* yr = year and cm = centimeter

**Table A.3 (continued)**

| Species FAO Code | BC (P score) | D Q | Ref. | $t_{mat}$/ $t_{max}$ (yr$^*$) | P score | D Q | Ref. | $L_{mat}$/ $L_{max}$ (cm$^*$) | P score | D Q | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GIT | 3 | 4 | 156 | 0.34 | 1 | 4 | 153; 158 | 0.47 | 3 | 4 | 154; 156 |
| PNI | 3 | 4 | 166 | 0.19 | 3 | 4 | 163; 165 | 0.65 | 1 | 4 | 154; 166 |
| PBA | 3 | 4 | 170 | 0.21 | 2 | 4 | 167; 169 | 0.64 | 1 | 4 | 154; 169 |
| TIP | 3 | 4 | 161 | 0.28 | 2 | 4 | 160; 162 | 0.68 | 1 | 4 | 154; 162 |
| MPN | 3 | 4 | 172 | 0.23 | 2 | 4 | 171; 174 | 0.67 | 1 | 4 | 154; 175 |
| MTJ | 3 | 4 | 183 | 0.17 | 3 | 4 | 180; 181 | 0.47 | 3 | 4 | 177; 182 |
| MPB | 3 | 4 | 179 | 0.17 | 3 | 4 | 176; 178 | 0.66 | 1 | 4 | 176; 177 |
| NAP | 3 | 4 | 187 | 0.17 | 3 | 4 | 184; 178 | 0.46 | 3 | 4 | 154; 187 |
| NAW | 3 | 4 | 190 | 0.17 | 3 | 4 | 184; 178 | 0.54 | 2 | 4 | 154; 190 |
| NAY | 3 | 4 | 186 | 0.20 | 2 | 4 | 188 | 0.52 | 2 | 4 | 154; 188 |
| SCD | 3 | 4 | 195 | 0.33 | 1 | 4 | 154; 191 | 0.53 | 2 | 4 | 192; 195 |
| MUD | 3 | 4 | 200 | 0.38 | 1 | 4 | 154; 196 | 0.39 | 3 | 4 | 192; 199 |
| EJA | 3 | 4 | 201 | 0.38 | 1 | 4 | 201; 205 | 0.43 | 3 | 4 | 202; 204 |
| OJD | 3 | 4 | 209 | 0.33 | 1 | 4 | 202; 208 | 0.26 | 3 | 4 | 206; 208 |
| DHV | 2 | 4 | 9, 10 | 0.16 | 3 | 4 | 1; 7 | 0.45 | 3 | 4 | 2; 3 |
| RHD | 2 | 4 | 14 | 0.08 | 3 | 4 | 11; 12 | 0.48 | 3 | 4 | 2; 3 |
| AUI | 2 | 3 | 4 | 0.40 | 1 | 4 | 3; 36 | 0.57 | 2 | 4 | 3; 37 |
| CAO | 2 | 2 | 4 | 0.38 | 1 | 4 | 40 | 0.55 | 2 | 4 | 3; 41 |
| UKY | 2 | 3 | 4 | 0.25 | 2 | 4 | 44 | 0.59 | 2 | 4 | 3; 45 |
| DRI | 2 | 4 | 83 | 0.27 | 2 | 4 | 3 | 0.59 | 2 | 4 | 5; 83 |
| LSJ | 2 | 4 | 69 | 0.08 | 3 | 4 | 3; 67 | 0.60 | 1 | 4 | 4; 69 |
| TUP | 3 | 4 | 74 | 0.22 | 2 | 4 | 71 | 0.30 | 3 | 4 | 4; 72 |
| POB | 2 | 1 | 87 | 0.22 | 2 | 4 | 3; 84 | 0.56 | 2 | 4 | 5; 85 |
| BIS | 3 | 4 | 79 | 0.14 | 3 | 4 | 3; 75 | 0.57 | 2 | 4 | 5; 78 |
| COI | 1 | 4 | 20 | 0.32 | 1 | 4 | 3; 15 | 0.51 | 2 | 4 | 3; 16 |
| YOB | 3 | 4 | 33 | 0.29 | 2 | 4 | 3 | 0.61 | 1 | 4 | 3; 5 |
| YOG | 3 | 4 | 33 | 0.28 | 2 | 4 | 3 | 0.60 | 1 | 4 | 3; 5 |
| RAS | 2 | 4 | 143 | 0.32 | 1 | 4 | 3 | 0.65 | 1 | 4 | 3; 5 |
| ECD | 3 | 4 | 25 | 0.50 | 1 | 4 | 3; 21 | 0.66 | 1 | 4 | 5; 25 |
| ESJ | 3 | 4 | 26 | 0.41 | 1 | 4 | 3; 26 | 0.59 | 2 | 4 | 5; 26 |
| EYY | 2 | 4 | 33 | 0.17 | 3 | 4 | 3; 30 | 0.52 | 2 | 4 | 31; 35 |
| GEF | 3 | 4 | 95 | 0.19 | 3 | 4 | 3 | 0.46 | 3 | 4 | 4; 95 |
| LGS | 2 | 4 | 90 | 0.57 | 1 | 4 | 3; 89 | 0.64 | 1 | 4 | 3; 4 |
| LGP | 3 | 4 | 92 | 0.45 | 1 | 4 | 3; 89 | 0.44 | 3 | 4 | 4; 92 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| LOB | 3 | 4 | 139 | 0.14 | 3 | 4 | 134; 140 | 0.42 | 3 | 4 | 135; 141 |
| LJH | 3 | 4 | 98 | 0.30 | 1 | 4 | 3; 97 | 0.60 | 1 | 4 | 3; 5 |
| LJL | 3 | 4 | 98 | 0.24 | 2 | 4 | 3; 99 | 0.34 | 3 | 4 | 4; 100 |
| MCG | 2 | 2 | 5 | 0.32 | 1 | 4 | 3 | 0.63 | 1 | 4 | 5 |
| NNJ | 3 | 4 | 105 | 0.11 | 3 | 4 | 3; 104 | 0.57 | 2 | 4 | 5; 105 |
| NNZ | 2 | 4 | 110 | 0.57 | 1 | 4 | 3; 106 | 0.44 | 3 | 4 | 107; 110 |
| NPS | 3 | 4 | 111 | 0.15 | 3 | 4 | 3 | 0.37 | 3 | 4 | 111 |
| PII | 2 | 4 | 47 | 0.30 | 1 | 4 | 3; 47 | 0.62 | 1 | 4 | 3; 4 |
| FOT | 3 | 1 | 121 | 0.14 | 3 | 4 | 3 | 0.35 | 3 | 4 | 4; 120 |
| OYD | 3 | 3 | 121 | 0.23 | 2 | 4 | 3 | 0.51 | 2 | 4 | 3; 123 |
| OAX | 3 | 4 | 4 | 0.29 | 2 | 4 | 3 | 0.62 | 1 | 4 | 3; 4 |
| CBA | 3 | 4 | 147 | 0.14 | 3 | 4 | 145; 147 | 0.36 | 3 | 4 | 4; 147 |
| JOU | 2 | 4 | 114 | 0.29 | 2 | 4 | 3 | 0.61 | 1 | 4 | 5; 116 |
| OTB | 3 | 4 | 119 | 0.18 | 3 | 4 | 8; 117 | 0.73 | 1 | 4 | 118; 119 |
| EEN | 2 | 4 | 59 | 0.24 | 2 | 4 | 3 | 0.53 | 2 | 4 | 3; 4 |
| MAR | 2 | 4 | 59 | 0.23 | 2 | 4 | 3 | 0.51 | 2 | 4 | 3; 4 |
| SCN | 3 | 4 | 152 | 0.24 | 2 | 4 | 148 | 0.57 | 2 | 4 | 149; 152 |
| ILS | 3 | 4 | 66 | 0.28 | 2 | 4 | 3; 34 | 0.56 | 2 | 4 | 4; 66 |
| KBR | 2 | 4 | 101 | 0.22 | 2 | 4 | 101 | 0.53 | 2 | 4 | 4; 101 |
| YRB | 2 | 2 | 4 | 0.29 | 2 | 4 | 3 | 0.61 | 1 | 4 | 3; 4 |
| SIP | 3 | 4 | 132 | 0.19 | 3 | 4 | 3; 131 | 0.53 | 2 | 4 | 85; 132 |
| CPO | 2 | 4 | 130 | 0.27 | 2 | 4 | 3 | 0.58 | 2 | 4 | 3; 85 |
| BUC | 3 | 4 | 55 | 0.37 | 1 | 4 | 52; 54 | 0.59 | 2 | 4 | 5; 52 |
| LIG | 2 | 4 | 51 | 0.13 | 3 | 4 | 49; 51 | 0.66 | 1 | 4 | 5; 51 |
| TJB | 2 | 2 | 5 | 0.44 | 1 | 4 | 3; 61 | 0.69 | 1 | 4 | 5; 65 |
| SVH | 3 | 1 | 127 | 0.14 | 3 | 4 | 3; 125 | 0.31 | 3 | 4 | 126; 127 |

* yr = year and cm = centimeter

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**Table A.4** Ten susceptibility (S) attributes of the listed species, i.e., areal overlap (AO), vertical overlap (VO), seasonal migrations (SM), schooling, aggregation, and other behavioral responses (SABR), morphological characteristics affecting capture (MCAC), management strategy (MSt), survival after capture and release (SCR), species market value (SMV), species market demand (SMD), fishing rate relative to natural mortality (F/M) are shown in below with 3–alpha FAO codes, scores (S score), data quality (DQ) and references (Ref.).

| Species FAO Code | AO (S score) | DQ | Ref. | VO (S score) | DQ | Ref. | SM (S score) | DQ | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| GIT | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 3 | 2 | 32; 33; FGD |
| PNI | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 3 | 3 | 32; 33; FGD |
| PBA | 2 | 1 | 31 ; FGD | 2 | 4 | 31 ; FGD | 2 | 2 | 31; 33; FGD |
| TIP | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 2 | 3 | 32; 33; FGD |
| MPN | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 2 | 2 | 31; 33; FGD |
| MTJ | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 2 | 2 | 31; 33; FGD |
| MPB | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 1 | 2 | 31; 33; FGD |
| NAP | 3 | 1 | 31 ; FGD | 3 | 4 | 31 ; FGD | 2 | 2 | 31; 33; FGD |
| NAW | 2 | 1 | 31 ; FGD | 2 | 4 | 31 ; FGD | 1 | 3 | 31; 33; FGD |
| NAY | 2 | 1 | 31 ; FGD | 2 | 4 | 31 ; FGD | 1 | 3 | 31; 33; FGD |
| SCD | 2 | 1 | 31 ; FGD | 2 | 4 | 31 ; FGD | 2 | 3 | 32; 33; FGD |
| MUD | 2 | 1 | 31 ; FGD | 2 | 4 | 31 ; FGD | 2 | 2 | 32; 33; FGD |
| EJA | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 4 | 40; FGD |
| OJD | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 4 | 40; FGD |
| DHV | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 4 | 2; 3; 4; FGD |
| RHD | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 4 | 2; 4; FGD |
| AUI | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 2; 3; 4; FGD |
| CAO | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 2; 3; 4; FGD |
| UKY | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 3 | 2; 3; 4; FGD |
| DRI | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 2; 4; FGD |
| LSJ | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 4 | 2; 4; FGD |
| TUP | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 3 | 4; FGD |
| POB | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 3 | 4; 9; FGD |
| BIS | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 4; FGD |
| COI | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 2; FGD |
| YOB | 3 | 3 | 10; FGD | 3 | 4 | 1; FGD | 2 | 3 | 4; 9; FGD |
| YOG | 3 | 1 | 10; FGD | 3 | 4 | 1; FGD | 3 | 2 | 4; 9; FGD |
| RAS | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 4 | 2; FGD |
| ECD | 3 | 1 | 10; FGD | 3 | 4 | 1; FGD | 2 | 2 | 2; 4; 9; FGD |
| ESJ | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 2; 3; 4; FGD |
| EYY | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 4 | 4; 9; FGD |
| GEF | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 2 | 4; FGD |
| LGS | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 4 | 2; 4; FGD |
| LGP | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 4 | 2; 4; FGD |
| LOB | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 4; 9; FGD |
| LJH | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 4; FGD |
| LJL | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 3 | 4; FGD |
| MCG | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 2 | 3; 4; 9; FGD |
| NNJ | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 2; 23; FGD |
| NNZ | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 2; 23; FGD |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NPS | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 3 | 4 | 2; 23; FGD |
| PII | 1 | 3 | 10; FGD | 1 | 4 | 1; FGD | 1 | 3 | 2; 4; FGD |
| FOT | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 2; 4; 9; FGD |
| OYD | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 2; 4; 9; FGD |
| OAX | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 3 | 4; FGD |
| CBA | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 3 | 4; FGD |
| JOU | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 3 | 4; FGD |
| OTB | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 3 | 4; FGD |
| EEN | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 3 | 4; FGD |
| MAR | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 4; FGD |
| SCN | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 4 | 4; FGD |
| ILS | 1 | 3 | 10; FGD | 1 | 4 | 1; FGD | 1 | 3 | 2; 4; FGD |
| KBR | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 3 | 2; FGD |
| YRB | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 4 | 2; FGD |
| SIP | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 2; 4; 9; FGD |
| CPO | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 2; 4; 9; FGD |
| BUC | 1 | 3 | 1; FGD | 1 | 4 | 1; FGD | 1 | 2 | 2; 3; 4; 9; FGD |
| LIG | 3 | 3 | 1; FGD | 3 | 4 | 1; FGD | 2 | 3 | 4; FGD |
| TJB | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 1 | 2 | 4; 9; FGD |
| SVH | 2 | 3 | 1; FGD | 2 | 4 | 1; FGD | 2 | 2 | 2; 9; FGD |

**Table A.4 (continued)**

| Species FAO Code | SABR (S score) | DQ | Ref. | MCAC (S score) | DQ | Ref. | MSt (S score) | DQ | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| GIT | 2 | 2 | 32; 34; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| PNI | 2 | 4 | 32; 34; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| PBA | 3 | 2 | 32; 34; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| TIP | 2 | 2 | 32; 34; 36; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| MPN | 3 | 2 | 32; 34; FGD | 3 | 4 | 31; FGD | 2 | 1 | 6; 7; FGD |
| MTJ | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| MPB | 3 | 2 | 32; 34; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| NAP | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| NAW | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| NAY | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| SCD | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| MUD | 2 | 4 | 32; FGD | 3 | 4 | 32; FGD | 2 | 1 | 6; 7; FGD |
| EJA | 2 | 4 | 40; FGD | 3 | 4 | 40; FGD | 2 | 1 | 6; 7; FGD |
| OJD | 3 | 4 | 40; FGD | 3 | 4 | 40; FGD | 2 | 1 | 6; 7; FGD |
| DHV | 2 | 4 | 3; 5; FGD | 1 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| RHD | 2 | 4 | 8; FGD | 1 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| AUI | 3 | 3 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| CAO | 2 | 1 | 2; 13; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| UKY | 3 | 3 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| DRI | 2 | 1 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| LSJ | 3 | 1 | 2; 18; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| TUP | 2 | 1 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| POB | 3 | 1 | 2; 13; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| BIS | 3 | 1 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| COI | 2 | 4 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| YOB | 2 | 4 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| YOG | 2 | 4 | 2; FGD | 3 | 4 | 3; FGD | 2 | 1 | 6; 7; FGD |
| RAS | 2 | 4 | 2; FGD | 3 | 4 | 2; 3; 28; FGD | 2 | 1 | 6; 7; FGD |
| ECD | 3 | 4 | 2; 3; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| ESJ | 2 | 1 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| EYY | 3 | 1 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| GEF | 2 | 3 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| LGS | 3 | 1 | 2; 18; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| LGP | 3 | 1 | 2; 13; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| LOB | 2 | 4 | 3; 27; FGD | 2 | 4 | 3; FGD | 2 | 1 | 6; 7; FGD |
| LJH | 3 | 3 | 2; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| LJL | 3 | 1 | 2; 22; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| MCG | 2 | 4 | 3; FGD | 3 | 4 | 3; FGD | 2 | 1 | 6; 7; FGD |
| NNJ | 3 | 1 | 2; 13; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| NNZ | 2 | 4 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| NPS | 2 | 4 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| PII | 3 | 1 | 2; 14; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| FOT | 2 | 2 | 2; 24; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| OYD | 2 | 4 | 2; FGD | 2 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| OAX | 2 | 3 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| CBA | 2 | 2 | 2; 30; FGD | 2 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| JOU | 3 | 3 | 2; FGD | 3 | 3 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| OTB | 3 | 3 | 2; FGD | 2 | 3 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| EEN | 2 | 4 | 2; FGD | 2 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| MAR | 3 | 4 | 2; FGD | 2 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| SCN | 3 | 1 | 2; 13; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| ILS | 2 | 4 | 2; 13; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| KBR | 3 | 1 | 2; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| YRB | 3 | 2 | 2; 29; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| SIP | 3 | 1 | 2; 13; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| CPO | 2 | 1 | 2; 13; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| BUC | 3 | 1 | 2; 16; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| LIG | 3 | 4 | 2; 3; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |
| TJB | 3 | 1 | 2; 17; FGD | 3 | 4 | 2; FGD | 2 | 1 | 6; 7; FGD |
| SVH | 3 | 2 | 13; 25; FGD | 3 | 4 | 2; 3; FGD | 2 | 1 | 6; 7; FGD |

**Table A.4 (continued)**

| Species FAO Code | SCR (S score) | DQ | Ref. | SMV (S score) (USD/kg) | DQ | Ref. | SMD (S score) | DQ | Ref. | F/M (S score) | DQ | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GIT | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 35 |
| PNI | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 12 |
| PBA | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 37 |
| TIP | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 35 |
| MPN | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 35 |
| MTJ | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | | | |
| MPB | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 12 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NAP | 3 | 4 | FGD | 3 | 1 | FGD | 2 | 1 | FGD | 3 | 2 | 38 |
| NAW | 3 | 4 | FGD | 3 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| NAY | 3 | 4 | FGD | 3 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| SCD | 3 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| MUD | 3 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD | 2 | 2 | 39 |
| EJA | 3 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| OJD | 3 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| DHV | 2 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| RHD | 2 | 4 | FGD | 2 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| AUI | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| CAO | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| UKY | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| DRI | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 19 |
| LSJ | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| TUP | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| POB | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 20 |
| BIS | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| COI | 2 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| YOB | 3 | 4 | FGD | 1 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| YOG | 3 | 4 | FGD | 1 | 1 | FGD | 1 | 1 | FGD |  |  |  |
| RAS | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| ECD | 3 | 4 | FGD | 1 | 1 | FGD | 1 | 1 | FGD | 2 | 2 | 11 |
| ESJ | 3 | 4 | FGD | 1 | 1 | FGD | 2 | 1 | FGD | 3 | 2 | 12 |
| EYY | 3 | 4 | FGD | 1 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| GEF | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| LGS | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| LGP | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| LOB | 2 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| LJH | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 21 |
| LJL | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| MCG | 2 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| NNJ | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD | 3 | 2 | 20 |
| NNZ | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| NPS | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| PII | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| FOT | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| OYD | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| OAX | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| CBA | 2 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| JOU | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| OTB | 2 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| EEN | 2 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| MAR | 2 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| SCN | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| ILS | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD | 3 | 2 | 12 |
| KBR | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| YRB | 3 | 4 | FGD | 2 | 1 | FGD | 3 | 1 | FGD |  |  |  |
| SIP | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 2 | 2 | 20 |
| CPO | 3 | 4 | FGD | 3 | 1 | FGD | 3 | 1 | FGD | 2 | 2 | 20 |
| BUC | 3 | 4 | FGD | 1 | 1 | FGD | 3 | 1 | FGD | 2 | 2 | 12 |
| LIG | 3 | 4 | FGD | 1 | 1 | FGD | 2 | 1 | FGD | 2 | 2 | 15 |
| TJB | 3 | 4 | FGD | 2 | 1 | FGD | 2 | 1 | FGD |  |  |  |
| SVH | 3 | 4 | FGD | 1 | 1 | FGD | 3 | 1 | FGD | 2 | 2 | 26 |

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# Appendix B

**Table B.1** Occurrence records of red tides in different enclosed bays during FY 2018 to FY 2019.

| **Prefectures** | **FY 2018** | | **FY 2019** | |
|---|---|---|---|---|
| | **Bays** | **Date of occurrences* (Month/Day)** | **Bays** | **Date of occurrences* (Month/Day)** |
| Miyagi** | Onagawa | 8/10 | | |
| Mie*** | Gokasho | 7/6 to 8/9<br>11/27 | Gokasho<br>Nie | 12/16<br>8/27 |
| | Owase | 5/21 to 6/1<br>8/21 to 8/29<br>12/5 | Owase | 7/2 to 7/12 |
| Kagoshima**** | Kagoshima | 5/9 to 5/10<br>10/29 to 11/9<br>2/27 to 4/3 | Nakakoshikiura<br>Kagoshima | 5/11 to 5/25<br>10/11 to 10/21 |

* Brief data of red tides are collected from the prefectural websites.

** Miyagi Prefectural Government. Red tide information.

https://www.pref.miyagi.jp/soshiki/suikisei/akasio.html (Accessed on: 11 September, 2021).

*** Mie Prefectural Government. Red tide in the coastal waters of Mie Prefecture.

https://www.pref.mie.lg.jp/suigi/hp/78550017262.htm (Accessed on: 11 September, 2021).

**** Kagoshima Prefectural Fisheries Technology and Development Center. Kagoshima Prefecture Red Tide Information.

http://kagoshima.suigi.jp/akashio/newHP/index.html (Accessed on: 11 September, 2021).

**Table B.2** The degree of closure of different enclosed bay areas.

| **Prefectures** | **Enclosed Bays** | **Surface Area ($km^2$)*** | **Bay Mouth Width (km)*** | **Maximum Water Depth in the Bay (m)*** | **Maximum Water Depth at Bay Mouth (m)*** | **Closure index (*C*)*** |
|---|---|---|---|---|---|---|
| Miyagi | Shizugawa | 46.8 | 6.6 | 54 | 54 | 1.04 |
| | Ogatsu | 19.82 | 3.01 | 46 | 46 | 1.48 |
| | Onagawa | 12.1 | 2.5 | 36 | 36 | 1.39 |
| Mie | Gokasho | 22.2 | 2.6 | 27 | 27 | 1.81 |
| | Nie | 12.24 | 3.25 | 58 | 58 | 1.08 |
| | Kamisaki | 9.75 | 2.68 | 53 | 53 | 1.17 |
| | Owase | 19.65 | 2.6 | 58 | 58 | 1.7 |
| | Kata | 12.6 | 2.82 | 82 | 82 | 1.26 |
| Kagoshima | Kagoshima | 1040 | 11 | 237 | 111 | 6.26 |
| | Nakakoshikiura | 8.47 | 2.42 | 60 | 60 | 1.2 |
| | Yakiuchi | 25.76 | 2.53 | 84 | 84 | 2.01 |
| | Kuji and Shinokawa | 11.17 | 2.79 | 76 | 76 | 1.2 |

* International EMECS (Environmental Management of Enclosed Coastal Seas) Center, n.d. https://www.emecs.or.jp/info (Accessed on: 7 August, 2021).