Level of Vulnerability of Fish Resources in Sunda Strait, Indonesia

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ABSTRACT

Labuan Coastal Fishing Port is one of the fish-landing ports that accommodates catches in the Sunda Strait. Five fish species constitute the main catch at the Labuan Coastal Fishing Port, Indonesia. The continuous increase in fishing for these five species has raised concerns about the degradation of fish resources. The aim of this research is to analyze the level of vulnerability of fish resources caught in the Sunda Strait and landed at Labuan Coastal Fishing Port. The study was conducted at Labuan Coastal Fishing Port, Banten Province. Primary data were obtained by collecting fish samples over six months. The fish examined were Indian mackerel (*Rastrelliger kanagurta*), bullet tuna (*Auxis rochei*), bigeye scad (*Selar crumenophthalmus*), purple-spotted bigeye (*Priacanthus tayenus*), and Japanese threadfin bream (*Nemipterus japonicus*). These five species were selected because they dominate catches at the location. The fish stock vulnerability index was estimated using productivity and susceptibility parameters. The results showed vulnerability index values of 1.24, 1.41, 1.04, 1.62, and 1.48 for Indian mackerel, bullet tuna, bigeye scad, purple-spotted bigeye, and Japanese threadfin bream, respectively. These values indicate a low vulnerability category because all are below 1.8. Bigeye scad is considered the most capable of surviving in nature because it has the highest productivity value (2.50). Purple-spotted bigeye is considered the most vulnerable to fishing activities because, in addition to having the highest vulnerability index, it also has the highest susceptibility value (2.50).

Keywords: Exploitation, Fishing, Labuan, Susceptibility, Vulnerability index

INTRODUCTION

The waters of the Sunda Strait supply much of Indonesia's fish needs, especially for West Java and surrounding areas. Some of the fish caught in the Sunda Strait are landed at the Labuan Coastal Fishing Port. Among the main catches are Indian mackerel (*Rastrelliger kanagurta*), bullet tuna (*Auxis rochei*), bigeye scad (*Selar crumenophthalmus*), purple-spotted bigeye (*Priacanthus tayenus*), and Japanese threadfin bream (*Nemipterus japonicus*). In addition to these five fish species, there are many other species that are caught and landed at the port.

Continuous fishing is one of the pressures faced by fish resources (Jesintha and Madhavi, 2020). This pressure can cause vulnerability among fish resources, defined as the level of sensitivity to damage caused by various disturbances or stressors (Silva *et al*., 2019). Vulnerability is the inability of a population, individual, or organization to anticipate and recover from the impact of a disaster (Iorhen and Terna, 2021). The types of vulnerability are physical, social, economic, and environmental. It also includes the risk posed by fishing gear to fish species, affecting productivity and susceptibility. Additionally, the increased risk of vulnerability can also be due to increasing

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demand and fishing intensity in fisheries (Yonvitner *et al*., 2020). Information regarding stocks and the vulnerability levels of fish resources is needed to reduce fishing pressure and support sustainable fisheries (Barman *et al*., 2021). Vulnerability can also be identified using internal factors, namely, biological characteristics related to fish growth and reproduction. Fish are more vulnerable when they have a long recovery time and are exploited continuously. High vulnerability indicates pressure from fishing activities that exceeds sustainable potential, emphasizing the need for efforts to maintain natural fisheries resources and balance (Maulana *et al*., 2024). Fishing carried out in areas of high exploitation will result in a decline in the population. Productivity and Susceptibility Analysis (PSA) can be used as an approach to determine the vulnerability of fisheries stocks (Patrick *et al*., 2009).

Issues related to productivity include changes in fish growth, decreases in the maximum fish length, reduction in fish growth rate, and the tendency toward reduced egg producing. Issues related to susceptibility include high fishing mortality, low fish catch biomass, and the use of fishing gear that can damage fish morphology and aquatic ecosystems. The high fishing mortality is due to the open-access nature of fish resources, which allows anyone to take advantage of them without any limits on the catches. High-value fish may also be continuously exploited, causing fish stocks to decline and affecting the sustainability of the resources.

The various issues related to productivity and susceptibility described above affect fish vulnerability in these waters, including the Sunda Strait. Therefore, the Productivity and Susceptibility Analysis (PSA) method is needed to analyze the vulnerability level of fish resources, and to provide information for sustainable fisheries management. It is a widely used and appropriate method to determine the level of fish resource vulnerability due to fishing activities, based on productivity and susceptibility parameters. The PSA method is considered the best approach for determining the vulnerability of data-poor stocks (Patrick *et al*., 2010), a situation that frequently occurs in Indonesian waters. Previous research on a similar topic conducted by Yonvitner *et al*. (2020) used complex data series and university laboratory facilities. As a continuation of that research, the present study maximizes the use of available field data. The research conducted by Yonvitner *et al*. (2020) focused on demersal fish, while this study focuses on pelagic and demersal fish. Therefore, this study is an extension of research by Yonvitner *et al*. (2020), to assess the vulnerability of pelagic and demersal fish.

This research aims to analyze the level of vulnerability of pelagic and demersal fish resources in the Sunda Strait waters landed at the Labuan Coastal Fisheries Port, Banten. The results of the research can provide information about the sustainability of fish resources as a basis for policymaking.

MATERIALS AND METHODS

Study location

The study was conducted at Labuan Coastal Fishing Port, Pandeglang Regency, Banten Province (Figure 1). The fish data analysis was conducted at the Fisheries Biology Laboratory, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, Indonesia.

Data collection

The data collected comprised primary and secondary data. Primary data were obtained through the collection of fish samples using a simple random sampling method. The fish that were the research objects were five species, namely: Indian mackerel, bullet tuna, bigeye scad, purple-spotted bigeye, and Japanese threadfin bream. Structured interviews were conducted with fishermen who caught these five fish species. The fishermen were selected using a purposive sampling method. Each month, 100 individuals of each species were sampled (500 individuals for the five species), spanning a period of 6 months. The total number of fish samples measured was 600 for one species, and 3,000 for the five species of fish combined. The sex and gonadal maturity stage (GMS) of the fish were identified through fish dissection. The anterior, middle, and posterior parts of each gonad were collected.

The data obtained consisted of total fish length (mm), fish weight (g), gonad weight (g), fish price (IDR), and catch production data (kg), which served as inputs for productivity and susceptibility parameters. These included growth parameters (L_∞, K, t_0), mortality parameters (natural mortality, catch mortality, exploitation rate), production data, GMS, SSB (spawning stock biomass), geographic concentration, area overlap, vertical overlap, management strategy, and other susceptibility parameters. All these parameters were used in assessing the level of fish stock vulnerability.

Secondary data were obtained by cmpiling data and information related to the stocks of the fish species used as the research objects. The secondary data were obtained from FishBase (www.fishbase.org), namely the mean trophic level and age at maturity.

Data analysis

The intrinsic growth rate was estimated using the Fox algorithm method. The intrinsic growth rate (r) was calculated using the following formula:

$$r = \frac{Kq^2}{\beta}$$

Note: r = intrinsic growth rate; K = carrying capacity; q = catchability coefficient; β = slope.

Growth parameters such as L_∞ and k were estimated using the Von Bertalanffy growth model:

$$L_t = L_\infty \left(1 - \exp^{(-k(t-t_0))}\right)$$

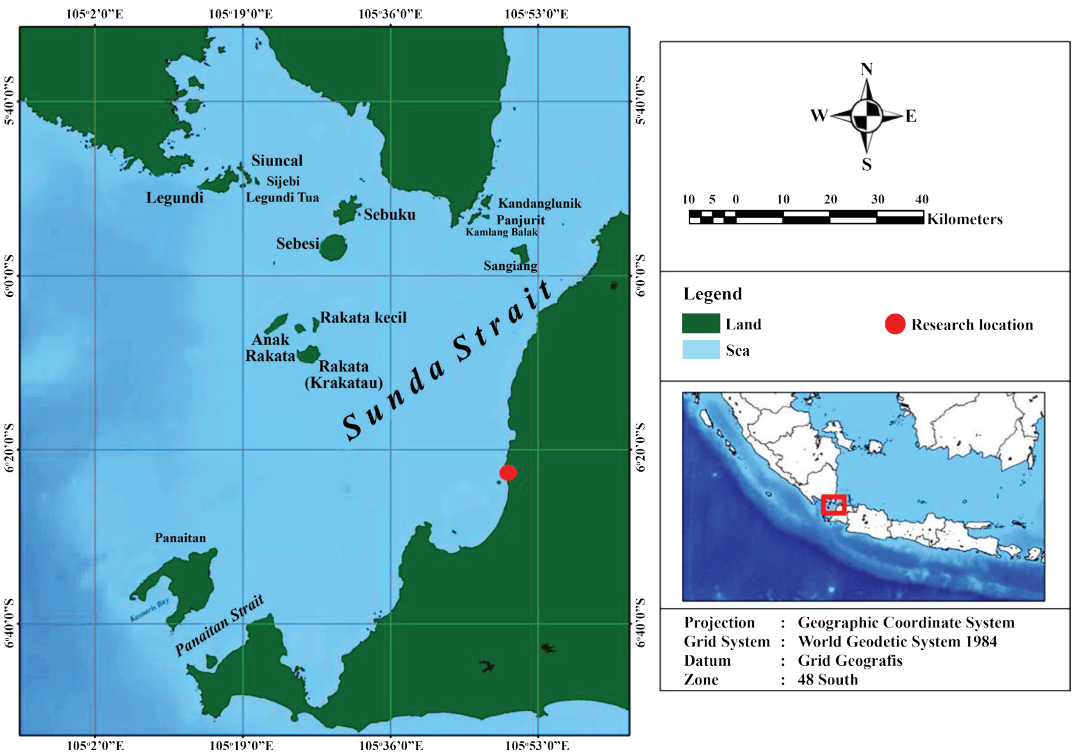


Figure 1. Study location (6º04'56.8''S and 107º00'07.2''E).

Note: L_t = the length of the fish at age t; L_∞ = asymptotic length or theoretical maximum length; k = growth coefficient; t_0 = theoretical age when length equals zero.

The value of t_0, the fish's theoretical age when length equals zero, was estimated using Pauly's equation:

$$\log(-t_0) = -0.0152-0.2752 (\log L_\infty) -1.038 (\log k)$$

The maximum age of a fish (t_{max}) was estimated based on the values of k and t_0. The maximum age of fish was calculated using the following formula:

$$t_{max} = \frac{3}{k} + t_0$$

The natural mortality and total mortality values were estimated through the FISAT (FAO-ICLARM Stock Assessment Tools) II version 1.2.2 program using the mortality estimation method. The total mortality value (Z) was estimated using a linearized catch curve based on length composition data. The calculation of the natural mortality rate (M) using Pauly's empirical formula (1984) is as follows:

$$M = 0.8 \times e^{(-0.0152-0.279 \ln L_\infty + 0.6543 \ln k + 0.463 \ln T)}$$

Note: M = natural mortality; L_∞ = asymptotic length or theoretical maximum length; k = growth coefficient; T = average temperature of the surface of the water (ºC).

The fishing mortality rate (F) was determined based on the total mortality rate (Z) and the natural mortality rate (M) using the following formula:

$$F = Z-M$$

Estimation of the exploitation rate (E) is conducted by comparing the fishing mortality rate (F) to the total mortality rate (Z):

$$E = \frac{F}{F+M} = \frac{F}{Z}$$

Fecundity was analyzed using a combined model, incorporating both graphimetric and volumetric methods. The combined method begins with a 10 mL dilution of each gonad section. The fecundity value was then determined from the number of eggs in a 1 mL sample. Fecundity analysis was carried out by:

$$F = \frac{G \times V \times X}{O}$$

Note: F = fecundity (number of eggs); G = total gonad weight (g); V = dilution volume (mL); X = number of eggs per mL (eggs·mL^{-1}); O = weight of the egg sample (g).

The mean trophic levels (TL) of Indian mackerel, bullet tuna, bigeye scad, purple-spotted bigeye, and Japanese threadfin bream were obtained from www.fishbase.org. Stergiou and Karpouzi (2002) classified trophic levels into four groups: herbivores (TL = 2.0–2.1), omnivores with herbivorous tendencies (2.1<TL<2.9), omnivores with carnivorous tendencies (2.9<TL<3.7), and carnivores (3.7<TL<4.5). The mean trophic level was used as input to the PSA (productivity and susceptibility analysis).

Estimating the spawning stock biomass (SSB) value was done using the following formula (Patrick *et al*., 2009):

$$SSB = \frac{Bt}{Bo}$$

Bt is the biomass of fish caught in the most recent year, while Bo is the initial biomass when the fish began to be caught.

The value of Bo was estimated by using the following formula:

$$Bo = \frac{Y_{1st}}{\exp(-F_{1st})}$$

Y_{1st} is the first catch in the first year of fishing, while F_{1st} is instantaneous fishing mortality.

$$F_{1st} = \frac{C_{total}}{x}$$

C_{total} is the total catch in the first year, while x is the proportion of initial biomass stock. According to Fauzi (2010), the carrying capacity (K) value in the last year and the assumption of fixed carrying capacity were used to obtain the x value with the formula:

$$x = \frac{K}{2}$$

The vulnerability index value (v) of a stock was estimated with the productivity and susceptibility analysis (PSA) method using productivity and susceptibility values. Both factors are assigned scores ranging from 1 to 3 for a standard set of attributes associated with each. Individual attribute scores are then averaged for each factor and displayed graphically on an x-y scatter diagram. The stock vulnerability index (v) is calculated as the Euclidean distance from the origin of the x-y scatter diagram (i.e. 3.0, 1.0) and the datum point using the following formula (Patrick *et al*., 2009):

$$v = \sqrt{(p-3)^2+(s-1)^2}$$

While: v = vulnerability index value; p = productivity score; s = susceptibility score.

If a fish stock has a vulnerability value (v) higher than 1.8, it indicates a high vulnerability risk to fishing activities. Fish with low productivity and high susceptibility have a low survival capacity; therefore, the risk of overfishing is high, and vice versa. There are three categories in the vulnerability index: less vulnerable ($v<1.8$), moderately vulnerable ($1.8\leq v<2.0$), and highly vulnerable ($v\geq 2.0$) (Patrick *et al*., 2010).

To assess the statistical robustness of the vulnerability index values generated from the PSA, sensitivity analysis (Saltelli, 2002) and bootstrap resampling methods were applied (Efron and Tibshirani, 1993). A sensitivity analysis was performed by systematically varying each attribute score, both productivity and susceptibility, by ±1 point. This approach enabled evaluation of how small changes in scoring impact the final vulnerability index for each species. In this study, 10,000 Monte-Carlo simulations (parametric) were performed for each species using a normal distribution centered on the observed index with a standard deviation of 0.05. Additionally, to test whether differences in vulnerability indices among species were statistically significant, a Kruskal-Wallis rank sum test was conducted. This non-parametric test is suitable for comparing multiple groups when data do not meet the assumptions of normality or equal variance (Zar, 2010).

The productivity and susceptibility analysis was carried out using PSA software developed by the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service. The analysis began by entering a database of each productivity and susceptibility parameter into an Excel format. The factors considered in PSA analysis are biological and ecological. The value weights range from 0 to 4 (0 = Not important; 1 = Less important; 2 = Important; 3 = More important; and 4 = Very important). The value weights, attribute scores, and data quality that were entered into the PSA software produced a graph showing the relationship between productivity and susceptibility parameters. The graph illustrates the relative vulnerability determined by the combination of productivity parameters (x-axis) and susceptibility (y-axis). Attribute scores are adjusted according to the criteria determined by NOAA (Figure 2). Data quality is determined based on the data source used in the analysis, with a value range of 1 to 5 (1 = Abundant and complete data; 2 = Limited data (temporal and spatial); 3 = Data from the same genus or family; 4 = New data that are unpublished information, and 5 = No data).

A correlation analysis was conducted to examine the relationship between productivity scores and susceptibility scores across species. Additionally, descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for each key parameter (productivity score, susceptibility score, and vulnerability index). This analysis helped assess the distribution and potential associations between biological traits and exposure risk (Das and Crépin, 2013).

RESULTS

Growth, mortality, and exploitation rate

Growth parameters comprise asymptotic length (L_∞), growth coefficient (K), and the theoretical age of the fish when its length is zero (t_0). The results of growth parameter estimation for each species are presented in Table 1.

The five fish species have different growth parameter values. These differences may be influenced by internal factors such as species or genetic differences, and external factors such as environmental conditions and differences in sampling time. The largest L_∞ value was found in bullet tuna, while the smallest was in Indian mackerel (Table 2).

The highest exploitation rate (E) was 0.64 for bullet tuna, followed by 0.60 for purple-spotted bigeye, while the lowest was 0.17 for bigeye scad. The commonly cited optimal E value for fish resources is about 0.5, where natural mortality and fishing mortality are approximately equal. Bullet tuna and purple-spotted bigeye have E values above 0.5, indicating that these two stocks resources are overexploited.

Productivity and susceptibility parameters

The results of the productivity parameters for the fish showed that the greatest recruitment success was 22.72% for bullet tuna (Table 3). The highest age at maturity or (gonadal maturity) was observed in the Japanese threadfin bream at 1.4 years (Table 3). The mean trophic level indicates that Indian mackerel is classified as an omnivorous fish with carnivorous tendencies, while bullet tuna, bigeye scad, purple-spotted bigeye, and Japanese threadfin bream are classified as carnivorous fish.

Fishing activities for the five fish species (Table 4) have no policy restrictions and are not subject to proper monitoring activities. The high area and vertical overlap are caused by the large number of fishing fleets. The highest F/M value was found for bullet tuna fish at 1.78, which indicates that bullet tuna experience more fishing pressure compared to the other species. The highest economic

Table 1. Estimation of fish growth parameters.

Type	Name of fish	L_∞ (mm)	k (year^{-1})	t_0 (year)
Pelagic	Indian mackerel	219.4	0.50	-0.3558
	Bullet tuna	358.9	0.58	-0.2663
	Bigeye scad	249.0	0.86	-0.1957
Demersal	Purple-spotted bigeye	336.4	0.71	-0.2198
	Japanese threadfin bream	278.4	0.36	-0.4686

Note: L_∞ = asymptotic length or theoretical maximum length; k = growth coefficient; t_0 = theoretical age when length equals zero

Table 2. Estimation of fish mortality and exploitation rate.

Type	Name of fish	M	F	Z	E
Pelagic	Indian mackerel	1.00	0.91	1.91	0.48
	Bullet tuna	0.97	1.71	2.68	0.64
	Bigeye scad	1.38	0.29	1.67	0.17
Demersal	Purple-spotted bigeye	1.12	1.68	2.80	0.60
	Japanese threadfin bream	0.76	0.56	1.32	0.43

Note: M = natural mortality; F = fishing mortality; Z = total mortality; E = exploitation rate

Table 3. Fish resource productivity.

Attribute	Unit	Name of fish				
		lm	Bt	Bs	Psb	Jtb
Intrinsic growth (r)	per year	0.06	0.10	0.22	0.21	0.05
Maximum age	years	5.64	4.91	3.29	4.01	7.86
Maximum size	cm	20.9	31.3	24	30	26
Growth coefficient (K)		0.5	0.58	0.86	0.71	0.36
Natural mortality (M)		1	0.97	1.38	1.12	0.76
Fecundity	eggs	3,676–93,072	7,418–105,300	19,048–171,753	48,444–138,891	9,796–108,768
Breeding strategy		Partial spawner				
Recruitment pattern	%	16.35	22.72	20.3	19.21	15.98
Age at maturity	years	0.5[1]	1.25[1]	0.58[1]	0.75[1]	1.4[1]
Mean trophic level		3.4[1]	4.4[1]	3.8[1]	3.8[1]	4.1[1]

Note: [1]Source: Fish base; lm = Indian mackerel; Bt = Bullet tuna; Bs = bigeye scad; Psb = Purple-spotted bigeye; Jtb = Japanese threadfin bream

Table 4. Fish resource susceptibility.

Attribute	Name of fish				
	lm	Bt	Bs	Psb	Jtb
Management strategy	Fish stocks management does not yet have fishing policy restrictions; there are no proper monitoring activities				
Area overlap	>50% in the fishing area				
Geographic concentration	>50% distributed in all fishing areas				
Vertical overlap	>50% at the same fishing depth				
F/M	0.91	1.78	0.21	1.50	0.75
SSB	36.2%	103.2%	46.4%	19.8%	25.7%
Seasonal migration	Fish migrate, thereby reducing the decline in catches				
Grouping and habitual responses	Swim in schools and increase catches				
The influence of fishing gear on fish morphology	Bottom gillnets are selective fishing tools, so they do not affect fish morphology			Longline is a selective fishing gear, so it does not affect fish morphology	
Fish survival after capture	33% < survival after capture approximately <67%				
Economic value	IDR 30,000 per kg (mp)	IDR 35,000 per kg (hp)	IDR 20,000 per kg (mp)	IDR 35,000 per kg (hp)	IDR 25,000 per kg (mp)
Impact of fishing gear on the environment	Does not disturb the habitat			Impact on its habitat is minimal	

Note: Im = Indian mackerel; Bt = Bullet tuna; Bs = bigeye scad; Psb = Purple-spotted bigeye; Jtb = Japanese threadfin bream; mp = moderate price; hp = high price value or selling price was for bullet tuna and purple-spotted bigeye, at US$ 2,19 per kg, while the lowest selling price was for bigeye scad at US$ 1,25 per kg. Bullet tuna also has the highest SSB value compared to the other four species.

Scoring was done for the results of the productivity and susceptibility parameters obtained, and it consists of weight values, attribute scores, and data quality. The scoring of productivity and susceptibility parameters refers to the values set by Patrick *et al*. (2009), with modifications from Yonvitner *et al*. (2017). The productivity and susceptibility scores are presented in Tables 5 and 6. The data listed in Table 5 and Table 6 are the output of the application used to measure productivity and susceptibility. The quality of the data used has been guaranteed by the standardized application. The measurement results in Tables 1, 2, 3, and 4 are data entered into the application. The output of the application is in the form of score data (Table 5).

Table 5. Fish resource productivity score.

Attribute	**Unit**	**Name of fish**				
		Im	**Bt**	**Bs**	**Psb**	**Jtb**
Intrinsic growth (r)	per year	1	1	2	2	1
Maximum age	years	3	3	3	3	3
Maximum size	cm	2	2	2	2	2
Growth coefficient (K)		3	3	3	3	2
Natural mortality (M)		3	2	3	3	3
Fecundity	eggs	2	3	3	3	3
Breeding strategy		2	2	2	2	2
Recruitment pattern	%	2	2	2	2	2
Age at maturity	years	3	3	2	3	3
Mean trophic level		2	1	3	1	1

Note: Im = Indian mackerel; Bt = Bullet tuna; Bs = bigeye scad; Psb = Purple-spotted bigeye; Jtb = Japanese threadfin bream

Table 6. Fish resource susceptibility score.

Attribute	**Name of fish**				
	Im	**Bt**	**Bs**	**Psb**	**Jtb**
Management strategy	3	3	3	3	3
Area overlap	3	3	3	3	3
Geographic concentration	1	1	1	1	1
Vertical overlap	3	3	3	3	3
F/M	2	3	1	3	2
SSB	2	1	1	3	2
Seasonal migration	1	1	1	1	1
Grouping and habitual responses	3	3	3	3	3
The influence of FG on FM	2	2	2	3	3
Fish survival after capture	2	2	2	2	2
Economic value	2	3	2	3	2
Impact of fishing gear on the environment	1	1	1	2	2

Note: Im = Indian mackerel; Bt = bullet tuna; Bs = bigeye scad; Psb = purple-spotted bigeye; Jtb = Japanese threadfin bream; FG = fishing gear; FM = fish morphology

The productivity and susceptibility analysis was conducted using PSA software developed by NOAA. A graph illustrating the relationship between productivity and susceptibility parameters was generated from the analysis (Figure 2).

Figure 3 shows that the bigeye scad has the highest productivity. The purple-spotted bigeye has the highest susceptibility compared with the other species. The productivity parameters for Indian mackerel, bullet tuna, and Japanese threadfin bream have identical values. The green color of the circle indicates that the quality of the data used is high. If the color of the circle is yellow, the quality of the data used is medium. Likewise, if the color of the circle is red, the quality of the data used is low.

To examine the relationship between productivity and susceptibility scores across species, a Pearson correlation analysis was conducted. The results showed a correlation coefficient of –0.235 with a p-value of 0.7, indicating no statistically significant relationship between the two variables (t = –0.4, df = 3, 95% CI: –0.925 to 0.816).

Vulnerability analysis

The fish vulnerability index was analyzed using the PSA method (Table 7). Analyzing fish vulnerability is essential in sustainable fisheries management. The parameters used in multispecies analysis are both biological and ecological.

The fish that has the highest vulnerability index value is the purple-spotted bigeye (1.62), and the lowest is the bigeye scad (1.04). However, all five fish have a vulnerability index <1.8, meaning the level of vulnerability is low. To assess the precision of these estimates, bootstrap resampling with 10.000 iterations was applied to each species.

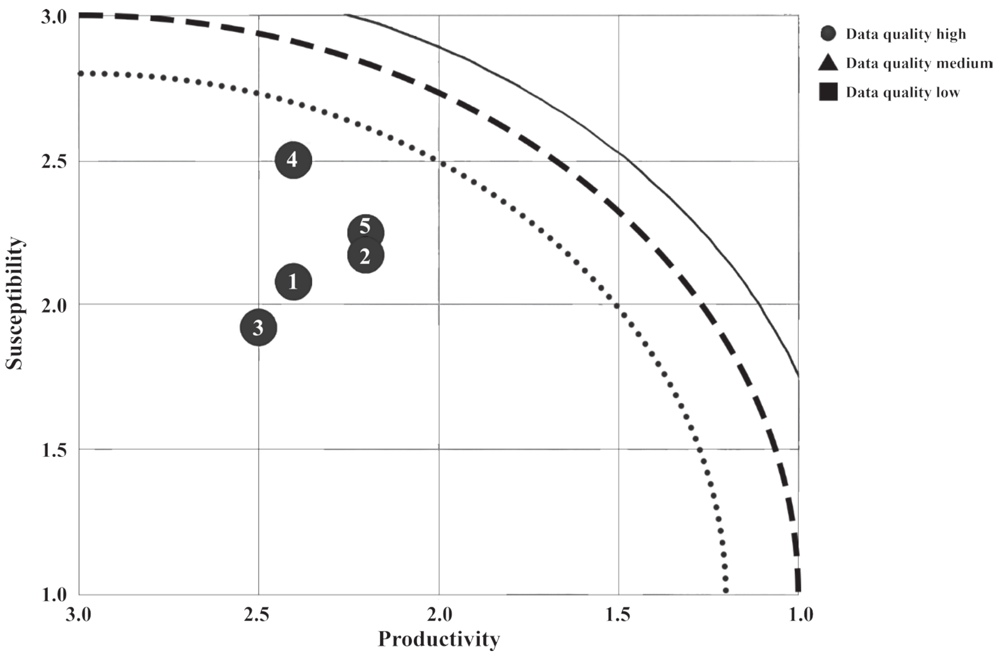


Figure 2. Productivity and susceptibility graph.
Note: 1 = Indian mackerel; 2 = bullet tuna; 3 = bigeye scad; 4 = purple-spotted bigeye; 5 = Japanese threadfin bream; dotted line = low vulnerability; dashed line = moderate vulnerability; solid line = high vulnerability. The color of the circle indicates data quality. High data quality (circle) = information is complete, consistent, and based on quantitative data; medium data quality (triangle) = some data are available but not complete or regularly updated (limited); low data quality low (square) = information is significant limited or absent, so the analysis must rely on many assumptions and the results have a low level of confidence.

To further examine whether the differences in vulnerability indices among species were statistically significant, a Kruskal-Wallis rank sum test was conducted. The result was not significant ($\chi^2 = 4.00$, df = 4, p = 0.400), indicating that the observed variation in vulnerability index values does not differ significantly among the five species. Although the statistical test did not show significant differences, the biological significance of the vulnerability index range (1.04 to 1.62) remains noteworthy. Species with higher VI values, such as the purple-spotted bigeye, may be more ecologically vulnerable due to traits such as high economic value and fishing mortality.

Table 7. Productivity, susceptibility, and vulnerability index for five target species. Scores are PSA outputs (productivity and susceptibility scaled 1–3). Vulnerability index values are shown with 95% CIs in parentheses.

Name of fish	Productivity score	Susceptibility score	Vulnerability index*
Indian mackerel	2.40	2.08	1.24 (1.19–1.39)
Bullet tuna	2.20	2.17	1.41 (1.31–1.51)
bigeye scad	2.50	1.92	1.04 (0.94–1.14)
Purple-spotted bigeye	2.40	2.50	1.62 (1.52–1.72)
Japanese threadfin bream	2.20	2.25	1.48 (1.38–1.58)

Note: The 95% confidence intervals were estimated using a bootstrap approach with 10,000 iterations, assuming a normal distribution centered on each species' Vulnerability Index with a standard deviation of 0.05.

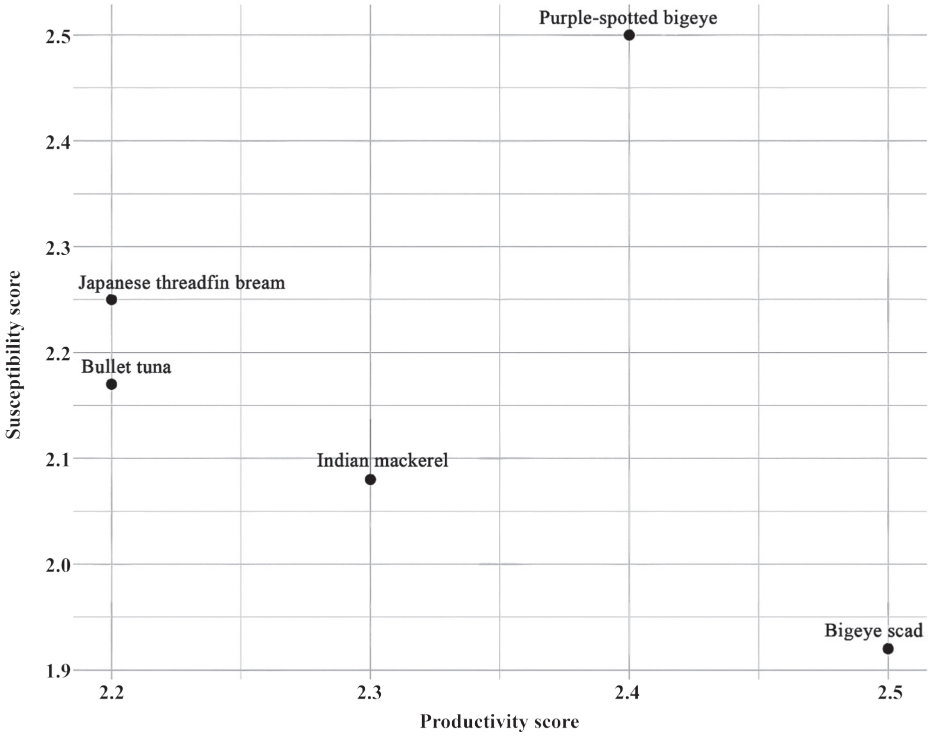
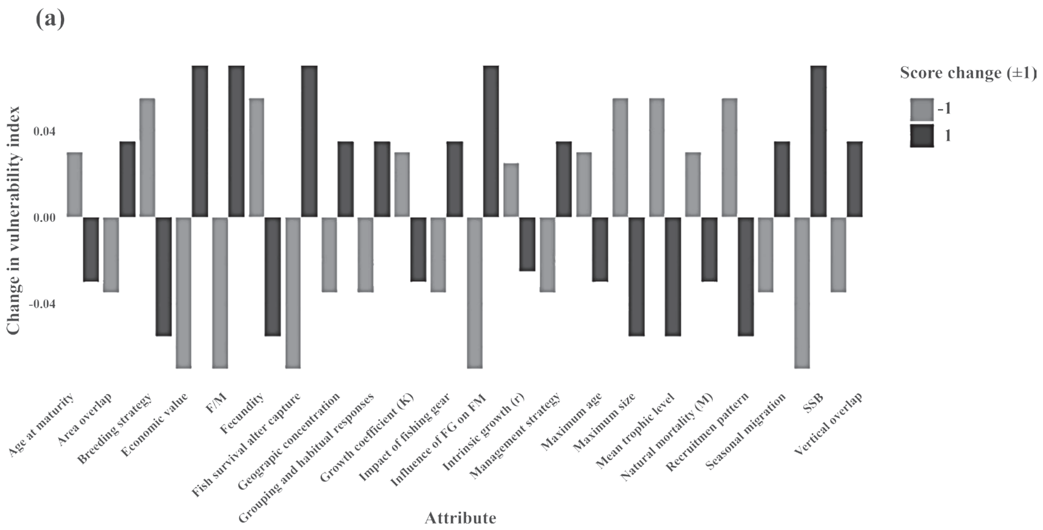


Figure 3. Productivity vs. susceptibility scores for each species. Scatterplot showing productivity against susceptibility; each point is labeled by species. No clear trend is evidenct, consistent with the non-significant correlation between the two parameters (Pearson r = −0.235, p = 0.70).

Sensitivity analysis

To evaluate the robustness of the vulnerability index (VI) derived from the productivity susceptibility analysis (PSA), a sensitivity analysis was conducted. Each attribute related to productivity and susceptibility was varied by ±1-point, and the resulting changes in *v* were recorded for all assessed species (Figure 4).

The analysis revealed that certain attributes, such as maximum age, natural mortality (M), and management strategy, had a moderate influence on the vulnerability index. For example, reducing the productivity score for maximum age in Indian mackerel from 3 to 2 increased the vulnerability from 1.29 to 1.35. Similarly, raising the susceptibility score for the management strategy raised the vulnerability from 1.29 to 1.30. These changes, although measurable, were generally small, indicating that the PSA results are not overly sensitive to minor scoring adjustments (Saltelli, 2002).



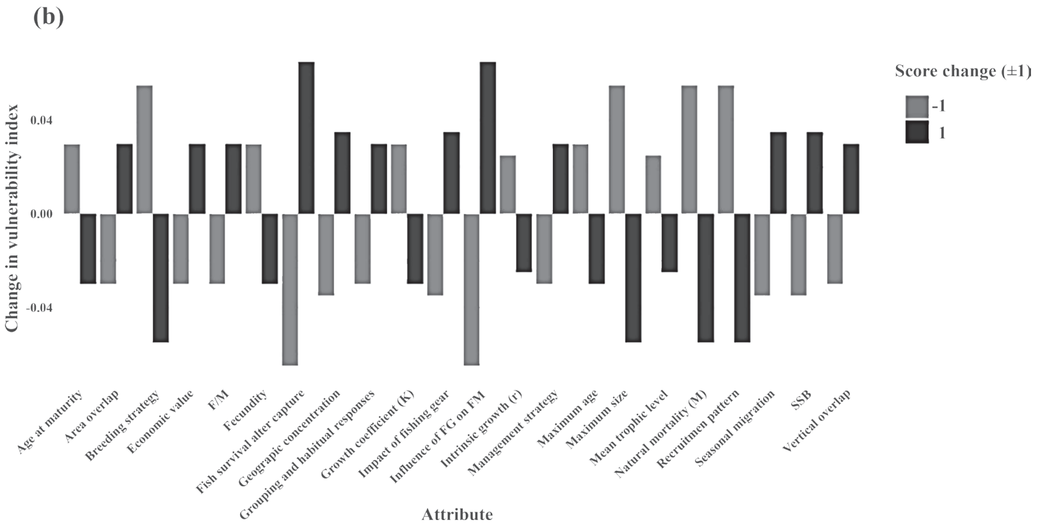


Figure 4. Sensitivity analysis of vulnerability index across species: (a) Im = Indian mackerel; (b) Bt = Bullet tuna; (c) Bs = Bigeye scad; (d) Psb = Purple-spotted bigeye; (e) Jtb = Japanese threadfin bream.

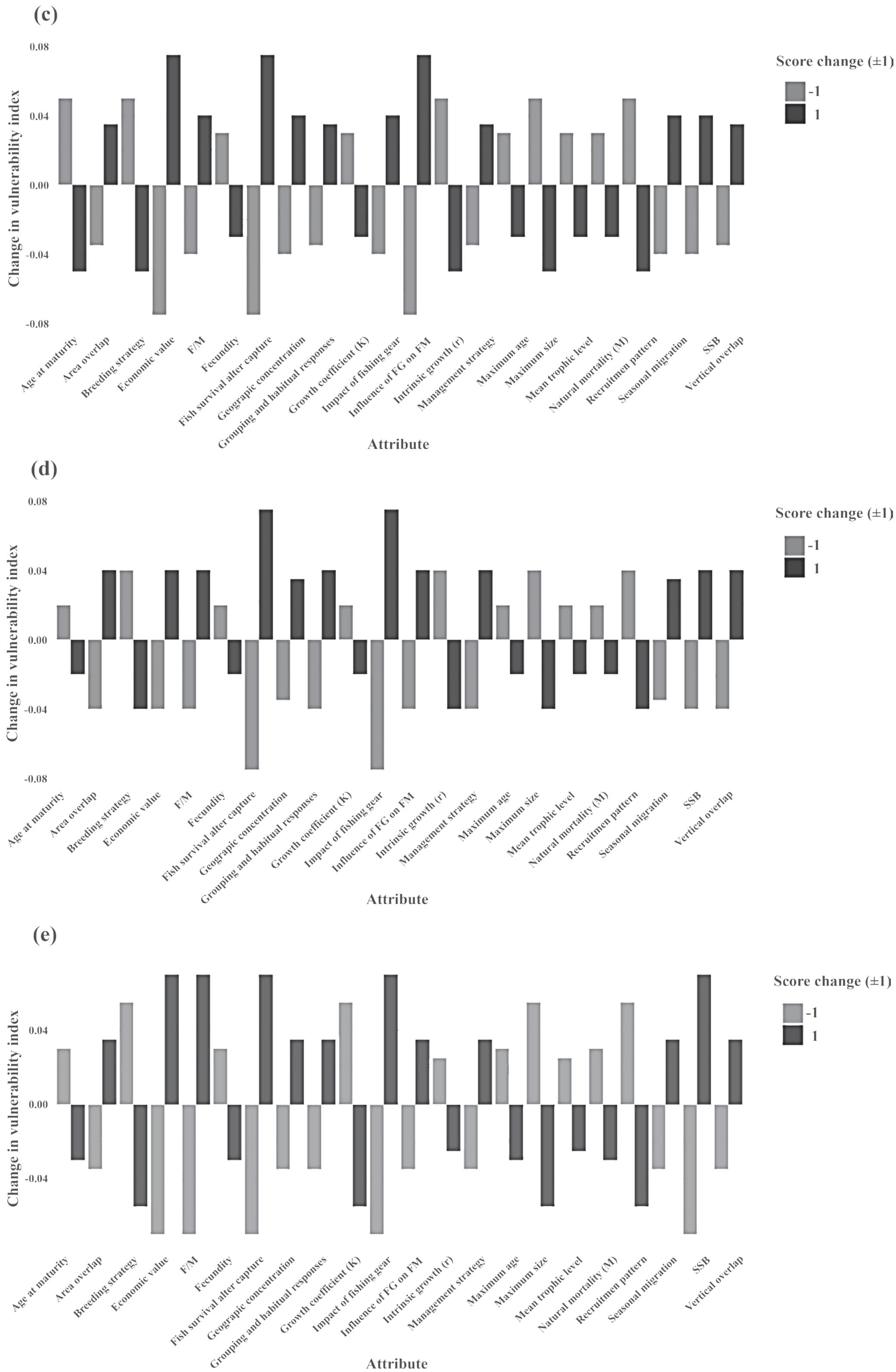


Figure 4. Cont.

DISCUSSION

Overall population traits and life-history parameters

The five fish species studied all have a maximum lifespan of less than ten years. According to Mehanna *et al*. (2018), a fish's maximum age (t_{max}) varies and is influenced by habitat conditions. An increased fishing rate can reduce the probability of fish surviving to reach their maximum age or growing to maximum size, leading to a younger age structure, smaller fish, and gonads that have not yet reached maturity (Stevens *et al*., 2019).

The intrinsic growth rate (r) is a key parameter for understanding population history and population dynamics. This parameter is fundamental for estimating limits on unintentional fish catch (bycatches) under data-limited conditions (Moore *et al*., 2013). In this study, the Japanese threadfin bream had the lowest intrinsic growth rate (r = 0.05 $year^{-1}$), while the bigeye scad had the highest (r = 0.22 $year^{-1}$). Because r tends to be lower when the von Bertalanffy growth coefficient (K) is low, these two parameters are generally directly related.

Fecundity is defined as the number of eggs in the ovaries of mature female fish ready to be released during spawning. Among the studied species, the bigeye scad had the highest fecundity (19,048–171,753 eggs), while Indian mackerel had the lowest (3,676–93,072 eggs). Fecundity is influenced by the fish's body size, so each fish will have a different fecundity. Fecundity is influenced by body size, so each species has a different fecundity. However, body size and fecundity are not always directly proportional because fecundity is also affected by gonad weight and egg size. The higher the fecundity of a fish, the more recruitment is expected to increase (Rickman *et al*., 2000).

Trophic level and productivity

The trophic level describes feeding relationships among species within a system and shapes the predation structure. According to Stergiou *et al*. (2007), four trophic-level categories are recognized: $2.1 \leq TL \leq 2.9$ (omnivores tending toward plants), $2.9 < TL \leq 3.7$ (omnivores tending toward animals, e.g., zooplankton), $3.7 < TL \leq 4.0$ (carnivores preferring decapods and fish), and $4.0 < TL \leq 4.5$ (carnivores preferring fish and cephalopods). In general, species with mean trophic level value below 2.5 tend to have high productivity, whereas those with $TL > 3.5$ tend to have low productivity. Herbivorous species tend to be less vulnerable, implying that high–trophic level fishes are more prone to overexploitation.

Exploitation status and spawning stock biomass

The exploitation rate (E) can be used to infer stock condition, with an optimal value of approximately 0.50 $year^{-1}$. Two of the study species, bullet tuna and purple-spotted bigeye, had $E > 0.5$, indicating that they are overfished or overexploited. These species also had the highest fishing mortalities (1.71 and 1.68, respectively). Interview information suggests that this overexploitation may reflect the absence of catch-limit policies and inadequate monitoring. Their higher market value compared with Indian mackerel, bigeye scad, and Japanese threadfin bream likely increases fishing pressure and risk.

According to (Patrick *et al*., 2010), SSB is a parameter that indicates how much the biomass of a fish stock has decreased since the start of fishing activities. In this study, purple-spotted bigeye had a relatively low SSB value of below 25%, supporting the inference that this species is more heavily depleted.

Productivity–susceptibility analysis (PSA) and species vulnerability

The PSA method used in fisheries management with limited data takes into account the biological conditions of fish and their ecosystem (Hordyk and Carruthers, 2018). According to Fitzgerald *et al*. (2018) developing sustainable fisheries management stategies should consider the level of fish vulnerability based on productivity parameters that contain data related to the life history of a fish species.

In this study, we estimated productivity and susceptibility scores for each species to derive a vulnerability index. A correlation analysis was then performed to assess the relationship between productivity and susceptibility. The analysis showed no statistically significant correlation ($r = -0.235$, $p = 0.7$), indicating that productivity and susceptibility vary independently among species. This finding supports the assumption that the PSA framework captures distinct dimensions of species vulnerability, with productivity reflecting biological resilience and susceptibility representing exposure to fishing pressure.

The five species studied had vulnerability index of less than 1.8, indicating low vulnerability and suggesting that these species have a relatively strong capability to maintain their populations under current fishing activities (Patrick *et al*., 2009). To evaluate the robustness of these vulnerability estimates, we applied a bootstrap resampling method, which is widely used in ecological and fisheries assessments to quantify uncertainty in small datasets (Efron and Tibshirani, 1993). The resulting confidence intervals were narrow, indicating stable estimates across species. Furthermore, a Kruskal-Wallis rank-sum test was conducted to assess whether differences in vulnerability indices among species were statistically significant. The test result was not significant ($p = 0.400$), suggesting that the observed variation in vulnerability is not sufficient to differentiate species statistically, a common outcome in vulnerability assessments with limited sample sizes (Zar, 2010).

Interpretation of vulnerability indices and ecological implications

Populations of fish with higher vulnerability indices are expected to decline more rapidly and to be more prone to overexploitation. Moreover, the exploitation of fish at low trophic levels can disrupt ecosystem balance. The vulnerability of fish stocks to fishing pressure is assessed using productivity and susceptibility parameters as measurement tools; therefore, productivity-susceptibility analysis provides a method for estimating stock vulnerability (Triharyuni *et al*., 2013).

Although all species are classified as having low vulnerability ($v<1.8$), the variation in vulnerability index values, from 1.04 for bigeye scad to 1.62 for purple-spotted bigeye, may still be ecologically significant. Species with relatively higher vulnerability values, such as purple-spotted bigeye, may be more at risk due to traits such as high economic value and high fishing mortality. These differences, while not statistically significant, can inform management priorities and conservation strategies.

Bullet tuna and purple-spotted bigeye are classified as having low vulnerability based on PSA (<1.8), yet both species show signs of overexploitation, with exploitation rates (E) exceeding 0.5. This apparent discrepancy underscores an important distinction: the PSA framework evaluates inherent biological and ecological vulnerability, based on life-history traits and exposure to fishing, rather than current stock status. Thus, a species may exhibit high productivity and moderate susceptibility, leading to a low vulnerability index, but still be overexploited because of external pressures such as intense fishing effort, high market demand, or weak regulatory enforcement. Therefore, PSA results should be interpreted together with exploitation indicators, such as E and SSB, to provide a more comprehensive understanding of stock condition and to guide effective fisheries management.

Management implications

Management of fisheries activities is required, especially for species with high susceptibility. Small pelagic fishes are often not considered vulnerable under the NOAA thresholds because they frequently fall within the minimum indicator interval. However, in practice, these small fishes have been overfished, and their production size is declining (Yonvitner *et al*., 2017). According to Mamauag *et al*. (2013), species-level fisheries management can be developed by prioritizing vulnerability estimation. Such vulnerability estimates can be used to maintain a balance between conservation and exploitation for long-term sustainability (Kalikoski *et al*., 2010).

Fishing activities can increase the vulnerability of fish resources; therefore, it is necessary to implement fisheries management measures such as regulating catch limits and controlling fishing efforts. Conscientious and precise management is particularly important for species with a high risk of capture. An ecosystem approach to fisheries management (Yuliana *et al*., 2019; 2020), which considers all components of the fishery system, can help achieve a better balance between ecological integrity and economic objectives.

CONCLUSIONS

Bullet tuna showed the greatest recruitment success based on productivity parameters, and the highest age at maturity (gonadal maturity) was found in the Japanese threadfin bream. The bigeye scad is considered the most capable of surviving in nature because it has the highest overall productivity value and the lowest vulnerability index. The fish with the highest vulnerability index is the purple-spotted bigeye, and the lowest is the bigeye scad. In general, all five fish species have a vulnerability index <1.8, indicating that their current level of vulnerability is low. However, the purple-spotted bigeye is considered the most vulnerable to fishing activities because, in addition to having the highest vulnerability index, it also has the highest susceptibility value. Overall, these results suggest that fish resources at the study location are not yet severely degraded; however, proactive management is needed to maintain this condition and ensure that fish stocks remain sustainable in the future.

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LITERATURE CITED

Barman, P.P., Q. Liu, M.A. Al-Mamun, P. Schneider and M.M.H. Mozumder. 2021. Stock assessment of exploited sardine populations from northeastern Bay of Bengal Water, Bangladesh using the length-based bayesian biomass (Lbb) method. **Journal of Marine Science and Engineering** 9(10): 1–13. DOI: 10.3390/jmse9101137.

Das, S. and A.S. Crépin. 2013. Mangroves can provide protection against wind damage during storms. **Estuarine, Coastal and Shelf Science** 134: 98–107. DOI: 10. 1016/j.ecss.2013.09.021.

Efron, B. and R.J. Tibshirani. 1993. **An Introduction to the Bootstrap.** Chapman and Hall/CRC, New York, USA. 16 pp.

Fauzi, A. 2010. **Fisheries Economics: Theory, Policy and Management.** PT Gramedia Pustaka Utama, Jakarta, Indonesia. 224 pp.

Fitzgerald, S.P., J.R. Wilson and H.S. Lenihan. 2018. Detecting a need for improved management in a data-limited crab fishery. **Fisheries Research** 208: 133–144. DOI: 10.1016/j.fishr es.2018.07.012.

Frédou, F.L., T. Frédou, F. Ménard, D. Beare, N. Abid and L. Kell. 2016. Preliminary ecological risk assessment of small tunas of the Atlantic Ocean. **Collective Volume of Scientific Papers ICCAT** 73(8): 2663–2678.

Hordyk, A.R. and T.R. Carruthers. 2018. A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the productivity susceptibility analysis (PSA). **PLoS ONE** 13(6): e0198298. DOI: 10. 1371/journal.pone.0198298.

Iorhen and P. Terna. 2021. Vulnerability: Types, causes, and coping mechanisms. **International Journal of Science and Management Studies (IJSMS)** 4(3): 187–194. DOI: 10. 51386/25815946/ijsms-v4i3p116.

Jesintha, N. and K. Madhavi. 2020. Marine capture fisheries: Sustainability issues. **International Journal of Fisheries and Aquatic Studies** 8: 34–37.

Kalikoski, D.C., P.Q. Neto and T. Almudi. 2010. Building adaptive capacity to climate variability: the case of artisanal fisheries in the estuary of the Patos Lagoon, Brazil. **Marine Policy** 34(4): 742–751. DOI: 10.1016/j.marpol.2010.02.003.

Mamauag, S.S., P.M. Aliño, R.J.S. Martinez, R.N. Muallil, M.V.A. Doctor, E.C. Dizon, R.C. Geronimo, F.M. Panga and R.B. Cabral. 2013. A framework for vulnerability assessment of coastal fisheries ecosystems to climate change-tool for understanding resilience of fisheries (VA-TURF). **Fisheries Research** 147: 381. DOI: 10.1016/j.fishres.2013.07.007.

Maulana, R., M.A. Jabbar and Yonvitner. 2024. Biodiversity and vulnerability of fisheries resources in Berau Bay, West Papua Province. **Journal of Tropical Fisheries Management** 8(1): 16–23. DOI: 10.29244/jppt.v8i1.55908.

Mehanna, S.F., A.G.M. Osman, M.M.S. Farrag and Y.A.A. Osman. 2018. Age and growth of three common species of goatfish exploited by artisanal fishery in Hurghada Fishing area, Egypt. **Journal of Applied Ichthyology** 34(4): 917–921. DOI: 10.1111/jai.13590.

Moore, J.E., K.A. Curtis, R.L. Lewison, *et al*. 2013. Evaluating sustainability of fisheries bycatch mortality for marine megafauna: A review of conservation reference points for data-limited populations. **Environmental Conservation** 40(4): 329–344. DOI: 10.1017/S037689291300012X.

Patrick, W.S., P. Spencer, O. Ormseth, *et al*. 2009. Use of productivity and susceptibility indices to determine the vulnerability of a stock: with example applications to six US fisheries. **Fishery Bulletin** 108: 305–322.

Patrick, W.S., P. Spencer, J. Link, *et al*. 2010. Using productivity and susceptibility indices to assess the vulnerability of united states fish stocks to overfishing. **Fishery Bulletin** 108(3): 305–322.

Pauly, D. 1984. **Population Dynamics in Tropical Waters: a Manual for Use with Programmable Calculators.** International Center for Living Aquatic Resources Management, Studies and Reviews 8, Manila, Philippines. 325 pp.

Rickman, S.J., N.K. Dulvy, S. Jennings and J.D. Reynolds. 2000. Recruitment variation related to fecundity in marine fishes. **Canadian Journal of Fisheries and Aquatic Sciences** 57(1): 116–124. DOI: 10.1139/cjfas-57-1-116.

Saltelli, A. 2002. Sensitivity analysis for importance assessment. **Risk Analysis** 22(3): 579–590. DOI: 10.1111/0272-4332.00040.

Silva, M.R.O., M.G. Pennino and P.F.M. Lopes. 2019. Social-ecological trends: Managing the vulnerability of coastal fishing communities. **Ecology and Society** 24(4): 4. DOI: 10.5751/ES-11185-240404.

Stergiou, K.I. and V.S. Karpouzi. 2002. Feeding Habits and trophic levels of Mediterranean fish. **Reviews in Fish Biology and Fisheries** 11(3): 217–254. DOI: 10.1023/A:1020556722822.

Stergiou, K.I., D.K. Moutopoulos, H.J.A. Casal and K. Erzini. 2007. Trophic signatures of small-scale fishing gears: Implications for conservation and management. **Marine Ecology Progress Series** 333: 117–128. DOI: 10.3354/meps333117.

Stevens, M.H., S.G. Smith and J.S. Ault. 2019. Life history demographic parameter synthesis for exploited Florida and Caribbean coral reef fishes. **Fish and Fisheries** 20(6): 1196–1217. DOI: 10.1111/faf.12405.

Triharyuni, S., S.T. Hartati and R.F. Anggawangsa. 2013. Productivity and susceptibility of threadfin bream (*Nemipterus* spp.) caught by demersal danish net in Java Sea. **Jurnal Penelitian Perikanan Indonesia** 19(4): 213–220. DOI: 10.15578/jppi.19.4.2013.213-220.

Yonvitner, I. Setyobudiandi, A. Fachrudin, R. Affandi, E. Riani and N. Triramdhani. 2017. Indicator review of NOAA PSA index for small pelagic fishes (tembang: *Sardinella* sp.; Famili Clupeidae) and demersal fishes (kurisi: *Nemipterus* sp.; Famili Nemipteridae). **Marine Fisheries** 8(2): 123–135.

Yonvitner, J. L. Ioret, M. Boer, R. Kurnia, S.G. Akmal, E. Yuliana, D.E. Yani, S. Gómez and L.E. Setijorini. 2020. Vulnerability of marine resources to small-scale fishing in a tropical area: The example of Sunda Strait in Indonesia. **Fisheries Management and Ecology** 27(5): 489–497. DOI: 10.1111/fme.12428.

Yuliana, E., M. Boer, A. Fahrudin, M.M. Kamal and S.T. Pardede. 2019. Using ecosystem approach indicators for assessing the ecological status of reef fisheries management in a marine protected area. **Biodiversitas** 20(7): 1802–1810. DOI: 10.13057/biodiv/d200703.

Yuliana, E., Nurhasanah, D.E. Yani and S. Agustina. 2020. Fisheries management of bullet tuna (*Auxis rochei*) in marine protected area of Nusa Penida, Bali. **Jurnal Ilmu dan Teknologi Kelautan Tropis** 12(3): 659–672. DOI: 10.29244/jitkt.v12i3.32195.

Zar, J.H. 2010. **Biostatistical Analysis,** 5th ed. Pearson Education Limited, Edinburgh Gate, Essex, England. 751 pp.