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

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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. Considering the available information on species-specific life-history and fishery-specific attributes, we used PSA to assess the relative risk of the 60 species interacting 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 in the moderate-risk category, while seven non-target bycatch species were in the high-risk category. PSA-derived vulnerability results were validated with IUCN extinction risk, exploitation rate and stocks' catch trend. The majority of the identified species showed high productivity (37%) and high susceptibility (46%), and all the moderately and highly vulnerable species were subjected to overfishing conditions by shrimp trawl fishery, which coincided with the vulnerability scores ($V \geq 1.8$). Species with $V \geq 1.8$ mostly showed a decreasing catch trend, while the species with a stable or increasing catch trend had a $V \leq 1.72$. Data quality analysis of productivity and susceptibility attributes indicated that the majority of species were considered data-limited, which emphasizes the acquisition of data on spatio-temporal abundance, catch and effort, and biological information specifically relating to species age, growth, and reproduction. However, our findings can assist fishery administrators in implementing an ecosystem approach to ensure the sustainability and conservation of marine biodiversity in the Bay of Bengal.



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

1. Introduction

The Bay of Bengal, the northeastern part of the Indian Ocean, is enriched with coastal and marine ecosystems and is considered a potential ground for marine species diversity, including shrimps [1,2]. 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 Exclusive Economic Zone (EEZ) of Bangladesh [3]. Being a multi-species tropical fishery, shrimp trawlers catch both target shrimps and non-target bycatch species by changing the fleet configuration and fishing technique [4]. The catch per unit fishing effort has been declining, and some species of marine shrimp and fish stocks are being depleted [5–7]. Consequently, the natural harmony of aquatic ecosystems has been disrupted by the over-exploitation of marine resources [8,9].

Shrimp and demersal trawl surveys in the Bay of Bengal by the research vessel “RV Meen Shandhani” indicated that large, slow-growing, and slow-reproducing species are being replaced by small-sized, fast-growing, and fast-reproducing species [5]. In marine ecosystems, small, low-trophic level forage species are key prey for large, high-trophic level predatory species [10]. The increase in the numbers of small species reflects a significant alteration to the ecosystem structure, and the ability of the ecosystem to rebuild the stocks of large and high-value species can be impaired consequentially [5]. For the conservation of marine ecosystems and improved fisheries resource management, the ecosystem approach involving species’ habitats protection, appropriate practice of fisheries and resources utilization, and improvement of gear specification to minimize bycatch in a specific fishery must be practiced [11,12]. To put the ecosystem approach into practice and to recover and protect seabed habitats and biodiversity, the government of Bangladesh has prohibited the introduction of new shrimp trawlers because they haul on the seabed, causing the destruction of marine flora and fauna [7]. To ensure the breeding of sea species populations and their conservation, the government of Bangladesh has also introduced a monsoonal fishery closure (65-day fishing ban) between May and July in the Bay of Bengal, which helps promote the ecological restoration of depleted fisheries resources [13].

Multi-gear and multi-species fisheries exploit traditional fishing grounds in the Bay of Bengal. Therefore, scientific research on species-specific fisheries and stock status is required for effective management strategies [7]. A high diversity of non-target bycatch species tends to be highly susceptible to shrimp trawl fishery because of areal and vertical overlap in the shrimp fishing grounds. Relative vulnerability analysis of these species, along with target shrimp stocks, has a significant impact on species conservation. However, the improvement of ecosystem sustainability through significant management efforts for tropical fisheries could be hindered by a lack of biological productivity data and species-specific fishery statistics for a particular species [14]. In the case of information inadequacy, data-limited evaluations can be valuable methods for ecological risk assessment, and guide the management and conservation of vulnerable marine species [15].

Productivity susceptibility analysis (PSA) is an example of a widely applicable, semi-quantitative ecological risk assessment tool for data-limited multi-species and multi-gear fisheries [15–17]. The PSA approach was originally developed in Australia to analyze bycatch sustainability in prawn trawl fisheries [18]. The method addresses the vulnerability of a species by considering both the productivity attributes, for example, life-history traits, and susceptibility attributes, such as fishery-specific activities [17,19]. Attribute selection and multiplicative models for calculating vulnerability can be varied with PSA [19,20], depending on the evaluation measures of fishery management [21,22]. 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 ecosystem approach [16], to identify species with similar risk categories, and provide qualitative management information for highly vulnerable species [19,21].

We used the PSA approach to evaluate the relative vulnerability of the species identified to shrimp trawl fishery to understand the effect of fishing on shrimp and other associated stocks in the Bay of Bengal. The PSA outcomes were further verified with the different risk categories of the International Union for Conservation of Nature (IUCN) Red List, the exploitation rate of the stocks estimated by the Food and Agriculture Organization–International Center for Living Aquatic Resources Management (FAO-ICLARM) stock assessment tools, and catch trends of the stock perceived by skippers and crews of the shrimp trawlers. We observed the impact of existing management strategies on the stock that interacted with shrimp trawl nets, and also emphasized the improvement of research design to recommend additional fishery management strategies.

2. Materials and Methods

2.1. Shrimp Trawl Fishery

In Bangladesh's 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 [23]. In total, 32 industrial shrimp trawlers operated by 15 different companies or organizations (Supplementary Material Table S1) are now actively engaged in catching target stock shrimps, and many other species as bycatch, including some non-target shrimps, finfishes, squids, and crabs, in these grounds [23]. These trawlers generally navigate for a 30-day period for each voyage, completing five to six hauls every day for a period of 3–4 h depending on the weather and sea environments as well as the fishing vessels' efficacy [7].

Trawler companies are provided with a catch log sheet to report their catch before obtaining permission for the next fishing voyage. After each haul, the skippers of these fishing vessels fill out the 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., an inspector, cross-checks the number and quantity of species landed in the shrimp trawlers' specific jetties with the species-specific quantity reported on the catch log sheet. 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 1). Therefore, we considered the "Fishery Ghat" as our major study site for conducting the necessary interview survey.

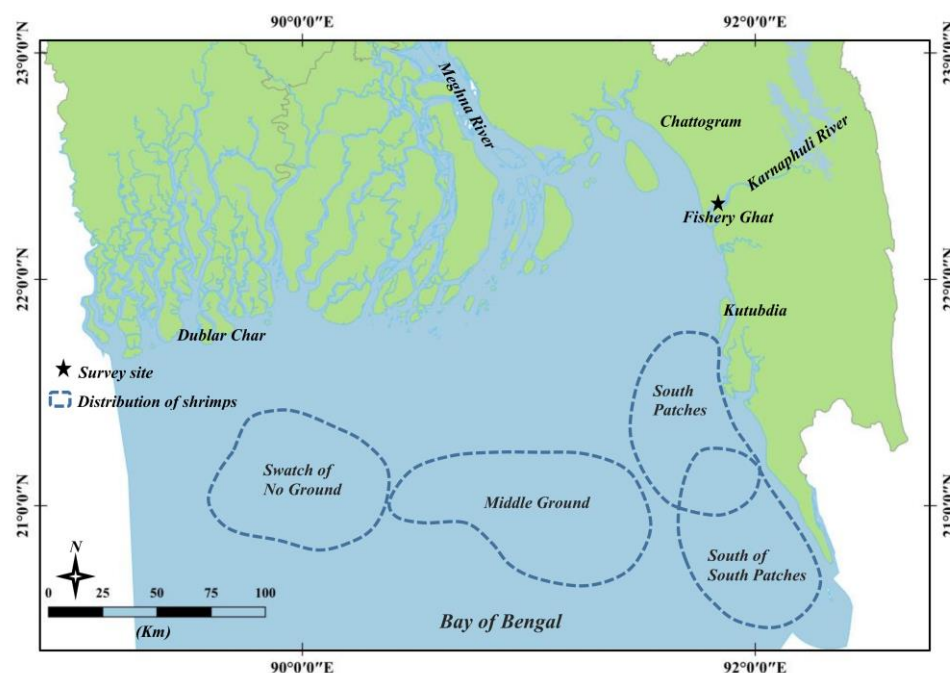


Figure 1. Map showing the distribution of shrimp in exclusive economic zone (EEZ) in the Bay of Bengal, and the survey site (star marked) for identifying the catch compositions of industrial shrimp trawlers.

Penaeus and *Metapenaeus* are the target genera of industrial shrimp trawling in Bangladesh. Giant Tiger Prawn, *Penaeus monodon*, is recognized as the most important target species of shrimp trawl fisheries in Bangladesh because of its high market demand and export value [5,24]. However, the Speckled Shrimp *Metapenaeus monoceros* contributed to approximately 42.8% of the total shrimp capture [25]. Adult *P. monodon* are habitually found in deep waters in the sea, while juveniles inhabit seagrass beds, mangrove swamps, and estuaries. Spawning occurs in offshore seas, where larval stages are successively found. This omnivorous and demersal species contributes to the maintenance of aquatic ecosystems by scavenging and predating aquatic species [26,27].

The length of the shrimp trawlers varies from 20 to 30 m, with a capacity of gross tonnage of 115–300 MT and engine power of 249.8–820.3 kW [23]. They trawl over sandy

bottoms to a depth of 40–100 m [23,24,28]. Generally, shrimp trawlers operate two to four nets at a time using outriggers, fishing beyond a depth of 40 m [23]. These trawlers use shrimp trawl nets attached to a turtle excluder device and a cod end with a mesh size of 45 mm [23]. The head rope length of the shrimp trawl net ranges from 15 to 35 m, and tickler chains are used in the bottom line to increase the shrimp catch composition [23].

2.2. Species Identification

To identify the species in shrimp trawl fishery, we prepared a list of common and commercially important marine species found in the Bay of Bengal from the existing literature. Of the 32 industrial shrimp trawlers, we compiled landing data of 20 trawlers from catch log sheets and catch reports collected from the Marine Fisheries Office and shrimp trawler companies during surveys conducted from November 2020 to April 2021. We also observed the landed catch of the shrimp trawlers to identify species using the taxonomic key suggested by Ahmed et al. [26], Quddus and Shafi [29], Rahman et al. [30], and Siddiqui et al. [31].

Then, we prepared another list of species including their photos as well as regional, common, and scientific names. A total of 100 skippers and crew (1 skipper and 4 crew from each of the 20 trawlers, who had at least 10 years of voyage experience) of the trawlers were requested to identify the species caught in their shrimp trawl nets from the species list throughout the entire fishing season in the Bay of Bengal. We cross-checked all the identified species at the time of discussion with the key informants, i.e., fisheries officers and fishery experts. We then compiled a final list of 53 bycatch species and seven target stocks of shrimp trawl fishery in the Bay of Bengal and validated their scientific names using SeaLifeBase [32] and FishBase [33].

2.3. Focus Group Discussions

A total of 50 skippers and crew (1 skipper and 4 crew members from each of 10 shrimp trawlers that had the highest species diversity and catch compositions) were selected for the focus group discussions (FGDs). For identifying suspected and subtle issues, as well as for understanding the stakeholders' perspectives on a specific topic of interest, FGD can be appropriate [34]. We conducted one FGD for each shrimp trawler (Supplementary Material Table S1) and the discussions lasted 2–3 h. At the beginning of each FGD, we provided a list of shrimp trawl net specific target and bycatch species, including their photos and local names, 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 nets, and environmental variables [35,36].

We also asked about shrimp fishing ground area, depth of fishing, trawl net selectivity, species survivability, bycatch discard tendency, the degree to which existing fishery regulations are enforced and followed, market prices, and demand for each species [37]. These data were used for the scoring the susceptibility attributes and vulnerability analysis of the stocks (Supplementary Material Tables S2 and S4). To understand the relative stock status of the target and bycatch species, we qualitatively obtained catch trend data. We asked the skippers and crew to score the species on a scale of 1–3, with 1, 2 and 3 indicating decreasing, stable, and increasing trends of stocks (Supplementary Material Table S2); we compared these catch trend data with the vulnerability scores for identified species [37].

2.4. Productivity Susceptibility Analysis

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) [21,22]. However, the choice of attributes is mostly determined by the availability of data and its applicability to vulnerability analysis [19]. For PSA of the target and bycatch species of shrimp trawl fishery, we

considered 12 productivity (e.g., species biological characteristics) and 10 susceptibility (e.g., impacts from fishery-specific activities) attributes [37] (Table 1).

Table 1. Scoring criteria for productivity (P) and susceptibility (S) attributes 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)	>73,854	13,182–73,854	<13,182
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

The productivity of a species is significantly influenced by its inherent traits [21]. 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, derived from the study of Patrick et al. [19]. Because of their strong correlation with the productivity of the stocks, these attributes are frequently used in PSA [17]. Species with a protracted breeding season or multiple broods per year, an annual cycle with a seasonal peak, or a bi/triennial breeding cycle are considered to be productive in that order [38]. Size at maturity and maximum size of a species also correlate with productivity, that is, species that mature quickly in relation to their maximum size have a higher productivity probability than species that mature slowly in relation to maximum size [21]. These phenomena are directly associated with species productivity. Therefore, the breeding cycle and size at maturity were considered, as in McCully Phillips et al. [38] and Hobday et al. [21], and the maturity size ratio and maturity age ratio were derived from Mejía-Falla et al. [39] (Table 1).

We considered the available species-specific information to compile the productivity attribute data. However, data on species of similar genera or taxa from the waterbodies of Bangladesh or the Indian subcontinent or outside of these regions were also considered in cases when species-specific data were not available [37]. All these data were gathered from the relevant literature and web-based global species databases, namely SeaLifeBase [32] and FishBase [33]. When data are not available, using an empirical equation to calculate productivity values for specified attributes can be a viable option [40,41]. Based on the empirical equations suggested by Froese and Binohlan [42] and Pauly [43], we calculated

the following correlated life history traits for fish species: maximum age (t_{max}) = $3/K$, length at maturity (L_{mat}) = $L_{\infty}10^{(0.8979-0.0782T)}$, age at maturity (t_{mat}) = $-\text{Log}_e(1 - L_{mat}/L_{\infty})/K$, and natural mortality (M) = $0.985 L_{\infty}^{-0.279} K^{0.6543} T^{0.4634}$, where K , L_{∞} , and T denote the von Bertalanffy growth coefficient, asymptotic maximum length, and water temperature (28 °C), respectively. However, for crustaceans and cephalopods, we did not apply any empirical equations and instead sorted the data from the relevant literature.

The susceptibility attributes (S), i.e., areal overlap, vertical overlap, seasonal migrations, schooling, aggregation, 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, and species market value and species market demand were partially modified from the attribute “desirability or value of the fishery” in the study of Patrick et al. [19]. We considered the attribute “fishing rate relative to M ” for stocks with available data because data on this attribute were not available from the waterbodies of Bangladesh for most of the assessed stocks in our PSA.

2.4.2. Data Scoring and Weighing

We used a scoring scale of 1–3 for the data on each of the productivity and susceptibility attributes (Supplementary Material Tables S3 and S4). The productivity attribute scores 1–3 indicated high (1), moderate (2), and low (3) risk corresponding to low, moderate, and high productivity of the stock, respectively [19]. The quantitative values of the productivity attributes were split into the 33rd and 67th percentiles to determine scoring thresholds of equal probabilities for each risk category, as done by Clarke et al. [15] and Duffy et al. [16]. For example, the von Bertalanffy growth coefficient (K) values for all stocks were within 0.11 to 1.7, so we scored the values > 0.90 (low risk), $0.38\text{--}0.90$ (moderate risk) and < 0.38 (high risk) as 3, 2, and 1, respectively (Table 1 and Supplementary Material Table S3). We modified the scoring categories for “breeding strategy” attributes based on the work of the Monterey Bay Aquarium [44] and Patrick et al. [19]. We considered a score of 3 for broadcast spawners, i.e., those that leave eggs in the water column, a score of 2 for external brooders or demersal egg layers or guarders, and a score 1 for mouth brooders or live bearers. When scoring the categories for the attribute of “breeding cycle”, we considered a score of 3 for species that have an annual cycle with a protracted breeding season, i.e., they breed throughout the year or have an extended breeding season, a score of 2 for species that have an annual cycle with a seasonal peak, and a score of 1 for species that have bi/triennial breeding cycles [38].

The susceptibility attributes of the stock were scored on a scale of 1–3, with 1 indicating low, 2 indicating moderate, and 3 indicating high risk (Table 1 and Supplementary Material Table S4). We considered similar scoring criteria for most susceptibility attributes listed by Patrick et al. [19]. However, we modified the scoring criterion for “morphological characteristics affecting capture” used by the Monterey Bay Aquarium [44] and FGDs. Therefore, we assigned a score of 3 to species that show high selectivity to trawl nets, i.e., species that can enter but cannot escape easily from the gear, a score of 2 for species that can enter into the gear and escape but have a moderate possibility of being caught (generally large, fast-swimming species have a tendency to escape from the trawl net [45]), and a score of 1 for the irregularly caught species. For the attributes “species market value” and “species market demand”, we assigned a score of 3 for high, 2 for moderate, and 1 for low market value and demand. Due to high fishing effort and high market demand, there is a desire to catch large quantities of high-valued species that have the potential to produce substantial revenues for fishers; however, this has a negative impact on fisheries resources [46]. In our study, we scored a species market value of >4 USD/kg as 3 (high risk), $2\text{--}4$ USD/kg as 2 (moderate risk), and <2 USD/kg as 1 (low risk).

After scoring both the productivity and susceptibility attributes, an equal weight score of 2 was assigned to each attribute value [19]. The scores assigned to each attribute were averaged, and we used the weighted average scores of the overall productivity and susceptibility because they are more commonly used than the multiplicative method, and to avoid the tendency to underestimate vulnerability [20].

2.4.3. Vulnerability Analysis of the Identified Species

The calculation of the overall vulnerability score (V) of a species depends on the two-dimensional nature of the PSA, defined as the Euclidean distance of the overall productivity (P) and susceptibility (S) scores; this can be graphically displayed on an x–y scatter plot [19,20]. The overall vulnerability score of a stock was calculated as $V = \sqrt{(P - 3)^2 + (S - 1)^2}$ [19]. In the biplot graph, the x-axis represents the weighted average P scores of the stocks on a scale of high (3) to low (1), while the y-axis represents the weighted average S scores of the stocks on a scale of low (1) to high (3). Low P and high S scores of the stocks signified the condition of being most vulnerable to being overfished, while high P and low S scores of the stocks indicated the least vulnerable condition [19]. The vulnerability scores of the stocks were categorized on a scale of low ($V < 1.8$), moderate ($1.8 \leq V < 2.0$), and high ($V \geq 2.0$) for further analysis [37].

2.4.4. Data Quality Score and Category

The scoring of data quality is a key outcome of the PSA analysis. This method could be used to identify species with limited data and recommend ways to improve data collection for those species [20]. The data quality of specific V scores was defined by a data quality table based on five tiers on a scale of 1–5, ranging from best data (1) to no data (5) [19] (Table 2). Therefore, the weighted average data quality scores for productivity and susceptibility reflect the overall quality of the data, and not the quality of the specific attributes' data type used in the PSA analysis (Table 3). We categorized the data into high ($DQ < 2.0$), moderate ($2.0 \leq DQ < 3.0$), and low quality ($DQ \geq 3.0$) [17]. In our study, we assigned the data quality score based on the availability of the data and the definition of data quality. However, data on life history traits resulting from the empirical equations were considered to be very limited data (4).

Table 2. Data quality (DQ) scoring tiers used in productivity susceptibility analysis (PSA), which is a slightly modified version of Patrick et al. [19] for the stocks caught by shrimp trawl fishery.

DQ Scores	DQ	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 which 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 the region, or data derived by equations using the correlated life history parameter	General data not referenced
5	No data	No information	

Table 3. Results of the productivity susceptibility analysis (PSA) for the species caught by shrimp trawl fishery are presented with their common and family names, as well as 3-alpha FAO codes. Scientific names and FAO codes of target stock species are listed as bold. Weighted average scores (*P*) of productivity attributes, with weighted average of data quality scores (PDQ), and weighted average scores (*S*) of susceptibility attributes, with weighted average of data quality scores (SDQ) shown. Vulnerability scores (*V*) of the species with vulnerability scores excluded management strategy (VeMSt) and overall data quality scores (ODQ) averaged from PDQ and SDQ are also displayed. The IUCN Red List of the species are categorized based on 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) indicate the decreasing (D), not significant (NS), stable (S), and increasing (I) status of the stocks. Exploitation rates (*E*) of the assessed stocks are also included.

Scientific Name	Common Name	Family	FAO Code	<i>P</i>	PDQ	<i>S</i>	SDQ	<i>V</i>	Vast	ODQ	IUCN		<i>E</i>
											(BD */G)	CTC	
<i>Penaeus monodon</i>	Giant Tiger Prawn	Penaeidae	GIT	2.58	3.33	2.80	2.20	1.85	1.93	2.77	LC *	D	0.65
<i>Penaeus indicus</i>	Indian White Prawn	Penaeidae	PNI	2.42	3.33	2.80	2.50	1.89	1.98	2.92	LC *	D	0.74
<i>Penaeus merguensis</i>	Banana Prawn	Penaeidae	PBA	2.42	3.33	2.60	2.20	1.70	1.77	2.77	LC *	S	0.68
<i>Penaeus semisulcatus</i>	Green Tiger Prawn	Penaeidae	TIP	2.42	3.33	2.70	2.30	1.80	1.87	2.82	LC *	D	0.60
<i>Metapenaeus monoceros</i>	Speckled Shrimp	Penaeidae	MPN	2.58	3.33	2.80	2.20	1.85	1.93	2.77	LC *	D	0.62
<i>Metapenaeus affinis</i>	Jinga Shrimp	Penaeidae	MTJ	2.67	3.42	2.67	2.44	1.70	1.78	2.93	DD *	S	
<i>Metapenaeus brevicornis</i>	Yellow Shrimp	Penaeidae	MPB	2.25	3.08	2.70	2.20	1.86	1.93	2.64	LC *	D	0.81
<i>Mierspenaeopsis sculptilis</i>	Rainbow Shrimp	Penaeidae	NAP	2.75	3.33	2.60	2.40	1.62	1.69	2.87	LC *	S	0.55
<i>Parapenaeopsis hardwickii</i>	Spear Shrimp	Penaeidae	NAW	2.67	3.67	2.22	2.56	1.27	1.29	3.11	DD *	S	
<i>Parapenaeopsis stylifera</i>	Kiddi Shrimp	Penaeidae	NAY	2.67	3.33	2.22	2.56	1.27	1.29	2.94	LC *	S	
<i>Portunus pelagicus</i>	Blue Swimming Crab	Portunidae	SCD	2.33	3.67	2.11	2.56	1.30	1.31	3.11	LC *	S	
<i>Scylla serrata</i>	Indo-Pacific Swamp Crab	Portunidae	MUD	2.08	3.17	2.10	2.40	1.43	1.44	2.78	LC *	S	0.39
<i>Sepia aculeata</i>	Needle Cuttlefish	Sepiidae	EJA	2.25	3.67	2.33	2.89	1.53	1.57	3.28	DD	S	
<i>Uroteuthis duvaucelii</i>	Indian Squid	Loliginidae	OJD	2.08	3.67	2.44	2.89	1.71	1.76	3.28	DD	S	
<i>Himantura uarnak</i>	Honeycomb Stingray	Dasyatidae	DHV	1.50	3.25	1.44	2.89	1.56	1.55	3.07	VU	S	
<i>Rhinobatos annandalei</i>	Annandale's Guitarfish	Rhinobatidae	RHD	1.58	3.58	1.67	2.89	1.57	1.55	3.24	DD	S	
<i>Arius arius</i>	Threadfin Sea Catfish	Ariidae	AUI	1.33	3.50	2.33	2.56	2.13	2.16	3.03	LC	D	
<i>Arius maculatus</i>	Spotted Catfish	Ariidae	CAO	1.25	3.50	2.11	2.33	2.07	2.08	2.92	NE	D	
<i>Plicofollis layardi</i>	Thinspine Sea Catfish	Ariidae	UKY	1.25	3.58	2.33	2.67	2.20	2.23	3.13	NE	D	
<i>Ariomma indicum</i>	Indian Driftfish	Ariommatidae	DRI	2.50	3.17	2.80	2.50	1.87	1.95	2.83	NE	D	0.62
<i>Alepes djedaba</i>	Shrimp Scad	Carangidae	LSJ	2.33	3.42	2.56	2.56	1.69	1.76	2.99	LC	S	
<i>Atropus atropus</i>	Cleftbelly Trevally	Carangidae	TUP	2.58	3.67	2.56	2.44	1.61	1.68	3.06	LC	S	
<i>Parastromateus niger</i>	Black Pomfret	Carangidae	POB	2.08	2.58	2.90	2.40	2.11	2.20	2.49	LC	D	0.52
<i>Selar crumenophthalmus</i>	Bigeye Scad	Carangidae	BIS	2.58	3.50	2.78	2.56	1.83	1.92	3.03	LC	D	
<i>Conger cinereus</i>	Conger Eel	Congridae	COI	1.42	3.67	2.67	2.89	2.30	2.36	3.28	LC	D	
<i>Cynoglossus bilineatus</i>	Fourlined Tongue Sole	Cynoglossidae	YOB	1.67	3.50	2.22	2.78	1.81	1.83	3.14	NE	D	
<i>Cynoglossus lingua</i>	Long Tongue Sole	Cynoglossidae	YOG	1.67	3.50	2.33	2.44	1.89	1.92	2.97	LC *	D	
<i>Dussumieria acuta</i>	Rainbow Sardine	Dussumieriidae	RAS	2.00	3.67	1.89	2.89	1.34	1.33	3.28	LC	S	
<i>Coilia dussumieri</i>	Goldspotted Grenadier Anchovy	Engraulidae	ECD	2.42	2.92	2.30	2.40	1.42	1.46	2.66	LC *	S	0.48
<i>Stolephorus tri</i>	Spined Anchovy	Engraulidae	ESJ	2.25	3.17	2.10	2.30	1.33	1.34	2.73	NE	S	0.85

Table 3. Cont.

Scientific Name	Common Name	Family	FAO Code	P	PDQ	S	SDQ	V	Vast	ODQ	IUCN	CTC	E
											(BD */G)		
<i>Thryssa mystax</i>	Moustached Thryssa	Engraulidae	EYY	2.33	3.67	2.22	2.56	1.39	1.42	3.11	LC	S	
<i>Gerres filamentosus</i>	Whipfin Silver-biddy	Gerreidae	GEF	2.83	3.67	2.67	2.56	1.67	1.76	3.11	LC	S	
<i>Aurigequula fasciata</i>	Striped Ponyfish	Leiognathidae	LGS	2.08	3.67	2.33	2.56	1.62	1.65	3.11	LC	S	
<i>Eubleekeria splendens</i>	Splendid Ponyfish	Leiognathidae	LGP	2.42	3.42	2.33	2.56	1.46	1.49	2.99	LC	I	
<i>Lobotes surinamensis</i>	Tripletail	Lobotidae	LOB	2.08	3.67	2.00	2.67	1.36	1.36	3.17	LC	S	
<i>Lutjanus johnii</i>	John's Snapper	Lutjanidae	LJH	1.67	3.00	2.60	2.50	2.08	2.13	2.75	LC	D	0.78
<i>Lutjanus lutjanus</i>	Bigeye Snapper	Lutjanidae	LJL	2.00	3.67	2.56	2.44	1.85	1.91	3.06	LC	D	
<i>Congresox talabonoides</i>	Indian Pike Conger	Muraenesocidae	MCG	1.42	3.33	2.44	2.50	2.14	2.18	3.00	NE	D	
<i>Nemipterus japonicus</i>	Japanese Threadfin Bream	Nemipteridae	NNJ	2.33	3.17	2.70	2.50	1.83	1.90	2.83	LC	NS	0.59
<i>Nemipterus randalli</i>	Randall's Threadfin Bream	Nemipteridae	NNZ	2.00	3.67	2.56	2.89	1.85	1.91	3.28	LC	NS	
<i>Parascolopsis aspinosa</i>	Smooth Dwarf Monocle Bream	Nemipteridae	NPS	2.50	3.83	2.56	2.89	1.63	1.70	3.36	LC	S	
<i>Plotosus lineatus</i>	Striped Eel Catfish	Plotosidae	PII	2.08	3.42	2.00	2.44	1.36	1.36	2.93	NE	S	
<i>Eleutheronema tetradactylum</i>	Fourfinger Threadfin	Polynemidae	FOT	1.83	3.00	2.44	2.44	1.86	1.90	2.72	NE	D	
<i>Leptomelanosoma indicum</i>	Indian Threadfin	Polynemidae	OYD	1.75	3.67	2.33	2.67	1.83	1.86	3.17	NE	D	
<i>Polydactylus sextarius</i>	Blackspot Threadfin	Polynemidae	OAX	1.83	3.50	2.44	2.67	1.86	1.90	3.08	NE	D	
<i>Rachycentron canadum</i>	Cobia	Rachycentridae	CBA	1.92	3.42	2.22	2.56	1.63	1.65	2.99	LC	S	
<i>Johnius dussumieri</i>	Sin Croaker	Sciaenidae	JOU	2.42	3.67	2.00	2.56	1.16	1.16	3.11	LC	S	
<i>Otolithoides biauritus</i>	Bronze Croaker	Sciaenidae	OTB	1.83	3.83	1.78	2.56	1.40	1.39	3.19	DD	S	
<i>Epinephelus lanceolatus</i>	Giant Grouper	Serranidae	EEN	1.75	3.42	2.00	2.78	1.60	1.60	3.10	DD	S	
<i>Epinephelus malabaricus</i>	Malabar Grouper	Serranidae	MAR	2.00	3.50	2.22	2.67	1.58	1.60	3.08	LC	S	
<i>Siganus canaliculatus</i>	White-spotted Spinefoot	Siganidae	SCN	2.42	3.67	2.00	2.56	1.16	1.16	3.11	LC	S	
<i>Sillago sihama</i>	Silver Sillago	Sillaginidae	ILS	2.17	3.33	2.10	2.70	1.38	1.39	3.02	LC	S	0.75
<i>Argyrops spinifer</i>	King Soldier Bream	Sparidae	KBR	1.50	3.67	2.00	2.44	1.80	1.80	3.06	LC	D	
<i>Sphyrnaena obtusata</i>	Obtuse Barracuda	Sphyrnaenidae	YRB	1.92	3.25	2.44	2.67	1.81	1.85	2.96	NE	NS	
<i>Pampus argenteus</i>	Silver Pomfret	Stromateidae	SIP	2.17	2.83	2.40	2.30	1.63	1.67	2.57	NE	S	0.40
<i>Pampus chinensis</i>	Chinese Silver Pomfret	Stromateidae	CPO	1.92	3.00	2.30	2.30	1.69	1.72	2.65	NE	S	0.39
<i>Harpadon nehereus</i>	Bombay-duck	Synodontidae	BUC	2.25	3.17	2.00	2.30	1.25	1.25	2.73	NT	S	0.38
<i>Saurida tumbil</i>	Greater Lizardfish	Synodontidae	LIG	2.00	3.17	2.40	2.70	1.72	1.76	2.93	LC	I	0.35
<i>Terapon jarbua</i>	Jarbua Terapon	Terapontidae	TJB	1.83	3.33	2.22	2.33	1.69	1.71	2.83	LC	S	
<i>Lepturacanthus savala</i>	Savalai Hairtail	Trichiuridae	SVH	2.08	2.67	2.30	2.40	1.59	1.62	2.53	NE	S	0.43

* IUCN Red List of Bangladesh [27,47].

2.5. Comparison of Species' Vulnerability with Other Assessments

The outcomes of the PSA were compared with three further analytical approaches, i.e., IUCN extinction risk, exploitation rate (E), and catch trend status of the stocks [37], to acquire an in-depth understanding of the relative status of the stocks identified in the shrimp trawl fishery. We verified the different risk categories of the stocks in the IUCN Red List of Bangladesh [27,47] and the global list [48], namely, critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), data deficient (DD), and not evaluated (NE) (Table 3).

Gulland [49] obtained the exploitation rate (E) of a specific stock as $E = F/(F + M)$, where M and F denote the natural mortality and fishing mortality coefficients, respectively. For most of the stocks, data of E were not available, and we found E values for 20 stocks to identify the stock status in the Bay of Bengal, which have been assessed by FAO-ICLARM stock assessment tools. When fishing mortality is equal to natural mortality, it indicates that the stocks are optimally exploited ($E = 0.5$) [49]; the stocks are over-exploited if $E > 0.5$, and under-exploited if $E < 0.5$ (Table 3 and Supplementary Material Table S2). The V scores resulting from PSA with E were compared. We found a substantial relationship between the V score ($V \geq 1.8$) and exploitation rate ($E > 0.5$).

The vulnerability scores were also compared with the identified stocks' catch trend status obtained during FGDs with 50 participants from the 10 shrimp trawlers. We considered their perceptions about the stock status of the species depending on catch frequency and catchability by shrimp trawl. If there were more than 30 participants who perceived the same category ($\sum_{x=31}^{50} C_x 0.5^x 0.5^{50-x}$), indicating $<5\%$ statistical significance, we evaluated the catch trend of that specific stock to be increasing (2), increasing or stable (1), or decreasing (-1); if not, we considered it to be insignificant (0) (Table 3 and Supplementary Material Table S2) [37].

3. Results

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, belonging to 32 families and four classes, namely Malacostraca, Cephalopoda, Elasmobranchii, and Actinopterygii (Table 3 and Figure 2). Species of the family Penaeidae were the most prominent, followed by Carangidae, Ariidae, Engraulidae, Nemipteridae, Polynemidae, and the remaining families. Eels (Congridae, Muraenesocidae), catfish (Ariidae, Plotosidae), ponyfishes (Leiognathidae), croakers (Sciaenidae), tongue soles (Cynoglossidae), pomfrets (Stromateidae, Carangidae), groupers (Serranidae), and ribbonfishes (Trichiuridae) were caught significantly as finfish bycatch in shrimp trawl fishery.

3.2. Vulnerability Assessment by Productivity Susceptibility Analysis

All the species identified 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). The overall productivity and susceptibility scores showed that 37% and 46% of all the identified species had high productivity and high susceptibility scores, respectively, while 36% and 27%, respectively, had moderate and low productivity scores, and 44% and 11%, respectively, had moderate and lower susceptibility (Figure 3a).

The PSA-derived vulnerability scores of the identified species ranged from 1.16 to 2.30. The most important target stock, Giant Tiger Prawn, *Penaeus monodon*, was considered moderately vulnerable ($V = 1.85$), given 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. merguensis* (1.70), *P. semisulcatus* (1.80), *Metapenaeus monoceros* (1.85), *M. affinis* (1.70), and *M. brevicornis* (1.86), where $V < 1.8$ indicates low vulnerability and $1.8 \leq V < 2.0$ indicates moderate vulnerability. The vulnerability scores of the bycatch species showed that seven species (*Arius arius*, *Arius maculatus*, *Conger cinereus*, *Congresox talabonoides*, *Lutjanus johnii*, *Parastro-*

mateus niger, Plicofollis layardi) from the Bay of Bengal were highly vulnerable to shrimp trawl fishery, as their *V* scores ranged between 2.07 and 2.30, while 12 stocks had moderate vulnerability scores ($1.80 \leq V \leq 1.89$), and the remaining 34 species had low vulnerability scores, ranging from 1.16 to 1.72 (Table 3 and Figure 4).

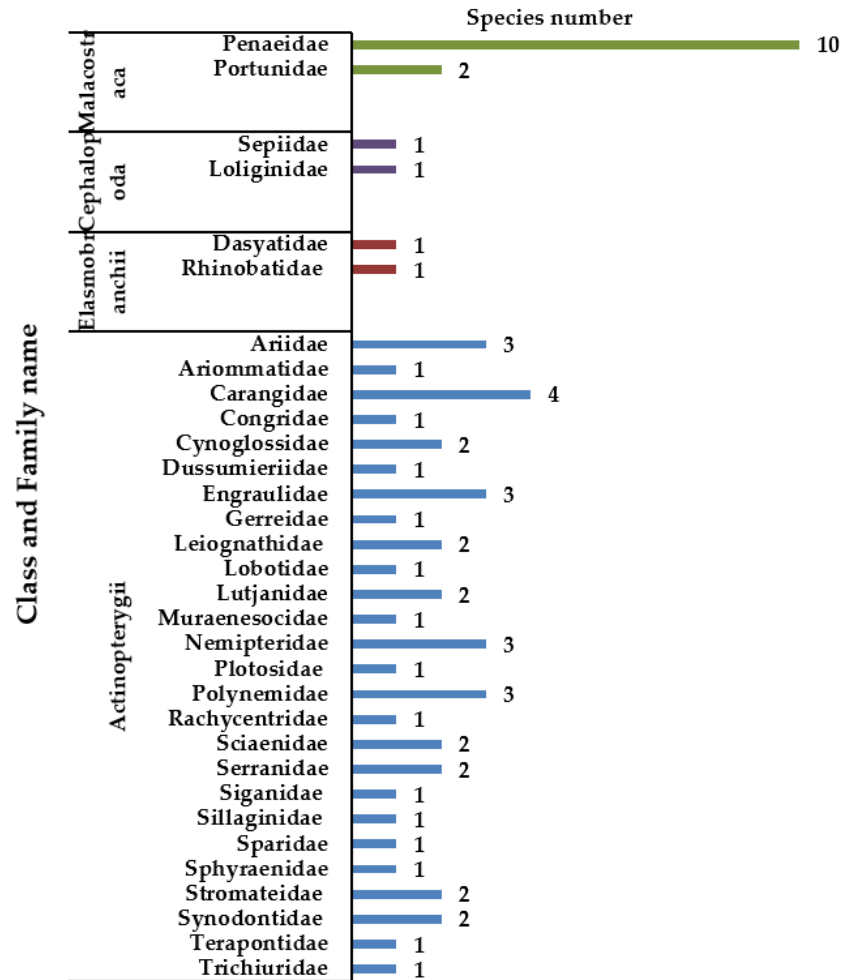


Figure 2. Composition of the species identified from shrimp trawl fishery. Data labels in the bars indicate the number of species belonging to the corresponding family.

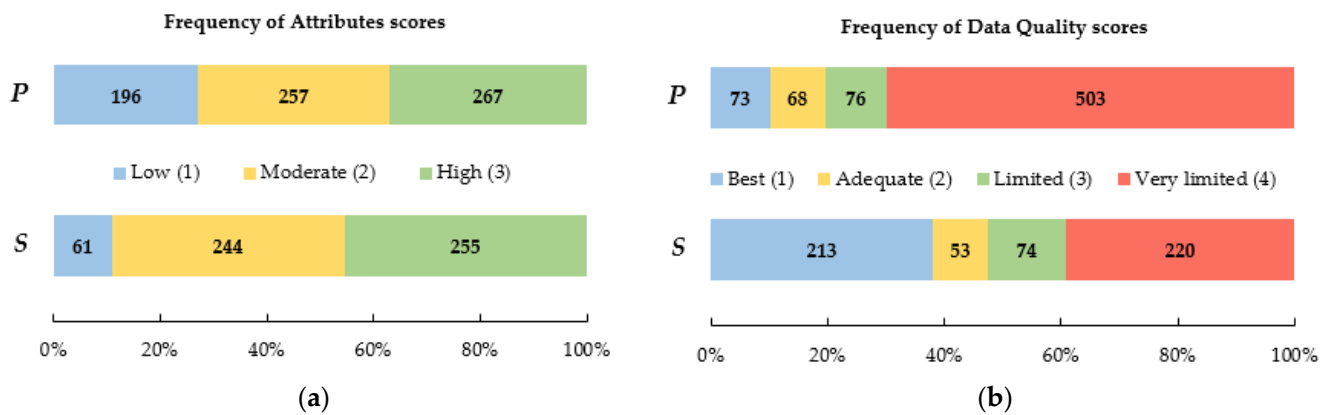


Figure 3. (a) Attributes scoring categories and (b) data quality scoring categories of overall productivity (P) and susceptibility (S). Data labels indicate the frequencies of both categories.

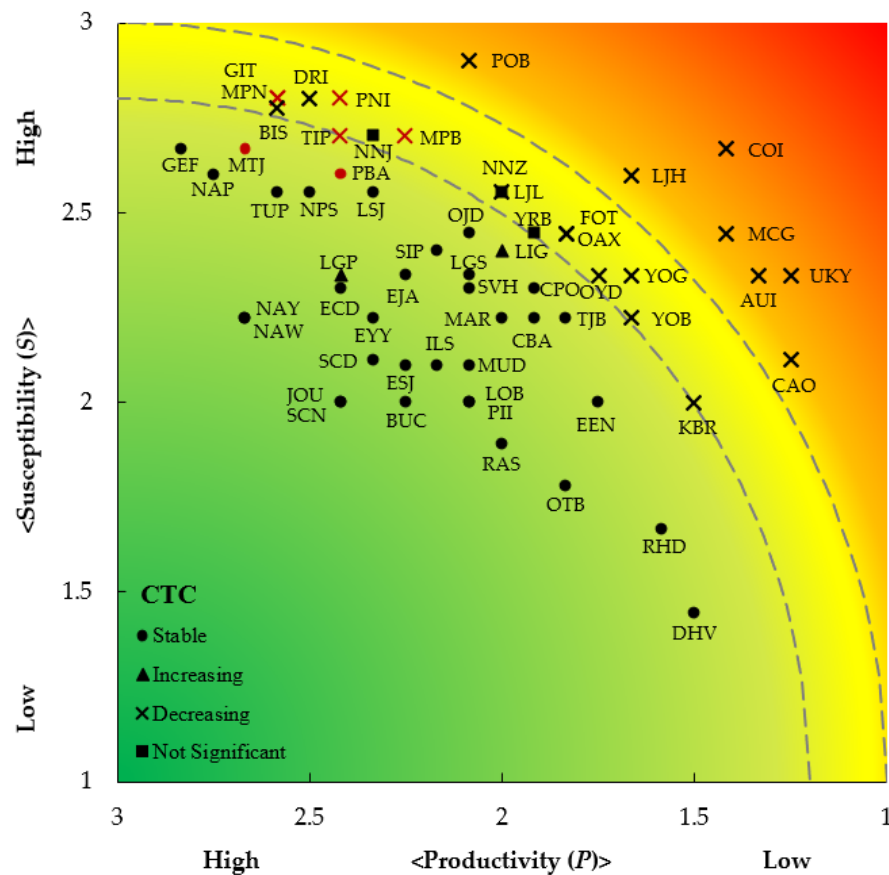


Figure 4. Productivity (P) and susceptibility (S) scores are displayed in two-dimensional (x - y scatter) plot to indicate the vulnerability (V) of identified species (labeled with 3-alpha FAO codes) from shrimp trawl fishery. V scores of 1.8 and 2.0 are shown by contour lines, along with “low” ($V < 1.8$), “moderate” ($1.8 \leq V < 2.0$), and “high” ($V \geq 2.0$) vulnerability categories. V values of target and bycatch stocks are marked with red and black, respectively. Catch trend categories (CTC) of the overall stocks are also expressed in the legend by different markers. Capital letters in the scattered plot refer to the FAO codes shown in Table 3.

Further, 69.9% of the data of the assessed stocks fell under the “very limited” data quality (DQ) category for the overall productivity attributes, followed by “limited” (10.6%), “best” (10.1%), and “adequate” (9.4%). As regards the susceptibility attributes, 39.3% of the data for the assessed stocks were in the “very limited” data quality category, followed by “best” (38.0%), “limited” (13.2%), and “adequate” (9.5%) (Figure 3b). The weighted average DQ scores for the productivity attributes ranged from 2.58 to 3.83, indicating the presence of 6.7% moderate- and 93.3% low-quality data, while the DQ scores for susceptibility ranged from 2.20 to 2.89, indicating moderate-quality data for all susceptibility scores (Table 3). The overall DQ scores for the vulnerability of target stocks were 2.64–2.93, indicating moderate DQ, while for the bycatch species, they ranged from 2.49 to 3.36, indicating the presence of 43.4% moderate- and 56.6% low-quality data (Table 3).

3.3. Comparison of Species’ Vulnerability with Other Assessments

We categorized the identified species based on Bangladesh and the global IUCN Red Lists. In most cases, our identified species were not present on the Bangladesh IUCN Red List; therefore, we considered the global list for the species that were not included in the Bangladesh list. We found one bycatch species each from the VU (*Himantura uarnak*) and NT (*Harpadon nehereus*) categories. Twelve species from the LC and two species from DD categories were found in the IUCN Red Lists of Bangladesh. Alternatively, 25 species from LC, 14 species from the NE, and 5 species from the DD categories were found in the global

IUCN Red List. We also categorized the species placed in both the global and Bangladesh IUCN; however, we did not find any species from the CR or EN categories (Figure 5 and Table 3).

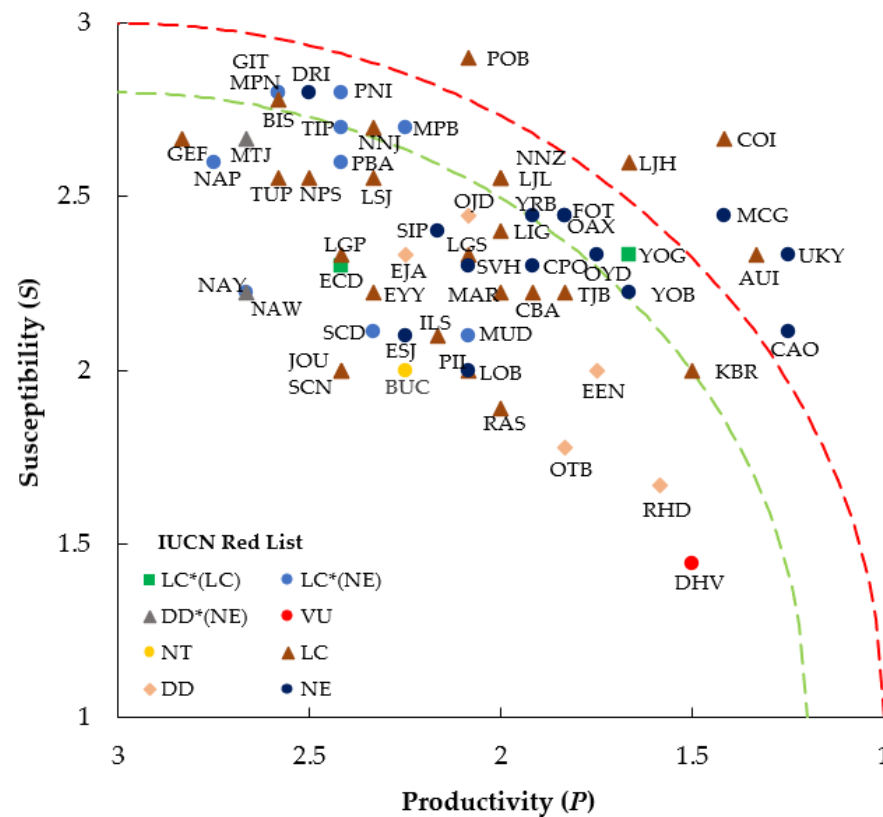


Figure 5. Species vulnerability to shrimp trawl fishery are categorized according to the IUCN Red List of Bangladesh * and the global list, i.e., vulnerable (VU), near threatened (NT), least concerned (LC), data deficient (DD), and not evaluated (NE). Species categorized according to the Bangladesh * IUCN Red List have been further categorized according to global IUCN Red List, as expressed in parenthesis. Species names are labeled with 3-alpha FAO codes. Capital letters in the scattered plot refer to the FAO codes shown in Table 3.

When comparing PSA-derived vulnerability scores with an IUCN extinction risk, we found that both the VU and NT category species, i.e., *H. uarnak* ($V = 1.56$) and *H. nehereus* ($V = 1.25$), were less vulnerable to shrimp trawl fishery. The most important target, *Penaeus monodon*, was categorized as LC in the IUCN Red Lists of Bangladesh and moderately vulnerable ($V = 1.85$) to shrimp trawl fishery. Except for *P. merguensis* (low vulnerability, LC) and *Metapenaeus affinis* (low vulnerability, DD), the other four moderately vulnerable target stocks were considered as LC in the IUCN Red List of Bangladesh. *Cynoglossus lingua* was ranked as LC and a moderately vulnerable bycatch species, while all five of the other low-vulnerability bycatch species were ranked in the LC category, and *Parapenaeopsis hardwickii* came under DD in the IUCN Red List of Bangladesh. Among the seven bycatch species with highest vulnerability, four species (i.e., *Arius arius*, *Conger cinereus*, *Lutjanus johnii*, *Parastromateus niger*) were ranked as LC, and three species (i.e., *Arius maculatus*, *Congresox talabonoides*, and *Plicofollis layardi*) were ranked as NE in the global IUCN Red List. For the remaining 37 bycatch species from the global IUCN Red List, 11 species had moderate vulnerability (13.51% for LC and 16.22% for NE), and 26 species had low vulnerability (43.24% for LC, 18.92% for DD, and 8.11% for NE) to shrimp trawl fishery (Figure 5 and Table 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 ($E < 0.5$) (Figure 6). When comparing with the V scores, we observed that $V \geq 1.8$

matched with $E > 0.5$ (nine stocks), while $V < 1.8$ matched with $E < 0.5$ (seven stocks), with some exceptions (four stocks); the degree of conformity was 80% between V and E among the 20 stocks. Therefore, we considered $V \geq 1.8$ for over-fishing and $V < 1.8$ for under-fishing status, and our analysis suggests that 24 (40%) of the stocks, including target (except for *P. merguensis* and *M. affinis*) and bycatch stocks, were in the over-fishing category, and 36 (60%) were in the under-fishing category (Table 3).

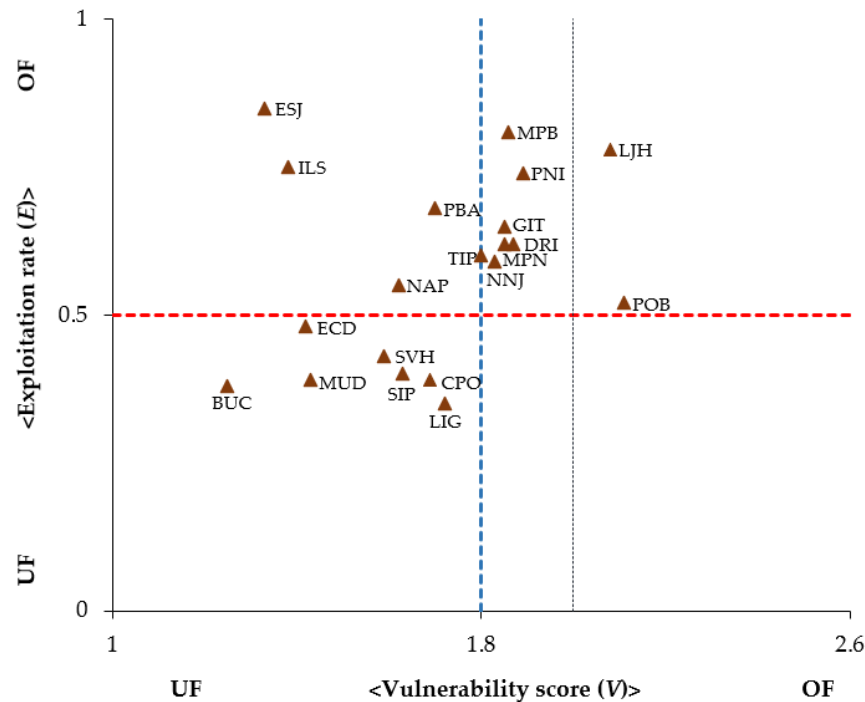


Figure 6. Vulnerability (V) scores are compared with exploitation rate (E), and species names are labeled with 3-alpha FAO codes. $V \geq 1.8$ and $E > 0.5$ signify over-fishing status (OF), while $V < 1.8$ and $E < 0.5$ signify under-fishing (UF) status of the stocks. Capital letters in the scattered plot refer to the FAO codes shown in Table 3.

There was a high correlation between the catch trend and vulnerability score by PSA. The vulnerability (V) scores of 21 (35%) species with “declining” catch trends and 3 (5.0%) species, i.e., *Sphyrna obtusata*, *Nemipterus japonicus*, 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 2 (3.3%) species, i.e., *Eubleekeria splendens* and *Saurida tumbil*, with “increasing” catch trends were ≤ 1.72 (Table 3 and Supplementary Material Table S2). Therefore, $V \geq 1.8$ indicated a substantial relationship not only with the exploitation status but also with the catch trends of the stocks identified from shrimp trawl fishery in the Bay of Bengal.

4. Discussion

4.1. Composition of the Identified Species

Of the 60 identified species, the highest number of species identified from shrimp trawl fishery belonged to family Penaeidae (class Malacostraca). Non-target finfish species from the shrimp trawl fishery comprised approximately 35–40% of the total catch [50], and a small percentage (0.47%) of sharks and rays were reported in industrial catches [28]. In our study, we identified 44 fin fish species from 26 families belonging to the class Actinopterygii. Species from the class Malacostraca, that is, crabs belonging to the family Portunidae as well as species from Cephalopoda and Elasmobranchii, also interacted with shrimp trawl nets (Figure 2). Impacts on the dynamics of marine ecosystems depend on the type 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 [51].

According to the Marine Fisheries Ordinance, 1983 (Rule 7) of Bangladesh, discarding trash fish/bycatch at sea is prohibited [28]. Therefore, almost all fish caught are brought ashore for alternate use, such as as reasonable protein sources—dried low-priced trash fish have high market value for the aquaculture and livestock industries [5,28]. However, the relative distribution of stock biomass, the functioning of trawl nets in fishing areas, and the degree of species sensitivity to each gear have an influence on the catchability and catch ratio of specific stocks [36].

4.2. Vulnerability Assessment by Productivity Susceptibility Analysis

Not all productivity and susceptibility attributes are equally significant in determining whether a stock is vulnerable to a particular fishery [19], and the susceptibility attribute score has a greater impact on calculating vulnerability than the productivity attribute score [52]. The impact of fishery-specific activities showed that a majority of the species had moderate-to-high scores of susceptibility attributes among the identified species, whereas the scores of productivity attributes signified the varying degrees of the biological characteristics of the species (Figures 3a and 4). This phenomenon also emphasizes the importance of 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 operations, and the fleet dynamics of trawlers in fishing grounds [53,54].

Penaeus monodon (GIT), *P. indicus* (PNI), and *Metapenaeus monoceros* (MPN) were more susceptible to shrimp trawl fishery than the other four target stocks (Figure 4). The bycatch species *Parastromateus niger* (POB) had the highest susceptibility score (2.90) among all species. Depending on the magnitude of fishing vessels and gear operation, bycatch species can be more susceptible to a specific fishery than the target species [16]. Alternatively, the productivity scores (2.42–2.58) of *P. monodon*, *P. indicus*, and *M. monoceros* were higher than those of the bycatch *P. niger* (2.08). However, *P. monodon*, *P. indicus*, and *M. monoceros* were moderately vulnerable ($V = 1.85$ – 1.89) and *P. niger* was highly vulnerable ($V = 2.11$).

The PSA-derived vulnerability scores of the other bycatch species showed that eels (MCG, COI) and Ariidae catfish (AUI, CAO, UKY) were highly vulnerable to shrimp trawl fishery (Figure 4). Species with an extended life cycle and large body size, but slow growth rate and late maturity, resulted in low behavioral responses; there was thus inevitable overlap in their vertical distribution in the fishing region that reduced their relative stock abundance, and increased vulnerability scores. The majority of catfish and eel also showed high and moderate vulnerability to the Hilsa gillnet fishery, respectively [37]. Alternatively, the target shrimp stocks received moderate to low vulnerability scores due to their short life cycle and body size, fast maturity, high growth, and areal and vertical overlaps with other fishing gears, i.e., set bag nets and drift nets. However, the overall abundance of shrimp and catfish biomass, as well as their catch amount in Bangladesh, has been consistently decreasing over the last three decades [5,55].

The weighted average data quality scores of productivity attributes and susceptibility attributes for the identified species fell under the moderate–low categories and moderate quality categories, respectively. Data on the life history traits and stock assessment of the identified species from the Bay of Bengal and adjacent waterbodies have not been adequately analyzed [8,56]. The majority of the data for productivity attributes were categorized as “very limited”, and for susceptibility attributes, the majority of the data were categorized as “best” (Figure 3b) since the fishery-specific information was collected from the relevant sources of shrimp trawl fishery, alongside the current comprehensive state of the stocks in the Bay of Bengal, which had an impact on species’ vulnerability analysis performed through the semi-quantitative approach [57,58].

4.3. Comparison of Species' Vulnerability with Other Assessments

Concerns about reliability can be raised in relation to the scoring of productivity and susceptibility attributes, which signify the vulnerability of a species [21]. Faruque and Matsuda [37] and Osio et al. [20] suggested that the results of species vulnerability derived by PSA can be compared with the IUCN Red List. *Conger cinereus* was found to be highly vulnerable ($V = 2.30$), but according to the global IUCN list, it was in the LC category [48]. We found *Himantura uarnak* in the VU category of the global Red List [48], and in our PSA study, it showed low vulnerability ($V = 1.56$). The species is mainly exploited by artisanal fishing gear, i.e., modified drift gill nets, set bag nets, hooks, and long lines [8,59]. *Harpadon nehereus*, was listed as an NT species in the global Red List (IUCN, 2021), whereas it showed low vulnerability in our analysis ($V = 1.25$) and was largely caught by set bag nets, seine nets, and gill nets [60].

Based on the exploitation rate (E) of the species as previously assessed by the FAO-ICLARM stock assessment tools, *Mierspenaeopsis sculptilis* (NAP), *Penaeus merguensis* (PBA), *Sillago sihama* (ILS), and *Stolephorus tri* (ESJ) were categorized as low vulnerability ($V < 1.8$) in the PSA, but had $E > 0.5$, which indicated the over-fishing status of the stocks (Figure 6, Table 3 and Supplementary Material Table S2). *M. sculptilis* and *P. merguensis* are mostly caught and exploited by set bag nets, drift nets, and seine nets [26], whereas *S. sihama* and *S. tri* are captured by estuarine set bag nets, purse seines, and beach seines [30]. The exploitation rate and vulnerability scores of the remaining species matched with each other (Figure 6), and the majority of these species were commonly caught using trawl nets [5,30,61]. This is probably because the magnitude of the exploitation rate of stocks can fluctuate depending on the spatio-temporal distribution of the stocks in the fishing area, species sensitivity to different gears, fishing effort, and fishing pressure [62,63].

The species that scored $V \geq 1.8$ had a “decreasing” or “not significant” catch trend, whereas the species that scored $V < 1.8$ had a “stable” or “increasing” catch trend. Catch trends were determined by stakeholders' perceptions of the relative abundance of shrimp trawl fishery-specific species. For instance, *Nemipterus japonicus* showed a “not significant” trend in shrimp trawl fishery (Table 3), but was considered “stable” in Hilsa gillnet fishery [37]. The majority of large and valuable species showed a decreasing catch trend (Table 3, Supplementary Material Tables S3 and S4). Thus, marine fisheries resources in the Bay of Bengal are being exploited and depleted, with declining trends in more valuable stocks [5].

4.4. Impact of Management Strategy on the Identified Species

In Bangladesh, a number of laws and regulations have been enacted to ensure the optimal resource utilization, conservation, and enhancement of fishery production, but conflicts frequently arise with the implementation of these laws and rules [64]. Thereafter, new policies and action plans have been implemented to sustain the potential of the blue economy in the Bay of Bengal [65]. As a result, current regulations prohibit the discarding of bycatch at sea, mandate the use of prescribed mesh sizes in gear, and specify the fishing zones on the continental shelf [28]. However, noncompliance with these regulations, such as the use of small-meshed nets, the failure of the turtle excluder device's installation, and fishing at a depth of less than 40 m, have been reported to some extent [23]. The present management strategy is expected to decrease the vulnerability scores of the majority of the species involved in shrimp trawl fisheries. 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), where V_{eMSt} gives the vulnerability scores obtained by excluding scores of the category “Management Strategy” in Table 1. Therefore, the present management strategy is not significantly effective in improving sustainable fisheries in the Bay of Bengal [5]. However, stakeholders' compliance with fishery regulations and a proper understanding of how fishery laws are being enforced are essential for sustainable resource management [66].

4.5. Limitations and Future Directions of This Research

We did not use molecular techniques, which are considered substantial analytical approaches for the identification of highly diverse and morphologically flexible species [67].

There are 9 CR and 30 EN species listed as freshwater fish, and 2 EN species listed as crustaceans in the Bangladesh IUCN [27,47]. It may be necessary to pay attention to the presence of those species as bycatch in shrimp trawl fishery.

Commercially important penaeid shrimp species are currently exploited by both artisanal and industrial fisheries in different stages of life, namely, juveniles and pre-adults by the artisanal and adults by the industrial fisheries [5]. The majority of the bycatch species are caught by set bag nets, gillnets, seine nets, drift nets, hooks, and long lines [30].

We did not include species sensitivity to other gear types in our study because of insufficient data. However, the inclusion of all types of gear sensitivity is effective for understanding the overall fishing status in the Bay of Bengal.

Therefore, a convenient framework with harvest control rules based on quantitative stock assessment and input control rules based on co-management could be incorporated for the evaluation of sustainable management [68,69]. Moreover, 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 [70–72].

5. Conclusions

Species vulnerability to shrimp trawl fisheries through PSA was validated with the previously assessed IUCN extinction risk and exploitation rate, and with the catch trends. We identified large information gaps in the species-specific life history attributes, emphasizing the need for species stock assessment in the Bay of Bengal. Given the situation of data-limited multi-species fishery, the findings from our semi-quantitative ecological risk assessment may aid the implementation of an ecosystem approach for the conservation of the species in the high-risk category.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su14031691/s1>, Table S1: Brief summary of the total shrimp trawlers. Number of interviews and participants, and in parenthesis, focus group discussions (FGDs) are shown, Table S2. 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, Table S3. Twelve productivity (P) attributes of the listed species (scientific names and 3-alpha FAO codes), 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 with respective scores (P score), data quality (DQ) and references (Ref.), Table S4. Ten susceptibility (S) attributes of the listed species (scientific names and 3-alpha FAO codes), i.e., areal overlap (AO), vertical overlap (VO), seasonal migrations (SM), schooling, aggregation, 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), and fishing rate relative to natural mortality (F/M), are shown with respective scores (S score), data quality (DQ) and references (Ref.). References [73–286] are cited in the Supplementary.

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