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SHORT COMMUNICATION

Impact of Fishing Pressure on Reproductive Biology of Mackerel Scad, *Decapterus macarellus* (Cuvier, 1833) in Sulawesi Sea and Maluku Sea, Indonesia

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Abstract

The high fishing pressure may cause species evolutionary changes toward smaller maturation sizes. In this context, the fishing practices of mackerel scad, *Decapterus macarellus* (Cuvier, 1833), in tropical eastern Indonesia provide an excellent opportunity to examine this hypothesis. Two distinct fishing grounds, the Sulawesi Sea and Maluku Sea, were selected to explore this phenomenon. Samples of *D. macarellus* caught by purse seine fishers operating were sourced from the two fishing grounds. Analysing the total length and maturity stage of each *D. macarellus* specimen from the two stocks were made to estimate key parameters such as the length at first maturity (L_m) and total mortality (Z). The results revealed that total mortality, used as an indicator of fishing pressure, was higher in the Maluku Sea (5.3 year^{-1}) than in the Sulawesi Sea (3.7 year^{-1}) and other areas. Additionally, the L_m of *D. macarellus* in the Maluku Sea was remarkably lower (22.9 cm) than in the Sulawesi Sea (23.9 cm), which can be attributed to the higher fishing pressure. These findings support the fisheries-induced evolution hypothesis, particularly within Indonesian tropical fish stocks and their respective regions, adding new growing evidence that fishing pressure affects fish reproductive biology. The length at first maturity may serve as a valuable proxy for assessing the intensity of fishing pressure on fish stocks.

Keywords: small pelagic, length at maturity, early maturation, fishing mortality, fisheries-induced evolution

Introduction

Fishing activities have been recognised to affect the species composition within marine ecosystems. The common practice in many fisheries is to target larger individuals. A healthy structure of fish stocks is often characterised by a high proportion of large, sexually mature fish. However, the selective removal of target species over time can lead to changes in the size structure of the population. Trends toward earlier maturation are frequently seen in fish stocks that are commercially exploited (Trippel, 1995), and evidence suggests that fishing pressure may have caused evolutionary changes, resulting in smaller maturation sizes (Heino et al., 2015).

Indonesia ranked second among the top seven fisheries capture producers globally, with China leading the list, followed by Peru, India, the Russian Federation, the United States of America, and Vietnam (FAO, 2022). In the context of the top ten national fish production commodities in 2021, scads (*Decapterus* Bleeker, 1851) were the second-highest recorded catch behind bullet tuna *Auxis rochei* Risso, 1810 (7.79 %) (MMAF, 2022a). This proportion highlights the significant role of small pelagic fish, including scads, in contributing to nationwide fish production, complementing the production of tuna (*Thunnus* South, 1845), skipjack (*Katsuwonus pelamis* Linnaeus, 1758), and tuna-like species, such as *Scomberomorus*. Among the seven identified *Decapterus* species recorded from the landing records in Indonesia (Atmaja and Sadhotomo, 2005; Zamroni, 2012; Kimura et al., 2013), *Decapterus macarellus* Cuvier, 1833 stands out as the main species caught in the Sulawesi Sea, contributing 58 % to the total production of small pelagic groups in the respective area (MMAF, 2016). Mitochondrial markers have revealed distinct stock units between the Sulawesi Sea and Maluku Sea (Zamroni et al., 2014), later confirmed by a parasite investigation (Retnoningtyas et al., 2023).

The use of length at first maturity (Lm), in addition to the mean length in the catch (Lc), may serve as a proxy for assessing the intensity of fishing pressure on a stock (Lappalainen et al., 2016; Ramírez-Amaro et al., 2020; Yanti et al., 2020). This study aims to demonstrate how fishing pressure affects the length at first maturity of mackerel scad *D. macarellus* in tropical eastern Indonesia. To achieve this, comparative analyses were made for the maturity lengths of *D. macarellus* and the corresponding fishing pressures between the distinct fishing areas in the Sulawesi and Maluku Seas.

Materials and Methods

Study sites and sample collection

Decapterus macarellus were collected from landing sites in North Sulawesi, Indonesia, from September 2019 to March 2022. Samples representing the Maluku Sea were also collected from landing sites in North Sulawesi, namely Kema Tiga and Tumumpa Dua, after confirming the fishing ground through consultations with local fishers (Fig. 1). A total of 22,497 and 10,493 individuals were measured at the landing sites where the fish were caught from the Sulawesi Sea and the Maluku Sea, respectively. The total length of each individual was measured to the nearest millimetre.

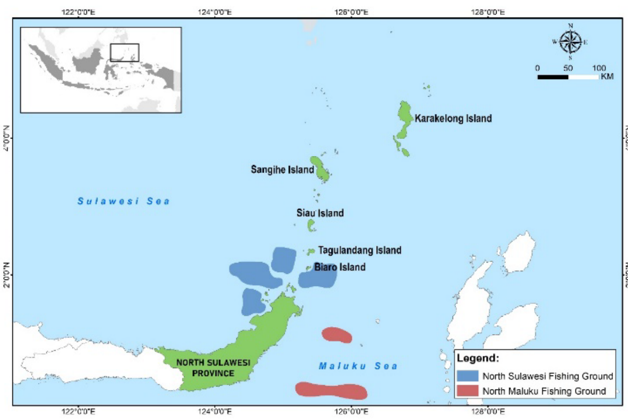

Fig. 1. Fishing grounds in the Sulawesi Sea (blue polygon) and in the Maluku Sea (red polygon). All fish samples were collected from landing sites in North Sulawesi Province (green polygon).

For gonad measurement, a macroscopic examination was performed following the dissection of 483 individuals from the Sulawesi Sea (52 % female, 48 % male) and 211 individuals from the Maluku Sea (44 % female, 55 % male, 1 % unidentified), all collected during July- August 2020. The shape and the colour of the testis and ovaries were used to assign gonad maturity levels (i.e., mature and immature) following the method outlined by West (1990).

Data analysis

Total length and maturity stages were used as key parameters to estimate length at first maturity (L_m) and length at first capture (L_c) of *D. macarellus*. The determination of the length at first maturity (L_m) of each unit stock (Sulawesi Sea and Maluku Sea) was analysed following the methodology by Tokai and Mitsuhashi (1998). This involved maximising the likelihood of binomial distribution in the logistic curve using a process facilitated through the "SOLVER" tool in Excel.

The life-history parameters essential for calculating the total mortality of *D. macarellus* in each unit stock encompassed asymptotic length (L_∞), growth coefficient (K), and natural mortality (M). The growth coefficient (K) and asymptotic length (L_∞) were estimated according to the von Bertalanffy growth model (Sparre and Venema, 1998). The parameter t_0 was computed using the equation formulated by Pauly (1979). For natural mortality, a combination of various sources was employed. Specifically, the length equation was from Pauly (1980), the joint equation from Hoenig (1983), the t_{max} equation from Then et al. (2015), and the growth equation from Then et al. (2015) (Table 1).

Table 1. Life history parameters of *Decapterus macarellus* in the Sulawesi Sea and Maluku Sea.

Parameter	Label	Unit	Value	
			Sulawesi	Maluku
Asymptotic length	L_∞	cm	38.80	37.53
Growth coefficient	K	year^{-1}	0.87	0.86
Theoretical age at length = 0	t_0	year	-0.17	-0.18
Natural mortality	M	year^{-1}	1.11	1.11

Total mortality was calculated using length-converted linearised catch curves following Pauly (1984). Length at first capture was also estimated from a detailed analysis of the ascending part of this curve, which expressed the length at which fish have a 50 % probability of getting caught. Life-history parameters, total mortality, and length at first capture were estimated using the "TropFishR" package in RStudio (Mildenberger et al., 2017; Taylor and Mildenberger, 2017). All statistical analyses were performed in

RStudio (RStudio Team, 2020).

Results

The total lengths of the *D. macarellus* in the Sulawesi Sea ranged from 7.7 to 38.3 cm, while in the Maluku Sea ranged from 8.1 to 38.3 cm (Fig. 2). The length at first maturity (Lm) of this species was higher in the Sulawesi Sea (23.9 cm) than in the Maluku Sea (22.9 cm) (Fig. 3), while the length at first capture (L_c) was higher in the Maluku Sea (21.6 cm) than in the Sulawesi Sea (19.6 cm). Total mortality (Z) of the *D. macarellus*, as a proxy for fishing pressure, was lower in the Sulawesi Sea (3.7 year^{-1}) than in the Maluku Sea (5.3 year^{-1}) (Fig. 4).

Fishing fleets targeting small pelagic fish in the Sulawesi and Maluku Seas were dominated by mini purse seines with one-inch (2.54 cm) mesh size. Following Indonesia's national regulation, the size of fishing vessels is categorised into three groups according to their capacity in gross tonnage (GT), i.e., large (>30 GT), medium (10–30 GT), and small (<10 GT). In both the Sulawesi and Maluku Seas, medium-size vessels were dominant, i.e., 48 % and 62 %, respectively. However, of all vessels operating in the Sulawesi Sea, a significant part of large-sized and medium-sized vessels, i.e., 88 % and 56 %, respectively, also operated in the Maluku Sea, contributing to higher fishing pressure in the respective waters.

Discussion

Total mortality can be used as a proxy of fishing pressure (Piet et al., 2007; Froese et al., 2015), and, therefore prompting an investigation of whether fishing pressure varies between the Sulawesi Sea and the Maluku Sea, for the target species, *Decapterus macarellus*. Total mortality of *D. macarellus* in the Sulawesi Sea (3.7 year^{-1}) was comparable to those already recorded from other sites in Prigi, Indian Ocean (3.0 year^{-1}; Bintoro et al., 2020), Cabo Verde, the coast of Africa (3.23 year^{-1}; Vieira, 2019), and even within the Sulawesi Sea (2.34 year^{-1}; Zamroni et al., 2019). In contrast, the total mortality of *D. macarellus* in the Maluku Sea was relatively higher than in other locations. This suggests that the fishing pressure of *D. macarellus* in the Maluku Sea was relatively higher than in the Sulawesi Sea and other regions.

Fishing shifts the life history traits of some fish species are well documented (Jennings et al., 1998; Law, 2000). The shift has been for the first time demonstrated for North Sea plaice, *Pleuronectes platessa* Linnaeus, 1758 (Rijnsdorp, 1993) and Atlantic cod, *Gadus morrhua* Linnaeus, 1758 (Hutchings and Myers, 1995), but most recently also for pikeperch, *Sander lucioperca* Linnaeus, 1758 (Lappalainen et al., 2016) and chondrichthyans (Ramírez-Amaro et al., 2020). The present study demonstrates for the first time such a shift for *D. macarellus* in tropical Indonesia, where the size at maturity in the Maluku

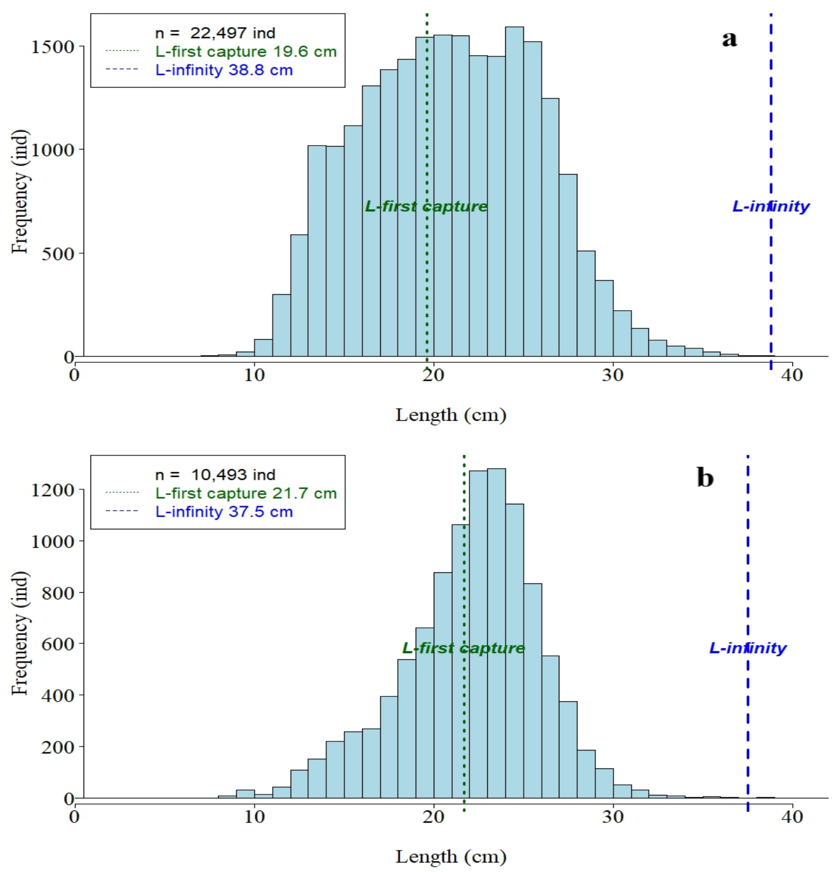

Fig. 2. Length frequency distribution of *Decapterus macarellus* sampled from (a) Sulawesi Sea and (b) Maluku Sea from September 2019 to March 2022.

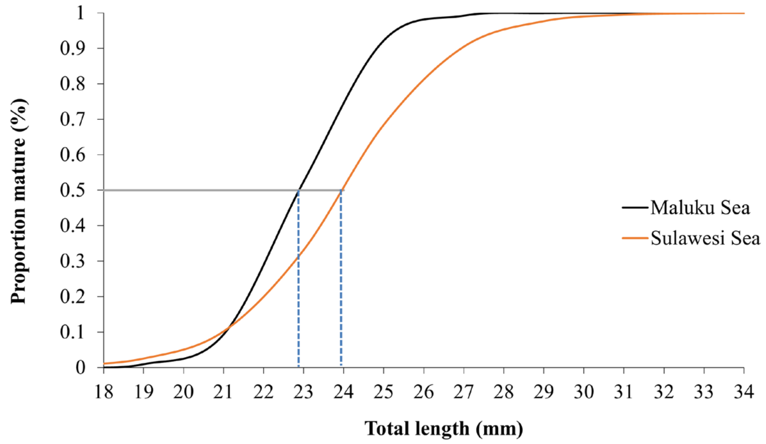

Fig. 3. Length at first maturity model of the mackerel scad *Decapterus macarellus* in the Maluku Sea (black line) and the Sulawesi Sea (red line) generated by the length-converted linearised catch curves. The curves show that *D. macarellus* in the Maluku Sea matured at a smaller size compared to those in the Sulawesi Sea.

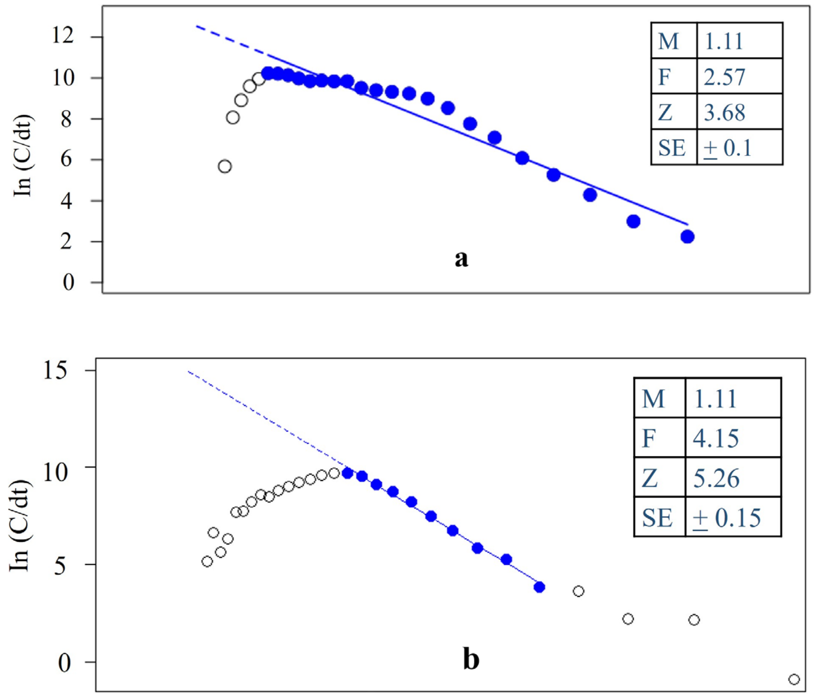

Fig. 4. Length-converted linearised catch curve was applied to estimate the total mortality (Z) of *Decapterus macarellus* in the (a) Sulawesi Sea and (b) Maluku Sea.

Sea was smaller than in the Sulawesi Sea and other areas. This result is most likely caused by differences in fishing pressure on the two examined fish stocks. Consequently, high fishing pressure in a specific region is presumed to have a distinct effect on the local populations of *D. macarellus*. High fishing efforts might induce a lower proportion of mature individuals (spawners) in the Maluku Sea, prompting them to mature at smaller sizes and younger ages as part of fish adaptation (Enberg et al., 2010; Neuheimer and Taggart, 2010).

Fishing pressure and life history traits can contribute to early maturation. Fishing pressure that happened for a long time may alter life history parameters, but the historical data on fishing pressure in the Sulawesi and Maluku Seas are unfortunately unavailable. The stock of *D. macarellus* from the Sulawesi Sea and Maluku Sea is known to be distinct from each other, as confirmed by genetics (Zamroni et al., 2014) and a parasite study (Retnoningtyas et al., 2023). Genetic differences caused or enhanced by exploitation pressure may indicate different lengths and reproductive parameters (De Croos and Pálsson, 2012). In the present study, the life history parameters between Sulawesi Sea and Maluku Sea stocks were similar. Direct environmental variations may also affect maturation probability (Barot et al., 2005).

According to Pauly (2021), a lower relative oxygen supply induces sexual maturation, as the distribution and concentration of dissolved oxygen have a more significant influence on the development of the life of most fish and aquatic invertebrates than food availability (Kramer, 1987). This theory, known as the Gill-Oxygen Limitation Theory (GOLT), predicts that maturation and reproduction are induced when a fish reaches a critical ratio of oxygen supply-demand related to the scaling of gill surface area (Chen et al., 2021). As a case study by Amarasinghe and Pauly (2021) showed how stressful environmental conditions prompted the early spawning of tilapia, reducing their growth and the size at which maturity commences.

According to the theory of fisheries-induced evolution, fishing serves as an artificial selection process that can affect the change of life history traits, where the most prominent impact of fishing is on the fish's reproductive biology, such as earlier maturation (Enberg et al., 2010; 2012). This research is the first evidence of fisheries-induced evolution detected for small pelagic fish in tropical Indonesia, particularly on how fishing influences the fish reproductive biology of an essential Indonesian fisheries resource. Fisheries-induced evolution remains underexplored in Indonesia since many species are currently facing overfishing and fully exploited conditions (MMAF, 2022b). Such conditions can shift fish biology and ecology, including habitat choice, diet choice, social behaviour, maintenance, immune defence, neural development and cognition, morphology, migration, energy storage, somatic growth, reproduction, and phenology (Neuheimer and Taggart, 2010). It is suggested that size and age at first maturity must be monitored regularly since these parameters are essential for the stock assessment. Precise calculations are crucial, as an incorrect conclusion on the length at first maturity can lead to an incorrect assessment of the fish stock condition (e.g., spawning potential ratio). The risk of overexploitation is one of the most immediate effects of inaccurate assessments. Suppose stocks are erroneously believed to be healthier than reality, this could lead to higher quotas and excessive fishing, thereby depleting the stock beyond its recovery capacity.

Moreover, the different lengths at first maturity caused by different fishing pressures in the Sulawesi Sea and Maluku Sea implies that a precautionary approach should be strongly encouraged in formulating the harvest strategy for *D. macarellus*. Under the current management framework, the fisheries management area (FMA) 716 covers the Sulawesi Sea and some parts of the Maluku Sea. Bitung Fishing Port, located in North Sulawesi, is a landing site for fish caught in the Sulawesi Sea and from the Maluku Sea. Consequently, separate management measures are necessary given the differentiated stock unit of *D. macarellus* between the Sulawesi Sea and Maluku Sea.

This study aimed to highlight the current fishing conditions and the mackerel scads' maturity sizes in two different yet adjacent fishing grounds, i.e., the Sulawesi Sea and the Maluku Sea, which appeared to be different. More studies are needed to investigate whether the early maturation is caused by long-term fishing pressure, different life history parameters due to distinct stock units, or environmental factors such as oxygen limitation. Such studies will contribute to the knowledge of the fisheries-induced evolution processes in Indonesia's fishery resources and provide valuable insights for more effective and sustainable fisheries management practices.

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