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Length-based stock assessment of *Scylla serrata* (Forskål, 1775) in Indragiri Hilir, Riau Province, Indonesia

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ABSTRACT

We assessed the stock status of mud crabs (*Scylla serrata*) in Indragiri Hilir, Riau Province, Indonesia, using a length-based spawning potential ratio (SPR) model. Between December 2021 and January 2023, we sampled 13,409 mud crabs (6434 males and 6975 females) from small-scale commercial fisheries. Their carapace length ranged from 5.60 to 17.50 cm, with the majority within a 9.60–10.30 cm range. The length at first capture was 8.32 cm for females and 8.47 cm for males, it is below their respective lengths at first maturity, measured at 11.00 cm for females and 9.77 cm for males, indicating harvest of immature crabs. Growth constants were 0.31 per year for females and 0.26 per year for males, with a natural mortality rate of 0.83 per year and 0.75 per year, respectively. The exploitation rate based on SPR was 4 % for females and 6 % for males, suggesting overfishing. To ensure sustainable management of mud crab fisheries, regulatory measures such as reducing fishing efforts, introducing seasonal fishing closures, and enforcing minimum size limits are recommended.

Introduction

Growing human population in coastal areas and increasing market demand for mud crabs in Indonesia has intensified fishing pressure on four commercially important species: *Scylla serrata* (Forskål, 1775), *Scylla paramamosain* (Estampador, 1950), *Scylla olivacea* (Herbst, 1796), and *Scylla tranquebarica* (Fabricius, 1798) (Iromo & Jabarsyah, 2018). Among these, *S. serrata*, predominantly found in mangrove and estuarine ecosystems across the Indo-Pacific region, is heavily exploited (Pati et al., 2023). The demand for mangrove mud crabs rises annually in both local and international markets (Hardiyanti et al., 2018). Indonesia's crab production between 2019 and 2022 reached 232,726 tons, with 194,928 tons (84 %) sourced from wild catches, and only 37,797 tons (16 %) derived from aquaculture (MMAF, 2022).

The high economic value of *S. serrata* makes it particularly vulnerable to overexploitation in the Indo-West Pacific region (Karniati et al., 2021; Putri et al., 2022). Fishermen in Indragiri Hilir rely heavily on harvesting *S. serrata* through small-scale fisheries, using traps and small boats, to sustain their livelihood. Artisanal fishermen primarily target mud crabs, with approximately 90–95 % involved in small-scale fisheries, making them the primary source of income for coastal communities living near mangrove forests. These fisheries often use multispecies fishing gears such as gillnet and traps that can catch various species such as reef fish, mud crabs, and prawns (Sari et al., 2021).

The Indragiri Hilir Regency in Riau Province lies within the Republic of Indonesia's National Fisheries Management Area (WPP-NRI) 711 and is characterized by extensive mangrove forests—crucial habitats for mud crabs. Between 2020 and 2022, the region recorded a remarkable mangrove crab catch volume of 199,701 tons (MMAF, 2022). *S. serrata* is the dominant species in this area and is frequently harvested, playing a vital role in the income of communities that depend on mangrove forests. These mangroves also serve as critical habitats for other economically important aquatic fauna (e.g., shrimp and fish). Despite their economic and ecological importance, mangroves are undervalued by local communities, whose livelihoods primarily depend on coconut farming and fishing activities (Permatasari et al., 2017).

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Fishing activities often involve the use of small canoes and traps to target mud crabs in small estuaries, tidal creeks, and mangrove forests (Mirera, 2017). Over the past few decades, intensified exploitation and mangrove degradation have increasingly threatened mud crab populations. Identifying the biological traits of *S. serrata* and assessing their stock status is crucial for developing exploitation strategies and management plans to ensure the sustainability of these fisheries.

Fish stock assessments often use biological indicators such as spawning potential ratio (SPR), which estimates the proportion of fish that can spawn over their lifetime under fishing pressure compared to an unfished population (Brooks et al., 2010). SPR is particularly valuable for evaluating stock status in data-limited fisheries, as it requires minimal data. Further, it relies on length measurements of the exploited stock, which are relatively easy and cost-effective to collect (Prince et al., 2020).

Previous studies have highlighted dramatic declines in mud crab populations in certain areas due to mangrove forest encroachment and habitat destruction (Le Vay, 2001; Sara, 2010; Ikhwanuddin et al., 2011; Varkey et al., 2023). The loss of fishing grounds has adversely affected fishing communities, who require guidance and support to improve fisheries management. Since 2021, Yayasan Mitra Insani (YMI), Yayasan Pesisir Lestari, and Blue Ventureshave have actively supported communities in Indragiri Hilir to manage and monitor their fisheries and mangroves. However, mud crab fisheries management is yet to be fully implemented at the community level.

This study evaluates the stock status of *S. serrata* in Indragiri Hilir based on the fishing mortality (F) to natural mortality (M) ratio (F/M), SPR, and selectivity. Carapace width data, which can be easily measured at fish landing sites, from the captured mud crabs were used. Length-based stock assessments are particularly suited for data-poor fisheries, where often only size data is readily available (Hordyk et al., 2015). The results of this study aim to improve area-based management boundaries and management strategies to balance resource use and conservation efforts for *S. serrata*.

Materials and methods

Study site

The study was conducted in two villages, Perigi and Sapat (0°19′29.7″S 103°18′47.3″E), located in the Indragiri Hilir District of Riau Province, Sumatra, Indonesia. Data collection spanned 14 months, from December 2021 to January 2023 (Fig. 1). In these villages, mud crab fishermen predominantly use wooden canoes to lay traps during high tides. These simple traps or pots are environmentally friendly, in compliance with Indonesian laws, and are made of monofilament nets and bamboo. They are bowl-shaped with a central wooden stake and two openings (Fig. 2).

Fishing trips last a day on average. Trap soaking times average up to 12 h, typically beginning in the morning and evening. The mud crab fishermen operated in two main locations: the nearest one approximately 500 m from the village, reachable within 30 min by canoe, and a more distant location approximately 7 km away, which requires 6 h of travel. The latter involves rowing across several small ditches (locally referred to as *suak* or *parit*) with minimum depths of 0.5–1.5 m and maximum depths of 6 m. Several ditches in Sapat Village serve as key mud crab fishing areas (Fig. 1).

Each trap required 80 cm of monofilament net, 110 cm of bamboo, 1 m of wooden stake, and 2.5 m of rope. The wooden stake serves as a bait holder and secures the trap to the seabed. Each fisherman utilized 11–90 traps. If well-maintained, the traps can remain functional for up to one year.

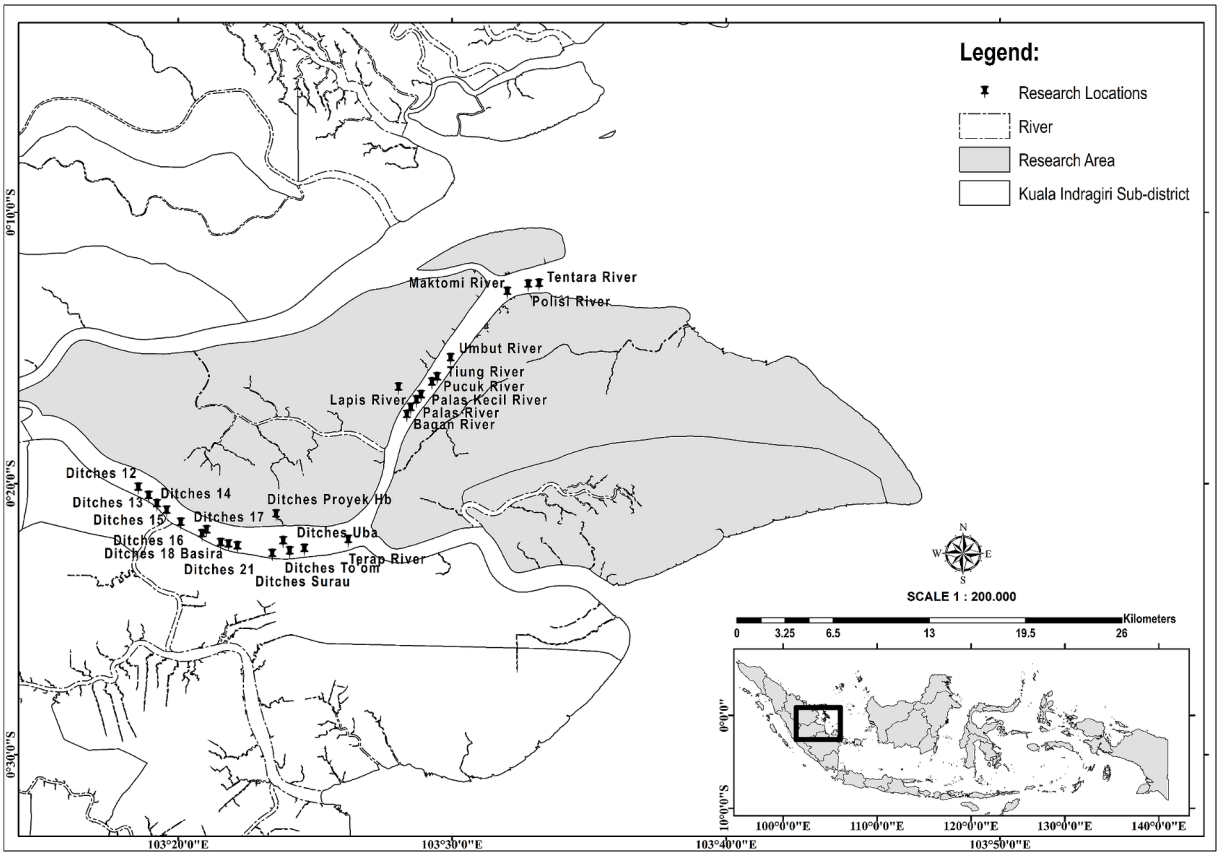

Fig. 1. The maps showing the study area in Indragiri Hilir, Riau Province, Indonesia, where data on *S. serrata* were collected.

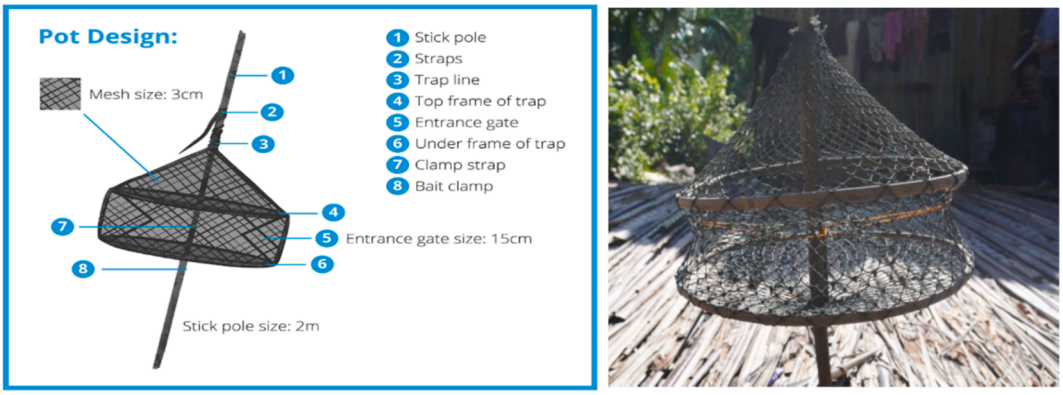

Fig. 2. Diagram showing the mud crab trap used by local fishermen in Indragiri Hilir, Riau Province, Indonesia.

Sample collection

Data on mud crab weight (g), carapace width (cm), and catch numbers were collected from 69 fishermen in Sapat Village and 23 in Perigi Village, across three landing sites. Daily data collection was carried out by a team of 10 data collectors from both villages over the 14-month study period. The body weight and carapace width of the mud crabs were recorded using a digital scale and a caliper, respectively, as shown in Fig. 3. Several data collectors from Sapat and Perigi collected all the data daily.

Data analysis

The stock status of mud crabs in Indragiri Hilir was assessed using the length-based SPR (LBSPR) model developed by Hordyk et al. (2015). The LBSPR model, as defined by Prince et al. (2015), provides a general framework for the stock assessment of data-limited fisheries. It incorporates the length frequency distribution data and life history parameters as input variables. The life history parameters were estimated using the "TropFishR" package in RStudio, following the methodology described by Mildenberger et al. (2017), utilizing the following formula:

$$Lt = L\infty[1 - \exp(-k(t - t0))]$$

where L∞ is the mean maximum carapace length, k is the growth rate constant, and t0 is the theoretical age at a length of zero.

The total mortality rate (Z) was estimated using the Linearized Catch Curve Method, as proposed by Pauly (1983). Age determination is a time and manpower consuming in fishery sampling. Thus, this method uses length as an alibi for age, based on the R package "TropFishR" when calculating the selection ogive by means of the catch curve, the assumption is made. It is assumed that Z remains constant across all year classes or length groups. According to Sparre (1998), this assumption may be held because fishing mortality (F) tends to be lower for younger fish due to selectivity, while natural mortality (M) is typically higher for

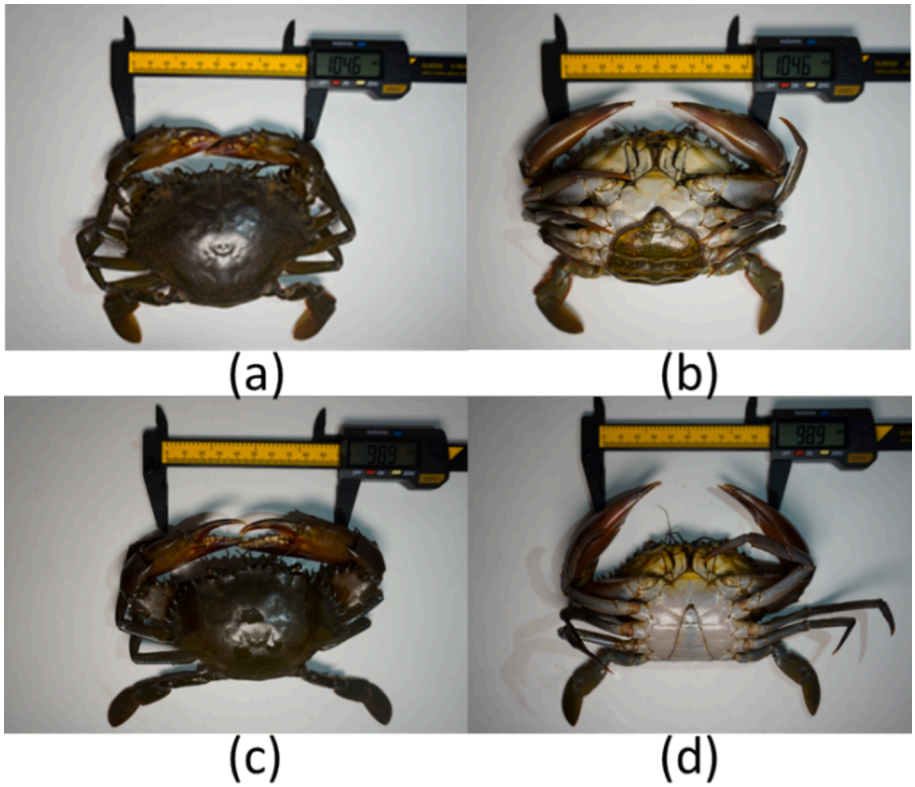

Fig. 3. Female *S. serrata*: (a) dorsal and (b) ventral view. Male *S. serrata*: (c) dorsal and (d) ventral view.

these younger fish. To implement this method, a plot of $ln\frac{c(L1,L2)}{\Delta t}$ against $t(\frac{L1,L2}{2})$ needs to be created.

Further, it is worth recalling that age and length are functionally linked through the Von Bertalanffy Growth Function (VBGF). Using the inversion of the VBGF length can be converted into age. The specific relationship is as follows:

$$t(L)Z = t_0 - \frac{1}{K}*\ln(1 - \frac{L}{L\infty})$$

where t(L) is the age at length L units (cm) and t_0, L∞, and K are the classical VBGF parameters. Using this in the equation relating to the logarithm of catch rate over a small-time interval and the mid-time interval which is as follows:

$$\ln\left(\frac{c(t, t+\Delta t}{\Delta t}\right) = c - Z*(t - \frac{\Delta t}{2})$$

which in turn can be rewritten using the catch and length information as

$$\ln\frac{C(l1, l2)}{\Delta t} = c - Z*t\left(\frac{L1 + L2)}{2}\right)$$

Here is the change in time

$$\Delta t \text{ is given by } \frac{1}{K}*\ln\left(\frac{L\infty - L1)}{L\infty - L2}\right)$$

Thus, from this linear function, the total instantaneous rate of mortality can be estimated as the negative slope. It can be noted that in the previous equations, c is a term that is made of constant terms or in other words by terms that do not involve either time or length at different classes.

Estimating the natural mortality is one of the major challenges for fishery biologists conducting stock assessments. Fortunately, it appears that M, the exponential rate of natural mortality, closely correlates with growth parameters and the mean habitat temperature of a given stock. To the extent of our knowledge, the asymptotic size of a stock, its stress factor (K), and its mean habitat temperature provide sufficient data to obtain reliable estimates of M for any fish species. Natural mortality (M) is calculated using Pauly (1980) empirical formula:

$$logM = 0.1228 - 0.1912logL\infty + 0.7485logK + 0.2391logT$$

where T is the mean environmental temperature (°C) (as given in an oceanographic atlas), and L∞ is expressed in cm. From the Z and M estimates, the fishing mortality (F; year − 1) was estimated using the equation:

$$F = Z - M$$

The growth performance index (ϕ') of *S. serrata* regarding length growth was estimated using the formula developed by Pauly and Munro (1984):

$$\phi' = 2\,\text{Log10}\,\text{CL}\infty + \text{Log10}\,\text{K}$$

The methods outlined above to "guesstimate" the asymptotic length (L∞) and k do not provide estimates of t_0. However, there may be cases where an estimate of t_0, even a rough one, is needed. This requires several input parameters, including k, asymptotic carapace width (CW in cm), and T in °C. Pauly (1979) empirical formula for determining t0 is given by

$$log(-t0) = -0.3922 - 0.2752\log(L\infty) - 1.038(k).$$

SPR with reference points (RP) provides an even clearer estimation of stock status for mud crab: <20 % indicates an "overexploited" stock (below the limit RP, LRP), 20–40 % indicates a "fully exploited" stock (between the LRP and target RP, TRP), and <40 % indicates an "underexploited" stock (the TRP; Prince et al., 2015).

We estimated spawning potential ratio (SPR) using the length-based SPR (LBSPR) model, gear selectivity at 50 and 95 % carapace selectivity (CL50 and CL95, respectively), and the ratio of fishing mortality (F) to natural mortality (M) as F/M. According to Hordyk et al. (2016), the SPR analysis and gonad maturity selectivity curves used the R Studio LBSPR program (https://CRAN.R-project.org/package = LBSPR).

Results

A total of 13,409 *S. serrata* individuals, comprising 6,434 males and 6,975 females, were collected from the landing sites (Fig. 3). Based on these numbers, the mud crabs caught in the Indragiri Hilir had a small size of 5.60 cm (Fig. 4).

The k values were 0.31/y and 0.26/y for female and male crabs, respectively. The L∞ values were 29.60 and 30.86 cm for females and males, with a mean length value of 9.92 ± 0.018 cm for females and 9.97 ± 0.020 cm for males. The value of M was 0.83/y for females and 0.75/y for males. In contrast, the value of F was 6.56/y for females and 2.86/y for males. The life history parameters and SPR for *S. serrata* in Indragiri Hilir are summarized in Table 1.

The LBSPR analysis reveals that the exploitation rates reached 4 and 6 % for females and males, respectively, suggesting the overexploitation of stock (Fig. 5).

Fig. 6 shows the intersections between the selectivity and maturity curves for male and female mud crabs. The length at first capture (Lc) was 8.32 cm for females and 8.47 cm for males. Which is smaller than the length at first maturity (Lm) of 11.00 cm for females, as well as for males, Lm of 9.77 cm for males.

Discussion

Mud crabs caught in Indragiri Hilir from December 2021 to January 2023 were predominantly females, contrasting with findings from, Tarakan waters, Sumatra, where male crabs dominated the catch (Salim et al., 2020). This disparity is due to the fact that the fishermen in Indragiri Hilir primarily target muddy river areas with depths of 1–6 m. Female crabs were more frequently caught due to their migration to deeper waters during gonadal maturation (Susiana et al., 2024).

The frequency distribution of carapace width (Fig. 4) reveals that male crabs are generally larger than females. The size of captured *S. serrata* ranged from a minimum of 5.60 cm to a maximum of 17.50 cm, with the majority falling within the 9.60–10.30 cm range. Male crabs exhibited carapace widths ranging between 5.60 and 17.50 cm, with an average of 9.97 cm (±0.020), while females ranged from 5.60 to 16.50 cm, with an average width of 9.92 cm (±0.018). Hubatsch et al. (2015) reported that male *S. serrata* reaches sexual maturity at carapace widths of 92–110 mm, while females mature at 80–120 mm. In other regions of Indonesia, males and females were reported to mature at 59–128 and 53–122 mm, respectively (Widigdo et al., 2017).

S. serrata is the dominant species found in muddy substrates associated with dense mangrove vegetation (Hubatsch et al., 2014). Therefore, protecting mud crab habitats in Indragiri Hilir is essential, as profound environmental damage is caused by mangrove destruction. Various environmental factors such as temperature, depth, pH, and turbidity improve mud crab growth, production, and reproduction in their natural habitat (Paital & Chainy, 2012; Spence & Tingley, 2020; Azra et al., 2020; Pati et al., 2023). Variations in mud crab sizes in Indragiri Hilir may also reflect seasonal changes, ecological connectivity, and proximity of fishing grounds, as mud crab distribution was strongly influenced by seasonal environmental factors (Leoville et al., 2021).

The values of k differed between sexes, with males exhibiting higher growth constant than females. The greater k value in male crabs is attributed to the fact that males use nutrients for somatic growth, while female crabs use the nutrients for both somatic and reproductive growth, including gonad development and egg production (Wijaya et al., 2018). Similar findings have been reported in studies by Ali et al. (2004), Ikhwanuddin et al. (2010), and Musa et al. (2017). The dominance of

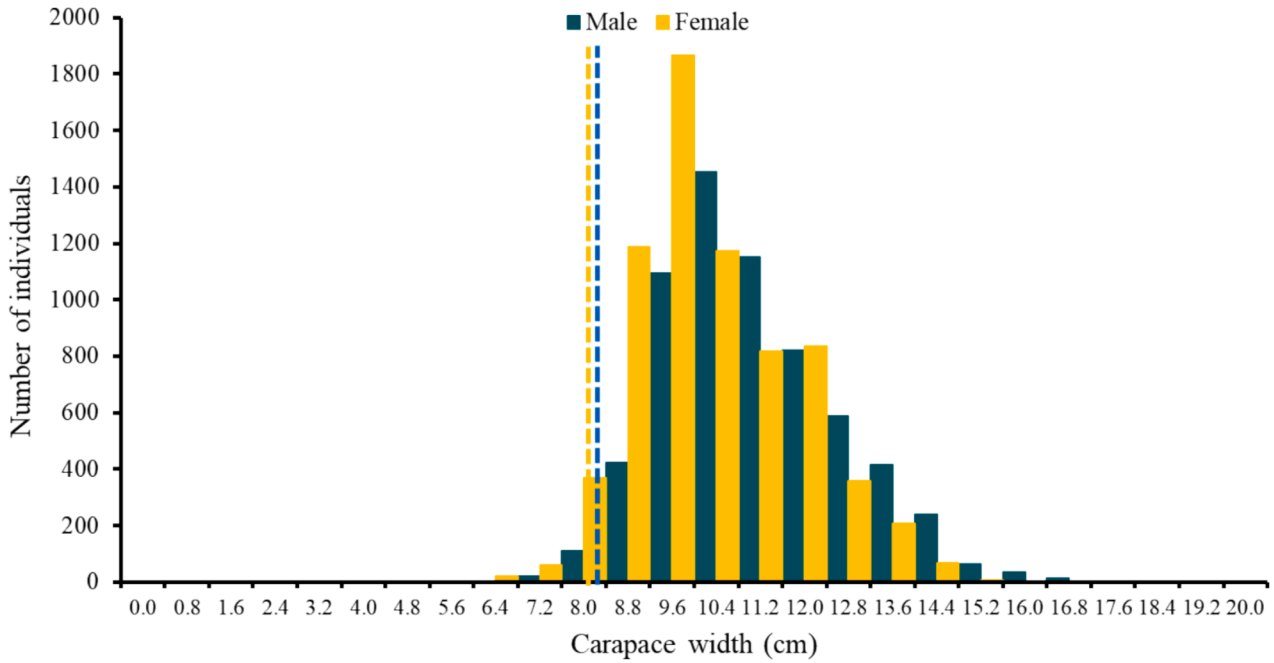

Fig. 4. Carapace width of male and female *S. serrata* individuals caught in Indragiri Hilir, Indonesia. The blue dashed vertical line indicates the CL50 for males, and the yellow dashed vertical line indicates the CL50 for females. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Life history and SPR parameters of *S. serrata* in Indragiri Hilir, Indonesia.

Parameter	Units	Female Life History Value	Male Life History Value
Length range	cm	5.60–16.50	5.60–17.50
Mean length ± SE	cm	9.92 ± 0.018	9.97 ± 0.020
L∞ (asymptotic length)	cm	29.60	30.86
Lmax (maximum length)	cm	16.50	17.50
k (growth constant)	per y	0.31	0.26
M (natural mortality)	per y	0.83	0.75
F (fishing mortality)	per y	6.56	2.86
Z (total mortality)	per y	7.39	3.61
ϕ′ (growth performance index)		2.43	2.40
M/k	per y	2.73	2.84
SPR	%	4	6
t_0	y	−0.55	−0.63
CL50*	cm	8.32	8.47
CL95	Cm	9.50	10.02

*CL50 = Lc (the mean length at first capture), SE = Standard error.

males over females is frequently observed in crab populations (Warburg et al., 2012).

S. serrata exhibited higher Z compared to M and F. Total mortality (Z) was estimated to be higher than natural mortality (M) and fishing mortality(F) for females and males, respectively (Khaksari et al., 2023). In both fishing areas studied, Lc was smaller than Lm, posing a threat to the long-term sustainability of resources (Suman et al., 2018). Our research findings indicate that traps frequently capture immature mud crabs below the minimum catchable size, reducing their chances to reproduce, and ultimately leading to a decline in their population.

The F values for female crabs in Indragiri Hilir were significantly higher than those for male crabs, indicating a greater exploitation rate for females. The M values appear to be smaller compared to the F, with the exploitation rate slightly exceeding the optimal value. This phenomenon indicates an overexploitation of mud crabs on the other small islands of Indonesia. On the other hand, fishing mortality of S. *serrata* in Bangladesh was lower than natural mortality for both males and females (Zafar et al., 2006). The higher F for males is primarily due to their predominance in intensively fished intertidal flats and shallow water (Sara, 2010). The growth performance index was recorded as 2.43 for females and 2.40 for males, which were lower than the values reported by Zafar et al. (2006) at 3.599 for females and 3.497 for males, and by Khaksari et al. (2023) at 4.63 for females and 4.85 for males.

Meanwhile, two studies in Wetan and Tarakan waters explained the different exploitation rates and stock conditions. Yudiati et al. (2020) reported an exploitation rate of 55 % for females, exceeding that for males. Furthermore, E values for *S. serrata* females were higher than the 50 % optimum threshold. Another study by Indarjo et al. (2020) showed that the estimated exploitation values for male and female mud crabs exceeded the optimum thresholds of 70.57 and 87.61 %, respectively. High mortality rates from continuous fishing can result in low survival rates and hinder crabs from reaching their maximum size (Froese et al., 2016).

The SPR of *S. serrata* in Indragiri Hilir was below 20 %, indicating overexploitation of stock. SPR represents the proportion of a fishery population in the waters. The SPR value of 20 % is considered the threshold replacement level for sustaining fish populations. An SPR below 20 % indicates reduced recruitment and a declining population (Prince et al., 2015). A low SPR demonstrates a decline in the population of juvenile mud crabs, a reduction in the spawning stock, and fewer eggs being produced. SPR is an indicator of the overall health of fishery harvests and provides benchmarks for evaluating the current status of fish stocks (Cousido-Rocha et al., 2022).

To address these challenges, targeted management actions in the Indragiri Hilir crab fishery are necessary to rebuild the biomass of *S. serrata* and increase its SPR value above the LRP by 20 %. Owing to the importance of this fishery in local livelihoods, management measures must adopt a bottom-up approach. Engaging the community and putting their integrated knowledge, priorities, and needs in decision-making can make fishery management at Indragiri Hilir more inclusive and adaptive. The sustainability of mud crabs is greatly influenced by several factors, including premature catching, consumer attitudes toward sustainability, and side effects of the fishing gear (Tetelepta et al., 2019).

We recommend continuing facilitated data feedback sessions to

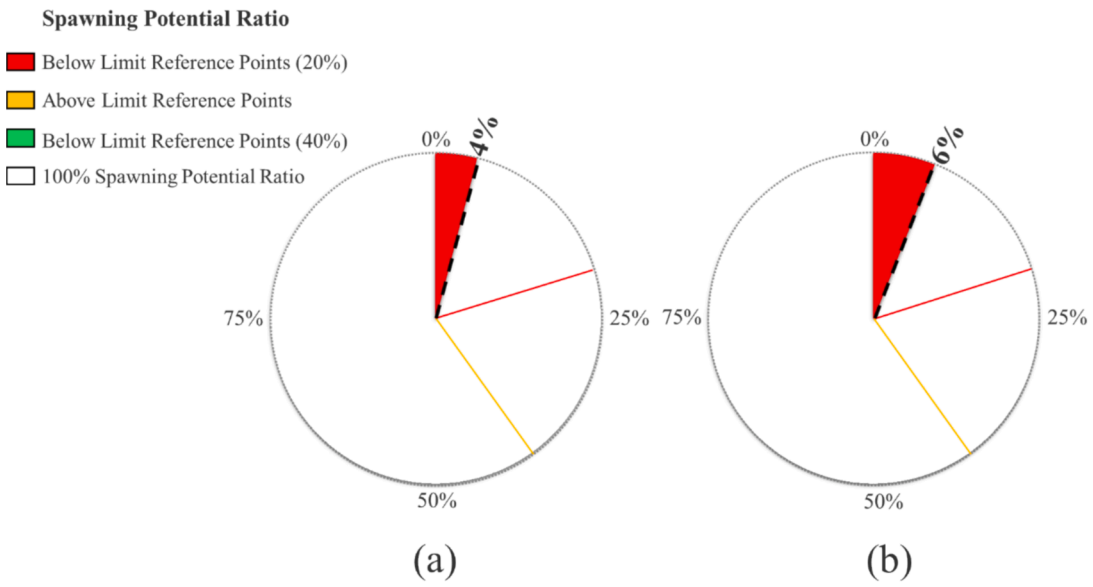

Fig. 5. SPR of (a) female and (b) male *S. serrata* in Indragiri Hilir, Indonesia.

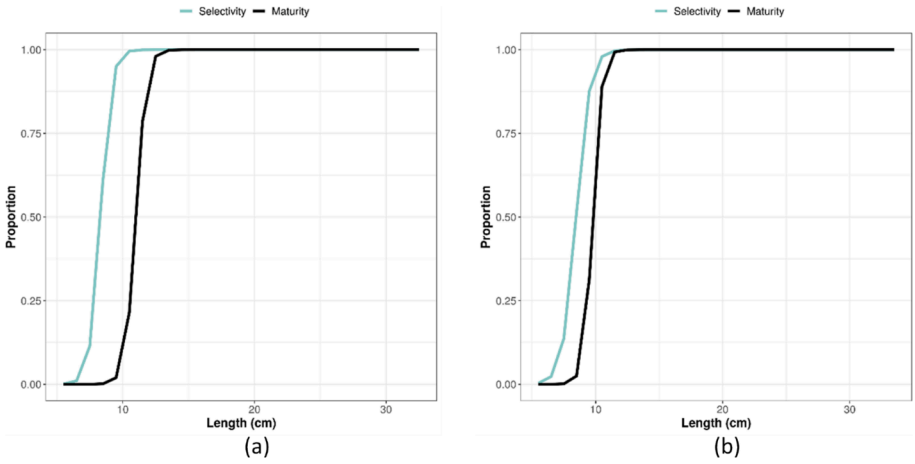

Fig. 6. Maturity and selectivity curves of (a) female and (b) male *S. serrata* in Indragiri Hilir, Indonesia.

enhance the community members' understanding of mud crab fisheries. These sessions bring together community members and relevant stakeholders to discuss the current factors affecting mud crab fisheries. Community members whose livelihoods are directly affected offer valuable knowledge that can inform more effective management measures and promote compliance with agreed-upon regulations. Given this, community members can collectively identify and agree on management measures to be implemented and impose regulations. The proposed management measures include reducing fishing efforts, implementing temporary fishing closures, and setting harvest size limits for mud crabs.

The communities implemented five temporary mud crab fishery closures to provide time and space for mud crabs to allow for their growth and reproduction. The community agrees upon and implements the closures, but village regulations still lack community inclusion. Therefore, further efforts are required to secure community rights for village-level fishery management. As these crabs are frequently threatened by overexploitation, fishing practices must consider the biological status of the crab populations to ensure sustainability.

Conclusion

This study found that the SPR value of mud crabs was below 20 % of the LRP. LBSPR is an index of the relative reproduction rate of overexploited fish resources. Directly impacted community members have a more nuanced understanding of their livelihoods, allowing them to provide valuable insights into the root causes. By incorporating their input, fishery management responses are more likely to be effective and have higher compliance with regulations. Given this, fishing community members can collaboratively determine their preferred fisheries management responses and develop applicable rules. The proposed management responses included reducing fishing efforts, implementing seasonal fishing closures, and establishing harvest size limits for mud crabs.

Ethical clearance

The authors declare that the sampling of the studied species was conducted in accordance with national procedures and international conventions regarding the use of animals in scientific research.

CRediT authorship contribution statement

Mochammad Riyanto: Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Sugeng Hari Wisudo:** Writing – review & editing, Supervision, Formal analysis. **Indah Rufiati:** Resources, Project administration, Conceptualization. **Faridz Rizal Fachri:** Project administration, Funding acquisition, Conceptualization. **Wahyu Dita Septiani:** Methodology, Formal analysis, Data curation. **Inayah:** Data curation, Methodology, Resources, Project administration. **M. Rukim:** Methodology, Formal analysis, Data curation. **Gian Nofrianda Ilyas:** Methodology, Formal analysis, Data curation. **Emilio de la Rosa:** Methodology, Conceptualization. **Riki Saputra:** Visualization, Validation, Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mochammad Riyanto reports administrative support, article publishing charges, statistical analysis, travel, and writing assistance were provided by IPB University and Blue Ventures Conservation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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