Regional Studies in Marine Science 36 (2020) 101309

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Length based assessment of spawning potential ratio in data-poor fisheries for blue swimming crab (*Portunus spp.*) in Sri Lanka and Indonesia: Implications for sustainable management

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ARTICLE INFO

Article history:
Received 14 January 2020
Received in revised form 28 April 2020
Accepted 4 May 2020
Available online 19 May 2020

Keywords:
Southeast Asia
Data-poor assessment
Sustainable management
Blue swimming crabs
Spawning potential ratio

ABSTRACT

Quantitative assessment and management of small-scale fisheries is a persistent problem for fisheries. Crustaceans are particularly challenging for conventional techniques because their lack of permanent hard body parts makes ageing difficult. While a growing body of literature is aimed at developing alternative approaches to small-scale fisheries assessment there are concerns about the indiscriminate application of generic methodologies and the need to address the specific circumstances of fisheries. The length-based assessment of spawning potential ratio (LBSPR) is appealing because it has simple data requirements, a well-developed theoretical foundation, and estimates Spawning Potential Ratio (SPR) an internationally recognized indicator of stock status. With the aim of establishing basic standards and providing structured discussion of the issues raised by its application, this study documents its application to the regionally important blue swimming crab (BSC) (*Portunus spp.*) fisheries, in Sri Lanka and Indonesia. Our study demonstrates the methods technical feasibility and cost-effectiveness for small-scale BSC fisheries and by extension other small-scale fisheries. In Sri Lanka and Indonesia, these LBSPR assessments are successfully informing discussions about sustainability; focusing discussion on managing size selectivity, one of the few management controls available to fisheries managers in many small-scale fisheries. In Indonesia BSC are first caught at around the size of maturity by trawling and with baited traps without escape gaps, reducing SPR to unsustainable levels. Despite similarly high fishing pressure, in Sri Lanka the larger size of first capture with bottom set nets preserves a sustainable level of SPR. Supported by these assessments, in 2018, that fishery attained a provisional sustainability rating from Seafood Watch. We suggest how LBSPR assessment might be used to adaptively manage size selectivity within the harvest strategy being developed in Indonesia. It is hoped this documentation of the methodology will assist other small-scale fisheries to use this technique similarly.

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1. Introduction

1.1. Small-scale, data-poor fisheries

Most of the world's fish stocks are too small-scale and have insufficient biological and fisheries trend data to be assessed with the conventional data intensive methods that rely on analysing time series of abundance indices, such as catch and effort, with biomass models (Walters and Pearse, 1996; Mullon et al., 2005; Andrew et al., 2007; Costello et al., 2012). Crustacean fisheries are particularly challenging for conventional assessment techniques because their lack of permanent hard body parts makes ageing and the estimation of longevity and growth particularly challenging (Caddy, 1986; Kilada et al., 2016). A growing body of literature is aimed at developing and documenting alternative approaches to assessing small-scale and data-poor fisheries (Dowling et al., 2018). Here we document the application of a recently developed methodology called the length-based assessment of spawning potential ratio (LBSPR) to the regionally important blue swimming crab (BSC - *Portunus spp.*) fisheries in Indonesia and Sri Lanka.

Small-scale fisheries are defined as such, not by their aggregate value and regional importance, but by their combination

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1 http://www.apri.or.id.

https://doi.org/10.1016/j.rsma.2020.101309
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of village-based fishers, deploying traditional hand hauled techniques from small vessels (<10 GT) in shallow coastal waters, and landing relatively small individual catches (Teh et al., 2018). Generally, in Southeast Asia, as in many parts of the world, the importance of small-scale fisheries is greatly under-appreciated in favour of the more visible industrial trawl fisheries because landings are notoriously hard to quantify and assess (Teh et al., 2018).

1.2. Outline of blue swimming crab biology

Formerly regarded as a single widely distributed species (*Portunus pelagicus*), blue swimming crabs have recently been recognized as comprised of a complex of four species; *P. pelagicus*, *P. armatus*, *P. segnis* and *P. reticulatus*, with *P. pelagicus* occurring in Indonesia and *P. reticulatus* in Sri Lanka (Lai et al., 2010). Here we discuss and analyse the science pertaining to this species complex using the term 'blue swimming crabs' or BSC.

Blue swimming crabs are found in sheltered tropical and subtropical estuarine and coastal waters to about 50 meters depth throughout the Indo-West Pacific (Stephenson, 1962; Williams, 1982; Edgar, 1990; Kailola et al., 1993). Although capable of actively swimming and substantial movements, tagging and genetic studies, along with latitudinal variation and regional fisheries dynamics, demonstrate that BSC occur in relatively discrete small-scale stocks along coast lines (Potter et al., 1991; Potter and de Lestang, 2000; Chaplin et al., 2001; de Lestang et al., 2003a). The megalopa of BSC settle into shallows of protected inshore environments where through the initial 12 months of their life cycle they grow rapidly to maturity around a carapace width of ∼100 mm (Potter et al., 1983; Sukumaran and Neelakantan, 1997). Adults, which may live to 2-3 years of age, seasonally migrate seaward to release their larvae into more oceanic waters outside the estuaries, coastal lagoons and embayments they occupy (Potter et al., 1983, 1991; Potter and de Lestang, 2000; Chaplin et al., 2001; de Lestang et al., 2003a). In temperate areas breeding is restricted to the warmer months (Potter et al., 1987), however in tropical regions reproductive periodicity is described as seasonal-continuous, with ovigerous females being observed in all months although with a distinguishable peak (Campbell and Fielder, 1986; Batoy et al., 1987).

1.3. The Southeast Asian blue swimming crab fishery and length-based spawning potential ratio assessment

Throughout the Indo-West Pacific BSC stocks support numerous small-scale, yet highly valuable commercial fisheries. Their wide distribution and increasing global demand, particularly from the USA for canned product, make them important in many countries (FAO, 2019). Beginning in the 1960s reported landings of BSC from the region have increased steadily, increasing from <50,000 t annum^{-1} prior to 1985, to around 260,000 t annum^{-1} in 2016, of which >200,000 t is landed by Southeast Asian countries, the largest suppliers being Indonesia (>50,000 t), Philippines (∼25,000 t) and Thailand (∼25,000 t). These fisheries are a valuable source of income for coastal communities both for the fishers who catch the crabs, but also for large numbers of women employed to pick and can crab meat.

The BSC fisheries of Southeast Asia were developed by a small group of international companies based in Malaysia, Philippines, Thailand, and USA, that specialize in canning and exporting pasteurized meat to the US. Starting in Malaysia and Thailand and working northeast into Vietnam and China, south and east through Indonesia and Philippines, and south-west into India and Sri Lanka, the companies serially established small local facilities called mini-plants to buy and process locally sourced crabs, sending the picked, graded and chilled meat to centrally located canneries. Unfortunately, production from specific fisheries has not been sustained. The steady increase in aggregate Southeast Asian catches, observed in the FAO statistics to date, masks the serial depletion that has occurred in the original fisheries in Malaysia, Thailand and Vietnam (FAO, 2019). With the aim of addressing rising concerns about sustainability the southeast Asian BSC fisheries combined to establish a Fishery Improvement Project (FIP) in 2007. The FIP has recently adopted LBSPR as a standard methodology for BSC stock assessment because of the utility and cost-effectiveness demonstrated, at least in part, by the work described here.

1.4. Overview of Sri Lankan blue swimming crab fishery

In Sri Lanka BSC are primarily found around the western and northern coasts, where there are two principal fisheries. The larger on the Sri Lankan side of Palk Bay which is the most south-western extension of the Bay of Bengal, and the smaller in the Gulf of Mannar (Fig. 1a). The two fisheries operate in a region that was heavily contested throughout Sri Lanka's ∼30 year-long civil conflict and although a large BSC fishery existed on the Indian side of the Palk Bay, restrictions on fishing during the conflict limited its development in Sri Lanka. A review of the region's fisheries potential undertaken during the civil conflict did not even list BSC as a commercially important species (Sivalingam, 2005), but the fishery developed rapidly when the conflict ended in 2009 and security restrictions were lifted. By 2011 it was Sri Lanka's second most important crab fishery (Jayamanne, 2011) with an export value of around USD6 million in 2015, 40% of which was exported directly to the US.

In Sri Lanka BSC are only caught with poly- and mono-filament bottom-set crab nets with mesh sizes that initially ranged in size from 3.5 to 6 inches (∼89–152 mm). In 2015 there were more than 24,000 BSC fishers, fishing from 7,358 vessels, of which 31% were traditional non-motorized craft, 8% motorized traditional crafts and 60% were outboard engine powered fibre-glass boats, and landing their catch into 77 landing sites (DFAR, 2015). Formal regulations relating to licencing of fishers, boats and engines apply to the BSC fishery in Sri Lanka, and the use of monofilament nets is prohibited throughout Sri Lanka. Since the inception of BSC fishing in 2001 the participating communities in the Palk Bay and the Gulf of Mannar fisheries have been developing and implementing informal rules with the aim of controlling fishing pressure and protecting stock productivity, including restrictions on mesh size, the number of nets per boat, net height and fishing grounds (F. Joseph, Poonaryn Fishermen's Cooperative Societies' Union, Kilinochchi District, Sri Lanka pers. comm.). In 2013 the Sri Lankan fishery joined the BSC FIP and almost immediately began applying the LBSPR methodology to inform management discussions. Selectivity studies conducted in 2015 (Creech, 2017) demonstrated the potential for bottom-set crab nets to be size selective with significantly larger crabs being caught with mesh sizes ≥114.3 mm, compared to the 88.9 mm mesh that were beginning to be adopted by fishers at that time, or the traps which some processors had begun importing but had not deployed. On that basis the Sri Lankan stakeholders amended the Fisheries and Aquatic Resources Act (No. 2 of 1996) to proscribe the use of baited traps, regulate a minimum mesh size ∼114 mm and prohibit mini-plant owners from buying < 100 g crabs. On the basis of those management measures and supported by the short time series of LBSPR assessments published here, the Sri Lankan fisheries attained a provisional sustainability rating from Seafood Watch in 2018 (Monterey Bay Aquarium, 2018).

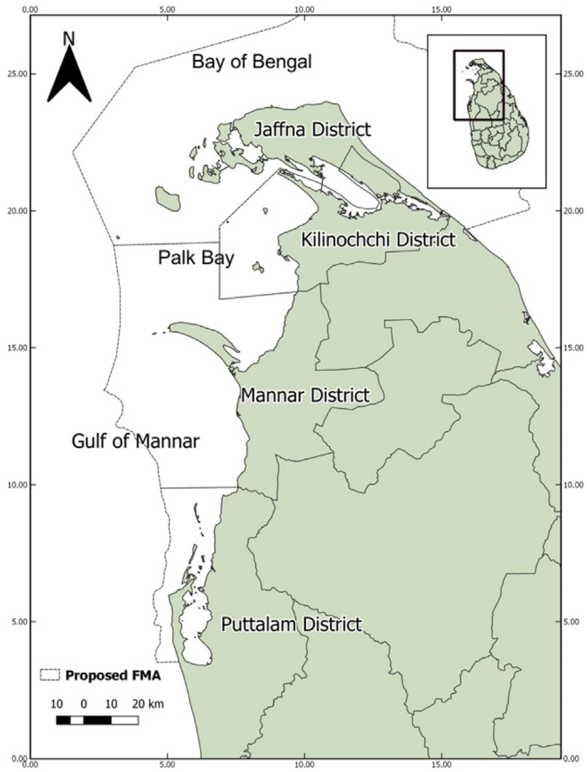

Fig. 1a. Map of Sri Lanka showing sampling locations where the size composition of BSC landings was monitored for LBSPR assessment.

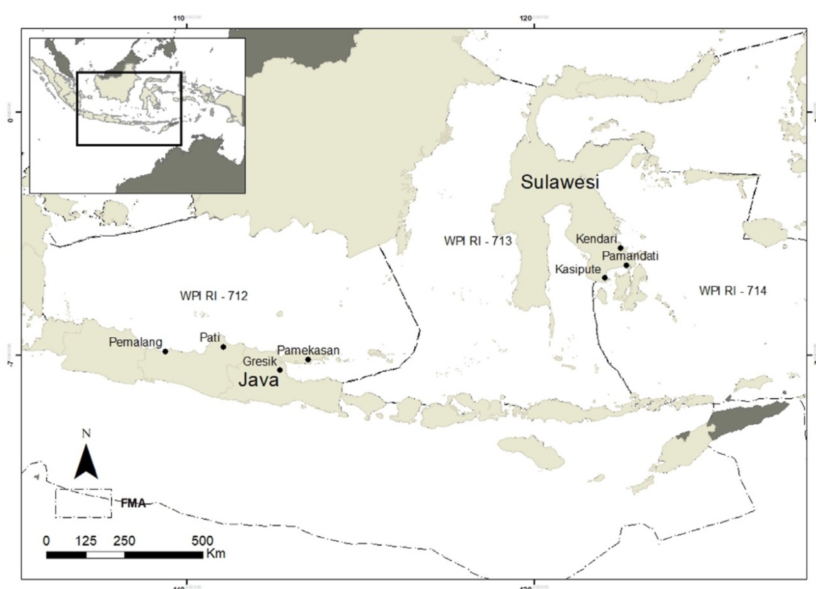

Fig. 1b. Map of Indonesia showing sampling locations where the size composition of BSC landings was monitored for LBSPR assessment.

1.5. Overview of Indonesian blue swimming crab fisheries

The commercial BSC fisheries in Indonesia, began in the west of the country in the 1970s and have now extended to all but the eastern-most provinces, growing with the expansion into Indonesia's third most valuable fisheries export. An estimated 65,000+ artisanal fishers deliver catch to 500+ mini-plants which employ >13,000 local women who pick out the crab meat that is sent to >30 processors of pasteurized crab meat (MRAG, 2015). The canned product they produce has an export value of ∼USD330 million annum^{-1} and >80% is exported directly to US markets (MRAG, 2015). The most productive fishing grounds are located along the east, north and south coasts of Sumatra, along Java's northern coast (Fig. 1b), and around the southern coast of Sulawesi Island (Ernawati et al., 2017).

At the current time BSC are mainly caught by fishers using small (<10 m) motorized vessels and baited traps, or small otter-board trawlers, locally called mini-trawlers (Madduppa et al., 2016). A transition in gears has been typically observed as BSC fisheries develop in each new location (Fig. 2). At first bottom set tangle nets are laid overnight in deeper water (5–20 m) to target the largest size classes of crabs, which are most mobile

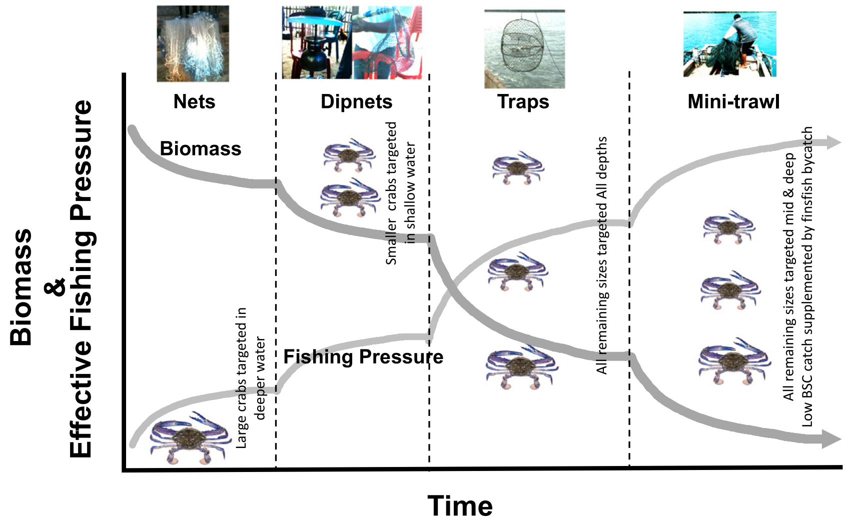

Fig. 2. An illustration of the evolution of fishing gear typically observed over time in an unmanaged BSC fishery, and its hypothesized relation to declining biomass and escalating fishing pressure. Fishing generally begins using bottom set crab nets to target larger deeper crabs, and then as their abundance declines transitions to using dipnets in shallow water to catch smaller crabs, and then to baited traps used across the depth range to target all remaining size classes. The process of gear transition ends with the introduction of mini-trawlers catching lower quality crabs and increasingly targeting fin-fish.

in their hunt for food, and in the case of males to seek females to mate with. However, as the mobile larger size classes are depleted fishing with bottom set nets gives way to dip-netting with lanterns for smaller crabs in the shallows (1–2 m), which are eventually augmented by laying baited longlines to aggregate the crabs. In time, dip-netting gives way to baited traps which can be used across the full depth range and left overnight. In some fisheries trapping is eventually displaced by mini-trawling, which produce a lower quality BSC but, for a time, enhances the catch of finfish.

Management arrangements for Indonesia's BSC fisheries are regulated by the Ministry of Fisheries and Marine Affair (MMAF) of Indonesia. A minimum carapace width of 100 mm, the prohibition of retaining berried females (Minister Decree No. 1, year 2015), and prohibition of trawling (Minister Decree No. 2, year 2015) were to be implemented in January 2016. To date they have not been effectively implemented. Partly as a consequence of this studies' demonstration of the feasibility and cost effectiveness of the LBSPR methodology the MMAF has adopted it for application to the BSC fishery (Ernawati et al., 2017; Tirtadanu, 2019), and are now applying it across a broader range of species as well (Tirtadanu and Sadhotomo, 2018; Ernawati et al., 2019; Warsa et al., 2019; Ernawati et al., 2016, 2019; Ernawati and Budiarti, 2019). More recently through the Decree of Director General of Capture Fisheries No. 17/PER-DJPT/2017, the Indonesian government has mandated that fisheries must develop harvest strategies (Smith et al., 2008) to codify their assessment and management processes. In the case of the BSC fishery it has been decided that the harvest strategy will incorporate LBSPR assessment.

1.6. Purpose of this study

Dowling et al. (2018) caution against the generic and indiscriminate application of data-poor assessment methodologies and stressed the need to account for the specific circumstances of particular fisheries. In this context the demonstration and evaluation of assessment methodologies for specific data-limited stocks is of high priority (Dowling et al., 2018) particularly for crustacean fisheries. The purpose of this study is to document the application of the LBSPR methodology to the Sri Lankan and Indonesian BSC fisheries. The aim being to establish some basic standards and provide structured discussion of the issues involved with its application. Finally, we also aim to initiate some discussion of the management issues raised by the techniques' application, and how it might be used within harvest strategies.

2. Methods

2.1. Overview of length-based spawning potential ratio assessment

There are now many options for data-poor assessment, but LBSPR assessment (Hordyk et al., 2015a,b, 2016) is appealing because it does not require estimates of catch, or local life history parameters of growth and natural mortality, which are frequently unavailable for small-scale fisheries. It estimates a reference point of stock status (Spawning Potential Ratio) which has been rigorously bench-marked in the international literature and the underlying model has a well-developed theoretical foundation (Beverton and Holt, 1959; Hordyk et al., 2015a; Prince et al., 2015; Thorson et al., 2017) that has now been extensively tested. (e.g. Hordyk et al., 2015b; Sun et al., 2017; Babcock et al., 2018; Pons et al., 2019; Chong et al., 2020).

Spawning Potential Ratio (*SPR*) is defined as the proportion of natural, or unfished, reproductive production left in a population under fishing pressure (Walters and Martell, 2004). By definition, unfished stocks have an *SPR* of 100% ($SPR_{100\%}$) and when the natural life-spans are shortened by fishing the natural spawning potential of the stock is reduced to some proportion, or ratio, of the natural unfished level ($SPR_{X\%}$ or < 1.0). For management purposes 30%–40% SPR is internationally recognized as a target level to be aimed for, while 20% SPR is accepted as the 'replacement level' below which stocks risk recruitment impairment and so is used as a limit reference point, which stocks should be managed above (Mace and Sissenwine, 1993).

The LBSPR methodology utilizes the fact that the size structure of an exploited population and its *SPR* are a function of relative fishing pressure (F/M), the ratio of fishing (F) to natural (M) mortality, and the two life history ratios (LHR), M/K and L_m/L_∞ (Beverton, 1963; Hordyk et al., 2015a). Where M is the rate of natural mortality, K is the von Bertalanffy growth co-efficient, L_m is the size of maturity at which 50% of a size class is mature and L_∞ is asymptotic size. The inputs to the LBSPR model are: (i) the M/K ratio, (ii) the mean asymptotic length (L_∞), (iii) the variability of length-at-age ($CV_{L\infty}$), which is difficult to estimate directly without reliable length and age data, and normally assumed to be around 10%; and (iv) an estimated size of maturity (L_m) specified in terms of the length at which 50% ($L_{50\%}$) and 95% ($L_{95\%}$) of a population is mature. In practice the L_∞ of a stock is unlikely to be known and practically impossible to estimate in a data poor fishery, however, L_m is more easily estimated, and with an estimate of L_m/L_∞ can be used to estimate L_∞.

The assessment model is applied to size composition data, in the case of BSC carapace width, which are assumed representative of the fisheries overall catch and the adult component of the stock. The LBSPR model uses maximum likelihood methods to simultaneously estimate the size at which individuals in a stock become vulnerable to capture and the relative fishing mortality (F/M), which are then used to calculate the SPR (Hordyk et al., 2015b, 2016). The size at which individuals in a stock become vulnerable to capture, is variously referred to as the size of first capture, the size selectivity of fishing or simply the selectivity ogive. The LBSPR model assumes it can be described by a logistic curve defined by the selectivity-at-length parameters SL_{50} and SL_{95}, corresponding to the sizes at where there is a 50% and 95% probability of selection, respectively.

The estimates of SPR derived by the model are primarily determined by the size of the individuals in a sample, relative to L_m and L_∞, with the size of the largest individuals in the sample relative to L_∞ being the most influential factor (Hordyk et al., 2015b). Like many length-based methods, the LBSPR model is equilibrium-based, and relies to differing degrees on a number of assumptions, which have to be made relatively arbitrarily in a data-poor fishery. These underlying assumptions include: (i) asymptotic selectivity, (ii) growth is adequately described by the von Bertalanffy equation, (iii) length-at-age is normally distributed, (iv) rates of natural mortality are constant across adult age classes, and (v) growth rates remain constant across the cohorts within a stock. Simulation testing of the LBSPR model has shown that the method is most sensitive to the under-estimation of L_∞, and large rapid changes in recruitment rates (Hordyk et al., 2015b). The LBSPR analysis was conducted using the LBSPR R package (Hordyk, 2019).

2.2. Parameter estimation

For LBSPR assessment where L_∞ is unknown, estimates of the two LHR (M/K, L_m/L_∞) are required, which by definition are unlikely to be available from studies of the specific data-poor fishery being assessed. Holt (1958) proposed that the physiological constraints of species and families imply that the LHR of species are more stable across geographical distributions and taxonomic groups than the individual life history parameters, and consequently expected they would be more informative for data-poor stock assessment. Extending that principle Prince et al. (2015) presented evidence of this, and demonstrated that the LHR characterize the life history strategies of species, genera and families, implying they can be 'borrowed' from well-studied species to inform the assessment of unstudied but taxonomically related species. A supposition subsequently also supported by the analysis of Thorson et al. (2017).

2.2.1. Synthesis of life history ratios

Applying this principle, we derived estimates of the LHR that characterize BSC from a synthesis of the literature on the *Portunus spp*. In this context the overarching criteria in estimating LHR is that the pairs of life history parameters used should be derived from studies conducted in close temporal and spatial proximity to each other so that they are likely to be drawn from the same population. This is because the individual parameters are expected to vary across ranges and within populations over time with changing productivity, biomass and temperature making it invalid to estimate the LHR by pairing parameters derived from different sources.

Twenty publications were collected for three *Portunus* species, 6 studies of *P. sanguinolentus*, 1 study of *P. segnis* and 17 BSC studies from which 42 estimates of M/K and 21 estimates of L_m/L_∞ could be derived (Table 1). Commonly male and female parameters were estimated independently, in which case we used the gender specific LHR estimates as distinct estimates of the LHR. This usefully increased our sample size, but could be criticized as being a form of pseudo-replication. From these data we initially estimate mean $L_m/L_\infty = 0.60$ (n = 21, S.D. = 0.13) and mean M/K = 1.15 (n = 42, S.D. = 0.37). Two of the collected publications, by de Lestang et al. (2003a,b), focused on the estuarine component of BSC populations in four southwestern Australian estuaries and clearly demonstrated that adults left the study site by moving out of the estuaries. Those studies produce anomalously high average estimates of $L_m/L_\infty = 0.73$ and low average estimates of $M/K = 0.69$, presumably because the largest adult crabs are absent from the sampled populations lowering estimates of L_∞ and increasing estimates of K. Excluding these studies from our sample we estimate mean $L_m/L_\infty = 0.52$ (n = 13, S.D. = 0.09) and mean $M/K = 1.26$ (n = 34, S.D. = 0.31).

Most of the other BSC studies use some variant of the Pauly approach to length-based assessment (e.g. Dash et al., 2013; Lee and Hsu, 2003) which involves tracking modal progression in size composition data over several seasons to estimate von Bertalanffy growth parameters with a version of ELEFAN (e.g. Gayanilo and Pauly, 1997). While M is estimated using the empirical technique of (Pauly, 1980) which is based on a correlation of teleost length, ambient temperature and M. Finfish biologists regard studies based on the direct ageing of hard body parts as providing the most reliable basis for estimating growth and mortality, however, the moulting of crustaceans and their lack of permanent hard parts makes direct ageing almost impossible (Caddy, 1986; Kilada et al., 2016). Apart from logistically challenging tagging studies, the tracking of modal progression is one of the few techniques available for studying growth and inferring age and mortality in crustaceans. In the case of BSC, growth remains relatively rapid throughout life so that modal sizes do not merge as much as they do in species that have strongly asymptotic growth patterns, and remain relatively distinct. Provided fishing has not truncated size compositions too severely this makes it possible to track modal progression until late in their short life span. Consequently, this aspect of the methodology is relatively sound.

However, the application of Pauly's (1980) correlative method to estimate M for BSC extends that particular methodology well beyond its original purpose and logical basis. The original correlation that methodology is based upon is between the maximum length of teleost, ambient temperature and M, so there is no basis for assuming it should also describe a relationship between carapace width in crabs and M. Our synthesis suggests that the estimates of M produced by applying Pauly's (1980) correlation to BSC are systematically too low. Studies of modal progression in BSC size compositions consistently show their natural longevity to be 18–36 months implying M of between 1.6 (longevity $\sim$36 months) and 3.0 (longevity $\sim$18 months), however, 19 of the 36 estimates of M in our synthesis are <1.6, suggesting improbable longevities of >36 months. If we substitute a higher minimum $M = 1.6$ into our synthesis instead of the lower published values ($M < 1.6$) which we infer to be too low, we re-estimate M/K = 1.40 (n = 36, S.D. = 0.05). This probably still underestimates the average M/K for BSC as it only 'corrects' estimates below our selected bound of $M < 1.6$ when the bias is probably systemic and influences most of the estimates in our sample.

In this context we infer from our synthesis that the best average estimates of the LHR for BSC are $L_m/L_\infty \sim 0.55$ and M/K = 1.25–1.50.

Table 1
Tabulated results of synthesis of the literature on the life history parameters (L_∞, K, L_{50}) of *Portunus spp.* from which the life history ratios (M/K, L_{50}/L_∞) needed for LBSPR assessment have been estimated; where L_∞ is the estimated asymptotic size (mm) in carapace width unless indicated as CL (claw length), K is the brody growth co-efficient from the von Bertalanffy growth curve in years, and L_{50} is the size at which 50% of a size class is sexually mature; M is the annual instantaneous rate of natural mortality estimated by the publication. 'Max Age' indicates the maximum age estimated by the study. 'Published Name' in the first column indicates the name used in publication from which the life history parameters have been extracted. 'Likely Name' in the second column indicates the likely actual species name according to Lai et al. (2010).

Published name	Likely name	Gender	L_∞	K	L_{50}	M	L_{50}/L_∞	M/K	Max age	Location	Reference
P. pelagicus	*P. armatus*	M	175	1.597	90	1.6	0.51	1.002		Australia, Eastern, Moreton Bay	Sumpton et al. (1994)
P. pelagicus	*P. armatus*	F	170	1.613	90	1.6	0.53	0.992		Australia, Eastern, Moreton Bay	Sumpton et al. (1994)
P. pelagicus	*P. armatus*	F	121	2.76	86.4	1.6	0.71	0.58	3	Australia, Western, Cockburn Sound	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	M	121	2.76	86.2	1.6	0.71	0.58	3	Australia, Western, Cockburn Sound	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	F	128	1.92	86.9	1.6	0.68	0.833	3	Australia, Western, Koombana Bay	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	M	128	1.92	87.1	1.6	0.68	0.833	3	Australia, Western, Koombana Bay	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	F	125	1.92	98	1.6	0.78	0.833	3	Australia, Western, Leshenault	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	M	125	1.92	87.2	1.6	0.70	0.833	3	Australia, Western, Leshenault	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	F	118	3.12	97.5	1.6	0.83	0.513	3	Australia, Western, Peel-Harvey	de Lestang et al. (2003a,b)
P. pelagicus	*P. armatus*	M	118	3.12	86.2	1.6	0.73	0.513	3	Australia, Western, Peel-Harvey	de Lestang et al. (2003a,b)
P. pelagicus	*P. pelagicus*	F	167	1.13	106	1.7	0.63	1.504		Gulf of Thailand, eastern, Kung Krabaen Bay	Kunsook et al. (2014)
P. pelagicus	*P. pelagicus*	F	173	0.68		0.86		1.265		Indonesia Central Buton, Lasongko Bay	Hamid and Wardiatno (2015)
P. pelagicus	*P. pelagicus*	M	152	0.93		1.09		1.172		Indonesia Central Buton, Lasongko Bay	Hamid and Wardiatno (2015)
P. pelagicus	*P. pelagicus*	F	187	1.13		1.18		1.044		Indonesia, Central Java Pati Coast	Ernawati (2013)
P. pelagicus	*P. pelagicus*	M	185	1.26		1.27		1.008		Indonesia, Central Java Pati Coast	Ernawati (2013)
P. pelagicus	*P. pelagicus*	M	CL81	1.2		1.53		1.275		Indonesia, Central Java, Brebes Coast	Sunarto (2012)
P. pelagicus	*P. pelagicus*	F	154	1.08		1.21		1.12		Indonesia, Sulawesi, Bone Bay	Kembaren et al. (2012)
P. pelagicus	*P. pelagicus*	M	159	1.27		1.33		1.047		Indonesia, Sulawesi, Bone Bay	Kembaren et al. (2012)
P. pelagicus	*P. pelagicus*	F	186	1.5		1.27		0.847		Indonesia, Sulawesi, Pagkep Coast	Ihsan Wiyono et al. (2014)
P. pelagicus	*P. pelagicus*	M	174	1.2		1.44		1.2		Indonesia, Sulawesi, Pagkep Coast	Ihsan Wiyono et al. (2014)
P. pelagicus	*P. pelagicus*	All	179	1.5		1.6		1.067		Thailand, Trang Province	Sawusdee and Songrak (2009)
P. pelagicus	*P. reticulatus*	F	211	1.14	80	1.9	0.38	1.667	2.5	India, Karnataka coast	Sukumaran and Neelakantan (1997)
P. pelagicus	*P. reticulatus*	M	204	0.97	87	1.9	0.43	1.959	2.5	India, Karnataka coast	Sukumaran and Neelakantan (1997)
P. pelagicus	*P. reticulatus*	F	170	1.4	96	1.6	0.56	1.143	3	India, Karnataka coast, south	Dineshbabu et al. (2008)
P. pelagicus	*P. reticulatus*	M	169	1.3		1.6		1.231	3	India, Karnataka coast, south	Dineshbabu et al. (2008)
P. pelagicus	*P. reticulatus*	M	168	1.2		1.27		1.058	3	Iran, Bandar, Abbas	Kamrani et al. (2010)
P. pelagicus	*P. reticulatus*	F	178	1.1		1.31		1.191	3	Iran, Bandar, Abbas	Kamrani et al. (2010)
P. pelagicus	*P. reticulatus*	M	CL103	1.85		3.15		1.703		Oman	Mehanna et al. (2013)
P. pelagicus	*P. reticulatus or pelagicus*	M	100	1.56		1.6		1.026	3	India, Mandapan Coast	Josileen and Menon (2007)
P. pelagicus	*P. reticulatus or pelagicus*	F	197	1.05		1.6		1.524	3	India, Mandapan Coast	Josileen and Menon (2007)
P. sanguinolentus	*P. sanguinolentus*	F	162	1.574	83	1.9	0.51	1.207		India, Calicut waters	Sarada (1998)
P. sanguinolentus	*P. sanguinolentus*	M	172	1.49		1.9		1.275		India, Calicut waters	Sarada (1998)
P. sanguinolentus	*P. sanguinolentus*	M	162	1.1		1.1		1		India, Chennai waters	Pillai & Thirumilu 2012 In Dash et al
P. sanguinolentus	*P. sanguinolentus*	F	169	1.3		1.2		0.923		India, Chennai waters	Pillai & Thirumilu 2012 In Dash et al
P. sanguinolentus	*P. sanguinolentus*	All	179	1.2	97	1.84	0.54	1.533		India, Gujarat	Dash et al. (2013)
P. sanguinolentus	*P. sanguinolentus*	F	188	0.82	80	1.43	0.43	1.744	3	India, Karnataka coast	Sukumaran and Neelakantan (1997)
P. sanguinolentus	*P. sanguinolentus*	M	195	0.99	87	1.43	0.45	1.444	3	India, Karnataka coast	Sukumaran and Neelakantan (1997)
P. sanguinolentus	*P. sanguinolentus*	F	170	1.6	90	1.9	0.53	1.188	2.5	India, Karnataka coast, south	Dineshbabu et al. (2007)
P. sanguinolentus	*P. sanguinolentus*	M	205	0.87		1.65		1.897		Taiwan	Lee and Hsu (2003)
P. sanguinolentus	*P. sanguinolentus*	F	194	0.97	135	1.8	0.70	1.856		Taiwan	Lee and Hsu (2003)
P. segnis	*P. segnis*	F	185	1.6	113	1.42	0.61	0.888		Persian Gulf & Gulf of Oman	Safaie et al. (2013a,b)
P. segnis	*P. segnis*	M	191	1.7		1.47		0.865		Persian Gulf & Gulf of Oman	Safaie et al. (2013a,b)

2.2.2. Reflection of uncertainty in parameter estimation

Rather than selecting point estimates of LHR, we chose to reflect our uncertainty with a triangular distribution for each of the LHR. For this purpose, we used the published life history parameters from our synthesis, excluding only those derived from de Lestang et al. (2003a,b) for the reasons outlined above. The triangular distribution we developed for each LHR used the minimum and maximum published values of L_m/L_∞ and M/K to define the ranges, and set the apices of each distribution at the median values (Fig. 3). From these triangular distributions we drew 10,000 samples of L_m/L_∞ and M/K to use in our analyses.

2.3. Data gathering protocols

In both Sri Lanka and Indonesia initial sampling trials were conducted to understand temporal and geographic variability of size compositions, and on this basis locally appropriate sampling protocols were developed and implemented.

2.3.1. Sri Lanka

In Sri Lanka BSC sampling was focused in January to February of each year during which multiple landing and collection sites through the two fisheries were sampled each for a few days. In the Palk Bay fishery data were collected and pooled from several landing sites and collection centres, in each of the three districts (Jaffna, Kilinochchi and Mannar) along the northern, western and southern shorelines of Palk Bay (Fig. 1a). In the Gulf of Mannar fishery sampling was focused on five collection centres that received BSC from about eleven landing sites along the shoreline of the Puttalam Estuary, and three sea fishing grounds along the coast of the Gulf of Mannar. Teams of local youth and women from the surrounding fishing communities were trained and employed to collect the data. At each sampling site all the BSC landed each day of sampling were measured; male and female crabs were measured to the nearest 1.0 mm and the reproductive status of female crabs was recorded. The data reported here were collected during the 2014–2018 fishing seasons.

2.3.2. Indonesia

In Indonesia representative landing sites in each of the 7 main fishing grounds, representing fisheries management area of 712 in Java Sea (Gresik, Pemalang, Pameskasan, Pati) and of 714 in Tiworo Strait of Southeast Sulawesi (Kasiputeh, Kendari, Pamandati) (Fig. 1b) were selected for monitoring, and trained data collectors were stationed at each to collect data for several days each month of the year. In addition to recording the daily catch and effort of individual fishers, the data collectors sub-sampled ∼20 kg of the landed BSC, recording gender, maturity, carapace width to the nearest 1.0 mm, and weight to the nearest gram. The data reported here were collected during the period November 2017 to October 2018.

2.3.3. Rationale for differing sampling protocols

In Indonesia juvenile and adult habitats of crabs tend to be in close proximity to each other making it possible for individual fishers to fish across the depth range in a single fishing day, consequently catches landed at any site are equally likely to represent all the size classes present on the fishing grounds. The observed variation in size compositions in Indonesia are mainly associated with season and the size-selectivity of the different gear types. If BSC stocks are lightly exploited there can be several year classes of adults in the catch (i.e. 0+, 1+, 2+) so that minimal seasonal variation in adult size is observed, however, as fishing pressure increases and size compositions become truncated, the fishery becomes increasingly reliant on the seasonal growth and recruitment of the 0+ cohort, which increases the seasonal variation observed in the size composition of the catch. This is now the situation in Indonesia which makes sampling across the year

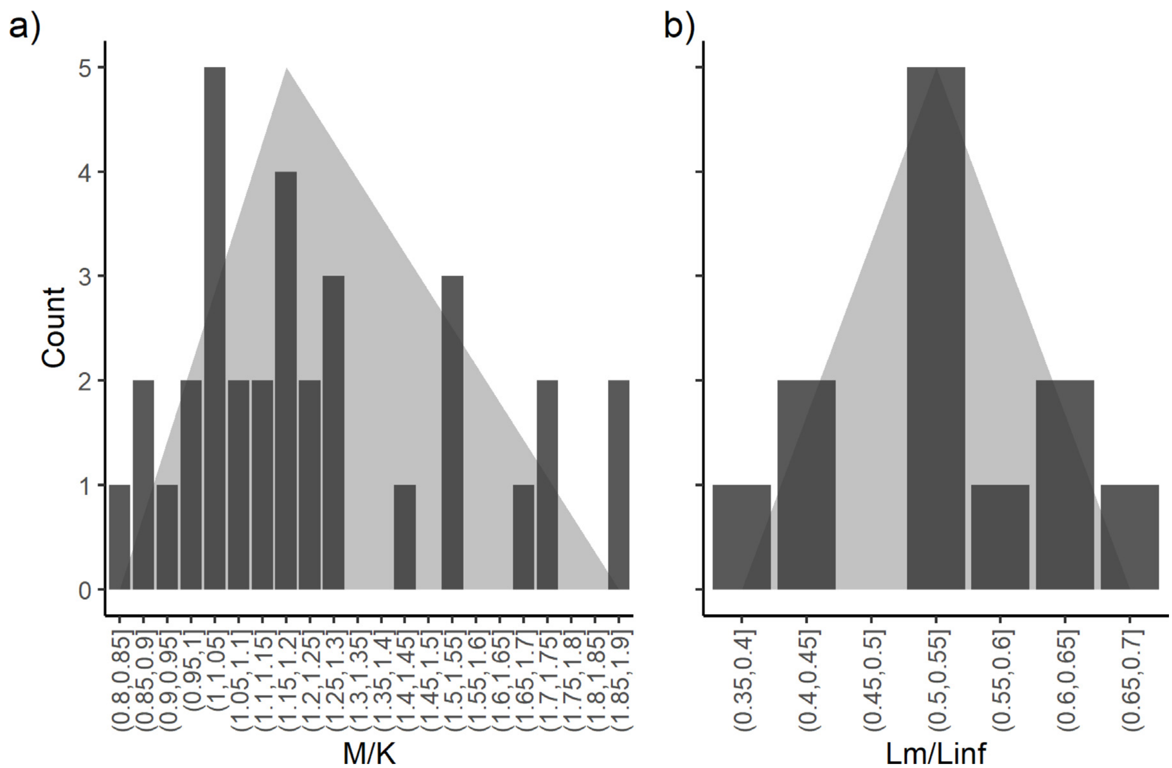

Fig. 3. Frequency histogram (bars) of the estimates of *Portunus* life history ratios derived from synthesis of the literature (see Table 1), (a) *M/K* and (b) L_m/L_∞, showing the triangular distributions (shaded grey areas) used for the analysis, defined by the minimum, maximum and median of the published values.

important to adequately record the size structure of the catch. In Indonesia there is also a determination to collect catch and effort trend data which also necessitates a year-round sampling system. However, the greater value of the Indonesian fisheries, in comparison to the small Sri Lankan fisheries, means there are more organizational resources available for catch monitoring, making the year-round sampling design more feasible.

In contrast to the fishery in Indonesia, the extensive shallow coastal waters, estuaries and lagoons occupied by BSC in Sri Lanka mean that juvenile and adult habitats can be considerable distances apart and considerable size variation is observed between differing landing sites, reflecting their specific site location (i.e. lagoon, estuary, coastal). Also, in contrast to Indonesia, the Sri Lankan fishery retains multiple year classes of BSC in its stock so that the seasonal variation in size composition is not as pronounced. In this context the Sri Lankan sampling program was conducted in January to February of each year during which multiple landing and collection sites across each fishery were sampled, with all the crabs landed at each site over several days being measured.

2.4. Estimating size of maturity

In both countries the gender and maturity of BSC was gauged by examining the abdominal flap, which in immature crabs is triangular and adheres tightly to the sternum (Van Engel, 1958; Ingles and Braum, 1989). With maturity the abdominal flap detaches from the sternum and assumes a slightly concave triangular shape in males in contrast to the mound-like or hemispherical shape of mature females (Fig. 4.). Although not considered a precise method for gauging the maturity of male BSC (de Lestang et al., 2003a), in females these morphological changes occur with the pubertal moult and so are considered to accurately reflect maturation (Potter and de Lestang, 2000). Female crabs were recorded as immature, mature or berried, males simply as immature or mature. Male and female crabs grow dimorphically, with males attaining larger carapace width and having bigger claws than females so in this study we applied the LBSPR technique to the size composition of the female populations only. Logistic curves were fitted to the size of maturity data in Excel using a sum of squares routine written for the purpose and the Solver add-in. A copy of this spreadsheet is available upon request from the corresponding author.

3. Results

3.1. Estimates of L_{50} and L_{95}

From the Indonesian size of maturity data (n=55,179) we estimated $L_{50} = 101$ mm and $L_{95} = 103$ mm and from the Sri Lankan size of maturity data (n = 15,012) we estimated $L_{50} = 104$ mm and $L_{95} = 124$ mm.

3.2. Results of length-based spawning potential ratio analysis

3.2.1. Sri Lanka

The mean estimates of $SL_{50\%}$ from the two Sri Lankan fisheries ranged from 116–142 mm which we take to be indicative of fishing with relatively large mesh nets (Fig. 5a). The mean estimates of *F/M* on the Sri Lankan fishing grounds were all relatively high, ranging from 2.7 to >4 (Fig. 5b). However, despite the high relative fishing pressure (and in contrast to the Indonesian results below) the mean estimates of *SPR* were also relatively high, ranging from 0.24–0.35 in the Gulf of Mannar, and similarly ranging from 0.24–0.37 in Palk Bay (Fig. 5c).

Fig. 4. Morphological differences in the abdominal flap of BSC used to gauge gender and maturity and following (Van Engel, 1958; Ingles and Braum, 1989). In immature crabs (left) the abdominal flap is triangular and adheres tightly to the sternum, with maturity the flap detaches from the sternum, assuming a mound-like or hemispherical shape in mature females (middle) and a slightly concave triangular shape in males (right).

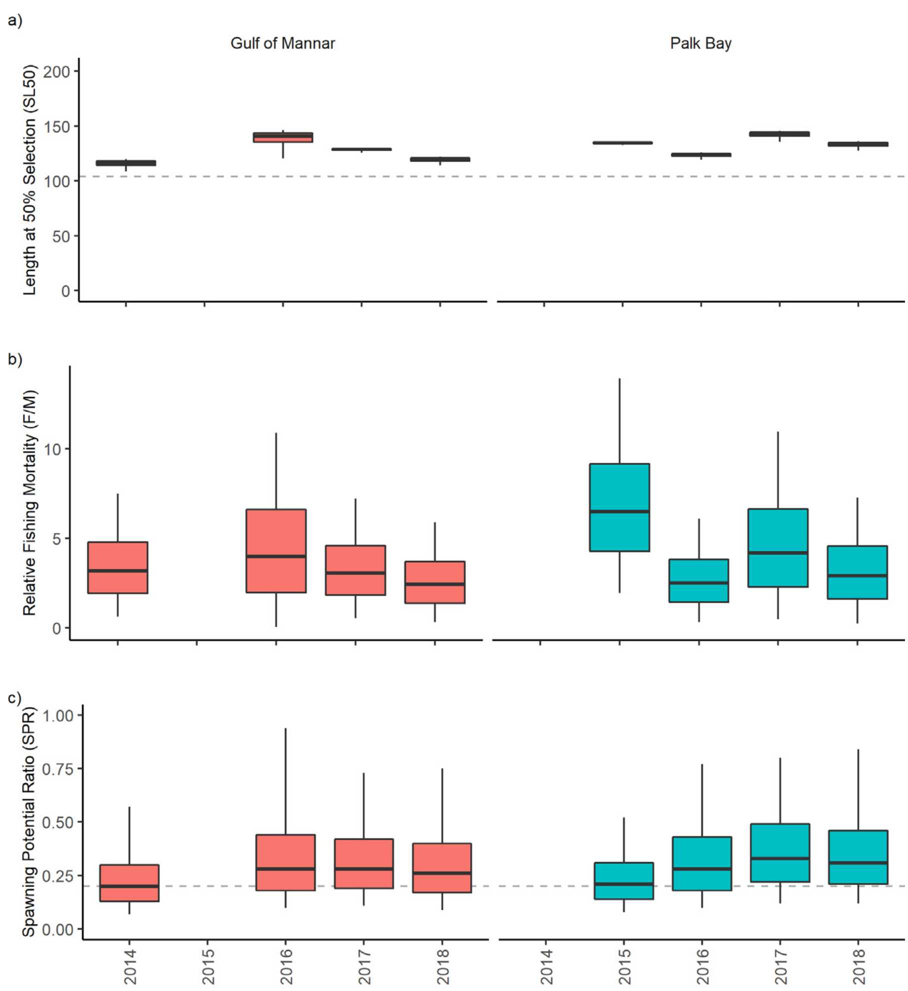

Fig. 5. Results of the analysis of blue swimming crab data for four years of data from the two regions in Sri Lanka with boxplots showing the estimated (a) length at 50% selectivity (SL_{50}), (b) relative fishing mortality (F/M), and (c) the spawning potential ratio (SPR). The dashed horizontal line shows (a) the estimated size of maturity and (c) a reference point of $SPR = 0.2$.

3.2.2. Indonesia

From the Indonesian sites most of the mean estimates of $SL_{50\%}$ (Fig. 6a) were around 100 mm (range 93–108 mm), considerably lower than estimated for Sri Lanka (116–142 mm) which look to be indicative of the fishing being mainly with traps. The outlier was Kendari with the smallest mean estimate of $SL_{50\%} = 74$ mm which we took to be indicative of fishing with mini-trawl in that area. The mean estimates of F/M from the Indonesian sites are all very high >4, but overlap with the Sri Lankan estimates. Contrasting with the Sri Lankan results the mean estimates of SPR in Indonesia are all very low, ranging from 0.04 in Kendari to 0.17 in Pamandati (Fig. 6b & c). Note that the smallest estimate of

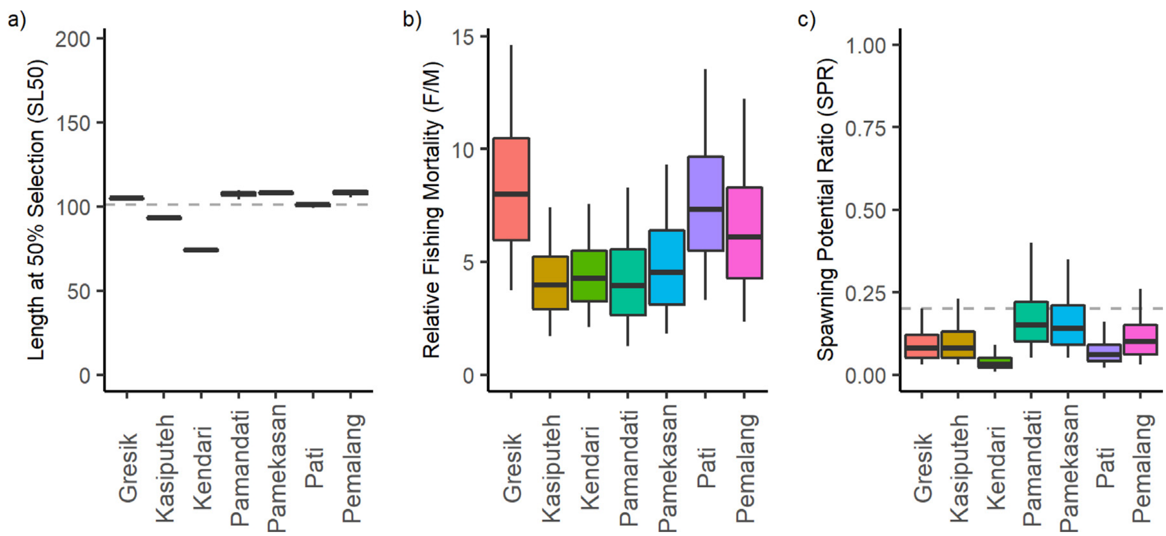

Fig. 6. Results of the analysis of blue swimming crab data from the seven areas in Indonesia (Java Sea: Gresik, Pati, Pemalang, Pamekasan; Tiworo Strait of Southeast Sulawesi: Kasiputeh, Kendari, Pamandati) with boxplots showing the estimated (a) length at 50% selectivity (SL_{50}), (b) relative fishing mortality (F/M), and (c) the spawning potential ratio (*SPR*). The dashed horizontal line shows (a) the estimated size of maturity and (c) a reference point of *SPR* = 0.2.

mean $SL_{50\%}$ corresponds with the lowest of our estimates of mean *SPR*.

4. Discussion

4.1. Comparative status of study sites

Comparing our assessments shows that in Sri Lanka the size of selectivity ($SL_{50\%}$) is markedly larger than in Indonesia (116–142 mm cf. 74–108 mm), the relative fishing pressure (F/M) slightly lower although still very high (2.7 - > 4 cf. >4), and that considerably greater levels of spawning potential (*SPR*) are being conserved (0.24–0.37 cf. 0.04–0.17). To some small degree the higher *SPR* in Sri Lanka will be partially attributable to the slightly lower relative fishing pressure, but in reality, fishing pressure is very high in both countries. Thus, the higher *SPR* in Sri Lanka is primarily due to the larger size at which the BSC are first vulnerable to being caught ($SL_{50\%}$). In Indonesia BSC first become vulnerable to being caught below or about L_{50}, while in Sri Lanka they are first caught ∼20% larger than L_{50} which protects a much greater level of spawning potential. Comparing the results from the various Indonesian sites reinforces this conclusion. All of the Indonesian sites have similarly very high F/M (>4), but the Kendari fishery with the lowest size of selectivity has the lowest estimate of *SPR*.

This is a clear demonstration of the principle that, the size of selectivity, relative to the size of maturity ($L_{50\%}$) is critical to determining the level of spawning potential that will be protected under heavy fishing pressure (Die and Caddy, 1997; Vasilakopoulos et al., 2011, 2016; Butterworth et al., 2014; Prince and Hordyk, 2018). These results graphically illustrate the well-established principle that stocks are particularly prone to depletion when they are vulnerable to being caught below or around their size of maturity. The converse being that stocks can be made robust to fishing pressure, and high *SPR* maintained, by ensuring the size of first capture is well above the size of maturity (Die and Caddy, 1997; Vasilakopoulos et al., 2011, 2016; Butterworth et al., 2014; Prince and Hordyk, 2018).

4.2. Fishing gears and stock status

Our results show the typical sizes of first capture by the differing fishing gears used in these fisheries; mini-trawl (∼74 mm), traps (∼93–108 mm) and nets (∼116–142 mm). These comparative estimates of $SL_{50\%}$ allow us to place the pattern of gear usage observed across these fisheries into a new context. To date relatively little importance has been attached to the wide range of fishing gears deployed by BSC fisheries. Implicitly it has been assumed that the pattern of gear usage is of little relevance to assessment and management; simply a function of the local preferences of mini-plant owners and fishers, and their access to technology and capital. We disagree with this assumption and instead believe our estimates of $SL_{50\%}$ reveal the central importance of gear type to understanding the status of these BSC fisheries, as well as providing the key to their sustainable management.

Our observation is that without management, the gear being used in each fishery is primarily a function of stock status, and that the characteristic sequence of gear use observed over time in each fishery (Fig. 2), is driven by resource depletion motivating fishers to increase their fishing efficiency to maintain catches. When stocks are lightly exploited fishing typically begins with nets which have the largest SL_{50}, partially due to the mesh size used, but principally due to the gear being set in deeper waters to entangle the larger more mobile adult crabs. As the largest size classes are depleted, catch rates with nets decline, so dip-nets are adopted to target smaller crabs which initially are found in large numbers in shallower waters. When catch rates on this part of the population begin declining, they are initially maintained with the added expense of using baited lines to aggregate the crabs, however, it eventually becomes necessary to take on the added expense of buying traps which can be used across the entire depth range and left in place overnight. When in turn the catch rates for traps fall too far, fishers adopt mini-trawling, which require a further increase in capital expenditure and additional operating costs but for a time allows the declining BSC catch to be supplemented by a bycatch of finfish. Each method in this succession of fishing gears escalates the fishing pressure being applied to the stock (Fig. 2), and is characteristic of a certain stage in the depletion of local BSC stocks.

4.3. Managing blue swimming crab fisheries by managing size selectivity

In this context, clearly understanding the impact of the various fishing gears and managing them is imperative to achieving the sustainability of BSC fisheries. Throughout the Indo-West Pacific jurisdictions in which BSC fisheries operate there is currently little if any governmental capacity to effectively control fishing pressure, let alone the magnitude of the catch. In this context, the only potential management solution is to manage the size of first capture to ensure sustainable levels of spawning potential are conserved in the unfished size classes, which coincidentally will also optimize yields (Prince and Hordyk, 2018). Minimum size limits (MSLs) set at 20% larger than L_{50} will conserve at least $SPR_{20\%}$ and confer sustainability on a fishery (Prince and Hordyk, 2018). In the context of our assessed BSC fisheries this implies an MSL of ∼120 mm, and if this could be effectively implemented it would reduce the importance of managing fishing gears. However, in the context of Sri Lanka and Indonesia, and most of the other BSC fisheries, there are relatively low resources for enforcement and a large number of poor fishers, so that low compliance with MSLs should be anticipated. A better approach would be to manage the type of fishing gear used, with the aim of reducing the catch of sub-optimal size classes and applying an MSL ∼120 mm to the selling and processing of BSC in order to minimize the incentive for catching sub-optimal size classes.

Our results from Sri Lanka show that crab nets have something like the desired size selectivity required for sustainability, and from this we conclude that if the development of the BSC fisheries in Indonesia had been stopped at the stage of using larger mesh nets, the issue with sustainability now being faced by Indonesia would not have evolved, or at least not to the same extent. It was on this basis that the Sri Lankan stakeholders amended their Fisheries and Aquatic Resources Act (No. 2 of 1996) to proscribe the use of baited traps, regulate a minimum mesh size of ∼114 mm in the fishery and prohibit mini-plant owners from buying < 100 g crabs: an initiative our results suggest is currently maintaining the sustainability of those fisheries. While the use of nets in many fisheries creates its own sustainability issues with species that are unintentionally caught as bycatch, we think this is less of an issue for BSC fisheries. Studies of BSC by-catch using nets in Sri Lanka reveal a relatively small catch of non-target species which are of low conservation concern, the majority of which is of value to the fishers (Gunasekera and Fairoz, 2016).

In this context the Sri Lankan fisheries have had the good fortune of becoming pro-active with regard to sustainable management early on in its development, while crab nets were still the primary fishing gear being used. In Indonesia the use of crab nets has now declined to a low level and traps or trawling have become the dominant fishing gears in most fisheries. Transitioning the Indonesian fisheries back to using crab nets is probably impossible because of the hardship and hunger, or lack of compliance, that would result. Instead the most feasible option for Indonesia might be to enforce its prohibition on trawling, at least within the depth range of BSC, and regulate the design of crab traps in order to make their size selectivity sustainable. Boutson et al. (2009) demonstrated how the size selectivity of traps can be increased by incorporating escape gaps into their construction to allow smaller BSC to exit as the traps are hauled. We suggest Indonesia's management policy should be modified to require BSC traps to be made of mesh with a minimum mesh size of 88.9 mm (3.5 inches) and fitted with escape gaps of ∼115 mm x 35 mm to maintain sustainable levels of spawning potential. Even this policy may not be feasible in the Indonesian context, in which case we expect BSC fisheries to continue declining towards the local and economic extinctions already observed in the original parts of this fishery.

4.4. Length-based spawning potential ratio and size selectivity as part of a harvest control rule

Increasingly the adaptive management of fisheries is being formalized and codified with harvest strategies, with the aim of making the process of adjusting management routine, disciplined and transparent, and as free as possible from political and vested influence (Smith et al., 2008). Harvest strategies are comprised of:

A. explicit management objectives for the fishery translated as explicit reference points;
B. indicators of fishery status that can be monitored and assessed in the context of the fisheries objectives and reference points;
C. an agreed assessment methodology based on the indicators being monitored;
D. a framework of management regulations that can be incrementally adjusted relative to the assessed status of the fishery, and
E. harvest control rules which explicitly define how the management regulations will be incrementally adjusted in response to assessment results.

Hordyk et al. (2015c) have demonstrated with simulation modelling how a time series of LBSPR assessments of catch size composition can be the basis of a harvest control rule that iteratively adjusts fishing pressure to robustly achieve sustainability. Recently that study was updated (Hordyk & Prince unpubl.) to demonstrate that harvest control rules can also be constructed to link a time series of LBSPR assessments with iterative and incremental adjustments of the size of selectivity (i.e. minimum size limits, dimensions of escape gaps in traps or mesh size of bottom set crab nets) and that, at least in simulation, such harvest control rules can also reliably achieve sustainability targets.

Harvest control rules based entirely, or almost entirely, on size composition data tend towards being overly precautionary (Prince et al., 2011; Hordyk et al., 2015c; Campbell et al., 2017). They respond quickly to stock depletion, because the depletion of the largest size classes is one of the first changes observed in a stock subject to increasing fishing pressure. Conversely, they are slow to rebuild catches from a recovering stock, because the repopulating of the largest size classes occurs during the final phase of a stock's recovery. This characteristic of purely size based harvest control rules means they can robustly achieve sustainability objectives, but this can be at the expense of the socio-economic objective of optimizing catches. Prince et al. (2011) and Campbell et al. (2017) demonstrate that this problem can be solved by combining size-based assessment with a basic CPUE indicator to make a harvest control rule as dynamic and responsive to stock status, as one based on aged based biomass modelling. So, while it should be entirely possible for Indonesia to develop a robust harvest control rule based entirely upon LBSPR assessment, their intention to incorporate CPUE trends as well, is to be commended.

5. Conclusions

This study demonstrates the technical feasibility of applying the LBSPR methodology to small-scale, data-poor BSC fisheries in Southeast Asia and by extension to other small-scale crustacean fisheries in developing countries, which due to data limitation and financial constraints, cannot be assessed using conventional assessment methods. Requiring only the simplest of data (i.e., size composition and size of maturity data) assessments can be completed with basically trained field staff, as demonstrated by the employment of community members in Sri Lanka. Its potential cost effectiveness even for small-scale fisheries is also demonstrated by the Sri Lankan assessments which, by using local village people, rather than scientifically trained technicians to collect and enter data, have reduced costs from an initial ∼USD2,500 per assessment in 2014/15 to < USD500 since 2017.

In both countries the LBSPR assessments are successfully informing and supporting discussions about sustainability, focusing them on the issue of managing size selectivity, one of the few management controls available to fisheries managers in many small-scale fisheries. In Sri Lanka the methodology is demonstrating that the larger size selectivity conferred by the use of crab nets with ∼114 mm mesh size can preserve a conservatively high level of SPR despite relatively high fishing pressure. The methodology has enhanced the value of the fisheries by successfully supporting attainment of a provisional sustainability rating from Seafood Watch (Monterey Bay Aquarium, 2018). In Indonesia application of the technique has increased focus on the need to fully implement previously promulgated regulations banning trawling and establishing an initial MSL, but suggest that escape gaps in traps, with dimensions of ∼115 mm x 35 mm also need to be implemented. We have suggested how the system of ongoing LBSPR assessment being implemented in Indonesia could be successfully used within the harvest control rule of the harvest strategy being developed for the fishery. The bigger challenge for Indonesia will remain how to effectively change the fishing gear being used by 65,000+ fishers spread across such a culturally diverse and extensive archipelago.

It is hoped that this documentation of how this methodology has been applied in Sri Lanka and Indonesia will assist other BSC and small-scale fisheries to make similar use of the technique.

Funding

This work was supported by the David and Lucile Packard Foundation, USA [grant number 2014-40057]; Indonesia Marine and Climate Support Project (IMACS) USAID Prime [Contract No. AID-EPP-I-00-06-00013 Task Order No. AID 497-TO-11-0003]; National Fisheries Institute Crab Council, USA [Grant No. SRL/2015, SRL/2016, SRL/2017]; IOM [Contract for Services CS.0525.LK.10.82.001 2014]; ILO UN [Contract Number M27012317807]; Taprobane Seafood Pvt Ltd (Corporate FIP Membership 2016–20); Fresh Catch LLC (Corporate FIP Membership 2016/17).

CRediT authorship contribution statement

Jeremy Prince: Conceptualization, Supervision, Methodology, Writing - original draft, Visualization, Funding acquisition. **Steven Creech:** Investigation, Validation, Writing - review & editing, Visualization, Funding acquisition. **Hawis Madduppa:** Investigation, Validation, Writing - review & editing, Funding acquisition. **Adrian Hordyk:** Methodology, Software, Validation, Formal analysis, Writing - review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge the support of the David and Lucile Packard Foundation for their support of the development and early applications of the LBSPR approach. SC acknowledges the support of the National Fisheries Institute Crab Council, the International Organisation for Migration, the International Labour Organisation of the United Nations, the Taprobane Seafood Group Pvt Ltd and Fresh Catch LLC each of whom co-financed one or more of the three annual stock assessments reported herein. HW and JP acknowledge the support of USAID through the IMACS project.

References

Andrew, N.L., Bène, C., Hall, S.J., Allison, E.H., Heck, S., Ratner, B.D., 2007. Diagnosis and management of small-scale fisheries in developing countries. Fish Fish. 8, 227–240.

Babcock, E.A., Tewfik, A., Burns-Perez, V., 2018. Fish community and single-species indicators provide evidence of unsustainable practices in a multi-gear reef fishery. Fish. Res. 208, 70–85.

Batoy, C.B., Sarmago, J.F., Pilapil, B.C., 1987. Breeding season, sexual maturity and fecundity of the blue crab, *Portunus pelagicus* (L.) in selected coastal waters in Leyte and vicinity, Philippines. Ann. Trop. Res. 9, 157–177.

Beverton, R.J.H., 1963. Maturation, growth and mortality of clupied and engraulid stocks in relation to fishing. Cons. Perm. Int. Explor. Mer, Rapp. p.-v. Réun. 154, 44–67.

Beverton, R.J.H., Holt, S.J., 1959. A review of the lifespans and mortality of fish in nature and the relation to growth and other physiological characteristics. Ciba Found. Colloq. Age 5, 142–177.

Boutson, A., Mahasawasde, C., Mahasawasde, S., Tunkijjanukij, S., Arimoto, T., 2009. Use of escape vents to improve size and species selectivity of collapsible pot for blue swimming crab *Portunus pelagicus* in Thailand. Fish. Sci. 75, 25–33.

Butterworth, D.S., Rademayer, R.A., Brandao, A., Geromont, H.F., Johnston, S.J., 2014. Does selectivity matter? A fisheries management perspective. Fish. Res. 158, 194–204. http://dx.doi.org/10.1016/j.fishres.2014.02.004.

Caddy, J.F., 1986. Modelling stock-recruitment processes in crustacea: some practical and theoretical perspectives. Can. J. Fish. Aquat. Sci. 43, 2330–2344.

Campbell, G.R., Fielder, D.R., 1986. Size at sexual maturity and occurrence of ovigerous females in three species of commercially exploited portunid crabs in SE Queensland. Proc. Roy. Soc. Qld. 97, 79–87.

Campbell, R.A., Prince, C.R., Davies, N.A., Dowling, J.D., Kolody, D.S., 2017. An empirical decision tree–based harvest strategy for in-country management of a shared pelagic resource. In: Quinn I.I., T.J., Armstrong, J.L., Baker, M.R., Heifetz, J., Witherell, D. (Eds.), Assessing and Managing Data-Limited Fish Stocks. Alaska Sea Grant, University of Alaska Fairbanks, http://dx.doi.org/10.4027/amdlfs.2016.10.

Chaplin, J., Yap, E.S., Sezmis, E., Potter, I.C., 2001. Genetic (microsatellite) determination of the stock structure of the blue swimming crab in Australia. In: FRDC Project 98/118. p. 84.

Chong, L., Mildenberger, T.K., Rudd, M.B., Taylor, M.H., Cope, J.M., Branch, T.A., Wolff, M., M., Stäbler., 2020. Performance evaluation of data-limited, length-based stock assessment methods. ICES J. Mar. Sci. 77, 97–108. http://dx.doi.org/10.1093/icesjms/fsz212.

Costello, C., Ovando, D., Hilborn, R., Gaines, S.D., Deschenes, O., Lester, S.E., 2012. Status and solutions for the world's unassessed fisheries. Science 338, 517–520.

Creech, S.P., 2017. A study of bottom-set crab net selectivity in blue swimming crab (*Portunus pelagicus*) fisheries in the Palk Bay and Gulf of Mannar, on the northern and northwestern coasts of Sri Lanka. In: Twenty Third Annual Scientific Sessions of the Sri Lanka Association for Fisheries and Aquatic Resources. SLAFAR, Colombo, Sri Lanka.

Dash, G., Sen, S., Koya, M., Sreenath, K.R., Mojjada, S.K., Zala, M.S., Pradeep, S., 2013. Fishery and stock assessment of the three-spot swimming crab *Portunus sanguinolentus* (Herbst, 1783) off Veraval, Gujarat. Indian J. Fish. 60 (4), 17–25.

de Lestang, S., Hall, N.G., Potter, I.C., 2003a. Reproductive biology of the blue swimmer crab (*Portunus pelagicus*, Decapoda: Portunidae) in five bodies of water on the west coast of Australia. Fish. Bull. 101, 745–757.

de Lestang, S., Hall, N.G., Potter, I.C., 2003b. Do the age compositions and growth of the crab *Portunus pelagicus* in marine embayments and estuaries differ? J. Mar. Biol. Ass. U.K 83, 971–978.

DFAR, 2015. Technical Report on Survey of Fishing Effort for Sri Lankan Blue Swimming Crab in the Northwest and Northern Coast of Sri Lanka and Development of a Management Plan. Department of Fisheries and Aquatic Resources, New Secretariat, Maligawatte, Colombo 10, Sri Lanka.

Die, D.J., Caddy, J.F., 1997. Sustainable yield indicators from biomass: Are there appropriate reference points for use in tropical fisheries? Fish. Res. 32, 69–79. http://dx.doi.org/10.1016/S0165-7836(97)00029-5.

Dineshbabu, A.P., Shridhara, B., Muniyappa, Y., 2008. Biology and exploitation of the blue swimmer crab, *Portunus pelagicus* (Linnaeus, 1758), from south Karnataka coast. India. Indian J. Fish. 55, 215–220.

Dineshbabu, A.P., Sreedhara, B., Muniyappa, Y., 2007. Fishery and stock assessment of *Portunus sanguinolentus* (Herbst) from south Karnataka coast. India. J. Mar. Biol. Ass. India 49, 134–140.

Dowling, N.A., Smith, A.D.M., Smith, D.C., Parma, A.M., Dichmont, C.M., Sainsbury, K., Wilson, J.R., Dougherty, D.T., Cope, J.M., 2018. Generic solutions for data-limited fishery assessments are not so simple. Fish Fish. 20, 174–188. http://dx.doi.org/10.1111/faf.12329.

Edgar, G.J., 1990. Predator-prey interactions in seagrass beds. II. Distribution and diet of the blue manna crab *P. pelagicus* Linnaeus at Cliff Head, Western Australia. J. Exp. Mar. Biol. Ecol. 139, 23–32.

Ernawati, T., 2013. Dinamika populasi dan pengkajian stok sumberdaya rajungan (*Portunus pelagicus*) di Perairan Kabupaten Pati dan Sekitarnya. [Tesis]. Bogor (ID): Institut Pertanian Bogor. [Population dynamics and stock assessment of blue swimmer crab (*Portunus pelagicus* Linnaeus) resource in Pati and adjacent waters]. Master Thesis. Bogor Agricultural University, Bogor, Indonesia, 80 pp. [in Indonesian].

Ernawati, T., Budiarti, T.W., 2019. Life history and length base spawning potential ratio (LBSPR) of malabar snapper *Lutjanus malabaricus* (Bloch & Schneider, 1801) in western of South Sulawesi, Indonesia. In: Embrio 2019 IOP Conf. Series: Earth and Environmental Science, vol. 404. pp. 1–8. http://dx.doi.org/10.1088/1755-1315/404/1/012023.

Ernawati, T., Kembaren, D.D., Sadhotomo, B., 2016. Stock evaluation of mangrove crab *Scylla serrata* (forskal, 1775) in Waters Pati and its surrounding and its management options. J. Penelitianware Indonesia (J. Indonesian Fish. Res.) 22, 95–103.

Ernawati, T., Priatna, A., Satria, F., 2019. Biological reference points of painted spiny lobster *Panulirus versicolor* (Latreille, 1804) in Karimun Jawa Waters, Indonesia. Indonesian Fish. Res. J. 25, 91–101. http://dx.doi.org/10.15578/ifrj.25.2.2019.91-101.

Ernawati, T., Sumioino, B., Madduppa, H., 2017. Reproductive ecology, spawning potential, and breeding season of blue swimming crab (Portunidae: *Portunus pelagicus*) in Java Sea, Indonesia. Biodiversitas 18, 1705–1713. http://dx.doi.org/10.13057/biodiv/d180451.

FAO, FAO Fisheries and Aquaculture Department, 2019. Global Capture Production Statistics. http://www.fao.org/fishery/statistics/en.

Gayanilo, F.C., Pauly, D., 1997. FAO-ICLARM Stock assessment tools (FISAT). In: Reference manual FAO Computerized information Series (Fisheries), no. 8, FAO, Rome, p. 262.

Gunasekera, G.G.E.M., Fairoz, M.F.M., 2016. An assessment of the ecological impact of the *Portunus pelagicus* fishery in the Puttalam Lagoon (Gulf of Mannar) on non-target species, using the Marine Stewardship Council's Risk Based Assessment Framework. In: Proceedings of the Twenty Second Scientific Sessions of the Sri Lanka Association Fisheries and Aquatic Resources, p. 15.

Hamid, A., Wardiatno, Y., 2015. Population dynamics of the blue swimming crab (*Portunus pelagicus* Linnaeus 1758) in Lasongko Bay, Central Buton. Indonesia. Aquac. Aquar. Conserv. Legis 8, 729–739, http://www.bioflux.com.ro/aad.

Holt, S.J., 1958. The evaluation of fisheries resources by the dynamic analysis of stocks, and notes on the time factors involved. In: ICNAF Spec. Publ., vol. 1. pp. 77–95.

Hordyk, A., 2019. LBSPR: length-based spawning potential ratio. R package version 0.1.5. https://CRAN.R-project.org/package=LBSPR.

Hordyk, A., Loneragan, N., Prince, J.D., 2015c. An evaluation of an iterative harvest strategy for data-poor fisheries using the length-based spawning potential ratio assessment methodology. Fish. Res. 171, 20–32. http://dx.doi.org/10.1016/j.fishres.2014.12.018.

Hordyk, A., Ono, K., Prince, J.D., Walters, C.J., 2016. A simple length-structured model based on life history ratios and incorporating size-dependent selectivity: application to spawning potential ratios for data-poor stocks. Can. J. Fish. Aquat. Sci. 73, 1787–1799. http://dx.doi.org/10.1139/cjfas-2015-0422.

Hordyk, A., Ono, K., Sainsbury, K., Loneragan, N., Prince, J.D., 2015a. Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio. ICES J. Mar. Sci. 72, 204–216. http://dx.doi.org/10.1093/icesjms/fst235.

Hordyk, A., Ono, K., Valencia, S.V., Loneragan, N., Prince, J.D., 2015b. A novel length-based estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. ICES J. Mar. Sci. 72, 217–231. http://dx.doi.org/10.1093/icesjms/fsu004.

Ihsan Wiyono, E.S., Wisudo, S.H., Haluan, J., 2014. A study of biological potential and sustainability of Swimming Crab population in the waters of Pangkep Regency South Sulawesi Province. Int. j. sci: basic appl. Res. 16, 351–363.

Ingles, J., Braum, E., 1989. Reproduction and larval ecology of the blue swimming crab *Portunus pelagicus* in Ragay Gulf, Philippines. Int. Rev. Hydrobiol. 74, 471–490.

Jayamanne, S.C., 2011. Crab resources of Sri Lanka. Vidu 1, 1–12.

Josileen, J., Menon, N.G., 2007. Fishery and growth parameters of the blue swimmer crab *Portunus pelagicus* (Linnaeus, 1758) along the Mandapam coast. India. J. Mar. Biol. Ass. India 49, 159–165.

Kailola, P.J., Williams, M.J., Stewart, P.C., Riechelt, R.E., McNee, A., Grieve, C., 1993. Australian Fisheries Resources. Bureau of Resource Sciences, Canberra.

Kamrani, E., Sabili, A.N., Yahyavi, M., 2010. Stock assessment and reproductive biology of the blue swimming crab, *Portunus pelagicus* in Bandar Abbas coastal water. Northern Persian Gulf. J. Persian Gulf (Mar. Sci.) 1, 11–22.

Kembaren, D.D., Ernawati, T., Suprapto, 2012. Biologi dan parameter populasi rajungan (*Portunus pelagicus*) di Perairan Bone dan sekitarnya [Biology and population parameters of blue swimming crab (*Portunus pelagicus*) in the Bone Bay and adjacent waters]. J. Lit. Perikan. Ind. 18, 273–281 [in Indonesian].

Kilada, R., Webb, J.B., McNeel, K.W., Slater, L.M., Smith, Q., Ferguson, J., 2016. Preliminary assessment of a direct age- determination method for 3 commercially important crustaceans from Alaska. Fish. Bull. 115, 42–49. http://dx.doi.org/10.7755/FB.115.1.4.

Kunsook, C., Gajaseni, N., Paphavasit, N., 2014. A stock assessment of the blue swimming crab *Portunus pelagicus* (Linnaeus, 1758) for sustainable management in Kung Krabaen Bay, Gulf of Thailand. Trop. Life Sci. Res. 25, 41–59.

Lai, J.C.Y., Kg, P.K.L., Davie, P.J.F., 2010. A revision of the *Portunus pelagicus* (linnaeus, 1758) species complex (Crustacea: Brachyura: Portunidae) with the recognition of four species. Raffles Bull. Zool. 58, 199–237.

Lee, H., Hsu, C., 2003. Population biology of the swimming crab *Portunus sanguinolentus* in the waters off northern Taiwan. J. Crust. Soc. 23, 691–699.

Mace, P., Sissenwine, M., 1993. How much spawning is enough? In: Smith, S.J., Hunt, J.J., Rivard, D. (Eds.), Risk Evaluation and Biological Reference Points for Fisheries Management. In: Can. Spec. Publ. Fish. Aquat. Sci., vol. 120, pp. 101–118.

Madduppa, H., Zairion Nuraini, S., Nugroho, K.C., Nugraha, B.A., 2016. Setting up a traceability tools for the Indonesian Blue Swimming Crab Fishery: a case study in Southeast Sulawesi. In: Fisheries and Aquaculture in the Modern World. Intech, Rijeca, Croatia, http://dx.doi.org/10.5772/64252.

Mehanna, S.F., Khvorov, S., Al-Sinawy, M., Al-Nadabi, Y.S., Al-Mosharafi, M.N., 2013. Stock assessment of the blue swimmer crab *Portunus pelagicus* (Linnaeus, 1766) from the Oman coastal waters. Int. J. Fish. Aquat. Sci. 2, 1–8.

Monterey Bay Aquarium, 2018. Seafood Watch, Blue Swimming Crab (*Portunus pelagicus*), Sri Lanka, Set gillnets, p. 1–65.

MRAG, 2015. Indonesian Blue Swimming Crab FIP. ID1972 Final Pre-Assessment Report. p. 69, https://fisheryprogress.org/system/files/documents_assessment/ID1972_Pre-Assessment_Reporting_FINAL.pdf.

Mullon, C., Freon, P., Cury, P., 2005. The dynamics of collapse in world fisheries. Fish Fish. 6, 111–120.

Pauly, D., 1980. On the interrelationship between mortality, growth parameters and mean temperature in 175 fish stocks. J. Cons. Int. Explor. Mer. 39, 175–192.

Pons, M., Kell, L., Rudd, M.B., Cope, J.M., Frédou, F.L., 2019. Performance of length-based data-limited methods in a multifleet context: application to small tunas, mackerels, and bonitos in the Atlantic Ocean. ICES J. Mar. Sci. 76, 960–973. http://dx.doi.org/10.1093/icesjms/fsz004.

Potter, I.C., Chrystal, P.J., Loneragan, N.R., 1983. The biology of the blue manna crab *P. pelagicus* in an Australian estuary. Mar. Biol. 78, 75–85.

Potter, I.C., de Lestang, S., 2000. Biology of the blue swimmer crab *Portunus pelagicus* in Leschenault estuary and Koombana Bay in south-western Australia. J. Roy. Soc. W.A 83, 221–236.

Potter, M., Sumpton, W., Smith, G., 1987. Queensland sand crab study highlights a need for changes in management. Aust. Fish 46 (6), 22–26.

Potter, M.A., Sumpton, W.D., Smith, G.S., 1991. Movement, fishing sector impact and factors affecting the recapture rate of tagged sand crabs, *Portunus pelagicus* (L.) in Moreton Bay, Queensland. Aust. J. Mar. Freshw. Res. 42, 751–760.

Prince, J.D., Dowling, N.A., Davies, C.R., Campbell, R.A., Kolody, D.S., 2011. A simple cost-effective and scale-less empirical approach to harvest strategies. ICES J. Mar. Sci 68, 947–960. http://dx.doi.org/10.1093/icesjms/fsMay2011.

Prince, J.D., Hordyk, A., 2018. What to do when you have almost nothing: a simple quantitative prescription for managing extremely data-poor fisheries. Fish Fish. http://dx.doi.org/10.1111/faf.12335.

Prince, J.D., Hordyk, A., Valencia, S.V., Loneragan, N., Sainsbury, K., 2015. Revisiting the concept of Beverton–Holt life history invariants with the aim of informing data-poor fisheries assessment. ICES J. Mar. Sci. 72, 194–203. http://dx.doi.org/10.1093/icesjms/fsu011.

Safaie, M., Kiabi, B., Pazooki, J., Shokir, M.R., 2013a. Growth parameters and mortality rates of the blue swimming crab, *Portunus segnis* (Forksal, 1775) in coastal waters of Persian Gulf and Gulf of Oman. Iran. Indian J. Fish. 60, 9–13.

Safaie, M., Kiabi, B., Pazooki, J., Shokir, M.R., 2013b. Reproductive biology of the blue swimming crab, *Portunus segnis* (Forskal 1775) in coastal water of the Persian Gulf and Oman Sea. Iran. Iranian J. Fish. Sci. 12, 430–444.

Sarada, P.T., 1998. Crab fishery of the Calicut coast with some aspects of the population characteristics of *Portunus Sanguinolentus, P. pelagicus and Charybdis cruciata*. Indian J. Fish. 45, 375–386.

Sawusdee, A., Songrak, A., 2009. Population dynamics and stock assessment of the blue swimming crab (*Portunus pelagicus* Linnaeus, 1758) in the coastal area of Trang Province, Thailand. Walailak J. Sci. Tech. 6, 189–202.

Sivalingam, S., 2005. General features and fisheries potential of Palk Bay, Palk Straits and its environs. J. Natl. Sci. Found. Sri Lanka 33 (4), 225–232.

Smith, A.D.M., Smith, D.C., Tuck, G.N., Klaer, N., et al., 2008. Experience in implementing harvest strategies in Australia's south-eastern fisheries. Fish. Res 94, 373–379.

Stephenson, W., 1962. Evolution and ecology of portunid crabs, with special reference to Australian species. In: Leeper, G.W. (Ed.), The Evolution of Living Organisms. Melbourne University Press, Melbourne, pp. 311–327.

Sukumaran, K.K., Neelakantan, B., 1997. Age and growth in two marine portunid crabs, *Portunus (Portunus) sanguinolentus* (Herbst) and *Portunus (Portunus) pelagicus* (Linnaeus) along the south-west coast of India. Indian J. Fish. 44, 111–131.

Sumpton, W.D., Potter, M.A., Smith, G.S., 1994. Reproduction and growth of the commercial sand crab, *Portunus pelagicus* (L.) in Moreton bay, Queensland. Asian Fish. Sci 7, 101–113.

Sun, M., Zhang, C., Chen, Y., Xu, B., Xue, Y., Ren, Y., 2017. Assessing the sensitivity of data-limited methods (DLMs) to the estimation of life-history parameters from length–frequency data. Can. J. Fish. Aquat. Sci. 75, 1563–1572.

Sunarto, 2012. Karakteristik Bioekologi Rajungan (*P. pelagicus*) di Perairan Laut Kabupaten Brebes [Disertasi]. Bogor (ID): Sekolah Pascasarjana, Institut Pertanian Bogor. [Bioecology characteristics of blue swimming crab (*Portunus pelagicus*) in Brebes waters]. Ph.D. thesis. Bogor Agricultural University, Bogor, Indonesia, 175 pp. [in Indonesian].

Teh, T., C., L., Pauly, D., 2018. Who brings in the fish? The relative contribution of small-scale and industrial fisheries to food security in southeast Asia. Front. Mar. Sci. 5 (44), http://dx.doi.org/10.3389/fmars.2018.00044.

Thorson, J.T., Munch, S.B., Cope, J.M., Gao, J., 2017. Predicting life history parameters for all fishes worldwide. Ecol. Appl. 27, 2262–2276.

Tirtadanu, U.C., 2019. Fishery, population parameters and exploitation status of blue swimming crab (*Portunus pelagicus*) in Kwandang Waters, Indonesia. AACL Bioflux 12, 1323–1334.

Tirtadanu, K.W., Sadhotomo, B., 2018. Growth, results and new additions potency rate of red fish scales (*Lutjanus malabaricus* Schneider, 1801) in the lines and surroundings. J. Penelitianware Indonesia (J. Indonesian Fish. Res.) 24, 31. http://dx.doi.org/10.15578/jppi.1.1.2018.1-10.

Van Engel, W.A., 1958. The blue crab and its fishery in Chesapeake Bay. Part 1. Reproduction, early development, growth and migration. Comm. Fish. Rev. 20, 6–17.

Vasilakopoulos, P., O'Neill, F.G., Marshall, C.T., 2011. Misspent youth: Does catching immature fish affect fisheries sustainability? ICES J. Mar. Sci 68, 1525–1534. http://dx.doi.org/10.1093/icesjms/fsr075.

Vasilakopoulos, P., O'Neill, F.G., Marshall, C.T., 2016. The unfulfilled potential of fisheries selectivity to promote sustainability. Fish Fish. 17, 399–416. http://dx.doi.org/10.1111/faf.12117.

Walters, C., Martell, S.J.D., 2004. Fisheries Ecology and Management. Princeton University Press, Princeton, NJ, p. 399.

Walters, C., Pearse, P.H., 1996. Stock information requirements for quota manage-ment systems in commercial fisheries. Rev. Fish Biol. Fish. 6, 21–42.

Warsa, A., Tjahjo, D.W.H., Astuti, L.P., 2019. Ukuran pertama kali matang gonad dan selectivtivitas jarring insand ikan Nila (*Oreochromis niloticus*) di Waduk Jatiluhur, Jawa Barat. Measurement first maturity and gillnet selectivity of Nile tilapia (*Oreochromis niloticus*) at Jatiluhur Reservoir, West Java. Berita Biol. 18, 283–293. http://dx.doi.org/10.14203/beritabiologi.v18i3.3720.

Williams, M.J., 1982. Natural food and feeding in the commercial sand crab *P. pelagicus* Linnaeus, 1766 (Crustacea: Decapoda: Portunidae) in Moreton Bay, Queensland. J. Exp. Mar. Biol. Ecol. 59, 165–176.