Assessment of the lobster puerulus (Panulirus homarus and Panulirus ornatus, Decapoda: Palinuridae) resource of Indonesia and its potential for sustainable harvest for aquaculture

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\textbf{ABSTRACT}

Indonesia has a unique opportunity to establish the world's largest lobster aquaculture industry, based on a significant natural resource of settling puerulus. These seed lobsters can be captured and on-grown to generate high value, consumption size lobsters. However, existing fisheries regulation prohibits fishing of these seed lobsters in Indonesia. Nevertheless, seed fishing occurs widely, and the seed are smuggled into Vietnam, where the Vietnamese gain most of the commercial benefit. By removing access to pueruli and grow-out opportunities, these regulations have diminished the capacity of Indonesian lobster farmers to develop a sustainable grow-out industry. Although the new policies were introduced as a management intervention to protect adult lobster stocks, they have had the unintended consequence of preventing development of lobster aquaculture while having no known benefit on abundance of adult lobsters. This study collected data on the puerulus available in Indonesia, species composition, seasonality, and capture methods.

A census of seed capture determined that 5,243,887 pueruli were shed from two bays in the southeast of Lombok in 2014, representing 64,787 pueruli per km\(^2\). Surveys beyond Lombok determined there was high abundance of seed in areas with similar environmental characteristics, where local communities had also engaged in seed fishing. The locations identified as having substantial puerulus abundance comprised the southern coast of Java, Bali, Lombok and Sumbawa covering a distance of 1500 km. Puerulus abundance is highest in enclosed bays with distinct currents, relatively high turbidity attributable to terrestrial inflows, and muddy/sandy substrates. Satellite imaging identified all such suitable locations for puerulus settlement, enabling an estimate of total puerulus catch of 103,480,283 per year. The composition of puerulus shed consisted of two species, Panulirus homarus and P. ornatus. P. homarus was most abundant representing between 63 and 87\%, while P. ornatus represented 37 to 13\%. Seasonality of catch was unclear, with low catch between December and March and higher catches from April to November. The magnitude of the estimated puerulus resource of Indonesia is > 20 times greater than that of Vietnam. If used for aquaculture, the seed available can support an industry generating > 12,500 t of market size lobster, and provide social and economic benefit to many thousands of households. To achieve this, fisheries policies could be revised and a regulatory framework established to manage the puerulus fishery and support lobster farming. Tropical marine rock lobster aquaculture is a major opportunity for high-value aquaculture production for the Indonesian economy.

\textbf{1. Introduction}

Aquaculture of marine spiny lobsters in Indonesia has been confined to the on-growing of wild-sourced pueruli captured in shallow coastal waters in Lombok, West Nusa Tenggara Province where natural settlement occurs, and their abundance is sufficient to justify the effort to fish for them (Jones et al., 2019; Jones et al., 2010). This has similarities to Vietnam, where puerulus fishing is well developed and there exists a stable lobster farming industry that produces around 1500 t of marketable (1 kg +) lobsters each year (Anh and Jones, 2015a; Jones, 2010; Jones et al., 2019).

Methods for the fishing of lobster pueruli were first developed in...
Vietnam in the mid-1990s (Jones et al., 2010). The puerulus is a transitional stage within the spiny lobster life cycle, intermediate between the phyllosoma larva and the juvenile lobster. It persists in the plankton, swimming towards the coastline, presumably responding to cues to direct it to suitable settlement habitat (Phillips et al., 2013). The puerulus is around 12 mm in total length, translucent and non-feeding, relying on an energy reserve comprising fat in its body. Its maximum life span is around 2 to 3 weeks, and it will perish if suitable settlement habitat is not found. The spiny lobster puerulus is commonly referred to as a seed lobster.

Entrepreneurial Vietnamese fishers recognised that small lobsters could be fattened to a more valuable product, as the Chinese demand and price per kilogram was greatest for lobsters larger than 1 kg (Anh and Jones, 2015a). In the early years of the Vietnamese industry, methods were developed for catching juvenile lobsters, typically by creating artificial habitat suitable for juvenile lobster settlement. To capture the settled juvenile lobsters, fishers would periodically dive to the sea floor or lift the habitats to the surface, to manually remove settled juveniles (Nguyen and Dao, 2009). Targeting juvenile lobsters was progressively replaced with fishing for the puerulus stage using various nets to capture the swimming pueruli as they actively moved through inshore waters seeking suitable habitat in which to settle.

Fishing for swimming pueruli proved to be far more effective than fishing for juveniles, as the abundance of pueruli was significantly higher. Fishing methods evolved and catch rates increased as innovative fishers developed their understanding of the oceanographic conditions associated with the highest abundance. Nets were set across the current to effectively intercept pueruli as they swam through the hours of darkness (Jones et al., 2010). Today, the most common and effective method for fishing of pueruli in Vietnam is a set seine net, deployed in a V-shape presentation, with the nets opening facing the prevailing current, and using lights positioned near the net apex to attract the pueruli (Anh and Jones, 2015; Jones et al., 2019). The seine nets are typically set in the hours on dusk and retrieved twice each night, firstly at around midnight and again at dawn, with the pueruli manually removed from the net as it is hauled aboard.

Farming of lobsters in Indonesia began in the early 2000s on the island of Lombok. The Indonesians, unaware of the Vietnam rock lobster aquaculture industry and its successful methods, developed their own techniques for catching lobster seed and then on-growing them to marketable size. Lobster seed fishing methods in Lombok were only partially effective with relatively low catch rates until 2013. A group of Indonesian lobster aquaculture participants including growout farmers, puerulus fishers, researchers, and associated industry representatives took part in a study tour of the Vietnam lobster farming industry in early 2013 (Priyambodo, 2015c). This provided a valuable positive stimulus that led in particular to more effective puerulus fishing methods now employed. The basic principles of the Indonesian technique mimics that of Vietnam, in intercepting pueruli as they swim; however, the catching gear is significantly different. The Indonesians use an array of artificial habitats rather than a seine net.

The development of puerulus fishing in Indonesia is well described by Bahrawi et al. (2015a, 2015c) and Jones et al. (2019), and the assessment of different habitat materials and methods of deployment to maximise catch are presented in Priyambodo et al. (2015); Priyambodo et al. (2017). The Indonesian method serves to present artificial materials comprising sharply creased crevices that are attractive to pueruli as a suitable habitat in which to settle. These habitats share characteristics of the crevice traps used for fisheries resource management assessment of commercial lobster fisheries settlement throughout the world (Booth and Tarring, 1986; Phillips and Booth, 1994).

Unlike Vietnam, where nets are actively deployed and removed each day, the puerulus fishing frames in Indonesia are moored in place and only shifted or removed if rough conditions develop. One of the most important methods borrowed from the Vietnamese was the application of lights to puerulus fishing devices, first applied in 2013 (Priyambodo, 2015c). A single fluorescent or incandescent light mounted above the frame results in significantly increased catch rates, presumably because of positive phototaxis of the swimming pueruli. Indonesian puerulus fishers visit their fishing frames early each morning to lift each panel of habitats and manually remove the settled seed hiding in the habitat crevices.

In both Vietnam and Indonesia, captured pueruli are immediately placed into containers with fresh seawater, sometimes aerated. Details of puerulus handling and transport are provided in the reports of Jones et al. (2010), Bahrawi et al. (2015c) and Anh and Jones (2015).

The on-growing of wild-caught pueruli is an established practice in Vietnam (Jones, 2010; Jones, 2015a; Jones et al., 2019), but is only in its developmental stage in Indonesia (Priyambodo, 2015a). Indonesian lobster farmers lack the skills to generate sufficient productivity to justify their commitment, and most who try lobster farming soon abandon it in favour of simply fishing for pueruli that are then sold to dealers who market them to other countries for grow-out there. A key obstacle for the Indonesian lobster farmer is the high mortality of pueruli immediately or soon after stocking to the grow-out system (floating sea-cage) (Jones et al., 2007; Priyambodo and Jaya, 2009; Priyambodo and Sariffin, 2009). Although there appears to be little if any variation in the quality of captured pueruli on the basis of their size and morphology, there is a likelihood that they do vary in regard to their condition. Extensive research (Jeffs, 2000; Jeffs and Holland, 2000b; Jeffs et al., 1999; Jeffs et al., 2001a; Jeffs et al., 2001b; Jeffs et al., 2005; Jeffs et al., 2002; Phillips et al., 2006a; Phillips et al., 2006b; Wilkin and Jeffs, 2011) on puerulus condition for Jasus edwardsii and other species for the purpose of understanding and managing recruitment to lobster fisheries provides a strong foundation for examining puerulus condition in the context of their quality for subsequent on-growing. Further, the high mortality of seed due to handling, and lack of farming ability can be addressed through appropriate technology extension and training.

Although there have been extensive studies on recruitment of palinurid lobsters as part of broader population research for resource management purposes, the cues that determine when and where pueruli settle are not well understood (Booth, 2002; Briones-Fourzán et al., 2008; Butler and Herrnkind, 1991; Herrnkind and Butler, 1994). For the tropical species P. ornatus and P. homarus, the developing puerulus 仔handing in Vietnam and Indonesia indicate that abundance is highest in areas of the coastline where there is some protection from prevailing wind and wave action and often in proximity to terrestrial outflows from creeks and rivers. These areas are often characterised by high turbidity, salinity < 33 ppt and with currents of either tidal or oceanic origin (Anh and Jones, 2015; Jones et al., 2010; Jones et al., 2019). Such physico-chemical characteristics may therefore be used as a predictor of puerulus settlement in areas where late-stage phyllosoma are delivered by prevailing currents (Hinojosa et al., 2015; Jeffs et al., 2005; Próo et al., 1996).

In Indonesia, the opportunity exists to establish a lobster farming industry like that of Vietnam, as a significant resource of pueruli has been identified (Bahrawi et al., 2015a; Jones, 2018). However, in 2015 there was a substantial change in the Indonesian spiny lobster aquaculture industry with announcement of a new policy (Indonesian Government, 2015) that imposed a 200 g, minimum legal size for spiny lobsters that could be caught and traded. This resulted in prohibiting the catch of pueruli for all species. Further, in 2016 another policy was announced (Indonesian Government, 2016) that prohibited grow-out activity involving spiny lobster. By removing access to pueruli and grow-out opportunities, these regulations have precluded the capacity of Indonesian lobster farmers to develop a sustainable grow-out industry. Although the new policies were aimed at supporting increased abundance of adult lobsters, there is no evidence (no increased fishery catch) they have been successful (Jones, 2018). Despite the regulations, puerulus fishing has continued unabated and illegally, and in 2019 it is estimated there are more puerulus fishers operating over a greater area.
than before the regulations were implemented. In short, the grow-out industry has now completely collapsed, while puerulus fishing continues, with benefits primarily to black market operators and the Vietnamese lobster farming industry. The small-scale puerulus fishers, with little alternative, risk arrest and penalties to maintain their livelihoods (Jones, 2018). It is important to note that lobster seed fishing provides a viable livelihood to many thousands of Indonesian households.

Harvesting of pueruli for the purpose of aquaculture has been considered and/or trialled for other rock lobster species, but never implemented at a commercial level due to the concern of potential impact on future fishery production and breeding stock. The consideration of such pueruli harvesting was based on achieving ‘biological neutrality’, that is, no net effect (Gardner et al., 2006; Jeffs and Davis, 2009; Phillips et al., 2003a). In New Zealand it was determined that retiring 1 t of quota (fishery catch of adult lobsters) of J. edwardsii would allow 40,000 pueruli per annum to be taken for aquaculture (Booth et al., 1999). For P. cygnus, the effect of puerulus removal on the subsequent catch was estimated to be slight (Phillips et al., 2003a; Phillips et al., 2003b). For example, it was estimated by Phillips, et al. (2003a) that the removal of 20 million P. cygnus pueruli in Western Australia in a year in which the puerulus settlement size was 600 million pueruli, would result in a reduction in adult catch of 0.62%.

While the extent of the puerulus resource in Vietnam appears to be fully developed, as evidenced by relatively stable annual catch over > 15 years, assessment of Indonesia’s seed resources is incomplete. Detailed catch data for puerulus were collected from 2007 to 2012, but were restricted to the island of Lombok (Bahrawi et al., 2015b). By late 2012, anecdotal data suggested pueruli were available in high concentrations (i.e., fishable abundance) over a much larger coastal range beyond Lombok, potentially representing a resource far larger than that of Vietnam. To evaluate the puerulus fishery resource of Indonesia more thoroughly, surveys were performed to gather data from coastal villages where pueruli were fished.

This study sought to collect data on puerulus catch, species composition, seasonality and capture methods in areas of Indonesia where puerulus abundance appeared to be relatively high, based on anecdotal fishery information. In addition to more thorough investigations into the fishery of the lobster puerulus resource already established in Lombok, research was performed to assess the availability of lobster puerulus in other parts of Lombok and other Indonesian provinces. The study also sought to estimate the entire resource by mapping suitable settlement locations and extrapolating from data representing quantified populations. Finally, the data compiled enabled estimates of the potential scale of future lobster farming in Indonesia. Policy recommendations to achieve this are presented.

2. Materials and methods

2.1. Puerulus census of Lombok

The puerulus fishery of Lombok is restricted to the southeast of the Island in two bays, Gerupuk Bay and Ekas Bay. Earlier research had confirmed that puerulus abundance elsewhere in Lombok was negligible. To record fishery catch data for lobster pueruli with accuracy and precision, a logbook was prepared that enabled recording of catch data from each fisher.

Data were recorded once a week from interviews with the lobster seed fishers in four locations in Lombok, as shown in Fig. 1, onto a standardised form recording the location, fishers’ name (later de-identified), capture dates, species captured and its numbers. Data were subsequently transcribed to Excel spread sheets to enable collation and analyses.

Through a research project (Jones, 2015a) from 2009 to 2013, the census was conducted covering four villages in Lombok (Fig. 1) and some 245 to 484 puerulus fishers in the two main puerulus fishing bays. It was estimated that the census covered > 90% of fishers operating in the designated area. For each main village a puerulus census officer was recruited and trained in the data collection method. Data were recorded on the standardised form, which when completed, was photographed and the images transmitted to the authors, for transcription to Microsoft Excel.

In 2014, the number of puerulus fishers increased substantially compared with previous years to > 4000. This number was based on interviews with the top puerulus dealers in Lombok who collectively purchased from all the fishers. Rather than interview each fisher, data were collected from the top six puerulus dealers who buy seed from the fishers. The number of puerulus fishers or dealers interviewed, and the total number of fishers or dealers operating each year from 2007 to 2014 is presented in Table 1. However, data on the puerulus catch for 2015 could not be gathered because puerulus dealers became more sceptical about sharing their data with researchers as a consequence of the new fisheries regulations introduced, which banned the collection of lobsters weighing < 200 g ( Indonesian Government, 2015).

2.2. Field survey of puerulus fishing

By the beginning of the 2013/14 puerulus season, puerulus fishing in Lombok had become a lucrative business involving both domestic demand to supply the emerging lobster grow-out sector (primarily in Lombok), and export demand from Vietnam to supply their well-established lobster farming industry. Consequently, fishers in other areas beyond Lombok began fishing for pueruli and anecdotal information at that time suggested fisheries were establishing with catch rates equivalent to those of Lombok. A field survey was therefore performed, comprising collection of quantitative and qualitative data on the puerulus fisheries in three villages: two on the south-east coast of Java and one on the south coast of Sumbawa. A structured questionnaire was used to gather information on the number of pueruli caught, species composition, seasonality, fishing methods, capture equipment and materials and general environmental characteristics of locations in which pueruli were fished. Ten puerulus fishers were interviewed at each location.

The survey was carried out under the UNSW Human Research Ethics Committee approval No. HC13346, ‘The development of spiny lobster aquaculture in Indonesia through the enhancement of puerulus catch and technology transfer’.

The surveys were performed in 2015 and 2016 in villages near Banyuwangi (8°36′8.50″S 114°13′29.75″E) and Trenggalek (8°17′11.60″S 111°43′42.02″E) in Java and near Labangka Sumbawa (8°53′19.3527″S 117°47′55.689″E) in Sumbawa (Priyambodo and Bahrawi, 2015, 2016). To provide verification of the data collected, interviews were performed with several main lobster puerulus dealers who had detailed knowledge of the number of fishers in their location, the number of other dealers in their region and the volumes of puerulus being marketed. Based on these data, an estimate of the total puerulus fishery catch was made.

2.3. Identification of puerulus fishing location using Google Earth

Based on the data collected from the census in Lombok, and the field surveys in Java and Sumbawa, a definition was generated of the broad physical and environmental characteristics associated with puerulus abundance. These characteristics included; bays with some protection from strong wave action, in proximity to coastal currents and with terrestrial inflows likely to elevate turbidity and nutrients. Using Google Earth™, a detailed examination of the southern coasts of Java and Sumbawa was made to identify locations with these characteristics. Additional verification of the location as being suitable for puerulus fishing was the presence of puerulus fishing frames, that were visible on satellite images on Google Earth.

Google Earth was used to estimate the area of puerulus fishing
within each bay via its polygon measurement tool. The fishing area was defined by the outer limits of the floating frames or, in bays where frames were not present, the area between 100 and 500 m from the coastline within the bay.

Based on the recorded number of pueruli captured in Lombok from previous puerulus censuses undertaken in 2014, an estimate of the typical number of puerulus caught per square kilometre per year was made. From this figure, an estimate of the puerulus that may be available at each of the locations was generated. In turn, this allowed estimation of the overall number of fishable puerulus available in Indonesia. Data gathered were analysed using Microsoft Excel and are presented using graphs and tables.

3. Results

3.1. Puerulus census of Lombok

Data gathered from the puerulus censuses from 2009 to 2014 are presented in Fig. 2. The data for 2013 and 2014 show a substantial increase in the total puerulus caught per annum compared with previous years. The increase in catch was significant, from around 600,000 pueruli per year between 2009 and 2012, to 3 million in 2013 and 5 million in 2014. The total catch of lobster pueruli by month from 2009 to 2014 is presented in Fig. 3. Total lobster puerulus catch by month for each year, 2009 to 2012 on a finer scale is presented in Fig. 4. Fig. 3 shows that seed are captured in all months of the year, with lowest catch from December through to March, higher catches from April to November, indistinct peaks and considerable inter-annual variability. When examining the catch data for 2009 to 2012 on a different scale, as in Fig. 4, inter-annual variability is less evident, with consistent increase in catch from March to June, some decrease in July and then a secondary peak. This pattern however is only partially consistent with the data for 2013 and 2014 when total catch was much higher. The suggestion of two peaks is consistent with likely recruitment of pueruli arising from twin reproductive input from summer breeding in northern and southern hemisphere populations. The location of puerulus settlement in Indonesia along the southern coastline of

Table 1

<table>
<thead>
<tr>
<th>Puerulus fishing season</th>
<th>Number of contacted puerulus fishers or dealers/total number</th>
<th>Estimated Proportion of all puerulus fishers (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/08</td>
<td>245/269</td>
<td>91.1</td>
</tr>
<tr>
<td>08/09</td>
<td>287/305</td>
<td>94.1</td>
</tr>
<tr>
<td>09/10</td>
<td>309/332</td>
<td>93.1</td>
</tr>
<tr>
<td>10/11</td>
<td>315/357</td>
<td>88.3</td>
</tr>
<tr>
<td>11/12</td>
<td>387/402</td>
<td>96.3</td>
</tr>
<tr>
<td>12/13</td>
<td>408/526</td>
<td>77.6</td>
</tr>
<tr>
<td>13/14</td>
<td>484/556</td>
<td>87</td>
</tr>
<tr>
<td>14/15</td>
<td>6/6</td>
<td>100</td>
</tr>
</tbody>
</table>

* top dealers of Lombok.
Java, Bali, Lombok and Sumbawa is relatively close to the Equator and therefore potentially exposed larval supply from northern and southern hemisphere breeding populations. Both *P. homarus* and *P. ornatus* display seasonal reproductive patterns with mating in spring and release of one or more batches of eggs during summer months (Jong, 1993; MacFarlane and Moore, 1986; Radhakrishnan et al., 2019). A peak in puerulus abundance in May to July corresponds with early summer reproduction and release of newly hatched phyllosoma larvae in mid-summer (around December to February) in the southern hemisphere. This accounts for the 5 to 6-month larval duration for the tropical species caught (Phillips et al., 2013; Smith et al., 2009). The secondary peak of puerulus abundance in November to December may relate to reproduction occurring in northern hemisphere stock, where breeding and release of newly hatched phyllosoma would occur around June to August. This pattern contrasts with a distinct single peak in puerulus abundance in Vietnam from November to March (Dao and Jones, 2015), which is presumably supplied from only northern hemisphere breeding populations. Further data are required on seasonality, taking into account the broad geographic spread within Indonesia and the effect this may have on timing of settlement.

Within the lobster puerulus catch, there are two dominant species, *P. homarus* and *P. ornatus*, which account for >99% of seed caught. The species composition appears to fluctuate between years: in 2012, 63.3% of seed were *P. homarus* and 36.7% *P. ornatus*, while in 2013, *P. homarus* represented 86.7% and *P. ornatus*, 13.3%. In 2014, the proportions of *P. homarus* and *P. ornatus* were 79.3% and 20.7%, respectively.

Although lobster pueruli of both *P. homarus* and *P. ornatus* were caught throughout the year, the relative proportion varied significantly from month to month as illustrated for the year 2012 (Fig. 5) and 2013 (Fig. 6).

### 3.2. Field assessment

Survey results from Java and Sumbawa, where pueruli were fished, are presented in Tables 2 and 3. A number of environmental characteristics were shared between the locations surveyed: they were all embayments protected from strong wind and waves, with the presence of rivers that resulted in low to medium turbidity. It was also evident that fishers placed their collectors in areas of similar depth from 20 to 40 m with a sandy mud substrate. However, the method of fishing varied from place to place with some fishers using modified fishing boats to deploy their collectors and others using fixed floating sea-cages. Nevertheless, the use of lights and the type of collector materials were common to all. The puerulus fishers in Banyuwangi and Tenggalek declared that they gained their knowledge of puerulus fishing methods from Lombok puerulus fishers who trained them in their home villages. The training was performed by middle persons/exporters.

### 3.3. Identification of puerulus fishing locations using Google Earth

In total, 83 main villages were identified that are likely to support lobster puerulus catch, based on macrogeographical features using satellite imaging. The number of identified locations in Sumbawa, Lombok, Bali and Java is presented in Table 4.

Of the four islands where pueruli are in high abundance (Priyambodo and Bahrawi, 2015, 2016), Java dominated with 75% of the total fishable area, followed by Sumbawa, Lombok and Bali, accounting for 16%, 5% and 4%. Java also dominated the proportion of puerulus hotspots, accounting for 70% (58 villages). This was followed by Sumbawa, Lombok and Bali, accounting for 17% (14 villages), 11% (9 villages) and 2% (2 villages). The details of each location and their...
area suitable for puerulus fishing in Sumbawa, Lombok and Bali are provided in Table 5, and for Java in Table 6.

Based on the puerulus census in Lombok, the total number of pueruli caught in 2014 was 5,243,887. The 2014 puerulus fishing season was assumed to represent maximum fishing effort for catching pueruli as it involved the highest number of fishers, puerulus catching devices and fishing locations to date. Data were collected from nine main villages where pueruli were fished. In contrast, the previous season involved only four main villages. Using Google Earth, it was estimated that the total area fished for pueruli in 2014 in Lombok was 80.94 km². Therefore, the mean catch of pueruli was calculated as 64,787 individuals per km². Extrapolating this estimate to the 83
identified locations (Tables 5 and 6) representing 1597.2 km² provides an estimate of 103,480,283 pueruli available per year. Maps showing each location described in Tables 5 and 6 are presented in Figs. 7 and 8. Additionally, more detailed maps of puerulus fishing locations in Sumbawa, Lombok, Bali and the eastern, central and western parts of Java are presented in Figs. 9 to 13, respectively. However, the present data do not include Sumatra Island where current anecdotal information suggests that a very large number of pueruli are also fished along the coasts of Lampung, Bengkulu, West Sumatra, North Sumatra, and Aceh.

4. Discussion

In the absence of commercially viable hatchery technology, spiny lobster aquaculture relies on a supply of seed lobsters from the wild. Natural settlement occurs widely throughout the distribution of the species of primary interest, P. ornatus and P. homarus. The nature of the reproduction and larval development of these species produces a dispersal pattern that generally takes these phyllosoma larvae far from the location of spawning, carried by ocean currents for up to 6 months (Phillips et al., 2013) and distances exceeding 1000 km, as the larvae progressively develop and grow until metamorphosing to the puerulus stage. Pueruli are likely to settle on all parts of the coastline within their broad distribution - so extensive is their dispersal. However, in some areas it is now evident that relatively much higher abundance occurs, aggregated by the nature of ocean and coastal currents and the puerulus behaviour, which involves directional swimming towards preferred environmental conditions (Caputi et al., 2001; Jeffs and Holland, 2000a; Phillips et al., 2013; Underwood et al., 2004). It is likely that habitat suitable for pueruli settlement is different from that suitable for both juveniles and adults. This study compiled knowledge of the environmental conditions associated with high abundance of pueruli, gathered from the puerulus fisheries of Vietnam and Lombok, and applied it more widely in Indonesia to predict where additional resources of pueruli may be found.

In Lombok, what began as a chance finding of a few pueruli settling on sea cages or seaweed farms in the early 2000s, progressively grew to a targeted puerulus fishery that evolved with increasing knowledge and skills among the Fishers. The growth was also bolstered by exposure to the advanced puerulus fishery of Vietnam, with catch rates growing per year by year until it was revealed that two relatively small bays - Ekas and Gerupuk Bays in south-east Lombok, were generating an annual catch of pueruli of > 3 million; equivalent to the entire puerulus fishery of Vietnam.

The basis for a significant lobster farming industry was provided by this one small area. However, other factors have intervened to constrain the development of the opportunity. Limited farming skills, the attractive case of selling seed as a cash crop to meet ever-growing demand from Vietnam and fisheries policy restrictions have been the most influential factors withholding further development of lobster farming in Indonesia. Nevertheless, the potential remains and has grown in magnitude as the puerulus fishery of Indonesia has expanded, beyond Lombok, where it has been revealed that the conditions that deliver the very high numbers of pueruli extend a significant distance to the east and west, providing a puerulus resource perhaps 20 times larger than that of Vietnam.

There is necessary wisdom in carefully managing the exploitation of natural resources, including those of a renewable nature such as fisheries that are cyclically replenished through annual reproduction. For tropical spiny lobsters, such resource management is complicated by the broad distribution of the species and homogeneous populations that span multiple countries and ocean regions (Dao et al., 2015). It is evident in Vietnam that the puerulus fishery is viable and has been sustained, with a relatively uniform catch over > 15 years (Anh and Jones, 2015; Anh and Jones, 2015a; Jones et al., 2010), and despite there being no resource management interventions. The puerulus fishery of Indonesia is relatively new, appears to be much larger and has a different species composition (P. ornatus pueruli are less common than P. homarus). Knowledge of the Indonesian puerulus resource's biological and physical dimensions as generated during the current study will help resource managers and policy makers to make informed decisions to most effectively manage the puerulus fishery.

4.1. Definition of Indonesia's puerulus resource

Data gathered during this study have enabled, for the first time, definition of the puerulus resource of Indonesia. Comprehensive data collected on fishery catch of pueruli from Lombok over several years has generated robust knowledge of species composition, daily catch rates, and seasonality along with an estimate of annual productivity. This, in turn, has allowed reasonable extrapolation to locations beyond Lombok where pueruli are known to be fished, but for which detailed...
Table 6
The details of puerulus locations and its area in Java Island using Google Earth.

<table>
<thead>
<tr>
<th>No</th>
<th>Village</th>
<th>Latitude Longitude</th>
<th>Area (km²)</th>
<th>No</th>
<th>Village</th>
<th>Latitude Longitude</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Brassan</td>
<td>8°28'8.11&quot;S 114°22'17.32&quot;E</td>
<td>16.00</td>
<td>55</td>
<td>Chikalong</td>
<td>7°46'43.49&quot;S 108°0'32.18&quot;E</td>
<td>43.00</td>
</tr>
<tr>
<td>27</td>
<td>Grajagan</td>
<td>8°36'51.76&quot;S 114°14'29.62&quot;E</td>
<td>72.00</td>
<td>56</td>
<td>Pelabuhan Ratu</td>
<td>6°59'51.64&quot;S 106°32'15.12&quot;E</td>
<td>9.10</td>
</tr>
<tr>
<td>28</td>
<td>Pantai Panrec</td>
<td>8°35'50.42&quot;S 114°0'5.14&quot;E</td>
<td>17.20</td>
<td>57</td>
<td>Ciletuh Bay</td>
<td>6°57'44.55&quot;S 106°13'58.36&quot;E</td>
<td>19.90</td>
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<td>8°8'3.07&quot;S 110°32'50.90&quot;E</td>
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Fig. 7. Puerulus fishing locations in Sumbawa and Lombok Islands.
4.1. Quantity

This study has provided an estimate for the total fishable resource of southern Indonesia of 103,480,283 pueruli per year and density of 64,787 pueruli per square kilometre. Without knowledge of the catch efficiency of the fishing gear used, it is not possible to accurately determine the absolute abundance of pueruli. However, it is reasonable to assume that a proportion of swimming pueruli may not encounter the fishing equipment and the catch efficiency of the gear might be relatively low. On this basis the absolute abundance may exceed several hundred million, which is complementary with estimates made for other species, such as the 600 million for *Panulirus cygnus* (Phillips, et al. 2003). Nevertheless, further investigation of absolute abundance and catch efficiency are justified to test this hypothesis.

4.1.2. Distribution

*P. homarus* and *P. ornatus* dominate the lobster puerulus captured, with relative proportions of the two varying from year to year and between locations. Overall, the ratio is approximately 80% *P. homarus* to 20% *P. ornatus*. Although other lobster species native to Indonesia are represented in the puerulus catch (*P. versicolour, P. longipes, P. penicillatus and P. polyphagus*), their absolute numbers are very low, and quantitative data were not recorded. It may be that they do not settle in the same locations as the two predominant species and/or the fishing gear used is not attractive to these species.

This study, in combination with that of others (Bahrawi et al., 2015a), confirms that settlement of pueruli is strongly correlated with specific physical environmental conditions, and does not appear to be associated with proximity to adult lobster populations. Puerulus assessment studies in Sumatra and Sulawesi demonstrated that relatively low numbers of pueruli settle in the locations examined (Idris and Bahrawi, 2015; Syafzal and Bahrawi, 2015). Similarly, in Lombok, it has been demonstrated that the west coast has a relatively low abundance of pueruli, while the south and particularly the south-east coast has very high abundance (Priyambodo and Bahrawi, 2012). It appears that two conditions must be met to render an area suitable for high puerulus abundance: presence of late-stage phyllosoma as provided by ocean and coastal currents; and local environmental conditions conducive to puerulus metamorphosis and settlement. These conditions are met along the southern coastline of Indonesia, from west Java to eastern Sumbawa. Semi-quantitative assessment of puerulus resources elsewhere in Indonesia (Bahrawi et al., 2015a) indicated that the area of high abundance was limited to the southern coast of Java, in the west, to Sumbawa in the east. However, recent anecdotal information suggests the high abundance may extend further westwards to Eastern Sumatra. In the earlier studies reported by Bahrawi et al. (2015a), puerulus catch on the southern coast of Western Sumatra was low as it was in West Timor. More comprehensive, quantitative assessment of Indonesia's puerulus resources is strongly justified.

Sufficient data were collected in this study to confirm that *P. homarus* and *P. ornatus* pueruli are most abundant in coastal environments characterised by enclosed bays with distinct currents, relatively high turbidity often attributable to nearby terrestrial inflows, and muddy/sandy substrates. The data support the hypothesis that late-stage phyllosoma along the coastal fringe are likely respond to the proximity of such environmental characteristics, metamorphosing to the puerulus stage and actively swimming towards preferred habitat, as suggested.

Fig. 8. Puerulus fishing locations in Bali and Java Islands.
for other species (Jeffs and Holland, 2000a).

4.1.3. Seasonality

The puerulus catch along the southern coastlines of Java, Bali, Lombok and Sumbawa occurs throughout the year, although with increased catch rates between March and November that may correspond with contributions from summer breeding in populations in both southern and northern hemispheres. The pueruli settling in southern Indonesia are likely to have originated from several breeding populations with spawning events likely to be spread over time. Given that larval development can range from 4 to 6 months for these tropical species (Booth, 2002; Booth and Phillips, 1994a; Dao et al., 2015; Dennis et al., 2001; Griffin, 2004) the supply of pueruli is protracted and seasonality is less distinct than in Vietnam where the supply is likely to have come solely from northern hemisphere spawning.

4.2. Sustainability of puerulus capture

The sustainability of puerulus fishing is an important consideration in the management of lobster resources in Indonesia. There may be little effect on adult populations and the associated fishery of removing the pueruli from the wild (Jones, 2018; Jones et al., 2019; Phillips et al., 2003a; Phillips et al., 2003b). Research on the Caribbean rock lobster P. argus (Lipcius et al., 1997) showed that in some locations adult abundance is low and post-larval (puerulus) abundance is high. The nature of regional and local oceanic currents plays a pivotal role in the presence of pueruli in such locations (Booth, 1979; Briones-Fourzán et al., 2008; Lipcius et al., 1997). These are termed ‘sink’ populations, because most of those pueruli will not survive or contribute to adult populations (Briones-Fourzán et al., 2008; Lipcius et al., 1997). The puerulus supply is effectively disconnected or decoupled from adult abundance. Occurrence of such sink populations of lobster pueruli is greatly enhanced by the biology of the species, particularly the long duration (4–6 months for tropical species) of the larval phase. The phyllosoma larvae are released, where they are subject to oceanic currents that physically transport them very long distances from where they were spawned (Dao et al., 2015; Dias, 1996; Griffin, 2004; Pulliam, 1988; Pulliam, 1996).

The P. homarus and P. ornatus puerulus resource of southern central Indonesia (along the southern coastline of Java, Bali, Lombok and Sumbawa) is likely to represent a sink population. In Indonesia, there is a confluence of geographic and oceanographic conditions that would likely lead to a concentration of late-stage phyllosoma larvae (particularly of P. homarus and P. ornatus) in the Java Sea generated by the pull of the Indonesian Throughflow - a powerful current running south through the strait between Bali and Lombok (Dao et al., 2015). As this current enters the Timor Sea to the south, it slows and eddies west to Java and east to Lombok and Sumbawa, where late-stage phyllosoma likely complete their development, transform into pueruli and then settle along the coastline in this region. Their concentration along this coastline appears to be far higher than elsewhere, based on semi-quantitative surveys undertaken in other Indonesian provinces (Bahrawi et al., 2015a; Idris and Bahrawi, 2015; Syafrizal and Bahrawi, 2015). In addition, there is very limited suitable natural habitat in the settlement locations to support juveniles and adults. The southern coastlines of Java, Bali, Lombok and Sumbawa are characterised by steep topography, with narrow strips of fringing reef adjacent to the coast before immediate drop off to depths unsuitable for lobster.
Consequently, the bulk of the lobster seed settling in these locations are likely to die from natural causes. Such high natural mortality of settling pueruli has been suggested for other species (Gardner et al., 2006; Herrnkind and Butler, 1994; Phillips et al., 2003a), with estimates of natural survival of lobster puerulus ranging from 1.3% to 3.0% from settlement to 1 year. The lobster seed population of southern Indonesia can accurately be described as a “sink population” as it is disconnected from the reproductive stock from which it arose (Dao et al., 2015; Jones, 2015b; Jones, 2018).

An additional factor affecting natural survival of pueruli in Indonesia is the nature of the environment where they settle. The habitat in much of the settlement area in Lombok, Java and Sumbawa is sub-optimal for adult lobsters, with highly turbid water, reduced salinity and muddy substrate; thus, survival of lobster seed there is likely to be even lower than it may be in other locations, possibly < 1%. The proposition of low pueruli survival due to habitat factors is hypothetical, but is nevertheless presented with confidence based on documented habitat data for the species involved (Dennis et al., 1997; Dennis et al., 2004; Milton et al., 2014; Phillips et al., 1983; Pitcher et al., 1997; Pitcher et al., 1992; Skewes et al., 1997a; Skewes et al., 1997b; Trendall and Bell, 1989). Additional field and laboratory studies to investigate habitat preferences of pueruli and early stage juveniles is strongly justified. The pueruli of *P. homarus* and *P. ornatus*, are likely to be quite resilient as has been documented for *J. edwardsii* (Jeffs et al., 2001a; Jeffs et al., 2005; Jeffs et al., 2002). However, their inability to feed (no functional mouthparts) and finite supply of lipids for their energy requirements, mean they will die if suitable settlement habitat is not found. The nature of such settlement habitat is conjectured. Based on the ecological studies of several other species (Booth and Phillips, 1994b; Jernakoff et al., 1993; Phillips et al., 1977; Phillips et al., 2006a) and the specific habitat preference studies for *P. ornatus* and *P. homarus* of Priyambodo et al. (2015) and Priyambodo et al. (2017), it is evident the puerulus seeks dark crevices as would be found in the leaves of algae or seagrasses. Such marine macrophytes are likely to be more abundant in the areas where pueruli are abundant – characterised as they are by elevated nutrients that would favour plant growth. Once this type of settlement habitat is found, pueruli settle, then moult to become pigmented and with the ability to feed. They presumably drop out of such macrophyte habitat to take on a benthic existence, seeking shelter within the sediment, as demonstrated by Dennis et al. (1997). While they may persist in this environment for a while, it does not represent suitable adult habitat and they must move on to seek out preferred habitat with coral or rocky reef substrate, low turbidity and full marine salinity. In the Indonesian circumstances where pueruli settle, such habitat is in limited supply within near proximity, so it is reasonable to assume mortality would be high in the absence of such habitat. Nevertheless, further research is warranted to assess the puerulus resources more quantitatively and to understand the location and movement of settled pueruli and subsequent early stage juveniles to verify the sink population hypothesis.

If the sink population hypothesis is supported, the lobster seed resource can be exploited to supply seed for farming with no significant effect on adult lobster populations (Jones, 2018). Although Milton et al. (2014) suggested a high degree of local recruitment in the south-central coast of Java, this is not inconsistent with the hypothesis of a sink, as their modelling also suggested that > 25% of recruitment to their study location was sourced remotely. It is noteworthy that Milton et al. (2014) recorded very few *P. ornatus* within the commercial catch in the
area, and yet *P. ornatus* pueruli are a significant component of the puerulus settlement in southern Java (Bahrawi et al., 2015a; Priyambodo and Bahrawi, 2015). Presumably the *P. ornatus* pueruli originated elsewhere and were transported to this location according to the Indonesian Throughflow model as suggested.

Based on the surveys of this study, the puerulus resource (of *P. homarus* and *P. ornatus*) in south-central Indonesia is particularly abundant and substantially greater than other coastal areas of Indonesia. This can be explained by a concentration of pueruli generated by the power and volume of the Indonesian Throughflow (Dao et al., 2015). There is very limited suitable adult habitat in the region where this puerulus population occurs, and on balance there is a high probability that the bulk of these pueruli perish. Their exploitation for the purposes of aquaculture is thus likely to be sustainable.

4.3. Puerulus fishery management

Indonesia’s lobster puerulus fishery originated on the island of Lombok where annual puerulus catch in 2014 was estimated at 5,243,887. At this time a burgeoning export industry was developing for the pueruli, as the Indonesian puerulus dealers became aware of the high demand from Vietnam. From 2015 to 2017 enforcement of the new fishery regulations, that prohibited the catch of pueruli, increased along with the frequency of seizure of shipments and the magnitude of penalties for offenders. Consequently, there was a decrease in puerulus fishing activity and of catch, and current catch data are uncertain. A marked increase in price from 2012 to 2013 is attributed to increased demand as export from Indonesia to Vietnam began. Although catching and trading of pueruli became illegal, the price continued to increase into 2015 with greater disparity between the species. Higher demand for *P. ornatus* saw the price increase to > 5 USD per piece, while that for *P. homarus* reached a high of 2 USD. It became evident that the catch of seed in Indonesia had continued undiminished and trade continued as a black market.

Marine aquaculture based on natural seed supply is not unique for species where the seed resources are typically abundant (Sadovy and Lau, 2002). In many parts of South-East Asia, artisanal aquaculture of mud crabs and reef fish species is largely based on wild seed supply (FAO, 2009). This applies also to spiny lobster aquaculture for which an independent hatchery supply has yet to be developed. Substantial aquaculture operations have been established for other crustaceans and fish using wild seed supply (Lucas and Southgate, 2012), although in most cases their long-term sustainability can only be assured if a hatchery supply is established. In the case of tropical spiny lobster farming, Vietnam has demonstrated that aquaculture based on a wild seed supply can be successful and sustained (Anh and Jones, 2015a; Jones, 2009; Van and Anh, 2009), and this might now be emulated in Indonesia, given the significant puerulus resource that has been identified (Priyambodo, 2015b; Priyambodo and Jones, 2015).

Because mortality of < 25% can be achieved for pueruli captured and on-grown under best practices (Jones, 2015a), aquaculture can provide a way of increasing lobster production, including potential for enhancement of natural populations. Given that the natural mortality of pueruli in Indonesia is likely to be > 99% (Jones, 2018), combining lobster grow-out of wild-caught pueruli and restocking a certain number of farmed lobsters back into the wild may provide a mutually beneficial outcome. The three management options presented below provide a quantitative example of how lobster aquaculture might
provide an economic stimulus and enhance natural populations. The calculations are based on capture of 1 million pueruli using P. homarus:

1. **Restocking only.** Translocate 1 million pueruli to a new habitat suitable for adult lobsters, with an expected 1% survival rate = 10,000 lobsters. Once on-grown, lobster fishers catch 50% of these = 5000 at 500 g = 2500 kg × 50 USD/kg = 125,000 USD, with benefits to around 25 fishers (100 kg each).

2. **Aquaculture only.** 1 million pueruli are farmed with 50% survival (500,000) to 300 g = 150,000 kg at 50 USD/kg = 7,500,000 USD, with benefits to around 1000 household farmers (150 kg each): 150 kg × 50 USD = 4500 USD for each household farmer.

3. **Combination of aquaculture and restocking.** 1 million pueruli are farmed with 50% survival (500,000) to 300 g; 10,000 of the 500,000 farmed lobsters are released into the wild. The restocked lobsters are large and robust, so their survival is likely to exceed 50%. Thus, the economic benefit will be 5000 lobsters (50% of 10,000) at 500 g = 125,000 USD of fishery lobsters plus 490,000 (500,000 less 10,000 used for restocking) farmed lobsters = 147,000 kg at 50 USD/kg = 7,350,000 USD. Thus, the combined economic benefit of farming lobsters with 1% returned to the wild is 125,000 + 7,350,000 USD = 7,475,000 USD.

Although the comparative economic benefits of options 2 and 3 are similar, option 3 has the least impact on wild adult populations, thus benefiting the environment and providing benefit to the greatest number of aquaculture and fisheries stakeholders involved. As the natural mortality of pueruli is very high (Jones, 2018; Phillips et al., 2003a; Phillips et al., 2003b), utilisation of the pueruli for the purpose of aquaculture is a viable solution to increase the production of market-size spiny lobster (Kittaka and Booth, 2000; Phillips and Matsuda, 2011). The relatively large number of pueruli available in Indonesia, as revealed in this study, presents an ideal opportunity to develop spiny lobster aquaculture. However, it will be necessary to revise fisheries regulations for this opportunity to be realised. An important consideration is determining how many pueruli can be sustainably removed from the wild.

This study has revealed that in Indonesia, more than 100 million pueruli can and are being fished in one year. It is likely that this number represents only a small proportion of the actual number of pueruli available, as the fishing equipment used is highly unlikely to catch every puerulus. Nevertheless, this 100 million pueruli figure provides a basis for consideration of how many should be allowed to be taken for aquaculture purposes. In Vietnam, a large, successful lobster farming industry has been established on an annual catch of 3 to 5 million pueruli (Anh and Jones, 2015; Dao and Jones, 2015; Jones et al., 2010; Nguyen and Dao, 2009; Van and Anh, 2009). In Indonesia, if 50% of the fishable lobster seed resource (i.e. 50 million pueruli) was permitted to be fished, this would be sufficient to support production of 12,500 t, assuming 50% survival from puerulus to harvest size of 500 g. This could provide a livelihood for > 50,000 households.

4.4. **Sustainable exploitation of puerulus for aquaculture and export**

The effect of puerulus collection on the catch of adult lobsters is projected to be insignificant based on evidence that as few as 0.9–3% of settling pueruli or less survive to recruit into the fishery (Phillips et al., 2003a; Phillips et al., 2003b). Jones (2018) suggested that spawning
populations of *P. ornatus* and *P. homarus* in Indonesia are likely not to be supported by the puerulus resources of the central south coast of Indonesia, and the low natural abundance of adults in the locality of puerulus populations in Lombok suggests natural survival to adulthood is very low, estimated to be $< 0.01\%$. Therefore, for example, if the 5.2 million pueruli caught each year in Lombok (Fig. 2) were not fished, fewer than 0.01\% would survive into adult stage, representing $< 520$ individuals and 262 kg at 500 g. By allowing fishing and their stocking into managed grow-out in sea-cages, and assuming an average of 70\% survival (as achieved in Vietnam), 1750 t of lobster could be produced at an average weight of 500 g, worth $87.5$ million USD and assisting many thousands of Indonesian smallholders.

This study has provided a quantitative estimate of 100 million pueruli being fished each year across the recognised area of high abundance from West Java to East Sumbawa. The economic development opportunity, consequently, is very large in terms of both a regulated puerulus fishery and a lobster grow-out industry. As an example, 50 million pueruli fished and exported would provide economic benefit to fishers valued at $USD 77$ million, based on reported pricing and relative proportions for the two species, and growout of 50 million pueruli, based on the scenario presented above, would generate 12,500 t of marketable lobsters with a value of $USD 875$ million (at an average market price of $70$ kg$^{-1}$). The combined value is $USD 952$ million, and the benefit flowing to many thousands of households. Such an economic benefit is worthy of consideration by the Government of Indonesia, to revise the current fisheries regulations and develop policies that enable establishment of a sustainable lobster seed fishery and aquaculture industry.

In contrast, and assuming the veracity of the proposed 0.01\% survival of pueruli in the designated area discussed here, 100 million pueruli left unfished would generate approximately 50,000 kg of market size lobster (average of 500 g each), with a value of $USD 3.5$ million.

The optimal policy and regulatory framework will comprise a regulated puerulus fishery and sanctioned and supported lobster farming, in combination with a stock enhancement program that provides a proportion of the farmed lobsters for restocking to identified suitable adult habitats. This will ensure greater sustainability of wild adult stocks, and the fisheries that rely on them, and foundation for a high value lobster seed fishery and lobster aquaculture industry. The Indonesian Ministry for Marine Affairs and Fisheries has the resources and capacity to implement this strategy, including on-going monitoring and evaluation to ensure sustainability and maximum positive impact. The strategy should include a comprehensive assessment of the lobster seed resources, to verify the findings of this study, a research for development program to define best practice lobster farming technology including effective extension to build capacity of farmers, and identification of suitable sites for the stock enhancement program.

Although the greatest economic benefit from each puerulus is through on-growing in aquaculture systems, the lure of immediate cash flow from puerulus fishing for export is sufficiently strong among the poor fisher communities, that prohibition is unlikely to be effective. A regulated fishery however, may be acceptable to the fishers and a practical way to ensure compliance, while ensuring that a significant proportion of the fished seed are retained in Indonesia for farming and restocking, to achieve even greater economic, social and environmental benefits. Under the current policy and regulatory settings, Indonesia is missing a significant opportunity, while surrounding countries (in
particular Vietnam, Singapore and Malaysia) gain the benefit from the lobster seed exported. The Government of Indonesia might consider a revision of fisheries policy to establish a regulatory and support framework that will allow the recognised benefits to be realised. Within 5 to 10 years, it is feasible that Indonesia could have the world’s largest and most sustainable lobster aquaculture industry.

4.5. Policy recommendations

To best achieve a viable and sustainable lobster aquaculture industry, Indonesia should establish a policy and regulatory framework that sustains existing adult lobster populations, protects and where possible enhances adult lobster habitats, and enables harvesting of puerulus resources for the purpose of farming them to marketable size. Such a framework may consider inclusion of the following:

- marine protected areas throughout the country to conserve breeding populations of lobsters
- habitat protection through banning of destructive fishing techniques (explosives and cyanide)
- habitat enhancement through strategic placement of artificial lobster habitats
- minimum size regulations that are specific to each lobster species to allow them to mature and breed at least once before capture
- a regulated puerulus fishery that allows pueruli to be captured with management protocols to ensure sustainability
- Government sanctioned and supported lobster aquaculture as a priority industry for development
- Stock enhancement of lobster populations through stocking of a small proportion of on-grown larvae from the farming sector
- Investment and collaboration in research for development of best practice lobster farming technology, including manufactured diets
- Strategies to attract corporate investment in lobster farming to provide the capital and expertise that will engage coastal communities to farm lobsters

Such a strategic approach will ensure efficient, effective and sustainable lobster grow-out technology in Indonesia that will be globally competitive. This will create more domestic demand for pueruli as the seed for farming, where the greatest economic and social benefits will accrue. This may be balanced however, with regulated export of pueruli to meet the already high demand from other countries, such as Vietnam. As such, local grow-out and pueruli export industries could co-exist. Adding to this, will be a strategy to allocate a proportion of on-grown larvae stocks to stock enhancement.

The research of Priyambodo et al. (2015); Priyambodo et al. (2017) demonstrated a distinct lunar periodicity to puerulus catch with relatively low catch during periods of full moon and significantly higher catch during the dark period of the new moon. This was attributed to the positive phototaxis of the pueruli, that is harnessed in the fishery by using lights on the habitat traps to attract the swimming pueruli. During periods of full moon, the light source on the fishing device is far less effective, as the moon light is broadcast, diminishing the effect of a point source of light on the fishing equipment. It is likely the pueruli are no less abundant during full moon, but significantly more difficult to catch. This presents a management strategy that would suit the Indonesian circumstance, where adherence to fisheries regulations is low and policing is very limited.

By permitting puerulus fishing for 2 weeks in each month around the time of the new moon, catch rates will be maximised, benefiting the fishers. Prohibiting puerulus fishing for 2 weeks around full moon allows the seed to seek out settlement habitat with impunity. Thus, a significant number of seed presenting to the coastline in any given month would be available to natural settlement and recruitment processes. Further investigations of absolute abundance of puerulus through the lunar cycle, to substantiate the basis of this management intervention are strongly justified. Pigmented post-puerulus juveniles are rarely found in collectors, so it is safe to assume that pueruli do not reside in habitats for more than a few days. Rather, having settled in the habitat provided by the collector, they moult to the first, pigmented, post-puerulus, juvenile stage and then drop out of the collectors to adopt a benthic existence. Such a short-term, temporal management approach, rather than seasonal or spatial closures, would provide maximum benefit to fishers while protecting the puerulus resource.

5. Conclusions

Indonesia has a puerulus resource exceeding 100 million pueruli per year, which is 20 times greater than that of Vietnam where a large and stable lobster farming industry based on its own puerulus resource is established. Indonesia’s puerulus resource is dominated by *P. homarus* with around 20% *P. ornatus*.

The high abundance of pueruli is now confirmed for the area of coastline along the southern perimeter of Java, Bali, Lombok and Sumbawa and is likely generated by prevailing ocean and coastal currents, particularly the Indonesian Throughflow, and suitable settlement habitats. Indonesia has a strong opportunity to sustainably harvest its puerulus resource to support a large lobster farming industry, with benefits to many thousands of coastal communities.

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.

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