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RESEARCH PAPER — OPEN ACCESS

Redclaw crayfish (*Cherax quadricarinatus*): spatial distribution and dispersal pattern in Java, Indonesia

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Abstract – *Cherax quadricarinatus* is a parastacid crayfish native to parts of north-eastern Australia and southern New Guinea. It is a relatively large and highly fecund species in comparison with other crayfish of this genus. Since *C. quadricarinatus* was previously assessed as an invasive species in Indonesia, further monitoring of this species in this region was recommended. Detailed understanding of its spatial behaviour can be the basis for further research aimed at improved management. Field sampling was performed outside its native range in Java, Indonesia from 2019–2020, resulting in data useful for modelling the species' spatial distribution. The occurrence of the species was confirmed in 66 of 70 surveyed localities with 51 new records for Indonesia. Future investigations focused on the relationship between the spatial distribution and dispersal pattern of *C. quadricarinatus* and its interactions with native biota and entire ecosystems were recommended.

Keywords: Biogeography / freshwater / invasive species / non-native species / Parastacidae / Southeast Asia

Résumé – L'écrevisse à pinces rouges (Cherax quadricarinatus): Distribution spatiale et schéma de dispersion à Java, Indonésie. *Cherax quadricarinatus* est une écrevisse parastacide originaire de certaines parties du nord-est de l'Australie et du sud de la Nouvelle-Guinée. C'est une espèce relativement grande et très féconde par rapport aux autres écrevisses de ce genre. Comme *C. quadricarinatus* a été précédemment évaluée comme une espèce envahissante en Indonésie, il est recommandé de suivre la surveillance de cette espèce dans cette région. Une compréhension détaillée de son comportement spatial peut servir de base à de nouvelles recherches visant à améliorer la gestion. Un échantillonnage de terrain a été effectué en dehors de son aire de répartition d'origine à Java, en Indonésie, de 2019 à 2020, ce qui a permis d'obtenir des données utiles pour modéliser la distribution spatiale de l'espèce. La présence de l'espèce a été confirmée dans 66 des 70 localités étudiées, avec 51 nouveaux enregistrements pour l'Indonésie. Des enquêtes futures axées sur la relation entre la distribution spatiale et le modèle de dispersion de *C. quadricarinatus* et ses interactions avec le biote indigène et les écosystèmes entiers ont été recommandées.

Mots clés : Biogéographie / eau douce / espèces envahissantes / espèces non indigènes / Parastacidae / Asie du Sud-Est

1 Introduction

Invasive species cause environmental and socio-economic losses throughout the world (Pimentel, 2011). In Indonesia also, several invasive species are known to pose serious threats to native biota and have profound impacts on the entire ecosystem via suppressed growth, non-native pathogen transmission, habitat alteration, competition, hybridization, and predation on native species (Torchin *et al.*, 2003; Peeler and Taylor, 2011; Strauss *et al.*, 2012).

The spread of invasive species has recently increased in aquatic ecosystems in Indonesia, both of vertebrates

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(Muchlisin, 2012; Marková *et al.*, 2020; Patoka *et al.*, 2020) and invertebrates (Marwoto *et al.*, 2018; Putra *et al.*, 2018). The increase in invasive species can sometimes be economically beneficial, but it is also necessary to consider and predict the impact of the introductions on aquatic ecosystems (Yonvitner *et al.*, 2020). The existence of non-native species complicates the management of aquatic species stocks and biodiversity conservation in invaded waters also because the current legislative regulations are ineffective in many cases (Patoka *et al.*, 2018a).

Introductions of non-native species are commonly perceived from both intercontinental and international perspectives but especially in island countries, the regional scale may be important (Lenzner *et al.*, 2020). Redclaw crayfish *Cherax quadricarinatus* (Decapoda: Astacidea: Parastacidae) is a known successful invasive species especially in tropical regions across the world (Haubrock *et al.*, 2021 and citations herein) and it has spread also within the Indonesian territory out of its native range (Patoka *et al.*, 2018b). This species is native to north-eastern Australia and southern New Guinea. Although the western part of New Guinea belongs to Indonesian territory, the species has to be perceived intranationally as non-native in the rest of the country (Bláha *et al.*, 2016). The purpose of new introductions of *C. quadricarinatus* is usually related to its economic value for human consumption and ornamental trade (Negara, 2012; Haubrock *et al.*, 2021). Both purposes were previously recorded also in Indonesia (Patoka *et al.*, 2018b).

In comparison with other members of this genus (Weiperth *et al.*, 2020), *C. quadricarinatus* is highly adaptable to various water quality parameters such as different levels of oxygen, ammonia, hardness, alkalinity, and pH (Rouse *et al.*, 1991). This crayfish is able to live in waters with water temperatures ranging from 10 to 31 °C (Haubrock *et al.*, 2021).

Since Indonesia has been identified as the leading exporter of ornamental crayfish globally (Patoka *et al.*, 2015), and *C. quadricarinatus* is one of the most popular pet-traded species (Kotovska *et al.*, 2016; Vodovsky *et al.*, 2017), the further intentional spread of this species in the country is expected. Another invasive and also popular ornamental crayfish found established in Indonesia, the North American red swamp crayfish *Procambarus clarkii*, is classified as being much more harmful than *C. quadricarinatus*. Nevertheless, the latter is also perceived as a risky species potentially negatively impacting the native Indonesian biota (Patoka *et al.*, 2016; Putra *et al.*, 2018).

Mitigation efforts need to be based on investigating the distribution of invasive species in the landscape (Glen *et al.*, 2013; Padalia *et al.*, 2014). These efforts form the basis for the preparation of mitigation and eradication plans, knowing distribution patterns, and protection of native species biodiversity from non-native threats (Molnar *et al.*, 2008). Research related to the spatial distribution and dispersal patterns of invasive species in Indonesia in general and of invasive crayfish in particular has not been widely carried out. Since crayfish are transported across the majority of Java via various routes and in huge quantities, we have updated the data about the distribution of *C. quadricarinatus* in this Indonesian island.

2 Materials and methods

2.1 Study area

The research was conducted in freshwaters on the island of Java, Indonesia, by field surveys. The selection of locations was carried out after considering the local aquatic conditions, with a special focus on streams, lakes, and reservoirs. In total, 70 locations (47 natural lakes and streams, 23 artificial ponds and reservoirs) were selected and sampled. Crayfish were collected from each of the surveyed locations when they occurred there. In the initial stage, the current status of the recorded populations was evaluated and their spatial distribution was determined.

2.2 Data collection

Data were collected during the whole season between August 2019 and August 2020. Crayfish were captured during a one-night sampling session at each selected locality using bamboo and/or foldable net traps baited with fish and gastropod meat. The types of data collected were biological, ecological, socio-economic and community data. Temporal information was also needed as a follow-up step from the results of spatial analysis in different periods to obtain dynamic patterns of spatial change. For each site, all collected crayfish specimens were preserved in 70% ethanol for later laboratory identification. Relative abundance was recorded for each locality. All voucher specimens were deposited in the Fisheries Biology Laboratory, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, IPB University in Bogor, Indonesia. The species was identified based on morphological characteristics suggested by von Martens (1868), Holthius (1949), Souty-Grosset *et al.* (2006), and Haubrock *et al.* (2021).

2.3 Data analysis

Data processing software used was QGIS Standalone version 3.16.0-Hannover (64 bit). Several aspects need to be considered in making a database design, including (a) describing the object; (b) analyzing the available data; (c) physical design; (d) linking spatial data with the database; and (e) implementation. Results of the distribution survey and statistical analysis were compared with range-wide distribution records of the species to determine possible relationships among distributions. The morphological parameter measurements included: ocular carapace length, chela length, propodal membrane length, dactyl length, chela width, cephalon width, thorax width, carapace depth, total carapace length, abdominal length, telson length, telson width, abdominal width, uropod length, cheliped (1st pereiopod) length, 2nd-5th pereiopod lengths, weight, and rostral spine count. Morphological parameter measurements were used for strain comparison. All linear measurements were made with vernier calipers (accuracy 0.1 mm) to nearest mm. Weight was measured on an Adam CB-1001 1,000 g/0.01 g digital electronic weight scale to nearest gram. Abnormal deformations such as bifid or curved rostrum (Yuliana *et al.*, 2019) and regenerated claws were excluded from the morphological analysis. The Kruskal Wallis method was used to determine significant morphometric

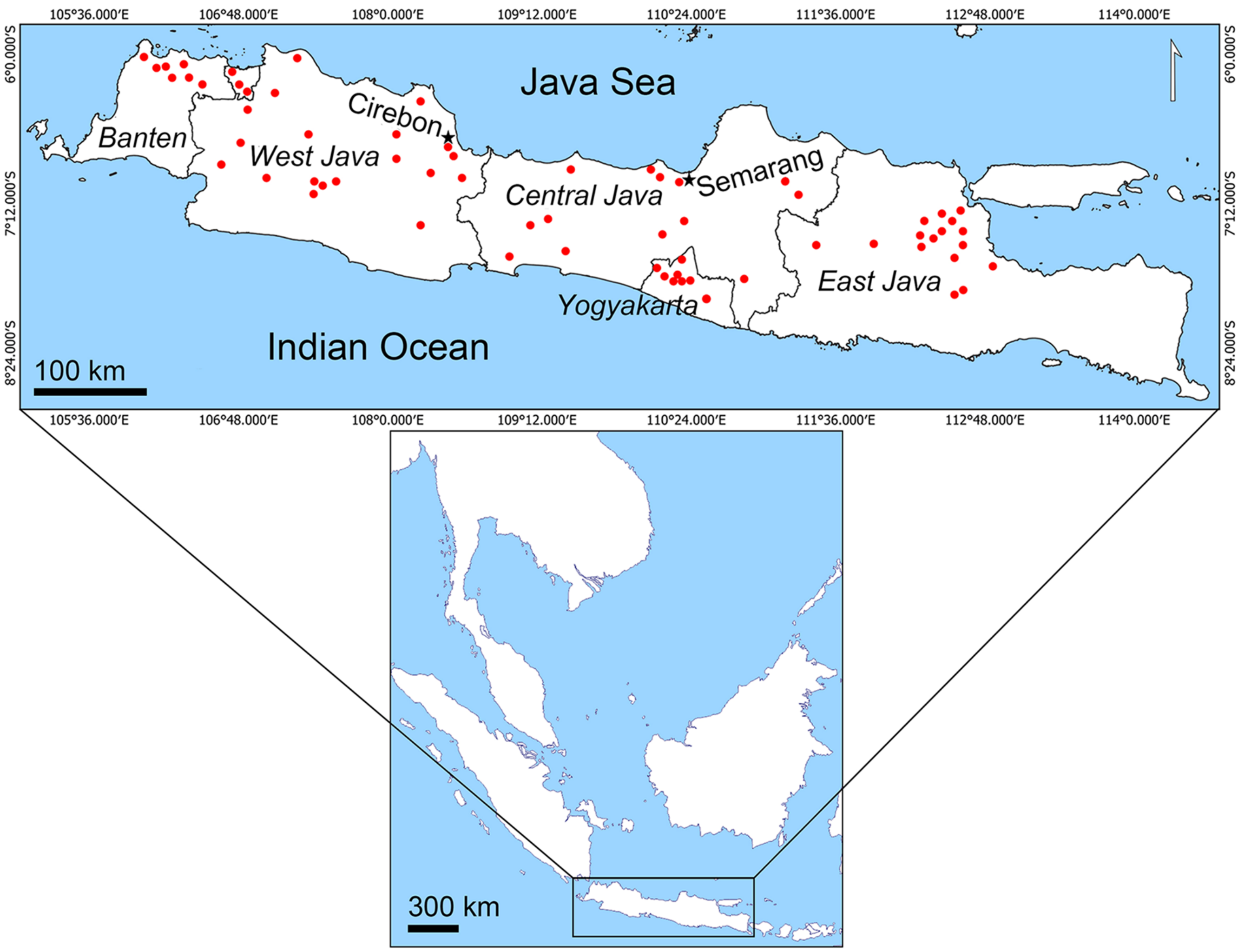

Fig. 1. The current distribution of *Cherax quadricarinatus* in Java island. The red dots indicate the established populations. Name of provinces are italicized while source regions are indicated by an asterisk, except for Yogyakarta which is the name of the province and also of a source region.

differences between the *C. quadricarinatus* groups at their source regions. Discriminant analysis was used to determine population groupings based on different locations. The software used for discriminant analysis was the IBM SPSS Statistics for Windows, Version 23.0. Armonk.

3 Results

Cherax quadricarinatus was found to occur at 66 of 70 sampled locations (43 natural and 23 artificial, Tab. S1). Its scattered distribution in several regions on Java island is presented in Figure 1. A reproducing population was found in each locality where *C. quadricarinatus* occurred. Most of them were being cultured in ponds and tanks for ornamental purposes and some of them also for human consumption. All populations found in the wild originated from one of the three following source regions: Cirebon, Semarang, and Yogyakarta (Tab. 1). The total body length range was 52.88–139.77 mm (mean = 103.06 mm; N = 17) in Cirebon, 69.74–177.58 mm

Table 1. Results of global positioning system measurements of wild *Cherax quadricarinatus* populations in three Javanese source regions: Cirebon, Semarang, and Yogyakarta.

Region	GPS		Habitat type
	Latitude	Longitude	
Cirebon	−6.879271	108.578073	Lake
Cirebon	−6.784961	108.567211	Lake
Cirebon	−6.734638	108.564482	River
Semarang	−7.285690	110.435825	Lake
Semarang	−7.254928	110.458398	River
Yogyakarta	−7.786604	110.381592	Reservoir
Yogyakarta	−7.754888	110.413565	Reservoir
Yogyakarta	−7.788148	110.296371	Reservoir
Yogyakarta	−7.749287	110.489223	River
Yogyakarta	−7.824455	110.123569	Reservoir

Table 2. The significantly different morphological characters of *Cherax quadricarinatus* populations in Java.

Morphological parameter (length = mm; weight = g)	Average ratio				
	Cirebon	Semarang	Yogyakarta	df	*p*-Value
Ocular carapace length	0.7615 ± 0.0253	0.8120 ± 0.0292	0.7966 ± 0.0587	2	0.0030
Dactyl length	0.3156 ± 0.0333	1.0031 ± 0.2112	0.3220 ± 0.0349	2	<0.0001
Chela length	0.2135 ± 0.0580	0.8867 ± 0.2749	0.1937 ± 0.0388	2	<0.0001
Cephalon width	0.3697 ± 0.0103	0.9255 ± 0.1163	0.3929 ± 0.0172	2	<0.0001
Thorax width	0.4360 ± 0.0166	1.2035 ± 0.2154	0.4457 ± 0.0237	2	<0.0001
Telson length	0.3197 ± 0.0213	0.3282 ± 0.0188	0.3381 ± 0.0186	2	0.0030
Telson width	0.2471 ± 0.0185	0.2430 ± 0.0124	0.2227 ± 0.0222	2	<0.0001
Uropod length	0.3828 ± 0.0278	0.3933 ± 0.0202	0.4083 ± 0.0296	2	<0.0001
2nd pereiopod length	0.8185 ± 0.0622	0.8410 ± 0.0672	0.7962 ± 0.0443	2	0.0040
3rd pereiopod length	1.0240 ± 0.0881	1.0583 ± 0.0671	0.9994 ± 0.0647	2	0.0010
4th pereiopod length	0.9171 ± 0.0449	0.9511 ± 0.0668	0.9051 ± 0.0461	2	0.0010
5th pereiopod length	0.8233 ± 0.0583	0.8587 ± 0.0648	0.8154 ± 0.0519	2	0.0020

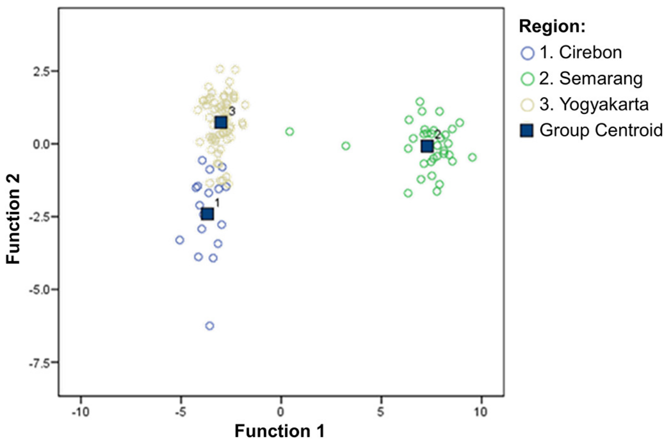

Fig. 2. Discriminant result grouping of *Cherax quadricarinatus* on standard morphological measures. The discriminant analysis serves to show clear groupings characterized by differences in the centroid position. The analysis showed significant differences among groups in Cirebon (1), Semarang (2), and Yogyakarta (3).

(mean = 110.38 mm; N = 33) in Semarang, and 66.97–144.6 mm (mean = 89.23 mm; N = 59) in Yogyakarta. *Cherax quadricarinatus* locality tracing was based on pathways in Java. We found the *C. quadricarinatus* being commonly traded as a popular ornamental creature in Java.

Based on the discriminant function in statistical analysis, the results of grouping *C. quadricarinatus* on standard measurements indicated three groups marked by differences in the centroid location (Fig. 2). Individuals in each population from mainland waters in Cirebon, Semarang and Yogyakarta were grouped appropriately at 88.24%, 96.97%, and 91.53% respectively. Discriminant analysis was carried out to see the closeness of the correlation based on the similarity of certain crayfish body sizes. Morphometric characters that had the same values indicated a mix of measured populations from one population to another. Discriminant analysis from standard morphometric methods showed that the populations of *C. quadricarinatus* in the three localities differed significantly. Significantly different morphological characters were the following: chela length, cephalon width, dactyl length, ocular carapace length, telson length, telson width, thorax length, uropod length, 2nd pereiopod length, 3nd pereiopod length, 4rd pereiopod length and 5th pereiopod length (Tab. 2).

4 Discussion

In total, we found *C. quadricarinatus* to be well-established in 66 localities in Java, Indonesia, with 51 new records of the species on this island in addition to previous records reported by Patoka *et al.* (2018b). As suggested previously, climatic conditions in Java are suitable for its establishment (Patoka *et al.*, 2016) and the largest populations were found in Cirebon, Semarang, and Yogyakarta. The encounter points are in line with the pathways of ornamental and thus *C. quadricarinatus* can probably inhabit many different streams, reservoirs, lakes, and other inland freshwater bodies in Java.

Discriminant analysis showed that populations of *C. quadricarinatus* found in Cirebon, Semarang, and Yogyakarta are significantly different. Different environmental conditions lead to adaptations that are marked by differences in morphological characters (Webster, 2007). Variations in morphological characters occur as an adaptation response to environmental conditions (Patoka *et al.*, 2017). Such variation could be caused by differences related to altitude (Cirebon: from 0 to 300 masl; Semarang: from 0 to 1500 masl; Yogyakarta: from 0 to 450 masl) or to local environmental conditions (Snovsky and Galil, 2011; Fahri *et al.*, 2013; Darmansyah *et al.*, 2014; Vitasurya, 2016).

The occurrence of a non-indigenous crayfish population in any ecosystem worldwide needs to be managed properly so that it can be utilized optimally and appropriately and does not negatively interfere with other crustaceans and native species in general. This point is crucial and is often not easy to follow up in many species and many regions. *Cherax quadricarinatus* has a high environmental tolerance, is easy to sell alive and ship worldwide, demand is relatively high and the market is wide open (Wu *et al.*, 2018; Ghanawi *et al.*, 2019; Lin *et al.*, 2020). This crayfish is very popular in the aquaculture industry because it has good resistance, adaptability to various food types, and is fast growing (Vodovsky *et al.*, 2017). Indonesia is one of the countries that have carried out a lot of *C. quadricarinatus* cultivation. This species is cultivated there both in natural and artificial waters such as lakes, reservoirs, ponds, indoor tanks and aquaria, and traded both locally and exported abroad (Patoka *et al.*, 2018b).

Given both the positive and negative aspects related to *C. quadricarinatus* culture in Indonesia, it is necessary to educate the general public. Control measures that can be taken to reduce or mitigate the unwanted feral populations of *C. quadricarinatus* released into public waters can be implemented through economic uses, such as consumption and sales. However, when management is carried out the most important thing is to avoid release of the captured crayfish elsewhere (Patoka *et al.*, 2018a). This must be a major concern because these freshwater crayfish also jeopardize the environment. For example, by reducing biomass of aquatic plants, crayfish reduce the availability of shelters for macroinvertebrates and fishes (James *et al.*, 2015). *Cherax quadricarinatus* can also negatively affect native species, through direct competition, predation, or habitat modification, and may host parasites previously absent in native populations (Haubrock *et al.*, 2021). For instance, various species of bacteria are known to infect *C. quadricarinatus* (Hayakijkosol *et al.*, 2017).

In line with previous records (Patoka *et al.*, 2016, 2018b), it is obvious that spread of *C. quadricarinatus* is increasing at least in Java. Regarding related risks in Indonesia, *C. quadricarinatus* should be cultured strictly in isolated systems. Feral populations of this crayfish can be also controlled through increasing the exploitation rate for human consumption. On the other hand, the increasing demand can cause an unwanted future spread of *C. quadricarinatus* in the region, and hence the directed education of the general public is crucial in this regard. Future investigations focused on relationships between the spatial distribution and dispersal pattern of *C. quadricarinatus* and its interactions with native biota and entire ecosystems are recommended. Also, the further detailed monitoring of introduced species including crayfish in Indonesian waters is strongly recommended.

Supplementary Material

Table S1. The full record list of Cherax quadricarinatus populations recorded in Java, Indonesia: name of the region, GPS, type of the habitat: natural (lakes, streams) or artificial (ponds, reservoirs).

The Supplementary Material is available at https://www.kmae-journal.org/10.1051/kmae/2021015/olm.

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