**CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE**
**Faculty of Agrobiology, Food and Natural Resources**
**Department of Zoology and Fisheries**

**DOCTORAL DISSERTATION**

**2023** **Surya Gentha Akmal**

**CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE**
**Faculty of Agrobiology, Food and Natural Resources**
**Department of Zoology and Fisheries**

# Aquatic Invasive Species and Related Impacts on Native Biota in Indonesia

--------------------------------------------------------

Doctoral Dissertation

Author : **Surya Gentha Akmal, M.Sc.**

Supervisor: **doc. Ing. Jiří Patoka, Ph.D., DiS.**
Česká zemědělská univerzita v Praze

**Prague 2023**

I hereby declare that I have written this Doctoral Dissertation with the title "*Aquatic Invasive Species and Related Impacts on Native Biota in Indonesia*" using results of my own work or collaborative work of me and colleagues, and with help of other publication resources which are properly cited and it was prepared under the supervision of doc. Ing. Jiří Patoka, Ph.D., DiS.

I agree with publishing this Doctoral Dissertation according to Czech law 111/1998 Sb. about the universities in its current valid wording. This agreement is independent from the results of defense.

June 27th, 2023, Prague ______________________

# Acknowledgments

I humbly express my gratitude to the honorable Rector of ČZU, prof. Ing. Petr Sklenička, CSc., and to the former Dean of the Faculty of Agrobiology, Food and Natural Resources, and also as Head of Department of Zoology and Fisheries, prof. Ing. Iva Langrová, CSc., for giving me the opportunity to complete my dissertation and for availing me of all the requirements. I would like to express my sincere gratitude to my supervisor, doc. Ing. Jiří Patoka, Ph.D., DiS., for accepting me as his doctoral student and allowing me to pursue this doctoral program, for his constant support, guidance, and freedom throughout my research. His continuous support and knowledgeable guidance helped me to give my first steps as a scientist, and his genuine interest and esteem in our discussions enriched me with many everlasting lessons. Last but not least, I would also like to thank my family for their support throughout my studies.

Then I am also very grateful and thankful for the financial support from the Department, the Faculty and the University so that I can be well focused on completing my PhD studies. Then for the financial support from the European Regional Development Fund – Project "Centre for the investigation of synthesis and transformation of nutritional substances in the food chain in interaction with potentially harmful substances of anthropogenic origin: comprehensive assessment of soil contamination risks for the quality of agricultural products" (number CZ.02.1.01/0.0/0.0/16_019/0000845) that make our work and research activities run successfully.


**"Alam Takambang Jadi Guru"**
**[*Nature be a teacher*]**

*A philosophy that has long been one of the teachings and guidelines of the Minangkabau people. So, the definition literally means that all elements that exist in this vast nature can be used as guidelines for life and can become knowledge. All phenomena that occur in nature can be taken as lessons both in terms of philosophy and as principles that are closely related to social life.*

# SUMMARY

SURYA GENTHA AKMAL. Aquatic Invasive Species and Related Impacts on Native Biota in Indonesia. This research is under supervised by JIŘÍ PATOKA

The research on aquatic invasive species and how they are impacting Indonesian native biota has revealed the serious ramifications that the introduction of invasive species has on Indonesian freshwater and marine ecosystems. This study highlighted the escalating problems caused by invasive species, in terms of both biodiversity and the entire ecosystem.

This research has shown the aquatic invasive species introduced into Indonesian waters can successfully compete with indigenous biota for limited resources. They commonly have strong competitive advantages allowing them to spread out rapidly and occupy habitats that were previously inhabited by native species. In some cases, the invasive species can completely replace indigenous species, resulting in a dramatic decrease in biodiversity.

The research also brings to the attention the importance of invasive species control and prevention efforts. With meticulous research and monitoring efforts, it is possible for scientists to identify new invasive species entering Indonesian waters and take necessary actions to prevent their spread. The controlling of existing invasive species is also necessary to reduce their impact on native biota and ecosystems.

Overall, the study on aquatic invasive species and their impacts on Indonesian native biota highlights the significance of raising consciousness and protecting the biodiversity of Indonesian waters. The conservation, surveillance and controlling of invasive species should be improved to protect indigenous species and ensure the ecosystem balance in Indonesian waters.

# TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.1 Background

The introduction of aquatic invasive species is the starting point for the main cause of biodiversity loss (Williams-Subiza and Epele, 2021). Invasive alien species whose presence and spread are environmentally, economically, and human health damaging (Akmal et al., 2021; Pimentel, 2011; Williams-Subiza and Epele, 2021). Indonesia is rich in biodiversity, Wallace noticed a sharp divide in the distribution of animals in the Indonesian archipelago (Fig. 1) (Brewer, 2022). Based on data from the Ministry of Maritime Affairs and Fisheries, there are at least 4,720 species of both marine and freshwater fish in Indonesia.

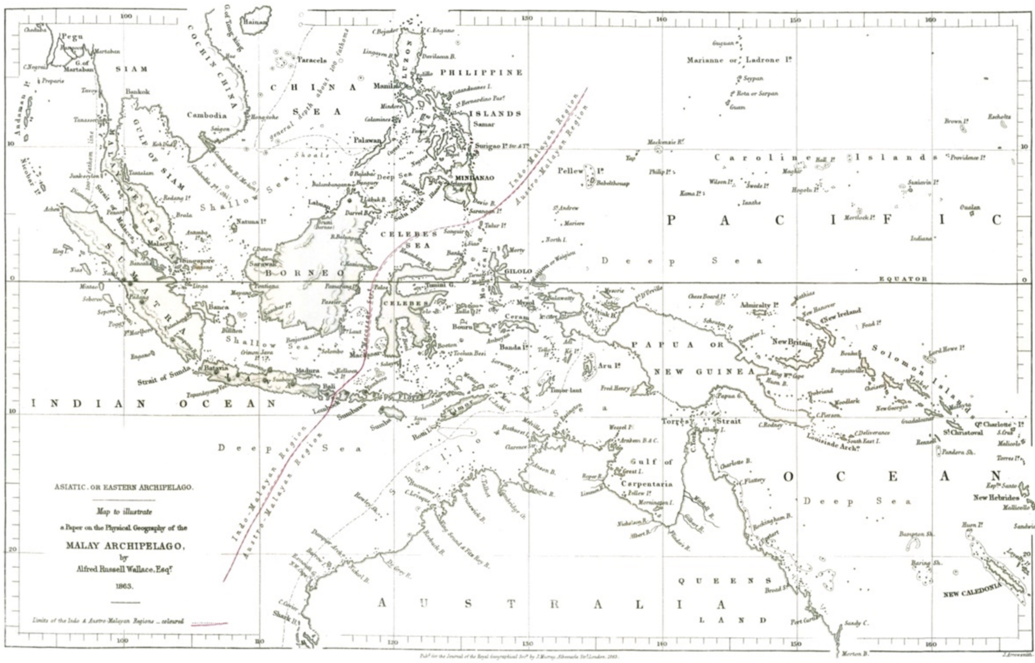


Figure 1 The original drawing of the Wallace Line; the division between Asian and Australasian animals and plants (Brewer, 2022).

Aquatic ecosystems in Indonesia are adaptive for both native and non-native organisms (Patoka et al., 2016b). Invasive species are known to have serious impacts on biodiversity (McNeely, 2001). Naturally, the movement of organisms is isolated by nature thus forming a unique diversity. Natural isolation in the form of oceans, rivers, deserts and mountains limits the distribution of organisms in ecosystem areas. International trade and the global movement of livestock, wildlife and animal products are enormous and cross the natural borders (Fèvre et al., 2006).

Thus, the increased risk of biological invasion is a consequence of globalization (Meyerson and Mooney, 2007). Several invasive species are known to pose serious threats to native biota and have profound impacts on entire ecosystem via suppressed growth, pathogen transmission, competition, hybridization, habitat alteration, and prey on native species (Peeler and Taylor, 2011; Strauss et al., 2012; Torchin et al., 2003).

Invasive species cause environmental and socio-economic losses throughout the world (Pimentel, 2011). The spread of invasive species has recently increased in aquatic ecosystems in Indonesia both in vertebrates (Marková et al., 2020; Muchlisin, 2012; 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 introduction on aquatic ecosystems (Yonvitner et al., 2020a). The existence of new species complicate the management of fish stocks and biodiversity conservation in invaded waters also because the current legislative regulations are ineffective in many cases (Patoka et al., 2018).The decline in freshwater biodiversity due to species invasion is one form of ecological losses. Early prevention can be done by monitoring the spread of alien species so that their invasion can be controlled in the environment. Early and accurate detection is an effective strategy to control the ecological impacts of species that enter (Mehta et al., 2007).

## 1.2 Research objectives and scientific hypotheses

The primary objective of this research was to describe alternatives to management to mitigate the effects of non-native invasive species, including preventive, control, and eradication strategies as well as taking socioeconomic effects into account for each management strategy. Thus, it can provide recommendations for policy development and management actions that are effective and sustainable, including monitoring, research, and public education. To achieve these main objectives, there are several steps of research that need to be carried out and become the specific objectives of this research, i.e.:

a. To determine the invasive species present in Indonesian aquatic environments and evaluate the likelihood of their spread.

b. To assess the impact of invasive species on native biota, including alterations to community structure, ecosystem function, and natural characteristics.
c. To evaluate factors affecting species invasions and their impacts, such as environmental conditions, biological characteristics of invasive species, and interactions with other species.

The hypotheses used in this research are:

$H_0$ = The number of invasive species in Indonesia is not increasing.

$H_1$ = The number of invasive species in Indonesia is increasing.

$H_2$ = Education of general public in case of risks related to release of non-native species is poor.

### 1.3 Benefit of research

The purpose of this research is to provide the following advantages:

a. To know about the types of invasive species and their impact on native biota in certain waters so that effective and appropriate control efforts can be implemented.
b. To increase the understanding on species invasion process and the factors that contribute to it, so more effective strategies for prevention can be improved.
c. To provide useful information regarding cost-effective and sustainable management approaches to mitigate the consequences of non-native invasive species, which can help to minimize both economical and ecological losses.
d. To increase the community's awareness regarding the importance of protecting biodiversity and healthy aquatic ecosystems.
e. To provide advice and recommendations for policy development and better management actions regarding the mitigation of invasive species and the conservation of indigenous biota.
f. To expand insights and scientific knowledge on species invasions and their impacts on aquatic ecosystems, which can be the basis for further

investigations and developing innovative methods and technologies to manage species invasions.

## 1.4 Research framework

One of the most important ecosystems for the survival of human beings and other biota is the aquatic ecosystem. However, the waters are frequently targeted by invasive species which can negatively impact on biodiversity and ecosystem health (Alidoost Salimi et al., 2021). Aquatic Invasive Species are introduced species that originate from other ecosystems and then spread to other waters, harming the surrounding environment and affecting the indigenous biota.

The occurrence of Aquatic Invasive Species can affect aquatic ecosystems in multiple ways. They may compete with indigenous biota for resources such as nourishment and habitat, affect nutrient availability, and also introduce new diseases or parasites (Gallardo et al., 2016; Hassan and Nawchoo, 2020a; Havel et al., 2015). Consequently, the spreading of Aquatic Invasive Species may lead to a reduction in populations of native biota, decreasing biodiversity and interfering with the functionality of aquatic ecosystems (Hassan and Nawchoo, 2020a; Thomaz et al., 2015).Therefore, it is important to understand and solve the issues related to the invasion of species and their impacts on native biota in a certain water body. If we understand the varieties of Aquatic Invasive Species present in certain waters and how they might be interacting with native biota, it is possible to implement appropriate and effective management to reduce the negative consequences of Aquatic Invasive Species on aquatic ecosystems and indigenous biota (Vander Zanden and Olden, 2008).

Moreover, the importance of species invasion research is to understand the factors that impact species invasion, such as climate, geography and human activities. Through understanding these factors, it is feasible to develop more effective prevention strategies to discourage the introduction of Aquatic Invasive Species (Heilman, 2014). It will provide recommendations for policy development and effective and sustainable management actions, including monitoring, research, and public education.

# 2. LITERATURE REVIEW

## 2.1 Definition and characteristics of Aquatic Invasive Species

Aquatic invasive species is a species that introduces into a new aquatic or aquatic environment and has the possibility to spread and have negative impacts on the environment (Havel et al., 2015; Kovalenko et al., 2021a), including on the indigenous biota inhabiting it, these species can originate from different regions or countries and then spread to a new area, either by human activities or naturally occurring pathways (Baker et al., 2022; Lodge et al., 2006; Mooney and Cleland, 2001; Wilson, 2010).

The general characteristics of aquatic invasive species are quick and highly adaptable reproduction, and the possibility of altering the environment in which they occur through physically or biochemically modifying it, thereby inhibiting the establishment of native species and damaging ecosystems (Thomaz et al., 2015). Some characteristics which make them potentially a significant threat to the viability of aquatic ecosystems include (Rafferty, 2023):

a. Rapidly growing and reproducing species that are highly adaptable to new environments.
b. The species capable of competing with indigenous species in the same waters can replace the indigenous species and reduce biodiversity.
c. The species is capable of efficiently exploiting the resources of the water body, thus causing resource competition between the alien species and the native species in the same water body.
d. Easily dispersed species that occupy a large range of aquatic habitats, both the deepest and the shallowest, as well as exploiting a variety of substrate types throughout the waters they inhabit.

## 2.2 Habitat and environment of Aquatic Invasive Species

The increasing intensity of global trade and transportation systems has led to an increase in the introduction of non-native species in Indonesia (Nijman et al., 2022a, 2021). The introduction of non-native aquatic species is one of the activities that originated from human activities and has impacts that are not predictable (Ju et al., 2020; Tarkan et al., 2021). The development of recreational fisheries and aquaculture activities has a significant effect on the spread of alien fish (Cambray, 2003; Davis and Darling, 2017; Haubrock et al., 2022; Lauber et al., 2020; Smith et al., 2020).

Non-native species can potentially become invasive and cause ecological disasters such as extinction of native species and ecosystem imbalance (Manchester and Bullock, 2000). One of the impacts that can occur is the disruption of fish community structure and changes in ecosystem food webs (Durante et al., 2022; He et al., 2021). Biomass changes of the community structure will show the impact of alien species on the ecosystem balance (Hedianto & Purnamaningtyas 2011). The study of non-native species is part of the management of alien species. This is important because the sooner management occurs, the more easily it can be anticipated the impacts of alien species in an ecosystem (Wittenberg & Cock 2001; Koehn & MacKenzie 2004).

The impacts of invasive aquatic species can also be felt economically (Akmal et al., 2021; Cuthbert et al., 2021). They can be devastating to fishing and aquaculture industries, impair water quality, damage infrastructure such as irrigation canals or hydropower installations, and disrupt the tourism and recreation sectors associated with waterways (Lin et al., 2022). The control of invasive aquatic species is a challenging endeavor. Several methods of control include monitoring and early detection, removal of invasive species from infested habitats, use of natural predators, trapping, and selective use of chemicals (Rafferty, 2023).

Prevention is also an important aspect of invasive aquatic species control. Through strict regulations on the trade and transportation of invasive species, as well as public awareness and education campaigns, it is possible to reduce the risk of invasive species introducing into aquatic habitats (Heilman, 2014; Sulpizio, 2020). Ongoing studies and research on aquatic invasive species are important to fully comprehending their impacts, enhancing control methods, and developing effective protection strategies for aquatic ecosystems.

Cooperation between the government, research institutes, universities, businesses and communities is crucial in dealing with the problem of invasive aquatic species. It is only through concerted efforts, strict supervision, and appropriate control measures that we can protect aquatic habitats and environments from invasive species invasion and maintain the biodiversity that is essential to ecosystems and the balance of nature.

### 2.3 Impact of Aquatic Invasive Species in the ecosystem

As the trade of living aquatic products, both animals and plants, is increasingly dynamic between countries and between areas within the country, the introduction of various types of aquatic species in the destination area has proven to pose a significant threat to the sustainability of the local ecosystem (García-Berthou et al., 2005). The introduction of exotic aquatic species is generally dominated by the trade of aquatic products, ornamental fish trade, fish restocking, including the introduction and rearing of new aquatic animal species at fishing sites, which has become a worldwide trend and Indonesia is no exception (Muchlisin, 2012; Yanuarita et al., 2020). Various fishing locations that offered the sensation of hunting monster/predator fish became a new business field and stimulated people to develop the same thing in various places.

Some invasive species can be effective predators of indigenous species (Doherty et al., 2016; Rafferty, 2023). They may lack natural predators in their new environments, so they can prey on indigenous species with high success and reduced abundances and diversity of native species (Hejda et al., 2009; Mooney and Cleland, 2001). Aquatic ecosystems' habitat structure and species composition may be impacted by invasive aquatic species. As an example, they could modify the structure of aquatic plants or their density on the water's substrate (Gallardo et al., 2016; Mayfield et al., 2021). Such alterations may have an impact on both organisms that rely on specific habitat structures and biodiversity (Astegiano et al., 2015; Decena et al., 2020; Dennis, 2018; Jackson and Fahrig, 2013; Pinho et al., 2020). The movement of energy and nutrients in the ecosystem can be hampered by the introduction of invasive aquatic species into the food chain. They have the power to alter the food cycle and the structure of interdependence among organisms in the food chain (Gallardo et al., 2016; Hassan and Nawchoo, 2020b; Havel et al., 2015).

Aquatic invasive species can have a variety of negative effects on native species' the ability to reproduce and chances of surviving (Havel et al., 2015). They might feed on eggs, larvae, or juveniles, which could decrease the likelihood of the following generation surviving (Mayfield et al., 2021). Some aquatic invasive species have the potential to spread pathogens or parasites that can harm native species (Foster et al., 2021). The spread of these diseases may have a detrimental effect on the numbers of indigenous species and the stability of the ecosystem. Although invasive aquatic species are frequently seen as threats, they can fill deficiencies or add new advantages to ecosystems (Havel et al., 2015; Katsanevakis et al., 2014; Kovalenko et al., 2021b). For example, they can act as predators that help control populations of other potentially harmful organisms. Invasive aquatic species can also affect nutrient cycling in aquatic ecosystems (Vanni, 2021). They can alter the composition of nutrients in the water or change the process of decomposing organic matter (Capps and Flecker, 2013; Jo et al., 2017). This can affect water quality and affect other organisms in the ecosystem that depend on a balanced nutrient cycle.

On the other hand, aquatic invasive species can also provide a new food resource for other organisms in the ecosystem (Havel et al., 2015). Some invasive species may become abundant prey for indigenous predators or become an alternative food supply when native species are declining in population. Although rare, there is also the possibility of invasive species forming symbiotic relationships with native organisms in the ecosystem (Linders et al., 2019). This can involve a relationship of mutualism, where both species mutually benefit each other (Prior et al., 2015), or a relationship of parasitism (Yuan and Li, 2022), where the invasive species benefits and the native organisms are harmed (Drew et al., 2021). It is important to note that although aquatic invasive species can have complex roles in ecosystems, the negative impacts they have on native species and ecosystems as a whole often outweigh the benefits they provide (Havel et al., 2015; Thomaz et al., 2015). Therefore, efforts to control and prevent the invasion of invasive species are essential to protect the biodiversity and balance of aquatic ecosystems.

## 2.4 Distribution and dispersal of aquatic invasive species

Aquatic invasive species spread and dispersal refers to the way an invasive species spreads from its native habitat to a new aquatic environment (Jones et al., 2021; Sulpizio, 2020). The spread of invasive species can occur through various mechanisms and factors. One of the main factors in the spread of aquatic invasive species is human transportation (Ascensão and Capinha, 2017; Hulme, 2009; Yuliana et al., 2021). Invasive species can spread through ships, boats, or other means of transportation used to transport goods or people between waters (Hulme, 2009; Rothlisberger et al., 2010). Eggs, larvae or adults of invasive species may attach to the exterior of the vessel or transportation device and then be released into a new environment when the vessel or device is used in other waters (Rothlisberger et al., 2010). This is especially true when rivers or waterways connect different ecosystems or when floods carry invasive species from one region to another.

Environmental changes such as climate change, changes in water temperature, deterioration in water quality or changes in habitat can also affect the distribution and spread of aquatic invasive species (Sulpizio, 2020). Environmental changes can create more favorable conditions for invasive species to survive and reproduce in new environments (Hanley and Roberts, 2019; Havel et al., 2015). For example, increased water temperatures caused by climate change can allow invasive species from warmer regions to invade waters that were previously too cold for them (IUCN, 2021; NISAW, 2021).

Human activities such as the introduction of invasive species for fishing, aquarium or aquaculture purposes can also lead to the dispersal of aquatic invasive species (Giovos et al., 2019). When invasive species are introduced to new environments by humans, they can quickly spread and settle in waters that were previously inaccessible to them. The high adaptability and reproductive ability of invasive species also affect their spread. Invasive species often have the ability to adapt to a wide range of environmental conditions and have high reproductive rates (Cleeland et al., 2020; Deacon et al., 2011; Tiebre et al., 2007; Whitney and Gabler, 2008). This allows them to quickly populate and dominate the environment.

Biological control is the intentional manipulation of natural enemies by humans for the purpose of controlling pests and reducing the population of the prey. This method targets the invasive species and can involve different organisms, such as insects, mites, nematodes, and pathogens (USDA, n.d.). Introduction of biological control agents, which are usually nonindigenous themselves, is a common management response to disease or pest outbreaks. Breadth of impact of biological control agents is one of the primary criteria used to evaluate and rank the risks that control agents pose to nontarget organisms (Ewel et al., 1999).

Beginning in the mid-1980s, Indonesia introduced integrated pest management (IPM) as a new crop management approach (Thorburn, 2015; Wiyono, 2020). The Indonesian IPM program is an example of a large-scale participatory approach to the management of complex pest problems. The program is best known for introducing the innovative farmer field school model of agroecosystem-based experiential learning. IPM can be a sustainable approach to pest management, but it requires careful consideration of the ecological and economic factors involved (FAO, 2019).

It is important to note that while pest control can introduce pests, it can also be used to prevent their introduction. IPM, for example, can be used to manage pests in a sustainable way and prevent the introduction of exotic pests (Wiyono, 2020).

### 2.5 Management efforts for aquatic invasive species

In an effort to manage aquatic invasive species, prevention and control measures are essential. Prevention efforts involve strict oversight of human transportation, such as vessel inspections and effective water ballast management (Ascensão and Capinha, 2017; Giovos et al., 2019; Rothlisberger et al., 2010). Public awareness campaigns can also help prevent the spread of invasive species by increasing understanding of their negative impacts (Tricarico, 2022).

Aquatic invasive species control can involve actions such as population monitoring, culling and removal of invasive species (Giovos et al., 2019). The control methods used may vary depending on the species involved and the environment affected. A few control methods include the use of naturally occurring predators, application of insecticides and herbicides, commercial fishing, and using mechanical methods such as trimming or trapping (Kovalenko et al., 2021a; Thomaz et al., 2015).

It is important that effective management of aquatic invasive species requires cooperation between authorities, scientists, stakeholders, and the general public. Attempts made to reduce the distribution of invasive species and recover ecosystems affected by these invasions are imperative to preserve the ecological balance and sustainability of water resources.

## 2.6 Regulations and policies in Indonesia

The concern of the government in preventing the spread of invasive and harmful aquatic species has started since the 80s with the enactment of the Decree of the Minister of Agriculture No. 179/Kpts/Um/3/1982 on the Prohibition of the Import of Several Dangerous Fish Species from Abroad. In the following decade, the participation of Indonesia in the international level in terms of environmental sustainability was proven by its involvement in the ratification of the United Nations Convention on Biological Diversity in 1992 and the ratification of the convention in Law No. 5 of 1994 concerning the Ratification of the United Nation Convention of Biological Diversity.

The convention recognizes that human activities in utilizing biological resources have disrupted the balance of ecosystems in various parts of the world. Therefore, all countries are required to participate in maintaining the sustainability and preservation of global biodiversity because the conservation and sustainable use of diverse biological resources is a collective interest shared by all countries to meet the needs of food, health and other needs for the world's growing population, where access and utilization must be carried out fairly both in managing these biological genetic resources and in terms of developing technology for their utilization.

To anticipate the increasingly dynamic distribution of invasive and dangerous aquatic species, the government then issued several regulations to replace the Decree of the Minister of Agriculture No. 179/Kpts/Um/3/1982, including the Regulation of the Minister of Marine Affairs and Fisheries No. 17 of 2009 concerning the prohibition of the entry of several dangerous fish species into the territory of Indonesia. In this ministerial regulation, there are 30 species of fish both fresh and marine that are prohibited from entering the territory of the Republic of Indonesia where if these types of fish are found at the place of entry, namely seaports, river ports, airport crossing ports, post offices, border posts with other countries determined by the Minister, then destruction by fish quarantine officers is mandatory. If the dangerous aquatic species are found outside the place of entry, it is mandatory to carry out the orderly implementation of laws and regulations in the field of fisheries by fisheries inspectors.

During the implementation of Ministerial Regulation No. 17 of 2009, it was found that there were more types of aquatic animals that could potentially threaten the preservation of environmental resources so that in 2014 a revision of Ministerial Regulation No. 17 of 2009 was issued through Ministerial Regulation No. 41 of 2014 which contained a ban on the entry of 152 types of aquatic animals into the territory of Indonesia. Unfortunately, the ministerial regulation does not regulate the prohibition, procedures and rules for the traffic of dangerous fish species between areas within the territory of Indonesia so the Head of the Fish Quarantine and Inspection Agency in 2016 issued a notification letter no 1140/BKIP.2/K.140/X/2016 that in regulating the traffic of dangerous fish species to be rejected in accordance with Ministerial Regulation No. 41 of 2014 except for export activities are still allowed if they have met the requirements of the destination country.

Furthermore, in 2016, the Ministry of Environment and Forestry issued Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.94/MENLHK/SETJEN/KUM.1/12/2016 concerning Invasive Species. Considering the massive trade of invasive and dangerous fish species, especially between areas within the territory of Indonesia that are not through the entry and exit gates and the high economic value of trading these fish species so that some people are still not moved to have awareness to prevent the distribution of prohibited aquatic animals, it is necessary to remember that Law Number: 45 of 2009 concerning Amendments to Law Number: 31 of 2004 concerning Fisheries strictly regulates the prohibition of stocking aquatic species that can pose a threat to local fish resources, fish source environments, and human health.

Realizing the high threat of the spread of invasive and dangerous aquatic species through various activities of trade in live fish products and activities of utilizing exotic aquatic species for various other purposes, public participation and awareness need to be increased, one of which is through dissemination and empowerment of all stakeholders who utilize aquatic resources so that the implementation of KP Ministerial Regulation No. 41 of 2014 and Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.94 / MENLHK / SETJEN / KUM.1 / 12/2016 concerning Invasive Species can run optimally.

# 3. MATERIAL AND METHODS

Various methods were developed through conventional approaches (direct observation) and molecular approaches. The conventional approach has several weaknesses, including that it is difficult to collect, takes a long time to process, costs a lot of money, and tends to destroy the habitat (Minamoto et al., 2012; Santas et al., 2013). Therefore, other methods that are more effective and efficient are needed to validate the existence of target species, one of which is the molecular approach.

## 3.1 Study area

Indonesia, the largest archipelago in the world with no less than 13,466 named islands and about 11,000 of them inhabited, is known as one of the Mega-Biodiversity countries with a high level of endemicity (Maskun et al., 2021; Sanka et al., 2023). Due to the history of geological activity that led to the formation and dispersal of large and small islands, there was a long-standing isolation of plant and animal species (Boedhihartono, 2017; Handayani et al., 2021). The location between two continents, Asia and Australia, and between two oceans, the Pacific and the Indian, also has a significant role in the rich biodiversity of Indonesia. The western region is strongly linked to Peninsular Malaysia and Asia, known as the Sunda Shelf, while the eastern region is strongly linked to Papua and Australia, known as the Sahul Shelf. But in between is an area that is not linked to either Asia or Australia, namely Sulawesi and its surrounding islands, which have a unique and complex geological history, resulting in a very high level of endemicity in Indonesia.

As one of the ten countries with high biodiversity, Indonesia occupies an important position in the world biodiversity map. This biodiversity has a very important role for human life and the environment, including as a source of food and medicine, reservoirs, maintaining the carbon cycle and so on. In terms of endemicity, Indonesia has 20% of the 1,605 bird species (323 species) and 53% of the 720 mammal species (382 species) in the world that are found to live naturally in Indonesian territory. As an archipelago, Indonesia has no less than 95,181 $km^2$ of coastline surrounded by tropical oceans, which adds to its high level of biodiversity. Conservation International (CI) has designated Indonesia as one of the 17 "Megadiversity Countries" that has 2 of the 25 "Biodiversity Hotspots" in the world. In addition, Indonesia also has 18 of WWF's (World Wide Fund for Nature) "200 Global Eco-regions", 24 of Birdlife International's 218 "Endemic Bird Areas", and has 10% of the world's flowering plant species and is a center of biodiversity and animal husbandry, as well as a center of coral reef diversity, both plant and animal.

The alarming decline in biodiversity richness needs to be addressed immediately because without a comprehensive response, this decline is expected to continue until it reaches a point of no return. In addition, the spread of invasive species, both from within the country (inter-island and local/foreign) and from abroad, has caused increasing pressure on native species and ecosystems. These natural changes can be caused by climate change that affects the growth rate of a species both locally and on a wider scale and reduced competition with other species.

A full range of all relevant habitats for Indonesia will be covered, including large rivers and small streams, a thermal streams, natural lakes and man-made reservoirs, flooded quarries, small islands, marine, and fishponds. We also personally visited exporters/wholesalers in Indonesia, as well as government agencies related to the research. freshwater invasive species will be actively searched for at most sampling locations by manual examination of suitable shelters to confirm their in-situ presence. More activities will be added according to obtained data. An inventory of ornamental fish in Indonesia was conducted by contacting ornamental fish hobbyists, fish sellers, the Regional Fisheries Agency and the Fish Quarantine Agency in Indonesia via telephone and WhatsApp. Findings indicating the species' presence were confirmed by data, photographs, and personal interviews with residents and fishers. All activities were carried out in compliance with Indonesian laws and ethical rules and warranted by Indonesian academic staff from the IPB University. Data on domestic production and trade, export and import were obtained from the Fish Quarantine and Inspection Agency and the Ministry of Marine Affairs & Fisheries of the Republic of Indonesia.

### 3.2 Data analysis

The data collecting and analysis will be processed in cooperation with the Charles University, the University of South Bohemia, the IPB University, and the Indonesia Open University.

#### 3.2.1 Climate matching analysis

Contemporary climate data were downloaded at a 10 arcminutes spatial resolution from the WorldClim dataset (Fick and Hijmans, 2017) and environmental layers of future climate data (CSIRO A1B) were obtained from the CliMond database (v.1.2, https://www.climond.org/; Kriticos et al. 2012) at a 10 arc-minutes spatial resolution. We calculated 19 bioclimatic variables (Table 1); these represent the average, extreme and variation of temperature and precipitation and are widely used in ecological niche modelling. Both datasets were assembled in QGIS 3.22.2 'Białowieża' and were released on 17.12.2021 (https://qgis.org/en/site/) to ASCII format for use with the MaxEnt algorithm (Phillips, 2005). MaxEnt was chosen because it is one of the best performing algorithms with presence-only data (Elith et al., 2010). The model describes an area of the continued likelihood of habitat relevance in the target area. Bioclimatic variables provide a statistical summary of the climate within a set of static spatial variables that are appropriate for bioclimatic modelling. Climatic similarity based on temperature characteristics was modelled from a dataset of environmental layers and the native range of species using the MaxEnt program (v.3.4.1; https://biodiversityinformatics.amnh.org /open_source/maxent) to test its environmental suitability. As a cumulative result, a continuous map was created and visualized in QGIS 3.22.2 'Białowieża'. If the climate suitability value reaches or exceeds a certain threshold value, this is interpreted as no evidence of a climate constraint on the survival of the species and is indicated by a red area on the map within the expected native range of the species. MaxEnt was trained using all 19 bioclimatic variables with default features and regularization multipliers (Default model), which are based on empirical tuning studies (Phillips and Dudík, 2008).

Additionally, the conservation status, trends and threats of each listed species by the IUCN Red List of Threatened Species (https://www.iucnredlist.org/) were included if known. Following categories are included in the IUCN Red List: Extinct (there is no reasonable doubt that the species is no longer extant); Extinct in the wild (survives only in captivity); Critically endangered (facing an extremely high risk of extinction in the wild); Endangered (facing a very high risk of extinction in the wild); Vulnerable (facing a high risk of extinction in the wild); Near threatened (close to being at high risk of extinction); Least concern (unlikely to become extinct in the near future); and Data deficient (more information is required for a proper assessment of conservation status).

Table 1. Bioclimatic variables are used in the variable selection strategy to build a climate similarity model in Indonesia.

| Bioclimatic variables | |
|---|---|
| BIO1 | Annual Mean Temperature |
| BIO2 | Mean Diurnal Range (Mean of monthly (max temp - min temp)) |
| BIO3 | Isothermality (BIO2/BIO7) (×100) |
| BIO4 | Temperature Seasonality (standard deviation ×100) |
| BIO5 | Max Temperature of Warmest Month |
| BIO6 | Min Temperature of Coldest Month |
| BIO7 | Temperature Annual Range (BIO5-BIO6) |
| BIO8 | Mean Temperature of Wettest Quarter |
| BIO9 | Mean Temperature of Driest Quarter |
| BIO10 | Mean Temperature of Warmest Quarter |
| BIO11 | Mean Temperature of Coldest Quarter |
| BIO12 | Annual Precipitation |
| BIO13 | Precipitation of Wettest Month |
| BIO14 | Precipitation of Driest Month |
| BIO15 | Precipitation Seasonality (Coefficient of Variation) |
| BIO16 | Precipitation of Wettest Quarter |
| BIO17 | Precipitation of Driest Quarter |
| BIO18 | Precipitation of Warmest Quarter |
| BIO19 | Precipitation of Coldest Quarter |

### 3.2.2 Morphological analysis

The morphological parameter measurements were species-specific, for example, in crayfish, thes 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.

### 3.2.3 Statistical analysis

Statistical analysis is the process of collecting and analyzing data to discern patterns and trends. In the papers part of this dissertation, we use descriptive statistics which involves collecting, interpreting, analyzing, and summarizing data to present it in the form of charts, graphs, and tables. For exaple, in crayfish, the Kruskal Wallis method was used to determine significant morphometric differences between the crayfish 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.

## 4. THE PLANNED OUTPUTS

The collected data will be continuously published in impacted scientific journals such as Scientific Reports, Knowledge and Management of Aquatic Ecosystems, Coastal Management, Management of Biological Invasions, Aquatic Living Resources, Aquaculture Environment Interactions, Biologia, etc. The results are presented in the form of scientific publications in the aforementioned dissertation. Some of our research results are in preparation and under review. The manuscripts are expected to be published as soon as possible, some of them are:

a. Akmal SG, Yonvitner, Yulianda F, Adrianto L, Patoka J. Potential spread of invasive crayfish used as life bait by Indonesian anglers. **Under review** in Human Dimensions of Wildlife.
b. Akmal SG, Yonvitner, Yulianda F, Jerikho R, Slavík O, Bláha M, Kouba A, Patoka J. The farmer's enemy: The hazards of freshwater crab *Parathelphusa convexa* de Man, 1879 spreading to paddy fields in West Sumatra, Indonesia. **In preparation** and will be submitted to journals with impact factors indexed by WoS or Scopus.
c. Patoka J, Akmal SG, Bláha, M, Kouba A. *Cherax woworae*, a new crayfish (Decapoda: Parastacidae) from West Papua Province, Indonesia. **Under review** in Zootaxa.
d. eDNA of aquatic invasive species in Indonesi. **In preparation** and will be submitted to journals with impact factors indexed by WoS or Scopus.

## 5. LIST OF REFERENCED LEGISLATION

The list of legislation referenced in this study are:

a. Decree of the Minister of Agriculture No. 179/Kpts/Um/3/1982 on the Prohibition of the Import of Several Dangerous Fish Species from Abroad.
b. Law No. 5 of 1994 concerning the Ratification of the United Nation Convention of Biological Diversity.
c. Regulation of the Minister of Marine Affairs And Fisheries of the Republic of Indonesia No. 17 of 2009 concerning the prohibition of the entry of several dangerous fish species into the territory of Indonesia.
d. Regulation of the Minister of Marine Affairs And Fisheries of the Republic of Indonesia No. 41/Permen-Kp/2014 concerning the prohibition of the entry of several dangerous fish species into the territory of Indonesia.
e. A notification letter no 1140/BKIP.2/K.140/X/2016 that in regulating the traffic of dangerous fish species.
f. Minister of Environment and Forestry of the Republic of Indonesia Number P.94/MENLHK/SETJEN/KUM.1/12/2016 concerning Invasive Species.
g. Law Number: 45 of 2009 concerning Amendments to Law Number: 31 of 2004 concerning Fisheries.

# 6. RESULTS AND LIST OF PUBLISHED STUDIES

The results obtained from the research continue to be published as independent studies in scientific journals. The inclusion of articles in this paper cannot be considered a publication. The articles are intended exclusively for defending the author's doctoral thesis at the Czech University of Life Sciences Prague. All unpublished data are the property of the authors and co-authors of the respective scientific papers, all rights reserved. The scientific publications presented in this dissertation are sorted chronologically.

## 6.1 Marine ornamental trade in Indonesia

**Akmal SG**, Zámečníková-Wanma BPD, Prabowo RE, Khatami AM, Novák J, Petrtýl M, Kalous L, Patoka J. 2020. Marine ornamental trade in Indonesia. *Aquatic Living Resources*. 33(25). https://doi.org/10.1051/alr/2020026

In this study, we searched the ornamental trade in Indonesia focused on marine species. The marine ornamental trade in Indonesia involves the export of ornamental marine fish and other biota, with the red lionfish and endangered species being the most commonly traded. From 2015 to 2019, Indonesia exported 3,353,983 kgs of ornamental marine fish, which were sold for 33,123,218 USD. Bali was identified as the province with the highest volume of exports. Indonesia and the Philippines are the main exporters of marine ornamentals from Southeast Asian coral reefs. The marine ornamental trade is a significant industry, with over 46 million organisms representing 2500 species traded annually, and a value exceeding US$ 300 million (Palmtag, 2017).

Marine ornamental trade in Indonesia is an important sector of the international pet trade. The vast majority of these species are collected from the wild. Detailed evidence on trade with marine resources in Indonesia is lacking or it is hardly accessible. Moreover, the exploitation of ornamental species seems to be mostly uncontrolled. The existence of ornamental fish market regulation in Europe requiring export of ornamental fish to be from cultivation presents an opportunity for regulation.

Aquat. Living Resour. 2020, 33, 25
© EDP Sciences 2020
https://doi.org/10.1051/alr/2020026

Aquatic Living Resources
Available online at:
www.alr-journal.org

RESEARCH ARTICLE

# Marine ornamental trade in Indonesia

Surya G. Akmal[1,2], Brigitta P.D. Zámečníková-Wanma[1], Romanus E. Prabowo[3], Aulia M. Khatami[4], Jindřich Novák[1], Miloslav Petrtýl[1], Lukáš Kalous[1] and Jiří Patoka[1,*]

[1] Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, Praha-Suchdol 16500, Czech Republic
[2] Centre for Disaster Studies, Research and Community Empowerment, IPB University, 166 80 Bogor, Indonesia
[3] Faculty of Biology, Universitas Jenderal Soedirman, Jalan dr. Soeparno 63, Purwokerto 53122, Indonesia
[4] Directorate General of Fisheries Product Competitiveness, Ministry of Marine Affairs and Fisheries, Gambir, Jakarta 10110, Indonesia

Received 14 February 2019 / Accepted 8 December 2020

*Handling Editor*: Olivier Thebaud

**Abstract** – Trade with marine species as ornamentals is an important sector of the international pet trade. The vast majority of these species are collected from the wild and one of the top supplying countries is Indonesia. Detailed evidence on trade with marine resources in Indonesia is lacking or it is hardly accessible. Moreover, the exploitation of ornamental species seems to be mostly uncontrolled. This study presents detailed characteristics of such trade for Indonesia, including the offered species, their sizes, prices, and conservation status, based on data and information obtained from wholesalers in 2018. The main provinces of marine wildlife collecting are also identified. In total, 777 marine vertebrate and invertebrate species were traded, belonging to 174 families including two species classified as endangered: Banggai cardinal fish (*Pterapogon kauderni*) and zebra shark (*Stegostoma fasciatum*). Commonly traded was red lionfish (*Pterois volitans*), known to be a successful invader. The volume of ornamental marine fish exported from Indonesia in period 2015–2019 was 3 353 983 kgs sold for 33 123 218 USD. The province of Bali was identified as the main exporter of ornamental marine fish within Indonesia. These findings should help to establish sustainable exploitation of marine resources in relation to conservation and wildlife management.

**Keywords:** Aquarium / coral reef / export / ornamental species / pet trade / price

## 1 Introduction

The keeping of ornamental species in aquaria is amongst the most popular hobbies worldwide and represents a steadily growing sector of aquaculture and a multi-billion dollar industry (Tlusty, 2002; Padilla and Williams, 2004; Livengood and Chapman, 2007; Novák et al., 2020). In the past, setting up and maintaining marine aquaria was much more expensive in comparison to freshwater ones. Recent rapid improvements in husbandry methods and technologies have resulted in a change whereby moderately experienced fish keepers are now able to build and keep marine aquaria of relatively small volumes for reasonable prices (Cato and Brown, 2003; Ribeiro et al., 2009). Moreover, the popularity of marine animals as ornamentals has greatly increased due to the release of children's movies in which charismatic and attractively coloured marine biota are the star characters (Livengood and Chapman, 2007). Contrary to freshwater species, the vast majority of ornamental marine organisms do not reproduce in captivity and they are captured in the wild, especially in tropical coral reefs (Tlusty, 2002; Cato and Brown, 2003). It is clear that along with the growing popularity of marine animals as pets, the pressure on wild populations is on the rise.

Moreover, due to the development of hobbyists preferences, the global trade in live tropical marine organisms shifted from fish-only tanks to small coral reefs with diverse biota including also many invertebrates (Rhyne et al., 2009). This shift of preferences has already increased pressure on tropical coral reefs, one of the most overexploited and critically endangered ecosystems on the planet, from which originate the vast majority of ornamental marine species (Bruckner, 2005; Leal et al., 2016a,b).

Although there is no evidence that collecting and fishing for the pet trade has led to extinction of some marine species, local depletion is well documented (Lunn and Moreau, 2004; Nañola et al., 2011; Madduppa et al., 2014).

*Corresponding author: patoka@af.czu.cz

Collectors of ornamental marine biota are usually small-scale fishermen from tropical countries who work alone or in small family groups, and who supply these animals to intermediaries and middlemen, and consequently to large wholesale/exporter companies (Wabnitz et al., 2003). Despite suggested activities aimed at improving sustainable exploitation (Tlusty et al., 2013; Calado et al., 2014; Madduppa et al., 2014; Leal et al., 2016a,b), some local collectors still use very destructive techniques including application of potassium and sodium cyanide to capture fish (see Rubec et al., 2001).

Over 3000 marine species originating from more than 100 countries are known to be subjects of the international pet market annually (Rhyne et al., 2009; Leal et al., 2016a,b). The majority of traded organisms are exported to the United States, European Union and Japan (Rhyne et al., 2012), and one of the top suppliers is the Republic of Indonesia (Lunn and Moreau, 2004; Padilla and Williams, 2004; Leal et al., 2016a,b). Many people living in Indonesian coastal communities are economically dependent on the collection of marine animals for the pet trade and these communities are among the poorest in the country (Reksodihardjo-Lilley and Lilley, 2007).

Since intensive capture can cause a considerable decline in the abundance and density of target species, data about the trade are needed to evaluate related risks. Unfortunately, exact data on trade with marine resources in Indonesia are not easily accessible, and the exploitation of ornamental species is perceived as mostly uncontrolled (Lunn and Moreau, 2004).

In the present work, the current state of the Indonesian marine pet trade was summarised and the main areas of species collection and harvesting were identified. The information presented should help to establish sustainable exploitation of marine resources with respect to local and international conservation and wildlife management.

## 2 Materials and methods

### 2.1 Desktop research

Selected pet trade wholesalers in the Czech Republic were contacted to identify their main partners in Indonesia. Subsequently, a search of the literature that reports data on numbers of collected marine organisms in Indonesia was conducted. The standard search engine Google (in English and Indonesian languages) was used. Academic experts and stakeholders in Indonesia were interviewed by email to recommend studies, governmental reports and similar references. A useful source of data was identified and consisted of export statistics of fisheries products by commodity, province and port of export ("Statistik ekspor hasil perikanan menurut komoditi, provinsi dan pelabuhan asal ekspor") released annually in period 2015–2019 by the Ministry of Marine Affairs and Fisheries, Republic of Indonesia. These statistics sort each of the evaluated commodities regarding type, volume and value (in kg and USD, respectively), and the amount of local capture in each Indonesian province. Since the authorities keep records only for the total weight of collected animals, it is not possible to present the actual quantity of captured individuals.

### 2.2 On-site research

In 2018 (period between 1st January to end of June), we collected detailed information covering the offered species based on personal visits and obtained actual price lists of two of the major wholesalers/exporters in Jakarta, Indonesia, which were previously identified and contacted in advance via email communication. We also gathered information on common names used as trade names, and origin of traded species (wild-harvested or cultured).

### 2.3 Data analyses

A species list including common names, sex and colouration morphs (when listed separately), size categories and wholesale prices of each offered aquatic organism was compiled, based on the data obtained. Usually, ornamental marine species are not stocked in the exporter's facilities but obtained from suppliers and middlemen when wholesalers/importers order listed species in the target area (as done for a vast majority of imports to the United States, the European Union or Japan; Rhyne et al., 2017). The species names were verified using online databases FishBase (www.fishbase.org) and WoRMS (World Register of Marine Species, http://www.marinespecies.org). Misnomers, unaccepted, fuzzy and false names were recorded and discussed with livestock managers in the Indonesian wholesalers. Corrected names were later confirmed by livestock managers in one of the main European importers based in the Czech Republic, which is considered as a gateway for ornamental aquatic species to Europe. These organisms are imported here from supporting countries, partly sold locally and partly re-exported to other European countries upon customer request (Kalous et al., 2015). Additionally, the conservation status, trends and threats of each listed species by the IUCN Red List of Threatened Species (https://www.iucnredlist.org/) were included if known. Following categories are included in the IUCN Red List: Extinct (there is no reasonable doubt that the species is no longer extant); Extinct in the wild (survives only in captivity); Critically endangered (facing an extremely high risk of extinction in the wild); Endangered (facing a very high risk of extinction in the wild); Vulnerable (facing a high risk of extinction in the wild); Near threatened (close to being at high risk of extinction); Least concern (unlikely to become extinct in the near future); and Data deficient (more information is required for a proper assessment of conservation status).

## 3 Results

The results are given in Table 1. The total weight of marine fish captured and exported as ornamentals between 2015 and 2019 from Indonesia was 3 353 983 kg sold for 33 123 218 USD. Adult fish represented 3 287 432 kg (32 265 994 USD) while juveniles 66 551 kg (857 224 USD). Fish were exported from 18 Indonesian provinces. Bali was the province with the highest volume of captured and exported ornamental marine fish. Export statistics about another marine biota were not available.

In total, 777 marine species advertised both in Indonesia and abroad for sale as ornamentals in 2018 were identified

**Table 1.** Indonesian provinces with recorded exports of marine juvenile and adult fishes in period 2015–2019, their total weight and total price per year, and total price per whole period.

| Province | Commodity | Weight (kg) | | | | | Price (USD) | | | | | Total price (USD) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2015 | 2016 | 2017 | 2018 | 2019 | 2015 | 2016 | 2017 | 2018 | 2019 | |
| Bali | juveniles | | 410 | 3601 | 1402 | 15 617 | | 160 | 4008 | 10 133 | 269 319 | 22 555 584 |
| | adults | 485 603 | 616 486 | 450 956 | 490 413 | 252 453 | 3 153 205 | 5 465 053 | 4 490 620 | 4 470 989 | 4 692 097 | |
| Jakarta | juveniles | 14 | | 3415 | 2569 | 9535 | 45 | | 20 229 | 25 812 | 252 961 | 4 994 155 |
| | adults | 158 099 | 135 689 | 53 312 | 58 501 | 40 807 | 1 626 200 | 1 256 139 | 390 556 | 705 926 | 716 287 | |
| Banten | juveniles | 3144 | 22 055 | | | | 40 870 | 230 833 | | | | 3 242 999 |
| | adults | | | 47 688 | 44 623 | 51 732 | | | 970 121 | 1 267 562 | 733 613 | |
| West Java | Juveniles | | | | | | | | | | | 85 159 |
| | Adults | 9691 | 8074 | 9966 | 3647 | 16 058 | 80 613 | 101 864 | 132 372 | 215 651 | 321 090 | |
| Riau Islands | Juveniles | | | | | | | | | | | 505 756 |
| | Adults | | 972 | 3016 | 5102 | 5420 | | 2952 | 22 797 | 222 602 | 257 405 | |
| Aceh | juveniles | | | | | | | | | | | 296 906 |
| | adults | | 5263 | 18 958 | 25 691 | 16 141 | | 13 504 | 43 257 | 95 846 | 144 299 | |
| North Sumatra | juveniles | 1300 | 3489 | | | | 1770 | 1084 | | | | 22 055 |
| | adults | 9905 | 30 028 | 34 574 | 63 334 | 53 377 | 12 255 | 35 020 | 21 564 | 37 274 | 111 583 | |
| West Sumatra | juveniles | | | | | | | | | | | 220 267 |
| | adults | | 39 | 1036 | 20 576 | 38 457 | | 2167 | 67 679 | 42 118 | 108 303 | |
| North Sulawesi | juveniles | | | | | | | | | | | 107 816 |
| | adults | 5625 | 3305 | 2067 | 2601 | 1726 | 30 932 | 19 530 | 11 704 | 22 229 | 23 421 | |
| Southeast Sulawesi | juveniles | | | | | | | | | | | 56 035 |
| | adults | | | 791 | 45 | | | | 54 250 | 1785 | | |
| West Nusa Tenggara | juveniles | | | | | | | | | | | 32 231 |
| | adults | | 100 | 49 | 35 | | | 5980 | 16 305 | 9946 | | |
| Maluku | juveniles | | | | | | | | | | | 18 605 |
| | adults | 71 | 224 | 765 | | 44 | 4780 | 7000 | 3825 | | 3000 | |
| South Sulawesi | juveniles | | | | | | | | | | | 9034 |
| | adults | | | 325 | 905 | 1093 | | | 1110 | 3390 | 4534 | |
| West Kalimantan | juveniles | | | | | | | | | | | 5234 |
| | adults | | | 25 | 23 | 42 | | | 1143 | 819 | 3272 | |
| Central Java | juveniles | | | | | | | | | | | 2902 |
| | adults | | | 1451 | | | | | 2902 | | | |
| North Kalimantan | juveniles | | | | | | | | | | | 1549 |
| | adults | | | | | 43 | | | | | 1549 | |
| Jambi | juveniles | | | | | | | | | | | 1349 |
| | adults | | | 270 | | | | | 1349 | | | |
| Central Kalimantan | juveniles | | | | | | | | | | | 656 |
| | adults | | | | | 120 | | | | | 656 | |

**Table 2.** Groups of marine animals found being traded in Indonesia in 2018, and number of families, the most abundant family and number of traded species in the most abundant family in each group.

| Group | No. of families | Most abundant family | No. of species of the most abundant family |
|---|---|---|---|
| Fish | 52 | Labridae | 73 |
| Cnidarians | 38 | Lobophylliidae | 10 |
| Molluscs | 27 | Cypraeidae | 6 |
| Crustaceans | 22 | Diogenidae | 10 |
| Echinoderms | 20 | Goniasteridae | 5 |
| Elasmobranchs | 8 | Dasyatidae | 3 |
| Annelids | 2 | Sabellidae | 4 |
| Ascidians | 2 | Clavelinidae, Styelidae | 1 |
| Sponges | 2 | Chalinidae, Microcionidae | 1 |
| Flatworms | 1 | Discodorididae | 1 |

(Tabs. 2 and 3): 501 fish species (52 families; with 73 species, the family Labridae had the highest species diversity in the trade), 13 elasmobranchs (sharks and rays; 8 families; with 3 species, the family Dasyatidae had the highest species diversity in the trade), 56 crustaceans (22 families; with 10 species, the family Diogenidae had the highest species diversity in the trade), 113 cnidarians (38 families; with 10 species, the family Lobophylliidae had the highest species diversity in the trade), 41 echinoderms (20 families; with 5 species, the family Goniasteridae had the highest species diversity in the trade), 43

**Table 3.** Groups of marine animals found being traded in Indonesia in 2018, and number of families and species in each group.

| Group | Families | Species |
|---|---|---|
| Bony fish | 52 | 501 |
| Sharks | 5 | 8 |
| Rays | 3 | 6 |
| Shrimps | 9 | 22 |
| Spiny lobsters | 1 | 5 |
| Reef lobsters | 1 | 2 |
| Crabs | 7 | 12 |
| Anomurans | 2 | 12 |
| Penaeid shrimps | 1 | 1 |
| Mantis shrimps | 1 | 2 |
| Sea anemones | 6 | 17 |
| Tube-dwelling anemones | 1 | 1 |
| Jellyfish | 2 | 2 |
| Hard corals | 11 | 48 |
| Soft corals | 18 | 45 |
| Sea stars | 7 | 18 |
| Feather stars | 2 | 2 |
| Brittle stars | 4 | 6 |
| Sea urchins | 4 | 9 |
| Sea cucumbers | 3 | 6 |
| Cephalopods | 1 | 3 |
| Sea slugs | 11 | 18 |
| Sea snails | 15 | 22 |
| Bristleworms | 2 | 5 |
| Sea squirts | 2 | 2 |
| Sponges | 2 | 2 |
| Flatworms | 1 | 1 |
| **Total** | **174** | **778** |

molluscs (27 families; with 6 species, the family Cypraeidae had the highest species diversity in the trade), 5 annelids (2 families; with 4 species, the family Sabellidae had the highest species diversity in the trade), two ascidians (2 families, one species from both families Clavelinidae and Styelidae was advertised), two sponges (2 families; one species from both families Chalinidae and Microcionidae was advertised), and one flatworm (family Discodorididae).

In total, 368 species were found listed in the IUCN Red List of Threatened Species (Data deficient = 21, Least concern = 311, Near threatened = 19, Vulnerable = 15, and Endangered = 2; Fig. 1). The population trend was rated as decreasing in 28 species (including endangered zebra shark *Stegostoma fasciatum*), stable in 112 species, unknown (update required) in 227 species, and one species, red lionfish (*Pterois volitans*) was evaluated as increasing.

The species with the lowest price was mitra snail (*Atrimitra idea*) advertised for 0.15 USD per individual. The highest price of 700.00 USD was recorded for tawny nurse shark (*Nebrius ferrugineus*).

Only one recorded species was cultured in captivity: Banggai cardinal fish (*Pterapogon kauderni*), which is endangered with a decreasing population trend, but capture in the field was also recorded. Clownfishes are known to be

**Fig. 1.** Marine aquaria with animals offered for sale on the street in Jakarta, Indonesia.

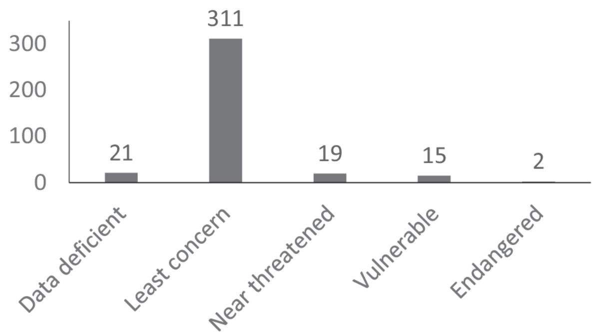


**Fig. 2.** Indonesian ornamental marine species listed in the IUCN Red List of Threatened Species and their categories.

produced on the north shore of Bali (Rhyne et al., 2017), but these species were not listed as domestically cultured in the surveyed price lists; and no sorting by colour morphs was recorded.

Most of the species were traded as adults, but some of them also in the juvenile stage, and in the single case of coral catshark (*Atelomycterus* sp.), the unhatched eggs were advertised.

The ratio between export and local trade was not evaluated due to a lack of data, but various species of fish, sharks, rays, anemones, corals, echinoderms and sea snails were recorded in the street markets in Jakarta (Fig. 2). A detailed list of all species with both their scientific and trade names, sizes, prices, IUCN status and population trend is given in the supplementary material (Tab. S1).

## 4 Discussion

Marine pet trade statistics are often uninterpretable because when available, they include the export of fish in water in total weight rather than as a number of individuals

(Lunn and Moreau, 2004). It is also a common practice to include all marine ornamental species into a single reporting category (such as "ikan hias" – ornamental fish in Indonesian) and/or combine their trade figures with those of other commodities. Therefore, it is important to extend statistics by species, with their detailed price and ecological characteristics, providing better insights into the composition of this trade. A large number of marine animal species traded as ornamentals within the international and local pet trade in Indonesia were identified. Some species are known to be decreasing in abundance in the wild and two of them are listed as endangered in the IUCN Red List of Threatened Species. In comparison with fishery, the volume of endangered species captured for ornamental trade is mostly overlooked. For instance, *Stegostoma fasciatum* was recorded as bycatch in Indonesian fishery (Lindfield and Jaiteh, 2019) but detailed information on exploitation of these sharks as ornamentals should be gathered from further research. With the exception of *P. kauderni*, all species are harvested solely from the wild. There are 34 provinces in Indonesia and the above animals are harvested in 11 of them, with the vast majority exported from Bali, sometimes with transhipment to wholesalers in Jakarta (Java). The price of traded animals varied from 0.15 to 700.00 USD depending on the species and size, the most expensive being sharks. One can expect that the real volume of captured fish is much higher than statistics suggest, due to post-capture mortality, which is not recorded. What is alarming, up to 98% of wild-harvested marine ornamental creatures die within one year of capture (Yan, 2016).

*Pterapogon kauderni* is a favourite ornamental species endemic to the Banggai Islands, Indonesian archipelago. It has an oral incubation (paternal mouthbrooding) of eggs and hatchlings with a direct development (Fishelson and Gon, 2008) and dispersal of its juveniles is very limited due to the lacking stage of pelagic larvae (Vagelli, 1999). Therefore, intensive capture is very risky for the sustainability of the genetically isolated populations of this species which are due to unique life history especially vulnerable to local extinction (Lunn and Moreau, 2004; Ndobe et al., 2018).

*Pterapogon kauderni* can serve as a model of an ideal ornamental fish suitable for breeding in marine aquaria. It is a small and peaceful species with an unusual colouration, in which white, black and blue tones predominate. This fish reproduces well in captivity. Relatively seamless breeding, limited mainly by the number of 40–60 eggs in the father's mouth and the requirement of offspring for significant content of highly unsaturated fatty acids (HUFA) in food have impact on reality that fish farmers are unable to saturate sufficiently the demand for this species (Dodds, 2009; Schum, 2009; Vagelli, 2002, 2011). The share of tank-bred fish, especially those originating from Thailand, has been growing since 2012 significantly, probably because hobbyists prefer captive-bred fish due to the likelihood of a higher survival rate (Ndobe et al., 2018). Within its native range, isolated populations of this species occur only in surroundings of 34 from 67 islands (Vagelli, 2011, 2015; Ndobe et al., 2013). Vagelli (2015) estimated potential habitat suitable for *P. kauderni* fish being ca. 30 km$^2$. Ndobe et al. (2018) pointed out that the habitat covers only 20–24 km$^2$.

Dodds (2009) and Vaggelli (2011) estimated current population of 2.4 million individuals with about 900 000 individuals being exported yearly and with together 18 million fish collected since 1995. Harvest of this species do not represent an important part of local economy, because only about 230 collectors are involved in fishing (Lunn and Moreau, 2004). At the current payment rate of 0.01–0.025 USD per fish, it represents an average number of less than 8000 fish per collector supplemental income for each collector of between 78 and 195 USD per year (Vagelli and Erdmann, 2002). Dodds (2009) further estimates mortality between collection and export at 55%. According to Lunn and Moreau (2004), only slightly over 10 000 individuals of *P. kauderni* are sold in the wholesale network. This means, according to Dodds (2009), the total mortality is at 99% level during shipping from the exporter to the distributor. Iridovirus (BCIV) and bacteria of the genus *Vibrio* in combination with stressful conditions have the significant negative effect on the mortality of this species in the store chain (Ndobe et al., 2018).

Since *P. kauderni* is known for being captured in large quantities, the capture is probably one of the main reasons why the population trend is decreasing. As part of the regulation of capture and export for the pet trade, it was proposed to include *P. kauderni* in the CITES Appendix II, but this was consequently withdrawn by the European Union (CoP 14 Prop. 19, www.cites.org). Indonesia was encouraged to implement conservation measures to ensure the sustainability of exploitation of this species and to reduce post-capture mortality, which is about 83% (Lunn and Moreau, 2004). A possible solution is substitution of fish harvested from the wild by fish bred and reared in captivity. However, it was previously noted that fish harvested from the wild are much cheaper than captive-bred fish, and therefore still widely traded (Vagelli, 2011). On the contrary, both categories were found advertised for sale at the same price of 2.0 USD. The price is relatively low, popularity high, and thus continued capturing is expected. In the case of clownfish species, no specific colour morphs like melanistic and aberrant were offered, and hence the price was not dependent on this factor contrary to clownfishes exported from Papua New Guinea, as recently reported by Militz et al. (2018). After detailed analysis, Ndobe et al. (2018) subsequently concluded that managing of this species and its microhabitats (fishing quotes, community-based aquaculture) could provide benefit to endemic populations and at the same time enhance potential for tourism and fisheries.

Intensive trade with this species is paradoxically accompanied by the expansion of its natural range to areas of highly restricted localities along trade routes in Sulawesi, in particular in Luwuk, Palu Bay, Lembeh Strait, Tumbak, Kendari (Erdmann and Vagelli, 2001; Vagelli and Erdmann, 2002; Moore and Ndobe, 2007; Vagelli, 2011; Moore et al., 2012), where traded fish probably escaped from net cages (Lunn and Moreau, 2004, Moore et al., 2012). One population has established in Gilimanuk, North Bali (Lilley, 2008) and future records in more sites in the Banggai Archipelago is expected (Ndobe et al., 2018). *Pterapogon kauderni* is recently categorized as Endangered in the IUCN Red List on the basis of a very small area occupied by fragmented populations, lack of dispersal mechanisms and decrease due to exploitation for the international pet trade (Allen and Donaldson, 2007). By jurisdiction of the European Union it is only listed in CITES Appendix D Council Regulation (EC) No. 338/97 of 9 December 1996 on the protection of species of wild fauna and flora by regulating trade therein (http://data.europa.eu/eli/reg/1997/338/2020-01-01).

The vast majority of traded species are of a small size (a few centimetres) but also bigger creatures (such as tawny nurse shark, *Nebrius ferrugineus*) were recorded. The trade size of this species is 100 cm and it can grow up to 320 cm in body length. *Nebrius ferrugineus* is classified as Vulnerable, *S. fasciatum* as Endangered and the other advertised shark species as Near threatened even though the population trend of *Carcharhinus melanopterus* is decreasing. Given the relatively high price of traded large shark individuals, their popularity as ornamentals is not particularly high, and hence their harvested quantities are probably also not high. Since these species are too big for home aquaria and in view of their conservation status, capture only for support of sustainable captive populations in zoos and public aquaria can be considered desirable (and might be of a high priority; Buckley et al., 2018). Recent research appears to indicate that strict conservation of reef sharks leads to the recovery of overexploited populations (Speed et al., 2018). Unfortunately, these species are harvested without apparent regulation from the wild in Indonesia, and their continued decrease could be expected.

On the other hand, some of the traded species are known to be invasive when introduced into new localities. For example, *P. volitans*, which is the only species with an increasing population trend on the presented list, is considered to be one of the most invasive species in the world (Albins and Hixon, 2013). Also, invertebrates can behave as invaders. For example, the Sally lightfoot crab (*Percnon gibbesi*), advertised for sale for 1.14 USD in Indonesia and 20 EUR in European pet shops (Calado, 2012), is considered to be non-native but established in the Mediterranean by many authors (Félix-Hackradt et al., 2010; Katsanevakis et al., 2011; Stasolla and Innocenti, 2014), even though the natural spread of long-living planktonic larvae into the Mediterranean by the Atlantic Current cannot be excluded as a causal factor (Ulman et al., 2017).

The commercial value of marine animals in the international pet trade is high, and the popularity of aquarium keeping as a hobby is increasing year by year globally. Thus, higher pressure on animals in their native ranges is expected because of their collection in the wild. Although there are logical suggestions to capture ornamental organisms in their non-native range to mitigate their spread and to alleviate the fishing pressure on species in their native range (Calado, 2012), significant reduction of import from Indonesia is not expected due to socio-economic reasons. Although the negative consequences on marine ecosystems of excess harvesting of ornamental species are well known, effective policy measures are lacking in many cases (Patoka et al., 2018).

The spectrum of traded species from Indonesia is broad, including vertebrates and invertebrates, mostly inhabiting coral reef environments. The lack of continuous and systematic monitoring precludes the establishment of harvesting targets and management strategies ensuring the sustainable exploitation of these living marine resources. In total, 502 species of fishes, 13 of sharks and rays, and 276 of invertebrates were found in the marine pet trade in 2018. In contrast, Rhyne et al. (2017) reported 992 species of fishes and 301 of invertebrates to be exported from Indonesia to the United States in 2011 which suggests that some species can be traded as misidentified and wrongly labelled in Indonesia. Further survey is needed in this regard.

## 5 Conclusion

Species-specific information on trade (local and exports-based) of ornamental species provides a better understanding of incentives which may drive the development of harvesting (knowing price ranges), as well as an indirect measure of fishing pressure, which can be related to the knowledge of the biological status of the resources. The geographical information also helps assess the location of this pressure, and whether it seems to apply to areas where the species may be invasive, or not. Gathered data can be used as pre-requisites to the development of species-specific targets and management strategies for the development of sustainable industries, with ensuing ecological, social and economic benefits.

To established sustainable exploitation of living marine resources, conservationists and wildlife managers must implement appropriate and effective monitoring, including both field surveys and market analyses, followed by local regulations or restrictions focused mainly on endangered species or selected populations. On the other hand, only regulation and restriction are not particularly effective, and efforts aimed at public education are crucial. Importantly, not only protection of local species is needed, but also awareness of potentially invasive species. This is because the regions that have climatic conditions and habitats suitable for tropical marine species common in the pet trade are also considered to be places with a high probability of non-native species establishment (Semmens et al., 2004).

Finally, it is worth mentioning that a detailed future survey of the local trade in marine ornamentals in Indonesia is very important. An understanding of the full environmental and socio-economic complexity of this growing sector of the pet industry is a premise for proper implementation of measures to improve marine wildlife management.

## Supplementary Material

**Table S1.** Detailed list of marine species traded in Indonesia as ornamentals; group of animals, family, scientific and common names, size in cm, price over the entire year in USD, IUCN conservation status (if known), and population trend based on data from IUCN (if known).

The Supplementary Material is available at https://www.alr-journal.org/10.1051/alr/2020026/olm.

*Acknowledgements.* This study was supported by the Internal Grant Agency of the Czech University of Life Sciences Prague “CIGA” (No. 20182013). We thank Julian D. Reynolds for proofreading the English.

## References

Albins MA, Hixon MA. 2013. Worst case scenario: potential long-term effects of invasive predatory lionfish (*Pterois volitans*) on Atlantic and Caribbean coral-reef communities. *Environ Biol Fish* 96: 1151–1157.

Allen GR, Donaldson TJ. 2007. *Pterapogon kauderni*. In: IUCN 2009. IUCN Red List of Threatened Species. Version 2009. 1. (www.iucnredlist.org)
Bruckner A. 2005. The importance of the marine ornamental reef fish trade in the wider Caribbean. *Rev Biol Trop* 53: 127–137.
Buckley KA, Crook DA, Pillans RD, Smith L, Kyne PM. 2018. Sustainability of threatened species displayed in public aquaria, with a case study of Australian sharks and rays. *Rev Fish Biol Fisher* 28: 137–151.
Calado R. 2012. Invasive alien crabs can be used for marine aquariums – turning a threat into profit. *Crustaceana* 85: 257–265.
Calado R, Leal MC, Vaz M, Brown C, Rosa R, Stevenson TC, Cooper CH, Tissot BN, Li YW, Thornhill DJ. 2014. Caught in the Act: how the US Lacey Act can hamper the fight against cyanide fishing in tropical coral reefs. *Conserv Lett* 7: 561–564.
Cato JC, Brown CL. Marine ornamental species: collection, culture and conservation, 1st edn, Iowa State Press, Ames, Iowa, 2003.
Dodds K. 2009. Cardinal sin: The plight of the Banggai cardinalfish *Pterapogon kauderni* Koumans 1933. *Trop Fish Hobbyist* 57: 92–98.
Erdmann MV, Vagelli A. 2001. Banggai cardinalfish invade Lembeh Strait. *Coral Reefs* 20: 252–253.
Félix-Hackradt F, Hackradt C, Treviño-Otón J, García-Charton J. 2010. Continued expansion of Percnon gibbesi (Crustacea: Decapoda: Plagusiidae) into western Mediterranean waters. *Mar Biodivers Rec* 3: e22.
Fishelson L, Gon O. 2008. Comparative oogenesis in cardinal fishes (Apogonidae, Perciformes), with special focus on the adaptive structures of the egg envelopes. *Environ Biol Fishes* 8: 397–414.
Kalous L, Patoka J, Kopecký O. 2015. European hub for invaders: Risk assessment of freshwater ornamental fish exported from the Czech Republic. *Acta Ichthyol Piscat* 45: 239–245.
Katsanevakis S, Poursanidis D, Yokes MB, Mačić V, Beqiraj S, Kashta L, Sghaier YR, Zakhama-Sraieb R, Benamer I, Bitar G. 2011. Twelve years after the first report of the crab *Percnon gibbesi* (H. Milne Edwards, 1853) in the Mediterranean: current distribution and invasion rates. *J Biol Res Thessalon* 16: 224–236.
Leal MC, Ferrier-Pagès C, Petersen D, Osinga R. 2016a. Coral aquaculture: applying scientific knowledge to ex situ production. *Rev Aquacult* 8: 136–153.
Leal MC, Vaz MCM, Puga J, Rocha RJM, Brown C, Rosa R, Calado R. 2016b. Marine ornamental fish imports in the European Union: an economic perspective. *Fish Fish* 17: 459–468.
Lilley R. 2008. The Banggai cardinalfish: an overview of conservation challenges. *SPC Live Reef Fish Information Bulletin* 18: 3–12.
Lindfield S, Jaiteh V. 2019. Assessing shark and ray bycatch in Indonesian deepwater snapper-grouper fisheries. The Nature Conservancy Indonesia, 1–13.
Livengood E, Chapman F. 2007. The ornamental fish trade: an introduction with perspectives for responsible aquarium fish ownership. University of Florida IFAS Extension FA124, 1–8.
Lunn K, Moreau M-A. 2004. Unmonitored trade in marine ornamental fishes: the case of Indonesia's Banggai cardinalfish (*Pterapogon kauderni*). *Coral Reefs* 23: 344–351.
Madduppa HH, von Juterzenka K, Syakir M, Kochzius M. 2014. Socio-economy of marine ornamental fishery and its impact on the population structure of the clown anemonefish *Amphiprion ocellaris* and its host anemones in Spermonde Archipelago, Indonesia. *Ocean Coast Manag* 100: 41–50.
Militz TA, Foale S, Kinch J, Southgate PC. 2018. Natural rarity places clownfish colour morphs at risk of targeted and opportunistic exploitation in a marine aquarium fishery. *Aquat Living Resour* 31:18.
Moore A, Ndobe S. 2007. Discovery of an introduced Banggai cardinalfish population in Palu Bay, Central Sulawesi, Indonesia. *Coral Reefs* 26: 569–569.
Moore A, Ndobe S, Salanggon A, Rahman A. 2012. Banggai cardinalfish ornamental fishery: the importance of microhabitat, Proceedings of the 12th International Coral Reef Symposium (July), pp. 9–13.
Nañola CL, Aliño PM, Carpenter KE. 2011. Exploitation-related reef fish species richness depletion in the epicenter of marine biodiversity. *Environ Biol Fish* 90: 405–420.
Ndobe S, Soemarno, Herawati EY, Setyohadi D, Moore A, Palomares MLD, Pauly D. 2013. History of Banggai cardinalfish, *Pterapogon kauderni* (Actinopterygii: Perciformes: Apogonidae), from Banggai Islands and Palu Bay, Sulawesi, Indonesia. *Acta Ichthyol Piscat* 43: 237–250.
Ndobe S, Yasir I, Noore AM, Biondo MV, Foster SJ. 2018. A study to assess the impact of international trade on the conservation status of *Pterapogon kauderni* (Banggai cardinalfish). International Union for Conservation of Nature AC30, 16.
Novák J, Kalous L, Patoka J. 2020. Modern ornamental aquaculture in Europe: early history of freshwater fish imports. *Rev Aquacult* DOI:10.1111/raq.12421.
Padilla DK, Williams SL. 2004. Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. *Front Ecol Environ* 2: 131–138.
Patoka J, Magalhães ALB, Kouba A, Faulkes Z, Jerikho R, Vitule JRS. 2018. Invasive aquatic pets: failed policies increase risks of harmful invasions. *Biodivers Conserv* 27: 3037–3046.
Reksodihardjo-Lilley G., Lilley R. 2007. Towards a sustainable marine aquarium trade: an Indonesian perspective. *SPC Live Reef Fish Inform Bull* 17: 11–19.
Rhyne A, Rotjan R, Bruckner A, Tlusty M. 2009. Crawling to collapse: ecologically unsound ornamental invertebrate fisheries. *PLoS One* 4: e8413.
Rhyne AL, Tlusty MF, Schofield PJ, Kaufman L, Morris Jr JA, Bruckner AW. 2012. Revealing the appetite of the marine aquarium fish trade: the volume and biodiversity of fish imported into the United States. *PLoS One* 7: e35808.
Rhyne AL, Tlusty MF, Szczebak JT, Holmberg RJ. 2017. Expanding our understanding of the trade in marine aquarium animals. *PeerJ* 5: e2949.
Ribeiro F, Collares-Pereira M, Moyle P. 2009. Non-native fish in the fresh waters of Portugal, Azores and Madeira Islands: a growing threat to aquatic biodiversity. *Fish Manag Ecol* 16: 255–264.
Rubec PJ, Cruz F, Pratt V, Oellers R, McCullough B, Lallo F. 2001. Cyanide-free net-caught fish for the marine aquarium trade. *Aquar Sci Conserv* 3: 37–51.
Schum T. 2009. Breeding Banggai Cardinalfish: a hobbyist́s perspective. *Trop Fish Hobbyist* 57: 96–98.
Semmens BX, Buhle ER, Salomon AK, Pattengill-Semmens CV. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. *Mar Ecol Prog Ser* 266: 239–244.
Speed CW, Cappo M, Meekan MG. 2018. Evidence for rapid recovery of shark populations within a coral reef marine protected area. *Biol Conserv* 220: 308–319.
Stasolla G, Innocenti G. 2014. New records of the invasive crabs *Callinectes sapidus* Rathbun, 1896 and *Percnon gibbesi* (H. Milne Edwards, 1853) along the Italian coasts. *BioInvasions Rec* 3: 39–43.
Tlusty M. 2002. The benefits and risks of aquacultural production for the aquarium trade. *Aquaculture* 205: 203–219.

Tlusty MF, Rhyne AL, Kaufman L, Hutchins M, Reid GMG, Andrews C, Boyle P, Hemdal J, McGilvray F, Dowd S. 2013. Opportunities for public aquariums to increase the sustainability of the aquatic animal trade. *Zoo Biol* 32: 1–12.

Ulman A, Ferrario J, Occhpinti-Ambrogi A, Arvanitidis C, Bandi A, Bertolino M, Bogi C, Chatzigeorgiou G, Çiçek BA, Deidun A. 2017. A massive update of non-indigenous species records in Mediterranean marinas. *PeerJ* 5: e3954.

Vagelli A. 1999. The reproductive biology and early ontogeny of the mouthbrooding Banggai cardinalfish, *Pterapogon kauderni* (Perciformes, Apogonidae). *Environ Biol Fish* 56: 79–92.

Vagelli AA. 2002. Notes on the biology, geographic distribution, and conservation status of the Banggai cardinalfish *Pterapogon kauderni* Koumans 1933, with comments on captive breeding techniques. *Trop Fish Hobbyist* 51: 84–88.

Vagelli AA. 2011. The Banggai cardinalfish: natural history, conservation, and culture of *Pterapogon kauderni*. Chichester, UK, John Wiley & Sons., pp. 1–203.

Vagelli AA. 2015. Update on populations' condition of the Banggai cardinalfish *Pterapogon kauderni*. Unpublished report (available upon request at: https://federalregister.gov/a/2016-00943).

Vagelli AA, Erdmann M. 2002. First comprehensive ecological survey of the Banggai cardinalfish, *Pterapogon kauderni*. *Environ Biol Fish* 63: 1–8.

Wabnitz C, Taylor M, Green E, Razak T. 2003. From ocean to aquarium: the global trade in marine ornamental species. Cambridge, UK, UNEP/Earthprint.

Yan G. 2016. Saving Nemo–Reducing mortality rates of wild-caught ornamental fish. *SPC Live Reef Fish Inform Bull* 21: 3–7.

**Cite this article as**: Akmal SG, Zámečníková-Wanma BPD, Prabowo RE, Khatami AM, Novák J, Petrtýl M, Kalous L, Patoka J. 2020. Marine ornamental trade in Indonesia. *Aquat. Living Resour.* 33: 25

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

**Akmal SG**, Santoso A, Yuliana E, Patoka J. 2021. Redclaw crayfish (*Cherax quadricarinatus*): spatial distribution and dispersal pattern in Java, Indonesia. *Knowledge & Management of Aquatic Ecosystems*. 422(16). https://doi.org/10.1051/kmae/2021015

The study investigated the spatial distribution and dispersal pattern of the redclaw crayfish (*Cherax quadricarinatus*) in Java, Indonesia. The occurrence of the species was confirmed in 66 of 70 surveyed localities with 51 new records for Indonesia. The encounter points are in line with the pathways of ornamental trade, and thus *C. quadricarinatus* can probably inhabit many different streams, reservoirs, lakes, and other water bodies. The study provides valuable information for future investigations focused on the relationship between the ornamental trade and the introduction of non-native crayfish species in Indonesia.

Several factors contribute to the spread of redclaw crayfish in Java, Indonesia. These include:

a. Ornamental trade: The encounter points of redclaw crayfish are in line with the pathways of ornamental trade, which suggests that the species can probably inhabit many different streams, reservoirs, lakes, and other water bodies.
b. Wide environmental tolerance: Despite generally preferring slow-moving streams in its native range, redclaw crayfish has a wide environmental tolerance, making it capable of establishing in various aquatic habitats.
c. Culture and release: The culture and release of redclaw crayfish to inland waters is undesirable and risky to native freshwater biota.
d. Invasive potential: redclaw crayfish is an intruder with high invasive potential, capable of causing biodiversity homogenization, at least at a local level.
e. Lack of management: The lack of management and monitoring of this species in the region is also a contributing factor to its spread.

Knowl. Manag. Aquat. Ecosyst. 2021, 422, 16
© S.G. Akmal *et al.*, Published by EDP Sciences 2021
https://doi.org/10.1051/kmae/2021015

www.kmae-journal.org

Knowledge & Management of Aquatic Ecosystems

Journal fully supported by Office français de la biodiversité

RESEARCH PAPER OPEN ACCESS

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

Surya Gentha Akmal[1,2,*], Agus Santoso[3], Yonvitner[2,4], Ernik Yuliana[5] and Jiří Patoka[1]

[1] Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Science Prague, Kamýcká 129, 165 00 Prague – Suchdol, Czech Republic
[2] Centre for Coastal and Marine Resources Studies, The Institute for Research and Community Service, IPB University, Bogor 166 80, Indonesia
[3] Department of Statistic, Faculty of Science and Technology, Indonesia Open University, Pondok Cabe, South Tangerang 154 37, Indonesia
[4] Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Jl. Agatis, Kampus IPB Dramaga, Bogor 166 80, Indonesia
[5] Department of Biology, Faculty of Science and Technology, Indonesia Open University, Pondok Cabe, South Tangerang 154 37, Indonesia

Received: 12 February 2021 / Accepted: 23 March 2021

**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

*Corresponding author: akmal@af.czu.cz

(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

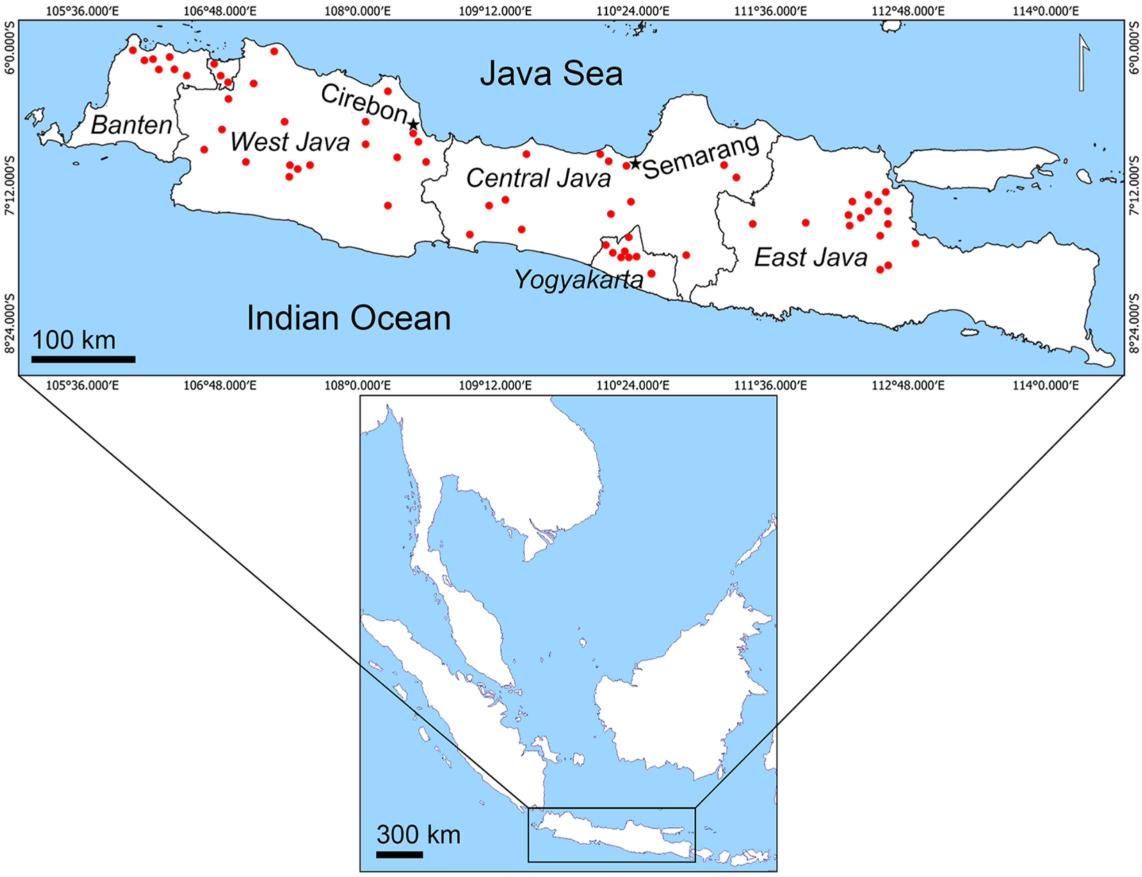


**Fig. 1.** The current distribution of *Cherax quadricarinatus* in Java island. The red dots indicate the established populations. Name of provinces are italicized while source regions are indicated by an asterisk, except for Yogyakarta which is the name of the province and also of a source region.

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 |

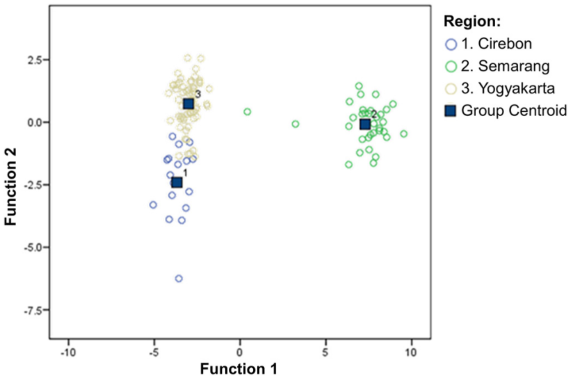


**Fig. 2.** Discriminant result grouping of *Cherax quadricarinatus* on standard morphological measures. The discriminant analysis serves to show clear groupings characterized by differences in the centroid position. The analysis showed significant differences among groups in Cirebon (1), Semarang (2),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

*Acknowledgments.* Thanks to colleagues and students who helped us with the survey, namely: Rafialwan Athariq Subing and Sultan Al Riza Ritonga, Fish Quarantine and Inspection Agency, and the local farmers. This study was funded by DIPA Indonesia Open University T.A. 2020 No. SP DIPA-023.17.2.677531. The cooperation was supported by The Indonesian Crayfish Research Group. English was proofread by Julian D. Reynolds.

## References

Bláha M, Patoka J, Kozák P, Kouba A. 2016. Unrecognized diversity in New Guinean crayfish species (Decapoda, Parastacidae): the evidence from molecular data. *Integr Zool* 11: 457–468.

Darmansyah A, Rochana SH, Sutardi A, Zuraida U. 2014. The new growth centres and strategy for building and accelerating agribusiness development in Cirebon Regency, Indonesia. *Procedia Soc Behav Sci* 115: 296–304.

Fahri S, Yohan B, Trimarsanto H, Sayono S, Hadisaputro S, Dharmana E, Syafruddin D, Sasmono RT. 2013. Molecular surveillance of dengue in Semarang, Indonesia revealed the circulation of an old genotype of dengue virus serotype-1. *PLoS Negl Trop Dis* 7: e2354.

Ghanawi J, Saoud G, Zakher C, Monzer S, Saoud IP. 2019. Clove oil as an anaesthetic for Australian redclaw crayfish *Cherax quadricarinatus*. *Aquac Res* 50: 3628–3632.

Glen AS, Pech RP, Byrom AE. 2013. Connectivity and invasive species management: towards an integrated landscape approach. *Biol Invasions* 15: 2127–2138.

Haubrock PJ, Oficialdegui FJ, Zeng Y, Patoka J, Yeo DCJ, Kouba A. 2021. The redclaw crayfish: a prominent aquaculture species with invasive potential in tropical and subtropical biodiversity hotspots. *Rev Aquac*. https://doi.org/10.1111/raq.12531

Hayakijkosol O, Owens L, Picard J. 2017. Case report of bacterial infections in a redclaw crayfish (*Cherax quadricarinatus*) hatchery. *Aquaculture* 475: 1–7.

Holthius LB. 1949. Decapoda Macrura, with a revision of the New Guinea Parastacidae. Zoological Results of the Dutch New Guinea Expedition 1939, No. 3. Nova Guinea 5, Tallahassee (US), pp. 289–328.

James J, Slater FM, Vaughan IP, Young KA, Cable J. 2015. Comparing the ecological impacts of native and invasive crayfish: could native species' translocation do more harm than good? *Oecologia* 178: 309–316.

Kotovska G, Khrystenko D, Patoka J, Kouba A. 2016. East European crayfish stocks at risk: arrival of non-indigenous crayfish species. *Knowl Manag Aquat Ecosyst* 417: 37.

Lenzner B, Latombe G, Capinha C, Bellard C, Courchamp F, Diagne C, Dullinger S, Golivets M, Irl S, Kühn I, Leung B, Liu C, Moser D, Roura-Pascual N, Seebens H, Turbelin A, Weigelt P, Essl F. 2020. What will the future bring for biological invasions on islands? An expert-based assessment. *Front Ecol Evol* 8: 280.

Lin W, Guo G, Zou C, Shi H, Ruan L. 2020. Large–scale screening of molecules involved in virus–host interaction by specific compounds in *Cherax quadricarinatus* hematopoietic tissue cells. *Aquaculture* 527: 735435.

Marková J, Jerikho R, Wardiatno Y, Kamal MM, Magalhães ALB, Bohatá L, Kalous L, Patoka J. 2020. Conservation paradox of giant arapaima *Arapaima gigas* (Schinz, 1822) (Pisces: Arapaimidae): endangered in its native range in Brazil and invasive in Indonesia. *Knowl Manag Aquat Ecosyst* 421: 47.

Marwoto RM, Isnaningsih NR, Joshi RC. 2018. The invasive apple snail (*Pomacea* spp.) in Indonesia. *Agric Dev* 35: 41–48.

Molnar JL, Gamboa RL, Revenga C, Spalding MD. 2008. Assessing the global threat of invasive species to marine biodiversity. *Front Ecol Environ* 6: 485–492.

Muchlisin ZA. 2012. First report on introduced freshwater fishes in the waters of Aceh, Indonesia. *Fish Aquat Life* 20: 129–135.

Negara FK. 2012. Budidaya Losbter Air Tawar, Persepktive Bisnis, Amikom Yogyakarta, Yogyakarta.

Padalia H, Srivastava V, Kushwaha SPS. 2014. Modeling potential invasion range of alien invasive species, *Hyptis suaveolens* (L.) Poit. in India: Comparison of MaxEnt and GARP. *Ecol Inform* 22: 36–43.

Patoka J, Kalous L, Kopecký O. 2015. Imports of ornamental crayfish: the first decade from the Czech Republic's perspective. *Knowl Manag Aquat Ecosyst* 416: 04.

Patoka J, Wardiatno Y, Yonvitner, Kuříková P, Petrtýl M, Kalous L. 2016. *Cherax quadricarinatus* (von Martens) has invaded Indonesian territory west of the Wallace Line: evidences from Java. *Knowl Manag Aquat Ecosyst* 417: 39.

Patoka J, Bláha M, Kouba A. 2017. *Cherax acherontis* (Decapoda: Parastacidae), the first cave crayfish from the Southern Hemisphere (Papua Province, Indonesia). *Zootaxa* 4363: 137–144.

Patoka J, Magalhães ALB, Kouba A, Faulkes Z, Jerikho R, Vitule JRS. 2018a. Invasive aquatic pets: failed policies increase risks of harmful invasions. *Biodivers Conserv* 27: 3037–3046.

Patoka J, Wardiatno Y, Mashar A, Yonvitner, Wowor D, Jerikho R, Takdir M, Purnamasari L, Petrtýl M, Kalous L, Kouba A, Bláha M. 2018b. Redclaw crayfish, *Cherax quadricarinatus* (von Martens, 1868), widespread throughout Indonesia. *BioInvasions Rec* 7: 185–189.

Patoka J, Takdir M, Yonvitner, Aryadi H, Jerikho R, Nilawati J, Tantu FY, Bohatá L, Aulia A, Kamal MM, Wardiatno Y, Petrtýl M. 2020. Two species of illegal South American sailfin catfish of the genus *Pterygoplichthys* well-established in Indonesia. *Knowl Manag Aquat Ecosyst* 421: 28.

Peeler EJ, Taylor NG. 2011. The application of epidemiology in aquatic animal health - opportunities and challenges. *Vet Res* 42: 1–15.

Pimentel D. 2011. Biological invasions. economic and environmental costs of alien plant, animal, and microbe species. Florida: CRC Press, p. 449.

Putra MD, Bláha M, Wardiatno Y, Krisanti M, Yonvitner, Jerikho R, Kamal MM, Mojžišová M, Bystřický PK, Kouba A, Kalous L, Petrusek A, Patoka J. 2018. *Procambarus clarkii* (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. *Aquat Conserv* 28: 1434–1440.

Rouse DB, Austin CM, Medley PB. 1991. Progress toward profits? information on the Australian crayfish. *Aquac Mag* 17: 46–56.

Snovsky G, Galil B. 2011. The australian redclaw crayfish *Cherax quadricarinatus* (Von Martens, 1868) (Crustacea: Decapoda: Parastactidae) in the Sea of Galilee, Israel. *Aquat Invasions* 6: 29–31.

Souty-Grosset C, Holdich DM, Noel PY, Reynolds JD, Haffner P. 2006. Atlas of crayfish in Europe. Paris, France: Muséum National d'Histoire Naturelle. p. 187.

Strauss A, White A, Boots M. 2012. Invading with biological weapons: the importance of disease-mediated invasions. *Funct Ecol* 26: 1249–1261.

Torchin ME, Lafferty KD, Dobson AP, McKenzie VJ, Kuris AM. 2003. Introduced species and their missing parasites. *Nature* 421: 628–630.

Vitasurya VR. 2016. Local wisdom for sustainable development of rural tourism, case on kalibiru and Lopati village, Province of Daerah Istimewa Yogyakarta. *Procedia Soc Behav Sci* 216: 97–108.

Vodovsky N, Patoka J, Kouba A. 2017. Ecosystem of Caspian Sea threatened by pet-traded non-indigenous crayfish. *BioInvasions Rec* 19: 2207–2217.

von Martens E. 1868. Über eine neue Art und Untergattung der Cyprinoiden, Homaloptera (Octonema) rotundicauda, über einige neue Crustaceen und über die neuholländischen Süsswasserkrebse. Monatsberichte der Königlichen Akademie der Wissenschaften zu Berlin. Physikalisch-mathematische Klasse, Berlin, pp. 607–619.

Webster M. 2007. A Cambrian peak in morphological variation within trilobite species. *Science* 5837: 499–502.

Weiperth A, Bláha M, Szajbert B, Seprős R, Bányai Z, Patoka J, Kouba A. 2020. Hungary: a European hotspot of non-native crayfish biodiversity. *Knowl Manag Aquat Ecosyst* 421: 43.

Wu D-L, Liu Z-Q, Huang Y-H, Lv W-W, Chen M-H, Li Y-M, Zhao Y-L. 2018. Effects of cold acclimation on the survival, feeding rate, and non-specific immune responses of the freshwater red claw crayfish (*Cherax quadricarinatus*). *Aquac Int* 26: 557–567.

Yonvitner, Patoka J, Yuliana E, Bohatá L, Tricarico E, Karella T, Kouba A, Reynolds JD. 2020. Enigmatic hotspot of crayfish diversity at risk: Invasive potential of non-indigenous crayfish if introduced to New Guinea. *Aquat Conserv* 30: 219–224.

Yuliana E, Yonvitner, Bláha M, Patoka J. 2019. Unusual rostral deformity in *Cherax quadricarinatus* (von Martens, 1868). Workshop on Biodiversity, Jevany, *Czech Republic* 11: 201–206.

**Cite this article as**: Akmal SG, Santoso A, Yonvitner, Yuliana E, Patoka J. 2021. Redclaw crayfish (*Cherax quadricarinatus*): spatial distribution and dispersal pattern in Java, Indonesia. *Knowl. Manag. Aquat. Ecosyst.*, 422, 16.

## 6.3 Import, trade and culture of non-native ornamental crayfish in Java, Indonesia

Yuliana E, Yonvitner, **Akmal SG**, Subing RA, Ritonga SAR, Santoso A, Kouba A, Patoka J. 2021. Import, trade and culture of non-native ornamental crayfish in Java, Indonesia. *Management of Biological Invasions*. 12(4): 846–857 https://doi.org/10.3391/mbi.2021.12.4.05

According to a survey conducted in Java, Indonesia, six non-native species of ornamental crayfish were recorded: *Cherax destructor*, *C. quadricarinatus*, and four *Procambarus* species. These crayfish are imported, traded, and cultured in Java for ornamental purposes. *Cherax quadricarinatus* is native only to the southern part of the Papua Province in Indonesia, but has invaded Indonesian territory west of the Wallace Line (Patoka et al., 2016c). Indonesia is known to be the main exporter of ornamental crayfish globally, and certain New Guinean species are exploited as ornamentals within the country (Yonvitner et al., 2020b). The local trade in ornamental non-native crayfish is booming in Java, and the invasive *Procambarus clarkii* is among the species being traded. The culture of non-native ornamental crayfish in Indonesia includes outdoor farms and indoor concrete tanks.

The potential ecological impacts of non-native ornamental crayfish in Java, Indonesia, include negative implications for the ecology and socio-economic dynamics of the recipient area. The introduction of non-native crayfish species can lead to intersectional adverse impacts. *Cherax quadricarinatus*, a non-native species of ornamental crayfish, can negatively affect native species through direct competition, predation, or habitat modification, and may host parasites (Akmal et al., 2021). Moreover, the introduction of non-indigenous crayfish species to New Guinea, which is close to Java, can have an invasive potential and put the enigmatic hotspot of crayfish diversity at risk (Yonvitner et al., 2020b).

**Short Communication**

# Import, trade and culture of non-native ornamental crayfish in Java, Indonesia

Ernik Yuliana[1], Yonvitner[2,3], Surya Gentha Akmal[3,4], Rafialwan A. Subing[2], Sultan A. Ritonga[2], Agus Santoso[5], Antonín Kouba[6] and Jiří Patoka[4,*]

[1]*Department of Biology, Faculty of Mathematics and Natural Sciences, Indonesia Open University, Jl. Pondok Cabe Raya, Pamulang, 15418 Tangerang Selatan, Indonesia*

[2]*Department of Aquatic Resources Management, Faculty of Fisheries, IPB University, Jl. Agathis No. 1 Kampus FPIK IPB Dramaga, 16680 Bogor, Indonesia*

[3]*Centre for Coastal and Marine Resources Studies, The Institute for Research and Community Service, IPB University, 16680 Bogor, Indonesia*

[4]*Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague - Suchdol, Czech Republic*

[5]*Department of Statistic, Faculty of Sciences and Technology, Universitas Terbuka, 15437 Tangerang Selatan, Indonesia*

[6]*South Bohemian Research Center of Aquaculture and Biodiversity of Hydrocenoses, Faculty of Fisheries and Protection of Waters, University of South Bohemia in České Budějovice, Zátiší 728/II, 38925 Vodňany, Czech Republic*

Author e-mails: *patoka@af.czu.cz (JP), ernik@ecampus.ut.ac.id (EY), yonvitr@yahoo.com (Y), akmal@af.czu.cz (SGA), rafialwan.athariq@gmail.com (RAS), sultanritonga@gmail.com (SAR), aguss@ecampus.ut.ac.id (AS), akouba@frov.jcu.cz (AK)*

**Corresponding author*

**Citation:** Yuliana E, Yonvitner, Akmal SG, Subing RA, Ritonga SA, Santoso A, Kouba A, Patoka J (2021) Import, trade and culture of non-native ornamental crayfish in Java, Indonesia. *Management of Biological Invasions* 12(4): 846–857, https://doi.org/10.3391/mbi.2021.12.4.05

**Received:** 2 February 2021
**Accepted:** 5 July 2021
**Published:** 30 August 2021

**Handling editor:** Christoph Chucholl
**Thematic editor:** Calum MacNeil



## Abstract

The pet trade is known to be one of the main sources of invasive species including freshwater crayfish, which cause socio-economic losses and negative impacts on native biota in many regions where introduced. Indonesia was identified as the leading supplier of ornamental crayfish globally but the local market has been neglected even though certain non-native species were reported previously. Based on the survey of pathways and culture of ornamental crayfish in Java, six non-native species were recorded: *Cherax destructor*, *C. quadricarinatus*, *C. peknyi*, *C. snowden*, *C. warsamsonicus*, and *Procambarus clarkii*. The latter species originates from North America and serves as a vector of crayfish plague, i.e. a disease lethal for non-North American crayfish species. Crayfish are cultured both in outdoor and indoor facilities as well as in natural lakes and reservoirs. Harvested crayfish are transported via numerous routes across most of the island of Java. It is obvious that the local market for ornamental crayfish is well-developed and Jakarta, Surabaya and Yogyakarta were identified as hotspots of this trade. Further monitoring, detailed analysis of the market and a ban of high-risk *P. clarkii* are recommended to improve management and existing legislation.

**Key words:** Parastacidae, Cambaridae, aquaculture, invasive species, pathway, transport, Asia

## Introduction

Freshwater crayfish (Decapoda: Astacida) inhabit various lotic and lentic habitats such as rivers, brooks, lakes, swamps, and even caves (Kozák et al. 2015; Stern and Crandall 2018). Several crayfish species are exploited by humans for various purposes such as consumption, pet trade, fish bait, food for fish, educational and scientific activities (Peay et al. 2010; Faulkes 2015a; Patoka et al. 2015b, 2016a; Hossain et al. 2018; Oficialdegui et al.

2019). In comparison with a long history of ornamental fish aquaculture (Novák et al. 2020), culture and trade with ornamental crayfish started not earlier than in the 1990s (Chucholl 2013; Faulkes 2015a). Crayfish are cultured both in outdoor and indoor facilities and also harvested from the wild (Holdich 1993; Jones and Geddes 1997; McClain 2020). Certain ornamental crayfish have escaped or were intentionally released out of their native range, subsequently establishing feral populations and behaving as invaders despite wildlife management activities and related legislative restrictions (Weiperth et al. 2017; Patoka et al. 2018b; Oficialdegui et al. 2020). Invasive crayfish cause environmental and socio-economic losses with negative impacts on the native biota and the entire ecosystem, and also on human communities (Ficetola et al. 2012; Oficialdegui et al. 2019). Crayfish are hard to detect in the early stages of an invasion and their later effective eradication is extremely difficult or even impossible, leaving prevention of further harmful introductions as the most effective management strategy (Gherardi et al. 2011; Lidova et al. 2019).

While the ornamental fish trade is led by Singapore (Evers et al. 2019), Indonesia has been identified as the leading exporter of ornamental crayfish (Faulkes 2015b; Patoka et al. 2015c). Indonesia is the world's largest island country covering three biodiversity hotspots, Sundaland, Wallacea and Sahul, with very rich endemic biota (Myers et al. 2000). The territory of Indonesia also includes the western part of the island of New Guinea (Dutch New Guinea in the past, currently Papua and West Papua Provinces), with numerous endemic *Cherax* crayfish species (Bláha et al. 2016). This group includes also the recently discovered and described *Cherax acherontis* Patoka, Bláha and Kouba, 2017, *C. alyciae* Lukhaup, Eprilurahman and von Rintelen, 2018, *C. gherardii* Patoka, Bláha and Kouba 2015a, *C. mosessalossa* Lukhaup, Eprilurahman and von Rintelen, 2018, *C. pulcher* Lukhaup, 2015, *C. snowden* Lukhaup, Panteleit and Schrimpf, 2015, and *C. warsamsonicus* Lukhaup, Eprilurahman and von Rintelen, 2017. Their scientific description has been promoted by a high popularity as ornamental pets due to their attractive colouration (Chucholl and Wendler 2017). These crayfish are exclusively collected from the wild and exported through the main crayfish market in Sorong, West Papua Province, Indonesia (Lukhaup 2015). More scientifically as-yet unknown species with a potential to be also pet-traded are expected to occur in this island (Patoka 2020; Weiperth et al. 2020).

Apart from these wild-captured crayfish, there is also one native *Cherax* crayfish which is relatively easy to rear and breed, i.e. *C. quadricarinatus* (von Martens, 1868). The species is native to the southern part of New Guinea and northwestern Australia (Haubrock et al. 2021) and has been introduced out of its native range to numerous new localities across the Indonesian territory where it is farmed and exploited for human consumption as well as for the pet trade (Patoka et al. 2016b, 2018a; Akmal et al. 2021).

Semi-intensive farms producing *C. quadricarinatus* were established in Indonesia as early as 2003 (Edgerton 2005).

In contrast to the previous assumption that just *Cherax* crayfish are cultured in Indonesia (Patoka et al. 2015c), the North American *Procambarus clarkii* (Girard, 1852) was recently also found being farmed as ornamental crayfish. As reported by Putra et al. (2018), this species is a vector of the crayfish plague pathogen (*Aphanomyces astaci* Schikora) whose occurrence was recorded in outdoor farming ponds with *P. clarkii* in Java. Infection with *A. astaci* was also confirmed in two other decapod species, i.e. the freshwater crab *Parathelphusa convexa* de Man, 1879 and the freshwater shrimp *Macrobrachium lanchesteri* (de Man, 1911). *Aphanomyces astaci* is known to be one of the most serious pathogens affecting decapod crustaceans (Lowe et al. 2000; Svoboda et al. 2017). Despite this serious threat to the native biota and the fact that importation of *P. clarkii* to Indonesia has been banned by Regulation No. 41/PERMEN-KP/2014, culture of this crayfish species and its transport within the country are legal (Putra et al. 2018).

The purpose of this study was to survey the history and pathways of non-native crayfish introductions in Java in order to prepare a recommendation on how to improve regulation and management of these decapod crustaceans.

## Materials and methods

In total, 33 localities in Bogor, Cilacap, Cirebon, Jakarta, Klaten, Magelang, Malang, Semarang, Surabaya, Tangerang, Wonosobo, and Yogyakarta regions were personaly surveyed between August and November 2019 in Java, Indonesia (Supplementary material Table S1). To obtain details about pathways and traded crayfish species, 13 farmers, 10 traders, four middlemen and eight crayfish owners were individually interviewed in Indonesian language (*Bahasa Indonesia*) on details such as the type of crayfish culture and management, lists of the stocked species and their origin, trends in their production, prices and sales, and distribution routes. The crayfish samples were identified morphologicaly based on previous descriptions (e.g. Clark 1936; Lukhaup and Herbert 2008; Yuliana et al. 2019).

## Results

In total, six non-native ornamental crayfish species were found to be cultured or imported. Five species belong to the genus *Cherax* (family Parastacidae), i.e., *Cherax destructor* Clark, 1936, *C. peknyi* Lukhaup and Herbert, 2008, *C. quadricarinatus*, *C. snowden* and *C. warsamsonicus*; and one species belongs to the genus *Procambarus,* i.e. *P. clarkii* (family Cambaridae). Of the recorded *Cherax* species, *C. destructor* is native to south-eastern Australia, while *C. peknyi*, *C. snowden* and *C. warsamsonicus*

**Table 1.** List of crayfish species exploited in Java, Indonesia: name of the species, native range, year of the introduction in Java, status (cultured or traded only), number of Javanese regions where the species occur, common price of adult individual (in USD).

| Species | Native range | Year of introduction | Status in Java | Regions | Common price for adults (USD) |
|---|---|---|---|---|---|
| *Cherax destructor* | Australia | 2005 | cultured | 2 | 50 |
| *Cherax peknyi* | New Guinea | 2005 | traded | 1 | 18 |
| *Cherax quadricarinatus* | Australia/New Guinea | 2000 | cultured | 24 | 7.5 |
| *Cherax snowden* | New Guinea | 2005 | traded | 1 | 18 |
| *Cherax warsamsonicus* | New Guinea | 2005 | traded | 2 | 18 |
| *Procambarus clarkii* | North America | 2009 | cultured | 13 | 2.5 |

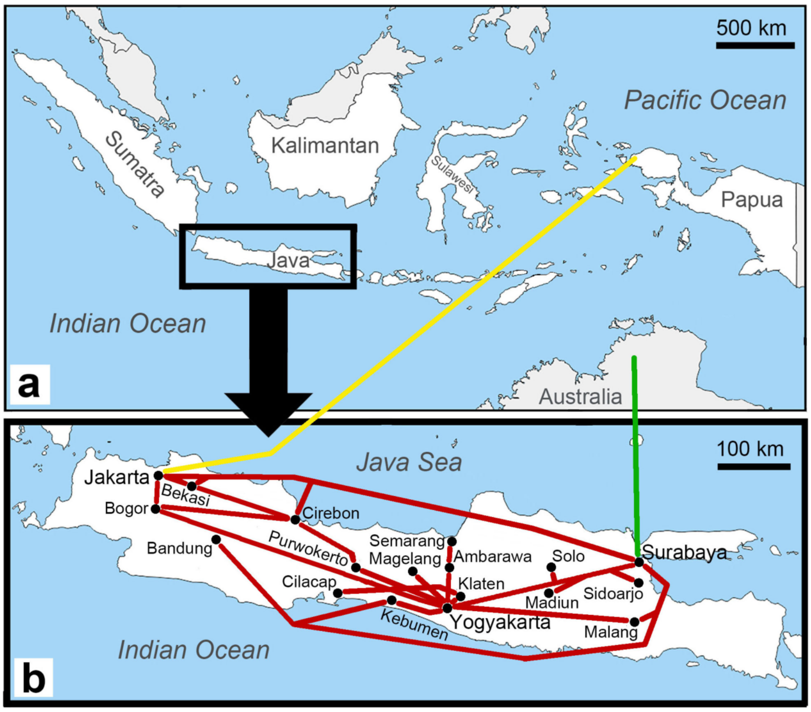


**Figure 1.** Map of Indonesia (a) and enlarged map of Java island (b) with the main routes of ornamental crayfish transportation highlighted as red lines. The first documented import is indicated by a green line. A yellow line indicates the main route used to transport of crayfish from Sorong in New Guinea to Jakarta for subsequent export abroad. Given lines do not show real traffic routes.

are native to New Guinea, and *C. quadricarinatus* is native to both Australia and New Guinea. *Procambarus clarkii* is from North America (Table 1).

The first recorded import of ornamental crayfish to Java was to Surabaya in 2000, involving *C. quadricarinatus* imported from Australia. Two peaks in the economic value of crayfish were recorded, one between 2008 and 2010 and one between 2014 and 2015. Surabaya and Yogyakarta were identified as hotspots of ornamental crayfish production in Java, while Jakarta was identified as the city where most of wholesalers and exporters are located. The main routes of ornamental crayfish transportation are given in Figure 1. Crayfish are cultured in outdoor ponds, concrete tanks, indoor aquaria and in natural lakes and reservoirs (Figures 2, 3c, d). Worms, bean sprouts, rice, corn, cassava, and pest gastropods from paddy fields

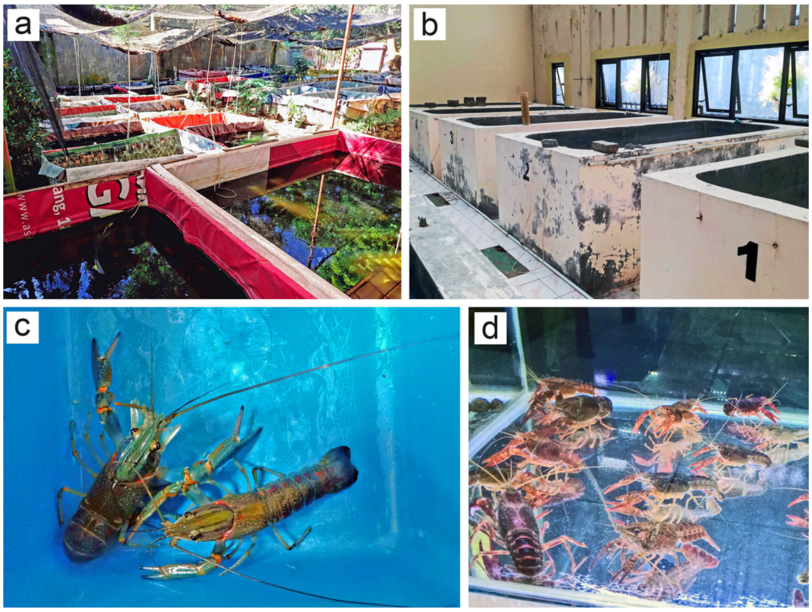

**Figure 2.** Culture of non-native ornamental crayfish in Indonesia: outdoor farm close to Purwokerto (a); indoor concrete tanks in Magelang (b); *Cherax quadricarinatus* produced in outdoor concrete reservoirs in Cirebon (c); *Procambarus clarkii* in a pet shop in Bogor (d). Author of the pictures: JP.

**Figure 3.** Culture of non-native ornamental crayfish in Indonesia: two types of outflow from farm, drainage (a) and hole (b); concrete tank equipped with shelters (c); outdoor concrete tank (d). Author of the pictures: JP.

(*Pomacea* sp.) are commonly used as feed for farmed crayfish. Since there are no official standard prices in Indonesia, the recorded prices can vary depending on the current demand. Waste water outflow is usually directly connected with streams in vicinity via drainage (Figure 3a, b).

*Details of surveyed regions:*

Bogor

Several pet shops in Bogor city trade in *C. quadricarinatus* and *P. clarkii* as ornamental crayfish. The latter is advertised in various colouration forms such as wild, white, orange, and full red (also known as "Marlboro"). The vast majority of these crayfish are locally produced in outdoor facilities in quantities of more than 1,000 individuals per month. Crayfish are reared in net cages in lakes and also in artificial pond systems from both of which they can easily escape.

Cilacap

The only crayfish species produced in this region is *C. quadricarinatus*. Middlemen in Cilacap town collect crayfish from three main local producers and obtain 1–5 kg of crayfish per week. Crayfish are produced mainly during the rainy season, from November to March. The common price is USD 6.80 per kg for adults, and USD 5.10 per kg for subadults. There are 5–6 crayfish collectors around Wadasilintang dam circa 120 km east of Cilacap town who harvest 3 kg of crayfish per day and collector. The harvested crayfish are usually delivered 160 km eastwards to Klaten city.

Cirebon

In three pet shops in Kanoman fishmarket in Cirebon, *C. destructor*, *C. quadricarinatus*, *C. snowden*, *C. warsamsonicus* and *P. clarkii* are traded. These crayfish are partly delivered from Bogor, Purwokerto and Surabaya, partly locally produced. *Cherax snowden* and *C. warsamsonicus* are strictly imported from West Papua Province and not bred in Java. *Cherax destructor* is rare and has a high price compared to other crayfish species, ranging from USD 49.25 to USD 56.28 per adult pair. The number is limited and the species is usually sold as adults. The common price for *C. quadricarinatus* is USD 0.34–0.68 per subadult individual, which are relatively common in the market, and USD 15.33 per adult pair. The common price for *C. snowden* and *C. warsamsonicus* is USD 3.52–5.63 per subadult individual and USD 35.18 per adult pair. The price is expensive because these species are rare in the market. The common price for *P. clarkii* is USD 0.34–1.02 per adult individual. In 2010, circa 100 individuals of all mentioned species were sold per week but subsequently the demand has gradually declined while the number of local producers has been increasing. Therefore, the production and trade in crayfish is currently perceived as unattractive in this region and is likely to be abandoned in the near future.

Jakarta

Ornamental crayfish of all recorded species are delivered to wholesaler facilities in the capital city Jakarta. These crayfish are stocked and subsequently offered and exported to the European Union, United States and Japan. Part of them is also delivered to local retailers, including pet shops and street markets. As previously reported, endemic crayfish (e.g. *Cherax boesemani*, *C. gherardii*, *C. holthuisi* or *C. pulcher*) wild-harvested in New Guinea are transported from Sorong to Jakarta but no local trade was recorded. Many New Guinean crayfish are injured and mortality is high (up to 90% depending on the experience of the importers). In pet shops, crayfish of different taxa are usually stocked in the same tank including *Cherax* species susceptible to crayfish plague, and *P. clarkii*, which is a carrier of the disease agent.

Malang

*Cherax quadricarinatus* is cultured in outdoor facilities around Karangkates reservoir, about 35 km south of Malang. In 2018, the demand for crayfish declined and just a single producer with 12 ponds continues in their production. Most crayfish are produced for human consumption, sold locally, transported to Bali and also delivered to Surabaya and exported to Japan. Some of these crayfish may also be sold as ornamentals even if clear evidence of this is lacking.

Semarang

There are two species produced in Semarang, i.e. *C. quadricarinatus* and a red form of *P. clarkii*. The production of crayfish started more than 10 years ago in this region. The peak was documented in 2010 with a price of USD 10.23 per kg of *C. quadricarinatus*. Currently, more producers are rearing *P. clarkii* than *C. quadricarinatus*.

Surabaya

Surabaya is the first place where the ornamental crayfish were introduced in Java. In 2000, *C. destructor* and probably also *C. quadricarinatus* were imported here from their native range in Australia. In subsequent years, *C. peknyi*, *C. warsamsonicus*, and *P. clarkii* were also introduced to the market as ornamentals. The common price was up to USD 6.80 per kg but fell to USD 3.40 per kg in 2008. In 2012, the price increased again to USD 6.80 per kg and production began to rise. Crayfish were delivered to the cities of Bandung, Bekasi, Jakarta, Madiun, Malang and Yogyakarta, and to the islands of Bali, Lombok, Sulawesi and Sumatra in Indonesia; and also to Japan, Malaysia, Singapore, Thailand, Taiwan, and Vietnam. Both purposes, for human consumption and the pet trade, were recognized within this period. Currently, exports to the mentioned countries have been largely terminated but some shipments are delivered to Taiwan, Thailand, and Vietnam.

Yogyakarta

Yogyakarta (also known as Jogja) represents the hotspot of crayfish production in Java. There are three species produced in Yogyakarta, namely

*C. quadricarinatus*, *C. destructor* and *P. clarkii*. Moreover, another species *C. peknyi* is imported from Surabaya and its culture was trialled in 2015 in Magelang but terminated after a short period due to its aggressiveness and the ineffectiveness of the culture. Crayfish produced in Yogyakarta are delivered to the cities of Ambarawa, Cirebon, Jakarta, Kebumen, Klaten, Magelang, Malang, Purwokerto, Semarang, Sidoarjo, Solo and Surabaya, and to Sulawesi island. Local farms were established also in the mentioned cities and in their vicinity, such as the outdoor facility close to Purwokerto. Farms in Yogyakarta are in intensive cooperation with those in Klaten. *Procambarus clarkii* is produced for further culture for ornamental purposes at a size of 2.5–4.0 cm and up to 1,000 individuals are sold per week. The common price for *P. clarkii* is USD 2.56–2.93 per individual. From 2004 to 2015, the production and prices of *P. clarkii* were the highest and declined from 2016. There were 14 pet shops in Yogyakarta before 2008 but after the price decline just four currently advertise crayfish as ornamentals, with up to 100 individuals sold per week. The common price for *C. quadricarinatus* and *C. destructor* is USD 0.34–21.34 per individual depending on the size class of the crayfish.

## Discussion

Since 2000, when the first crayfish were imported to Java, six ornamental crayfish species were found to be more or less frequently traded and transported to several places on this island. The list of species is probably incomplete with regard to highly valued endemic crayfish collected in the wild in New Guinea, which are not cultured in Java due to their high aggressiveness. Based on previous studies (Patoka et al. 2014; Faulkes 2015a; Kotovska et al. 2016), we assume that there are plenty of New Guinean crayfish harvested and exported directly from Papua Province for trade and keeping in aquaria worldwide.

Just one North American crayfish species was recorded in Indonesia, i.e. *P. clarkii*; we did not record more North American species, even if they might be expected to occur due to their popularity as ornamentals (Yonvitner et al. 2020). Further, *P. clarkii* was confirmed to be a vector of the crayfish plague pathogen (Putra et al. 2018). Its spread in Java is therefore highly alarming and a threat both to crayfish aquaculture and to the native freshwater biota in general.

The most commonly cultured crayfish is *C. quadricarinatus*. The species has escaped from aqucultural facilities such as net cages and established self-sustainable populations in many water bodies in Java. Since it is a large-growing, omnivorous crustacean able to prey on invertebrates and small vertebrates, this crayfish poses a threat to the native biota despite its sensitivity to crayfish plague (Hsieh et al. 2016; Haubrock et al. 2021).

Endemic New Guinean crayfish such as *C. peknyi*, *C. snowden*, and *C. warsamsonicus* are stocked and traded in much lower quantities than both the aforementioned species. Moreover, culture of these species is unprofitable because they are more difficult to rear and their environmental plasticity is probably limited. Their potential invasivness is therefore presumably low and these species can be classified as low risk to the Javanese biota. Furthermore, New Guinean endemic crayfish usually have very restricted native ranges (Bláha et al. 2016; Patoka 2020) and ongoing harvest for the international pet trade may cause dramatic consequences for these taxa (Tapkir et al. 2021). Unambiguous identification of collected and traded species is crucially important; in New Guinean crayfish, much confusion exists in the morphological characteristics used in species identification. Even if recent publications suggest some new characteristics (Kawai and Patoka 2020, 2021), the detailed revision of this group of parastacids is greatly needed.

Part of ornamental *Cherax* crayfish is exported from Jakarta and Surabaya abroad: to other Southeast Asian countries, to the Japan, European Union, and to the United States. Their assessed risks of biological invasion are low and hence these crayfish are not banned there (Patoka et al. 2014). Surprisingly, despite the higher price of ornamental New Guinean crayfish (Chucholl 2013; Patoka et al. 2015c), several individuals were recently recorded released in Hungarian thermal waters (Weiperth et al. 2020) where also tropical shrimps were previously found (Weiperth et al. 2019). The possibility of a future ban proposal based on further monitoring cannot be excluded. This assumption should reach the attention of Indonesian traders and wildlife managers who are dealing with the mentioned group of species.

Indonesia is generally perceived as being the supplier of ornamental aquatic organisms on a global scale but the local market is usually ignored or neglected (Patoka et al. 2015c; Evers et al. 2019). Based on the presented findings, it is obvious that the local market is well-developed and several crayfish are sold as ornamentals each week in plenty of places in Java, especially in the three identified hotspots Jakarta, Surabaya and Yogyakarta. It is likely that recorded trading routes connect the vast majority of the island and crayfish are commonly available for ornamental aquaculture enthusiastics in huge quantities. Since crayfish infected by the crayfish plague pathogen were previously found in a pet shop in Bogor (Putra et al. 2018), there is a high risk of further spread of the pathogen via this pathway. As is our knowledge, the farmers do not rigorously control neither potential escapes of crayfish larvae nor pathogen transmission via the waste water runoff. This is alarming especially for the conservation of endemic New Guinean parastacids (Yonvitner et al. 2020). For instance, stocking of North American and New Guinean crayfish in the same tank should be prohibited due to the high probability of crayfish plague pathogen transmission. Moreover, focused rigorous biocontrol measures in the existing culture of *P. clarkii* should be mandatory to prevent the pathogen spreading: different gear, separate water supply and disinfection of water runoff.

While the Indonesian government endorsed the inland water bodies management to regulate invasive species including crayfish, the further spread of at least *C. quadricarinatus* and *P. clarkii* is likely. Therefore, continuous monitoring of the distribution, trade and related environmental and socio-economic impacts of non-native crayfish are strongly recommended. Since *P. clarkii* is generally classified as a high-risk species and succesful invader (Chucholl 2013; Patoka et al. 2014; Putra et al. 2018), spread of this crayfish poses a serious threat for Indonesian biota and, in case of crayfish plague transmission, also for the aquaculture. For this reason, we propose the total ban of this species in Indonesia.

## Acknowledgements

Dr Julian Reynolds of Trinity College Dublin, checked the English language in this article.We thank the anonymous reviewers for their helpful and constructive comments and suggestions.

## Funding declaration

This study was supported by The Indonesian Crayfish Research Group. AK acknowledges the Czech Science Foundation (project no. 19-04431S). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

## Authors' contribution

EY, Y, JP: sample design and methodology; SGA, RAS, SAR: investigation and data collection; SGA, JP: data analysis and interpretation; JP: author of pictures; EY, Y, AS: ethics and field work approval; EY, Y, AK: funding provision; EY, Y, SGA: writing – original draft; JP, AK: writing – review and editing.

## References

Akmal SG, Santoso A, Yonvitner, Yuliana E, Patoka J (2021) Redclaw crayfish (*Cherax quadricarinatus*): Spatial distribution and dispersal pattern in Java, Indonesia. *Knowledge and Management of Aquatic Ecosystems* 422: 16, https://doi.org/10.1051/kmae/2021015

Bláha M, Patoka J, Kozák P, Kouba A (2016) Unrecognized diversity in New Guinean crayfish species (Decapoda, Parastacidae): The evidence from molecular data. *Integrative Zoology* 11: 457–468, https://doi.org/10.1111/1749-4877.12211

Chucholl C (2013) Invaders for sale: trade and determinants of introduction of ornamental freshwater crayfish. *Biological Invasions* 15: 125–141, https://doi.org/10.1007/s10530-012-0273-2

Chucholl C, Wendler F (2017) Positive selection of beautiful invaders: long-term persistence and bio-invasion risk of freshwater crayfish in the pet trade. *Biological Invasions* 19: 197–208, https://doi.org/10.1007/s10530-016-1272-5

Clark E (1936) The freshwater and land crayfishes of Australia. *Memoirs of the National Museum, Melbourne* 10: 5–58, https://doi.org/10.24199/j.mmv.1936.10.01

Edgerton BF (2005) Freshwater crayfish production for poverty alleviation. *World Aquaculture* 36: 48–64

Evers HG, Pinnegar JK, Taylor MI (2019) Where are they all from? - sources and sustainability in the ornamental freshwater fish trade. *Journal of Fish Biology* 94: 909–916, https://doi.org/10.1111/jfb.13930

de Man JG (1879) On some new or imperfectly known podophthalmous crustacea of the Leyden Museum. *Notes from the Leyden Museum* 1: 53–73

de Man JG (1911) On the West-African species of the subgenus *Eupalaemon* Ortm. *Notes from the Leyden Museum* 33: 261–264

Faulkes Z (2015a) The global trade in crayfish as pets. *Crustacean Research* 44: 75–92, https://doi.org/10.18353/crustacea.44.0_75

Faulkes Z (2015b) Marmorkrebs (*Procambarus fallax* f. *virginalis*) are the most popular crayfish in the North American pet trade. *Knowledge and Management of Aquatic Ecosystems* 416: 20, https://doi.org/10.1051/kmae/2015016

Ficetola GF, Siesa ME, De Bernardi F, Padoa-Schioppa E (2012) Complex impact of an invasive crayfish on freshwater food webs. *Biodiversity Conservation* 21: 2641–2651, https://doi.org/10.1007/s10531-012-0323-1

Gherardi F, Aquiloni L, Diéguez-Uribeondo J, Tricarico E (2011) Managing invasive crayfish: is there a hope? *Aquatic Sciences* 73: 185–200, https://doi.org/10.1007/s00027-011-0181-z
Girard CF (1852) A revision of the North American Astaci, with observations on their habits and geographic distribution. *Proceedings of Academy of Natural Sciences of Philadelphia* 6: 87–91
Haubrock PJ, Oficialdegui FJ, Zeng Y, Patoka J, Yeo DCJ, Kouba A (2021) The redclaw crayfish: A prominent aquaculture species with invasive potential in tropical and subtropical biodiversity hotspots. *Reviews in Aquaculture* 13: 1488–1530, https://doi.org/10.1111/raq.12531
Holdich DM (1993) A review of astaciculture: freshwater crayfish farming. *Aquatic Living Resources* 6: 307–317, https://doi.org/10.1051/alr:1993032
Hossain MS, Patoka J, Kouba A, Buřič M (2018) Clonal crayfish as biological model: a review on marbled crayfish. *Biologia* 73: 841–855, https://doi.org/10.2478/s11756-018-0098-2
Hsieh CY, Huang CW, Pan YC (2016) Crayfish plague *Aphanomyces astaci* detected in redclaw crayfish, *Cherax quadricarinatus* in Taiwan. *Journal of Invertebrate Pathology* 136: 117–123, https://doi.org/10.1016/j.jip.2016.03.015
Jones C, Geddes MC (1997) Australian freshwater crayfish: exploitation by fishing and aquaculture. Australian Biologist 10: 70–75
Kawai T, Patoka J (2020) Morphology of gastric mills and mandibles of New Guinean parastacid crayfishes, with comparisons with other Astacidea (Decapoda). *Journal of Crustacean Biology* 40: 692–703, https://doi.org/10.1093/jcbiol/ruaa081
Kawai T, Patoka J (2021) Gill morphology and formulae of crayfishes (Decapoda: Astacidea: Parastacidae) from New Guinea and New Zealand and a comparison with other selected species of crayfishes. *Journal of Crustacean Biology* 41, https://doi.org/10.1093/jcbiol/ruab004
Kotovska G, Khrystenko D, Patoka J, Kouba A (2016) East European crayfish stocks at risk: arrival of non-indigenous crayfish species. *Knowledge and Management of Aquatic Ecosystems* 417: 37, https://doi.org/10.1051/kmae/2016024
Kozák P, Ďuriš Z, Petrusek A, Buřič M, Horká I, Kouba A, Kozubíková-Balcarová E, Policar T (2015) Crayfish biology and culture. University of South Bohemia in České Budějovice, Faculty of Fisheries and Protection of Waters, 456 pp
Lidova J, Buric M, Kouba A, Velisek J (2019) Acute toxicity of two pyrethroid insecticides for five non-indigenous crayfish species in Europe. *Veterinární Medicína-Czech* 64: 125–133, https://doi.org/10.17221/136/2018-VETMED
Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the World's Worst Invasive Alien Species: A Selection from the Global Invasive Species Database. Invasive Species Specialist Group, Auckland, New Zealand, 12 pp
Lukhaup C (2015) *Cherax* (*Astaconephrops*) *pulcher*, a new species of freshwater crayfish (Crustacea, Decapoda, Parastacidae) from the Kepala Burung (Vogelkop) Peninsula, Irian Jaya (West Papua), Indonesia. *ZooKeys* 502: 1–10, https://doi.org/10.3897/zookeys.502.9800
Lukhaup C, Herbert B (2008) *Cherax* (*Cherax*) *peknyi* sp. nov., a new species of crayfish (Crustacea: Decapoda: Parastacidae) from the Fly River Drainage, Western Province, Papua New Guinea. *Memoirs of the Queensland Museum* 52: 213–219
Lukhaup C, Panteleit J, Schrimpf A (2015) *Cherax snowden*, a new species of crayfish (Crustacea, Decapoda, Parastacidae) from the Kepala Burung (Vogelkop) Peninsula in Irian Jaya (West Papua), Indonesia. *ZooKeys* 518: 1–14, https://doi.org/10.3897/zookeys.518.6127
Lukhaup C, Eprilurahman R, von Rintelen T (2017) *Cherax warsamsonicus*, a new species of crayfish from the Kepala Burung (Vogelkop) peninsula in West Papua, Indonesia (Crustacea, Decapoda, Parastacidae). *ZooKeys* 660: 151–167, https://doi.org/10.3897/zookeys.660.11847
Lukhaup C, Eprilurahman R, von Rintelen T (2018) Two new species of crayfish of the genus *Cherax* from Indonesian New Guinea (Crustacea, Decapoda, Parastacidae). *ZooKeys* 769: 89–116, https://doi.org/10.3897/zookeys.769.26095
McClain WR (2020) Crayfish aquaculture. In: Lovrich G, Thiel M (eds), Fisheries and Aquaculture. Oxford University Press, New York, pp 259–284, https://doi.org/10.1093/oso/9780190865627.003.0011
Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858, https://doi.org/10.1038/35002501
Novák J, Kalous L, Patoka J (2020) Modern ornamental aquaculture in Europe: early history of freshwater fish imports. *Reviews in Aquaculture* 12: 2042–2060, https://doi.org/10.1111/raq.12421
Oficialdegui FJ, Clavero M, Sánchez MI, Green AJ, Boyero L, Michot TC, Kristie K, Kawai T, Lejeusne C (2019) Unravelling the global invasion routes of a worldwide invader, the red swamp crayfish (*Procambarus clarkii*). *Freshwater Biology* 64: 1382–1400, https://doi.org/10.1111/fwb.13312
Oficialdegui FJ, Delibes-Mateos M, Green AJ, Sánchez MI, Boyero L, Clavero M (2020) Rigid laws and invasive species management. *Conservation Biology* 34: 1047–1050, https://doi.org/10.1111/cobi.13481
Patoka J (2020) Crayfish of New Guinea: Current status, exploitation and threats. In: Ribeiro F (ed), Crayfish: Evolution, Habitat and Conservation Strategies. Nova Science Publishers, New York, 43–69 pp
Patoka J, Kalous L, Kopecký O (2014) Risk assessment of the crayfish pet trade based on data from the Czech Republic. *Biological Invasions* 16: 2489–2494, https://doi.org/10.1007/s10530-014-0682-5
Patoka J, Bláha M, Kouba A (2015a) *Cherax* (*Astaconephrops*) *gherardii*, a new crayfish (Decapoda: Parastacidae) from West Papua, Indonesia. *Zootaxa* 3964: 526–536, https://doi.org/10.11646/zootaxa.3964.5.2
Patoka J, Bláha M, Kouba A (2015b) *Cherax* (*Cherax*) *subterigneus*, a new crayfish (Decapoda: Parastacidae) from West Papua, Indonesia. *Journal of Crustacean Biology* 35: 830–838, https://doi.org/10.1163/1937240X-00002377

Patoka J, Kalous L, Kopecký O (2015c) Imports of ornamental crayfish: the first decade from the Czech Republic's perspective. *Knowledge and Management of Aquatic Ecosystems* 416: 4, https://doi.org/10.1051/kmae/2014040

Patoka J, Kocánová B, Kalous L (2016a) Crayfish in Czech cultural space: the longest documented relationship between humans and crayfish in Europe. *Knowledge and Management of Aquatic Ecosystems* 417: 5, https://doi.org/10.1051/kmae/2015038

Patoka J, Wardiatno Y, Kuříková P, Petrtýl M, Kalous L (2016b) *Cherax quadricarinatus* (von Martens) has invaded Indonesian territory west of the Wallace Line: evidences from Java. *Knowledge and Management of Aquatic Ecosystems* 417: 39, https://doi.org/10.1051/kmae/2016026

Patoka J, Bláha M, Kouba A (2017) *Cherax acherontis* (Decapoda: Parastacidae), the first cave crayfish from the Southern Hemisphere (Papua Province, Indonesia). *Zootaxa* 4363: 137–144, https://doi.org/10.11646/zootaxa.4363.1.7

Patoka J, Wardiatno Y, Mashar A, Wowor D, Jerikho R, Takdir M, Purnamasari L, Petrtýl M, Kalous L, Kouba A, Bláha M (2018a) Redclaw crayfish, *Cherax quadricarinatus* (von Martens, 1868), widespread throughout Indonesia. *BioInvasions Records* 7: 185–189, https://doi.org/10.3391/bir.2018.7.2.11

Patoka J, Magalhães ALB, Kouba A, Faulkes Z, Jerikho R, Vitule JRS (2018b) Invasive aquatic pets: failed policies increase risks of harmful invasions. *Biodiversity Conservation* 27: 3037–3046, https://doi.org/10.1007/s10531-018-1581-3

Peay S, Holdich DM, Brickland J (2010) Risk assessments of non-indigenous crayfish in Great Britain. Freshwater Crayfish 17: 109-122

Putra MD, Bláha M, Wardiatno Y, Krisanti M, Jerikho R, Kamal MM, Mojžišová M, Bystřický PK, Kouba A, Kalous L, Petrusek A, Patoka J (2018) *Procambarus clarkii* (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. *Aquatic Conservation: Marine and Freshwater Ecosystems* 28: 1434–1440, https://doi.org/10.1002/aqc.2970

Stern DB, Crandall KA (2018) Phototransduction gene expression and evolution in cave and surface crayfishes. *Integrative and Comparative Biology* 58: 398–410, https://doi.org/10.1093/icb/icy029

Svoboda J, Mrugala A, Kozubíková-Balcarová E, Petrusek A (2017) Hosts and transmission of the crayfish plague pathogen *Aphanomyces astaci*: a review. *Journal of Fish Diseases* 40: 127–140, https://doi.org/10.1111/jfd.12472

Tapkir SD, Kumkar P, Gosavi SM, Kharat SS, Patoka J, Kalous L (2021) Far from home: tracking the global ornamental fish trade in endangered zebra loach, *Botia striata*, from freshwater ecoregion and biodiversity hotspot in India. *Journal for Nature Conservation* 61: 126007, https://doi.org/10.1016/j.jnc.2021.126007

von Martens E (1868) Über eine neue Art und Untergattung der Cyprinoiden, *Homaloptera* (*Octonema*) *rotundicauda*, über einige neue Crustaceen und über die neuholländischen Süsswasserkrebse. *Monatsberichte der Königlichen Akademie der Wissenschaften zu Berlin, Physikalisch-mathematische Klasse* 1868: 607–619

Weiperth A, Gál B, Kuříková P, Bláha M, Kouba A, Patoka J (2017) *Cambarellus patzcuarensis* in Hungary: The first dwarf crayfish established outside of North America. *Biologia* 72: 1529–1532, https://doi.org/10.1515/biolog-2017-0159

Weiperth A, Gábris V, Danyik T, Farkas A, Kuříková P, Kouba A, Patoka J (2019) Occurrence of non-native red cherry shrimp in European temperate waterbodies: a case study from Hungary. *Knowledge and Management of Aquatic Ecosystems* 420: 9, https://doi.org/10.1051/kmae/2019002

Weiperth A, Bláha M, Szajbert B, Seprős R, Bányai Z, Patoka J, Kouba A (2020) Hungary: a European hotspot of non-native crayfish biodiversity. *Knowledge and Management of Aquatic Ecosystems* 421: 43, https://doi.org/10.1051/kmae/2020035

Yonvitner Y, Patoka J, Yuliana E, Bohatá L, Tricarico E, Karella T, Kouba A, Reynolds JD (2020) Enigmatic hotspot of crayfish diversity at risk: Invasive potential of non-indigenous crayfish if introduced to New Guinea. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30: 219–224, https://doi.org/10.1002/aqc.3276

Yuliana E, Yonvitner, Jerikho R, Bláha M, Patoka J (2019) Unusual rostral deformity in *Cherax quadricarinatus* (von Martens, 1868). *Workshop on Biodiversity, Jevany* 11: 201–206

**Supplementary material**

The following supplementary material is available for this article:

**Table S1.** List of surveyed localities in Java, Indonesia: name of the region and GPS coordinates. This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2021/Supplements/MBI_2021_Yuliana_etal_SupplementaryMaterial.xlsx

## 6.4 Vulnerability Status of the Coral Ecosystem in Kepulauan Seribu Marine National Park, Indonesia

Yonvitner, Agus SB, Lestari DF, Pasaribu R, Supriyanto E, Widodo C, Sugara A, Patoka J, **Akmal SG.** 2022. Vulnerability status of the coral ecosystem in Kepulauan Seribu Marine National Park, Indonesia. *Coastal Management*, 50:3, 251-261. https://doi.org/10.1080/08920753.2022.2037388

The article "Vulnerability Status of Coral Ecosystems in the Thousand Islands Marine National Park, Indonesia" investigates the vulnerability of coral ecosystems in the Kepulauan Seribu National Marine Park, Indonesia. The study discovered that coral ecosystems in the marine national park are vulnerable to a variety of threats, including climate change, overfishing, and pollution. Based on the findings, islands in the park were classified as high vulnerability (64%), medium vulnerability (19.6%), and low vulnerability (16.07%). Our study has highlighted the importance of monitoring coral ecosystems to trace the changes over time and better inform conservation efforts. However, significant research on coral disease in Southeast Asia, including Indonesia, is lacking.

The study results do not provide a direct comparison of the vulnerability levels of the coral ecosystem in Kepulauan Seribu Marine National Park to those in other marine parks in Indonesia. However, other studies have shown that coral reefs across Karimunjawa National Park in Indonesia are being impacted by fishing, tourism, declining water quality, and climate change. The study "Community champions of ecosystem services: The role of local agency in protecting Indonesian coral reefs" highlights the serious impacts of destructive fishing practices on marine and coastal ecosystems in eastern Indonesia (Kennedy et al., 2020). Nonetheless, further research is needed to make a direct comparison of the vulnerability levels of the coral ecosystem in Kepulauan Seribu Marine National Park to those in other marine parks in Indonesia.

COASTAL MANAGEMENT
2022, VOL. 50, NO. 3, 251–261
https://doi.org/10.1080/08920753.2022.2037388



# Vulnerability Status of the Coral Ecosystem in Kepulauan Seribu Marine National Park, Indonesia

Yonvitner[a,b], Syamsul Bahri Agus[c], Dea Fauzia Lestari[c], Riza Pasaribu[c], Eko Supriyanto[c], Cahyo Widodo[c], Ayub Sugara[c], Jiří Patoka[d] and Surya Gentha Akmal[b,d]

[a]Department of Aquatic Resources Management, Faculty of Fisheries, and Marine Science, IPB University, Indonesia; [b]Centre for Coastal and Marine Resources Studies, IPB University, Indonesia; [c]Department Marine Science, Faculty of Fisheries and Marine Science, IPB University, Indonesia; [d]Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Czech Republic

**ABSTRACT**
Coral reefs are one of the most threatened ecosystems globally. Coral reef ecosystem (CRE) status is an essential indicator in measuring the potential for sustainable management of coral resources in small islands and islets. In this study, the parameters used are coral cover, coral mortality index, and potential exposure. The study was conducted on 56 islands in the Kepulauan Seribu Marine National Park in Indonesia during June 2019. Based on the findings, islands were classified as high-vulnerable (64%), moderate vulnerable (19.6)%, and low vulnerable (16.07%). Results indicated that the sustainability of surveyed coral reef ecosystems is seriously endangered. For this reason, a systematic effort is recommended to mitigate the risks. Among others, coral reefs need to be protected from various waste threats, overfishing, and tourist behavior damaging coral reefs would be regulated.

**KEYWORDS**
conservation; coral reef; exposure; mortality; risk

## Introduction

The Kepulauan Seribu (also known as Thousand Islands) is a group of small islands that have a coral reef ecosystem north of Java's coast in Indonesia. The Kepulauan Seribu coral reef ecosystem is classified as a small island ecosystem with a lot of pressure from human activities in coastal and marine surroundings. The threat of coral reefs in the Thousand Islands is caused by a combination of source impacts such as sea surface temperature, debris, and plastic waste, as well as oil spills and anthropogenic resources from local communities (McLeod et al., 2010), and fishing operation (Cinner et al. 2009). Jabbar, Soesilo, and Hamzah (2018) record since 20103-2018, Oil spills accidents have been occurred about 12 times and causing negative impacts to sensitive areas such as fisheries, corals, mangroves, and mariculture also, tourism areas. Since 1982, the Kepulauan Seribu has been designated as a marine nature reserve area, and

**CONTACT** Yonvitner yonvitr@yahoo.com Department of Aquatic Resources Management, Faculty of Fisheries, and Marine Science, IPB University, Indonesia

then in 1995, it became the Thousand Islands Marine National Park through Decree of the Minister of Forestry Ab 161/Kpts-II/95 with an area of 108,000 ha. Coral cover level was 33.00% in 2003, 31,98% in 2005, (Setiawan et, al 2009), 34,60% (2009), 32,27% (Zamani & Madduppa, 2011). The increasing touristic activities in these coral reef areas have a negative impact on the coral cover on Panggang Island between 8.10-27.20%. (Prasetyo and Yuliadi 2018), and Congkak Island by 27.41% (2019). Research by Yusnita (2014) showed that a huge increase in tourism began to occur in 2012 and 2013, where the coral cover was observed at 46.2% (3 m depth) and 34.3% (10 m depth). It was also found that the rate of damage due to diving reached 7.57% per year, and snorkeling 8.20% per year. The pressure on the Kepulauan Seribu ecosystem is caused by various natural, human, and environmental factors. Terrestrial anthropogenic activities affect this environment at least 45 km from the main island (Uneputty and Evans 1997). Moreover, Suhery, Damar, and Effendi (2017) note that the coral ecosystem on Holland Island (the core zone of the Marine National Park), which is more than 45 km from the main island, is already threatened and vulnerable. The distribution of suspended matter due to oceanographic dynamics in the southern part of the Kepulauan Seribu affected coral cover at a depth of 4 m which was recorded at 35.55% of the monitored area (Daniel and Santosa 2013). Environmental influences such as temperature change causing bleaching events on sponge corals were detected there, for instance, close to the Pari Island (Hoeksema 1991). For this reason, monitoring of the rate of degradation of coral ecosystems due to human activities needs to be continuously observed in this region. Generally, the risk indicators are coverage, richness, diversity (Cleary and Hoeksema 2006), which also illustrate the status of coral ecosystems. However, currently, an indicator used as a vulnerability criterium is the mortality or death rate in the coral ecosystem. These two indicators can be combined as part of an assessment of the level of vulnerability (susceptibility) of small islands from coral ecosystems' status.

Change in coral cover is an indicator to explain coral ecosystems' health status, stability, and vulnerability. An increase in the coral mortality index has also been caused by increased stress and risk to live corals. Both decreasing coverage and increasing coral mortality are parts of the indicator of vulnerability of small islands such as Kepulauan Seribu.

Based on the aforementioned indicators, the status of coral reefs can also be determined. This process is crucial to prioritizing the correct ecosystem-based management of small islands in the Kepulauan Seribu. This study aims to cluster the status of this chain of small islands based on their vulnerability status. The vulnerability status should be used as the basis for further management of Kepulauan Seribu and can provide benefits for the policy-makers, conservationists, and other stakeholders to ascertain the quality of the ecosystem and follow-up steps to improve the sustainability of this region.

## Material and methods

### *Research area*

The research was conducted on 56 small islands in the North Kepulauan Seribu divided into 11 segments (Figure 1).

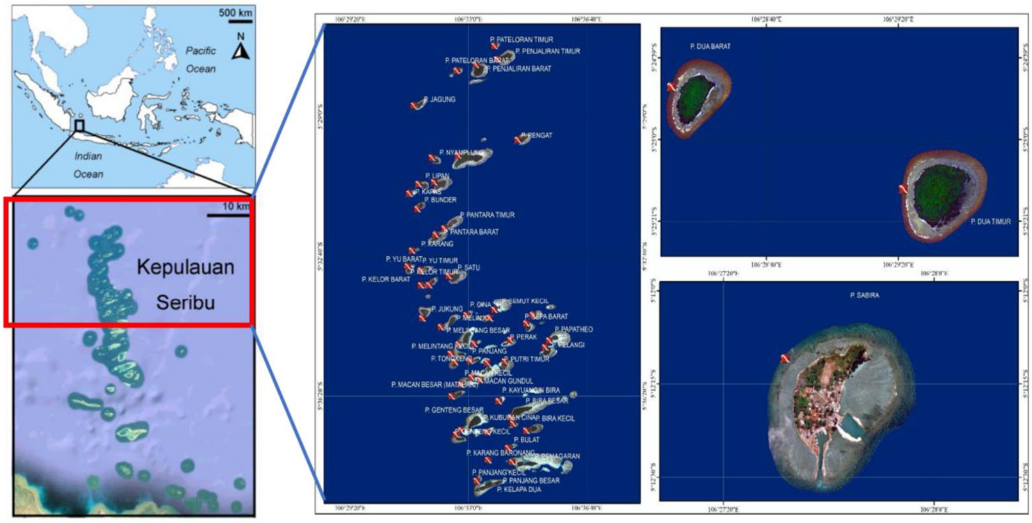


**Figure 1.** Research area in Kepulauan Seribu National Park.

### *Data collecting*

Coral cover was recorded using the line transect method, quadratic transect, and photo transect. Data were collected using the Underwater Photo Transect (UPT) method and by conducting SCUBA dives and Olympus TG5 and Canon Powershot G16 cameras. The quadrat transect size 60 × 60 cm was used to keep the photo areas uniform.

Transect installation was carried out at each research station with a 50-meter roll meter as the transect line, placed parallel to the coastline at a depth of 6–7 meters. When placing the roll meter, the position of the land/island coast was on the left side. After the roll meter was placed parallel to the coastline, the shoot was carried out along the transect line starting at the first meter to the 50th meter. Shooting for quadratic transects at odd-numbered meters was done to the right of the transect line, while even numbers were taken to the left of the transect line.

### *Data analysis*

The photo results were analyzed using a coral reef software, Point Count with Excel Extension (CPC) (Kohler and Gill 2006). In total, 50 transect photos were analyzed. Points were regularly selected with five rows and six columns for each photo frame. Each point was coded according to each biota category's code and the substrate type present on the point (Figure 2).

Photo transect processing was carried out at an intermediate level to determine all percentage cover of biota and substrate categories in line with English, Wilkinson, and Baker (1997) classes. Finally, the percentage cover of each category of biota and substrate was calculated.

$$\text{coverage}\,(\%) = \frac{\text{Coverage record}}{\text{Total line transect}}\ \text{x}\ 100\%$$

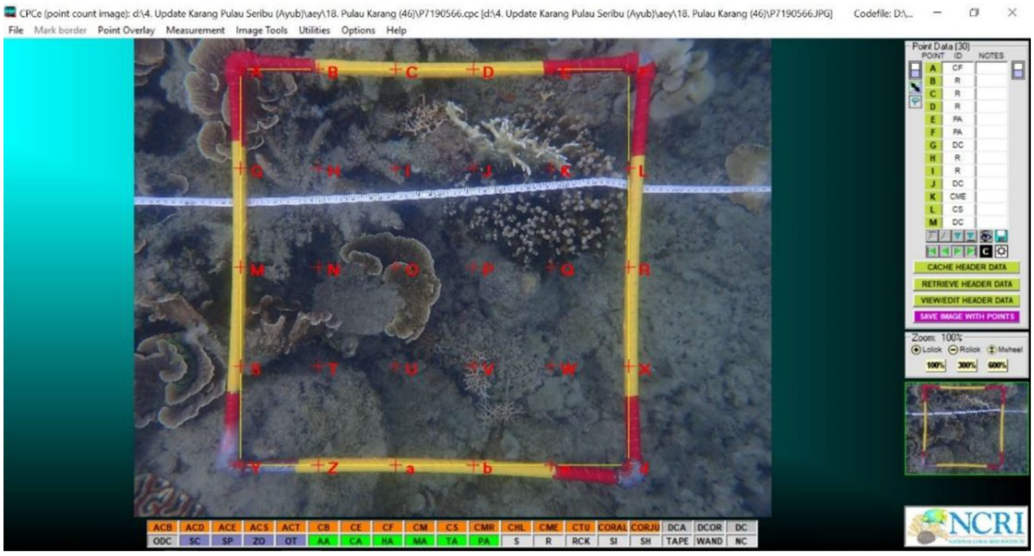


Figure 2. Example of photo transect used for further analysis.

Each biota that was successfully recorded was grouped according to the category and standard code used. The calculation results obtained were subsequently interpreted based on the categories given in Table 1.

## *Coral mortality index (CMI)*

CMI is defined as the ratio of dead corals to the total area of corals that are both dead and alive (in percentage). The higher the mortality index, the higher the level of threat to the coral community is. This index is crucial to evaluate the vulnerability of surveyed coral ecosystem.

Analysis of the CMI category was carried out using descriptive statistics as the mean value, standard deviation value, and confidence interval or following the quartile. The data obtained were the confidence interval. The range of CMI was obtained from 0.0-85.0% (0.32% ± 0.23). With a descriptive or univariate statistical approach and considering some of the variances of the data obtained (Makridakis et al., 2009), categories were arranged based on the data obtained as given in Table 2.

## *Exposure*

Coral exposure means various factors outside the coral ecosystem but affecting it negatively, such as human activities, pollutants, and temperature change. For this

Table 1. Coral criteria coverage (Gomez, 1979).

| Coverage live coral (%) | Category |
|---|---|
| 75–100 | Excellent |
| 50–74.9 | Good |
| 25–49.9 | Fair |
| 0–24.9 | Poor |

**Table 2.** Categories of Coral Mortality Index (CMI).

| CMI (%) | Category |
|---|---|
| >43 | Mortality High |
| 32–42 | Mortality Medium |
| 20–32 | Mortality Low |
| 0–20 | Mortality Very Low |

reason, exposure is classified based on the percent value of live corals found to the percentage of non-corals (interpretation of ratio measurement series, Makridakis et al., 2009).

$$P = \frac{C_l}{\sum_x^n C_{nl}}$$

P = Value of exposure potency
$C_l$ = Live coral coverage (%)
$C_{nl}$ = Non-living coral coverage (%)

The results of the analysis of potential exposure were then grouped into four categories to determine the exposure status, as given in Table 3.

The lower exposure value explains the higher level of exposure to the coral reef ecosystem. Simply, increasing exposure indicates decreasing coral coverage.

### *Vulnerability index (VI)*

The vulnerability index covers risks and threats that may occur in the evaluated ecosystem. In this study, the VI was defined as an aggregate function of coverage (X1), mortality (X2), and exposure (X3). The values of X1, X2, and X3 were obtained from the calculated value of coverage, CMI, and exposure and compared with the threshold value or the long-term sustainability of the ecosystem. The threshold value for the range was equal to 50, which means that coral reefs include of the live coral coverage of 50%. The threshold value for the mortality index was 0.32, which distinguishes evaluated mortality of ecosystem to very low and low, or medium and high. Meanwhile, the upper exposure threshold value was defined as the limit value of the ecosystem to survive properly. The Vulnerability index (VI) was then formulated, as shown below.

**Table 3.** Categories of exposure of coral ecosystem.

| Value | Category | Remark |
|---|---|---|
| <0.3 | Very high | A low value means that the coverage of live coral is low because most of the live dead coral increases, algae, and other biotas, due to high exposure of hazard sources. |
| 0.33–0.99 | High | The coverage value of live corals is between 20% and 50% of the total coverage, so that less than 50% of live corals are classified as damaged because exposure to hazard sources is still high. |
| 1–3 | Medium | The coverage value of live coral is between 50–75%, and coverage of dead coral is 20–55%. Increased live coral coverage indicates moderate exposure to moderate potential hazards. |
| >3 | Low | The percentage of live coral above 75% and dead coral below 25% indicates a low level of exposure. |

$$VI = \sum_{x}^{n} \left\{ \frac{C}{50} - \frac{CMI}{0.32} + \frac{E}{1} \right\}$$

The symbols used above indicate that C is the live coral coverage, CMI is the mortality index, and E is the value of the exposure. From the aggregate function, the threshold value for the susceptibility category (S) was the following: VI < −1 defines high susceptibility; VI −1 to 1 defines medium susceptibility, and low susceptibility was defined by VI > 1.

## Result

### *Coral coverage*

The transect photo analysis results obtained from coral cover on 56 surveyed islands are presented in Figure 3.

The cover of dead corals was recorded higher than those living in 13 islands, and four others were mostly equal in both parameters. The worst situation was recorded in Semut Besar, where live corals are close to the complete extinction, while less than 1% of dead corals were recorded for Bulat, Cina, Kayu Angin Putri, Papatheo, Satu, and Sepa Barat.

### *Coral mortality index (CMI)*

The results obtained from coral mortality analysis showed CMI = 0.00 to 0.85, with an average mortality rate of 0.32. Based on CMI, 32% of surveyed coral ecosystems were evaluated in the high-risk category, while 11% were in medium-risk, 21% in low-risk, and 36% in the very low-risk category (Figure 4).

### *Exposure*

Based on the analysis, exposure was found to affect surveyed coral ecosystems significantly negatively. There were 26 islands in the very high category, 24 in the high category, six in the medium category, and no islands in the low category (Figure 5). The found exposure reached a range from 0.02 to 1.62, and the average value was 0.39.

### *Vulnerability index and susceptibility*

The vulnerability Index of surveyed coral ecosystems reached a range from −2.58 to 2.19 with an average value of −0.09. Subsequent analysis showed that 12 islands were classified as with high susceptibility, 36 with medium susceptibility, and eight with low susceptibility (Figure 6).

## Discussion

On a large scale, there is a decrease in the density of corals globally (McClanahan et al). From 56 surveyed islands and coral ecosystems in Kepulauan Seribu Marine

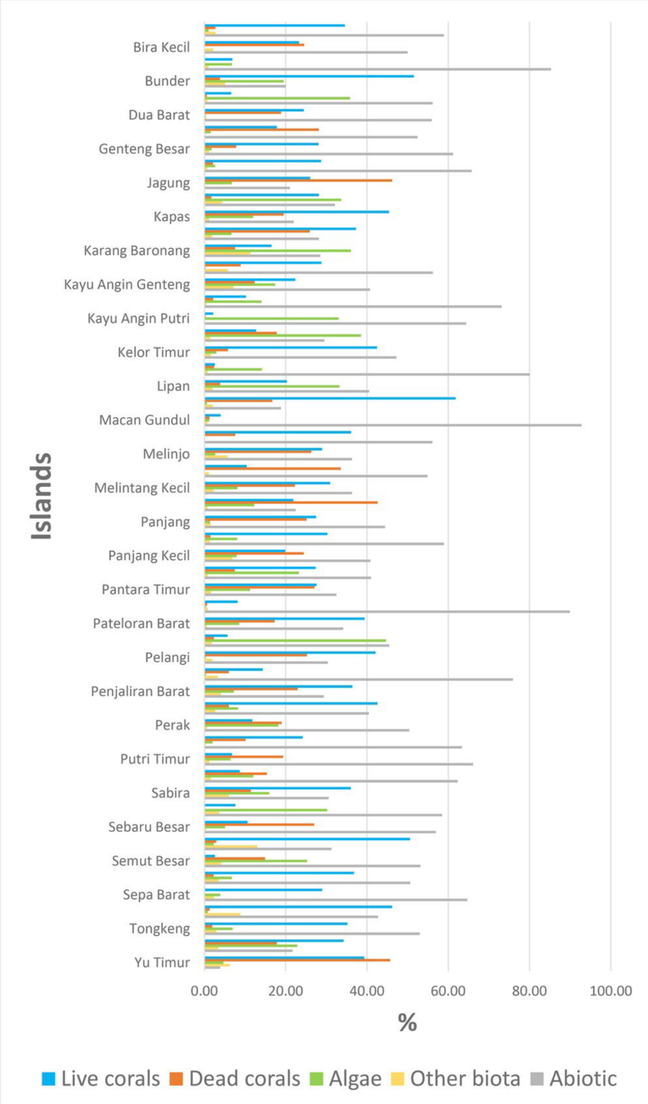


**Figure 3.** Surveyed islands and their cover included: live corals, dead corals, algae, other biotas, and abiotic or bedrock parts (in %).

National Park, Indonesia, we found 12 islands highly susceptible, 32% were in the high-risk category of coral mortality, and 26 islands were assessed in a very high category of exposure. Thus, the negative impact of various factors (Rachello-Dolmen and Cleary 2007) on the archipelago is obvious. Among others, also increasing scuba diving activity and associated tourist industry in the region should be mentioned (REF). Even if important for the socio-economic scale of local communities, it is alarming for sustainable and long-term exploitation of the area.

Besides the negative impact of irresponsible tourists, coral mortality can also be caused by predatory crown-of-thorn starfish (*Acanthaster planci*) spreading (Baird et al. 2013) and by rising sea surface temperature (Rudi 2012; Wisha and Khoirunnisa, 2017). Moreover, El Niño, volcanic and seismic activity, tsunami, storm-wave runup, and other

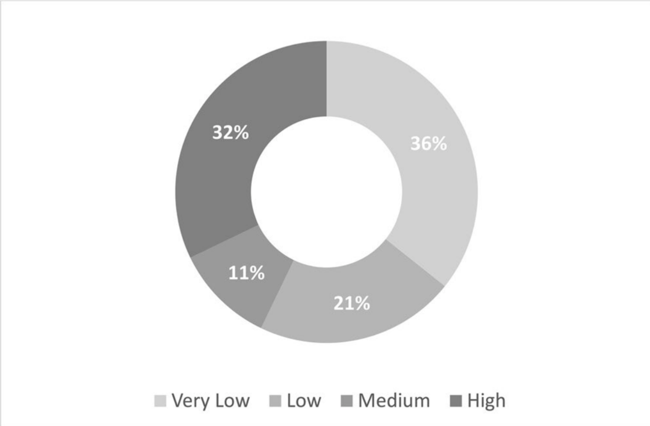


**Figure 4.** Coral Mortality Index in each Island Monitor and cumulative each mortality grade.

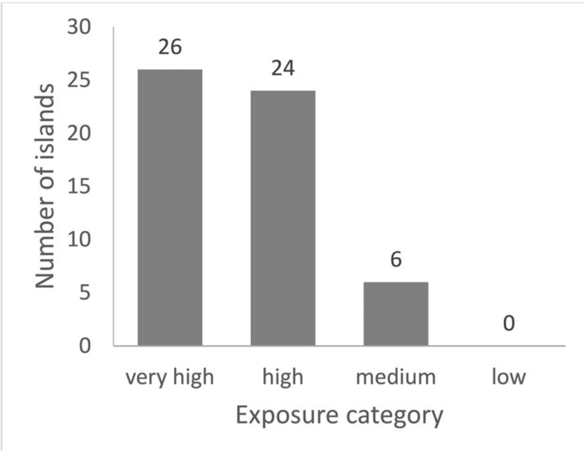


**Figure 5.** Exposure categories of coral ecosystems in 56 surveyed islands.

phenomena and natural disasters significantly affect coral mortality and must be considered (Brown 1990). For instance, El Niño impacts have resulted in coral bleaching and large-scale mortality reaching 85% in Bunaken Island, North Sulawesi, Indonesia (Ampou et al. 2017). The threat to corals is also caused by domestic sewage, urban runoff, and poverty of island communities, microalgae growth, and also the fishery and ornamental animals capture and microalgae (Akmal et al. 2021; Bonaldo and Hay 2014; Fauzi and Buchary 2002; Taofiqurohman 2013). According to Zamani, Wardiatno, and Nggajo (2011), coral reefs in healthy small islands have a mortality index of less than 25%. Based on our findings, just 26 (46%) of 56 surveyed islands and coral ecosystems can be considered healthy in this regard.

The level of exposure is usually higher on corals facing the wind direction (onward) from those facing the wind (off ward) (Panggabean and Setyadji 2017), such as on the surveyed islands Kuburan Cina and Pemagaran. Moreover, the exposure is also caused by pollutants such as oil pollution (Suhery, Damar, and Effendi 2017).

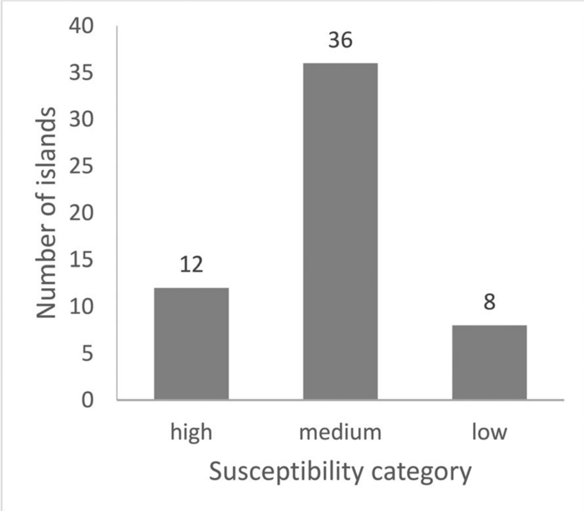


**Figure 6.** Susceptibility categories of coral ecosystems in surveyed 56 islands based on calculated vulnerability index.

Even if Kepulauan Seribu was established as a marine protected area to promote and protect a healthy coral reef ecosystem and its rich biodiversity, based on the found value of the vulnerability as a measure of sustainability, part of islands in this archipelago is at risk. Despite numerous efforts to protect the area, both external and internal factors threatening corals exist. For this reason, it is necessary to identify the threads and improve the management of the mentioned National Park (Khrisnamurti, Utami, and Darmawan 2017; REF).

The islands classified as having a low level of vulnerability reached 14% only. This means that the existence of the coral reef ecosystem can be sustainable in the long term without proper management effort just in a small part of the national park. Islands with high vulnerability should be prepared as a priority for the management. Several steps would be suggested to encourage the sustainability of the reefs, such as coral transplantation (Johan, Soedharma, and Suharsono 2016) and a limited number of tourists in Menjangan Island, Bali, Indonesia (Febrianti, Purwanti, and Hartoko 2018).

The management strategy for small islands and coral ecosystems should be in line with the status of the island. Based on the presented findings, a list of points regarding the susceptibility level was created (Table 4).

**Table 4.** Management strategy of the small island in Kepulauan Seribu.

| Susceptibility level | Management strategy |
|---|---|
| High | 1. Increasing coral coverage with a coral transplantation program |
| | 2. Zoning according to ecosystem status |
| | 3. Limited human activities |
| | 4. Regular monitoring and evaluation of trends |
| Medium | 5. Support the process of restoring coral reef ecosystems |
| | 6. Zoning according to ecosystem status |
| | 7. Regular monitoring and regulation of actions that can increase coral mortality |
| Low | 8. Regular monitoring and regulation of actions that can increase coral mortality |

## Conclusion

More than half of the surveyed islands and their coral reefs in Kepulauan Seribu Marine National Park are unhealthy and at risk. Thus, the improvement of the current management practices is required. We believe that the present study will help conservationists, wildlife managers, policy-makers, and other stakeholders protect this awesome area and its rich biodiversity for the future. This study can be perceived as preliminary, and further monitoring and evaluation of the archipelago is required and highly recommended.

## Acknowledgment

We thank the Department of Marine Affairs and Fisheries of the Seribu Islands Administration colleagues for their assistance.

## Reference

Akmal, S. G., Santoso, A., Yuliana, E., and J. Patoka. 2021. Redclaw crayfish (Cherax quadricarinatus): spatial distribution and dispersal pattern in Java, Indonesia. *Knowledge & Management of Aquatic Ecosystems*, 422:16.

Ampou, E. E., O. Johan, C. E. Menkes, F. Niño, F. Birol, S. Ouillon, and S. Andréfouët. 2017. Coral mortality induced by the 2015–2016 El-Niño in Indonesia: The effect of rapid sea level fall. *Biogeosciences* 14 (4):817–26. doi: 10.5194/bg-14-817-2017.

Baird, A. H., M. S. Pratchett, A. S. Hoey, Y. Herdiana, and S. J. Campbell. 2013. *Acanthaster planci* is a major cause of coral mortality in Indonesia. *Coral Reefs* 32 (3):803–12. doi: 10.1007/s00338-013-1025-1.

Bonaldo, R. M., and M. E. Hay. 2014. Seaweed-coral interactions: Variance in seaweed allelopathy, coral susceptibility, and potential effects on coral resilience. *PloS One* 9 (1):e85786. doi: 10.1371/journal.pone.0085786.

Brown, B. E. 1990. Damage and recovery of coral reefs affected by El Niño related seawater warming in the Thousand Islands, Indonesia. *Coral Reefs* 8 (4):163–70. doi: 10.1007/BF00265007.

Cinner, J. E., T. R. McClanahan, N. A. Graham, M. S. Pratchett, S. K. Wilson, and J. B. Raina. 2009. Gear-based fisheries management as a potential adaptive response to climate change and coral mortality. *Journal of Applied Ecology* 46 (3):724–32. doi: 10.1111/j.1365-2664.2009.01648.x.

Cleary, D. F., and B. W. Hoeksema. 2006. Coral diversity across a disturbance gradient in the Pulau Seribu reef complex off Jakarta, Indonesia. In *Marine, Freshwater, and Wetlands Biodiversity Conservation*, 285–306. Dordrecht: Springer.

Daniel, D., and L. W. Santosa. 2013. Karakteristik Oseanografis dan Pengaruhnya Terhadap Distribusi dan Tutupan Terumbu Karang di Wilayah Gugusan Pulau Pari, Kabupaten Kep. Seribu, DKI Jakarta. *Jurnal Bumi Indonesia* 3 (2).

English, S., C. Wilkinson, and V. Baker. 1997. Survey manual for tropical marine resources.

Fauzi, A., and E. A. Buchary. 2002. A socio-economic perspective of environmental degradation at Kepulauan Seribu Marine National Park, Indonesia. *Coastal Management* 30 (2):167–81. doi: 10.1080/089207502753504698.

Febrianti, M. I., F. Purwanti, and A. Hartoko. 2018. Analysis of the coral reef ecosystem exposure caused by tourism in Menjangan Island, West Bali National Park. *Jurnal Ilmu Dan Teknologi Kelautan Tropis* 10 (1):15–24. doi: 10.29244/jitkt.v10i1.19236.

Hoeksema, B. W. 1991. Control of bleaching in mushroom coral populations (Scleractinia: Fungiidae) in the Java Sea: Stress tolerance and interference by life history strategy. *Marine Ecology Progress Series* 74:225–37. doi: 10.3354/meps074225.

Johan, O., D. Soedharma, and S. Suharsono. 2016. Tingkat Keberhasilan Transplantasi karang batu di Pulau Pari Kepulauan Seribu, Jakarta. *Jurnal Riset Akuakultur* 3 (2):289–300.

Jabbar, M. A., T. E. B. Soesilo, and U. S. E. Hamzah. 2018. Oil spill incidents and their impacts to fisheries and tourism activities in Kepulauan Seribu. In *E3S Web of Conferences*, vol. 68, 03013. EDP Sciences. doi: 10.1051/e3sconf/20186803013.

Kohler, K. E., and S. M. Gill. 2006. Coral point count with excel extensions (CPCe): A Visual Basic program to determine coral and substrate coverage using random point count methodology. *Computers & Geosciences* 32 (9):1259–69. doi: 10.1016/j.cageo.2005.11.009.

Khrisnamurti, K.,. H. Utami, and R. Darmawan. 2017. Dampak Pariwisata terhadap Lingkungan di Pulau Tidung Kepulauan Seribu. *Kajian* 21 (3):257–73.

Makridakis, S., Hogarth, R. M., and A. Gaba. 2009. Forecasting and uncertainty in the economic and business world. *International Journal of Forecasting 25* (4):794 -812.

McClanahan, T. R., M. J. Marnane, J. E. Cinner, and W. E. Kiene. 2006. A comparison of marine protected areas and alternative approaches to coral-reef management. *Current Biology: CB* 16 (14):1408–13.

McLeod, E., Moffitt, R., Timmermann, A., Salm, R., Menviel, L., Palmer, M. J., ... and J. F. Bruno. 2010. Warming seas in the Coral Triangle: coral reef vulnerability and management implications. *Coastal Management 38* (5):518–539.

Panggabean, A. S., and B. Setyadji. 2017. Persentase Tutupan Karang Sebagai Pendukung Keanekaragaman Ikan Karang Di Pulau Pamegaran Dan Kuburan Cina. *Jurnal Penelitian Perikanan Indonesia* 15 (3):191–8.

Prasetyo, A. B., and L. P. S. Yuliadi. 2018. Keterkaitan tipe substrat dan laju sedimentasi dengan kondisi tutupan terumbu karang di perairan Pulau Panggang, Taman Nasional Kepulauan Seribu. *Jurnal Perikanan Kelautan* 9 (2)

Rachello-Dolmen, P. G., and D. F. R. Cleary. 2007. Relating coral species traits to environmental conditions in the Jakarta Bay/Pulau Seribu reef system, Indonesia. *Estuarine, Coastal and Shelf Science* 73 (3–4):816–26. doi: 10.1016/j.ecss.2007.03.017.

Rudi, E. 2012. Pemutihan Karang di Perairan Laut Natuna Bagian Selatan tahun 2010. *Biospecies* 5 (1)

Suhery, N., A. Damar, and H. Effendi. 2017. Indeks Kerentanan Ekosistem Terumbu Karang Terhadap Tumpahan Minyak: Kasus Pulau Pramuka dan Pulau Belanda di Kepulauan. *Jurnal Ilmu Dan Teknologi Kelautan Tropis* 9 (1):67–90. doi: 10.29244/jitkt.v9i1.17918.

Taofiqurohman, A. 2013. Penilaian tingkat risiko terumbu karang akibat dampak aktivitas penangkapan ikan dan wisata bahari di Pulau Biawak, Jawa Barat. *DEPIK Jurnal Ilmu-Ilmu Perairan, Pesisir Dan Perikanan* 2 (2)

Uneputty, P. A., and S. M. Evans. 1997. Accumulation of beach litter on islands of the Pulau Seribu Archipelago, Indonesia. *Marine Pollution Bulletin* 34 (8):652–5. doi: 10.1016/S0025-326X(97)00006-4.

Wisha, U. J., and H. Khoirunnisa. 2017. Sea surface temperature rising trend and its influence on the coral mortality in Pagai Strait, Mentawai Islands, Indonesia. *International Journal of Civil Engineering and Technology 8 (10):725–734.*

Yusnita, I. 2014. Kajian potensi dampak wisata bahari terhadap terumbu karang di Kelurahan Pulau Panggang, Kepulauan Seribu.

Zamani, N. P., and H. H. Madduppa. 2011. A standard criteria for assesing the health of coral reefs: Implication for management and conservation. *Journal of Indonesia Coral Reefs* 1 (2):137–46.

Zamani, N. P., Y. Wardiatno, and R. Nggajo. 2011. Strategi pengembangan pengelolaan sumberdaya ikan ekor kuning (Caesio cuning) pada ekosistem terumbu karang di Kepulauan Seribu. *Jurnal Saintek Perikanan* 6 (2):38–51.

### 6.5 Culture, trade and establishment of *Polypterus senegalus* in Indonesia with first record of wild populations

**Akmal SG**, Yonvitner, Jerikho R, Yulianda F, Wardiatno Y, Novák J, Kalous L, Slavík O, Patoka J. 2022. Culture, trade and establishment of *Polypterus senegalus* in Indonesia with first record of wild populations. *Aquaculture Environment Interactions*. 14:127-133. https://doi.org/10.3354/aei00433

A recent study has reported the culture, trade, and establishment of *Polypterus senegalus* in Indonesia, including the first record of wild populations. The African grey bichir *Polypterus senegalus* is a popular ornamental fish in Indonesia, and the pet trade with this species is increasing. Aquaculture production of this species is also well established. The study presents a detailed market survey and volume of trade data and highlights the importance of the pet trade as a pathway for the introduction of non-native aquatic species. The study also notes that Indonesia is a significant trade hub for ornamental fish.

The establishment of wild populations of *Polypterus senegalus* in Indonesia may have an impact on the pet trade industry in the country. The pet trade with this species is increasing, and aquaculture production is well established. The study on the establishment of wild populations of *Polypterus senegalus* in Indonesia highlights the importance of the pet trade as a pathway for the introduction of non-native aquatic species. However, it is unclear how the establishment of wild populations will affect the pet trade industry in Indonesia. Further research is needed to understand the impact of the establishment of wild populations on the pet trade industry in Indonesia.

Vol. 14: 127–133, 2022
https://doi.org/10.3354/aei00433

AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact

Published June 23



NOTE

# Culture, trade and establishment of *Polypterus senegalus* in Indonesia with first record of wild populations

**Surya Gentha Akmal[1,2], Yonvitner[2,3], Rikho Jerikho[4], Fredinan Yulianda[3], Yusli Wardiatno[3], Jindřich Novák[1], Lukáš Kalous[1], Ondřej Slavík[1], Jiří Patoka[1,*]**

[1]Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Science Prague, Kamýcká 129, 165 00 Prague – Suchdol, Czech Republic

[2]Centre for Coastal and Marine Resources Studies, The Institute for Research and Community Service, IPB University, 16680 Bogor, Indonesia

[3]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Jl. Agatis, Kampus IPB Dramaga, 16680 Bogor, Indonesia

[4]Ichthys-Alien Indonesia Project, Diponegoro Street 87, Jatirejo, Central Java, 57615 Wonogiri, Indonesia

ABSTRACT: The African grey bichir *Polypterus senegalus* is a popular ornamental fish in Indonesia. Pet trade with this species is increasing, and aquaculture production is well established. Here we present a detailed market survey and volume of domestic trade, export and import between January 2018 and February 2021. Climate similarity between the native range of *P. senegalus* and Indonesia was analysed by the MaxEnt algorithm. A significant number of areas of numerous Indonesian islands were identified as suitable for survival and establishment of this fish. This was confirmed by the records of 3 likely established populations in rivers in Java and Sumatra, where both wild type and albino juveniles were captured. The occurrence of more feral populations was suggested by local fishermen in Kalimantan, Java, and Lombok islands; however, verification via future field trips is required. The culture of *P. senegalus* is unregulated in Indonesia, and the potential risk of establishment of this predatory fish and its potential spread in this Southeast Asian country is alarming for wildlife managers. Although a total ban seems the best solution, an alternative risk mitigation strategy with minimal negative effects on the socio-economic situation in local communities is more feasible. The albino phenotype of *P. senegalus* is probably less of a risk because of its easier detection by predators, higher sensitivity to disease and stress, and disrupted social behaviour. Since albinos are popular in Indonesia, replacing the wild phenotype with this potentially less invasive phenotype could be a recommendation after experimental confirmation of the lower invasiveness of albinos.

KEY WORDS: Grey bichir · Asia · Invasive species · Ornamental fish · Aquaculture · Albino

## 1. INTRODUCTION

Ornamental aquaculture is one of the primary sources of invasion by non-native species globally (Novák et al. 2020). The sustainability of such aquaculture needs to consider the efficiency of breeding processes (Rohmy et al. 2010) and the prevention of the inadvertent release of non-native species to

*Corresponding author: patoka@af.czu.cz



Publisher: Inter-Research · www.int-res.com

avoid or mitigate adverse impacts (Yonvitner et al. 2020). Indonesia is one of the top suppliers of ornamental fish species globally (Akmal et al. 2020), and the non-native *Polypterus* spp. (Actinopterygii: Polypteriformes: Polypteridae) is widely traded there (Satyani & Subamia 2009). *Polypterus* spp. were imported into Indonesia for the first time in 1997 (described as introduced) (Diatin et al. 2015) and are cultured extensively in outdoor facilities, like other ornamental fish species (Putra et al. 2018, Marková et al. 2020). Alarmingly, evidence suggests that Indonesia's legislative regulations responsible for controlling invasive ornamental species are largely ineffective (Patoka et al. 2018).

The invasive potential of *Polypterus* spp., a nocturnal predatory fish, derives from aquarium studies (Arnoult 1964) that characterized them as opportunistic feeders, subsisting on insect larvae, shrimps, fish and also on artificial feed when available. The high intraspecific aggressiveness of their larvae ensures wide dispersal. In addition, they exhibit hypoxia tolerance and early maturation, as observed in *P. senegalus* (spawning in the same year as when they hatched; Schäfer 2004). Since *Polypterus* spp. can breathe and obtain oxygen from the atmosphere, they are very adaptable to low water aeration (Magid 1966). As Novák et al. (2020) noted, these fish have an advantage in areas with low oxygen levels and can be easily transported by humans to new localities. Moreover, *Polypterus* fishes are all carnivorous and capable of terrestrial locomotion with predominantly nocturnal activity (Du & Standen 2020). Thus, they seem to be perfectly equipped as potential invaders. Despite this assumption, there has been no published record of *Polypterus* spp. in the wild outside of their native range. However, Parenti & Soeroto (2004), in a report primarily focused on native fish species, indirectly stated that *Polypterus* spp. had been introduced to Sulawesi through ornamental aquaculture.

Human-driven biological invasions cause homogenisation and loss of biodiversity with substantial environmental and socio-economic losses (Pyšek & Richardson 2010, Haubrock et al. 2022). Thus, it is crucial to inform policy makers, stakeholders and managers of the potential for biological invasions and their possible adverse impacts to native biota and whole ecosystems (Yonvitner et al. 2020). Therefore, we decided to conduct a comprehensive study in Indonesia on the culturing and related risks of invasion of the African grey bichir *Polypterus senegalus* Cuvier, 1829, a species native to West Africa, and test the hypothesis that it is present in Indonesian freshwaters.

## 2. MATERIALS AND METHODS

### 2.1. Data collection

Records of *Polypterus senegalus* in Indonesian freshwaters were collected between 1 April and 30 September 2021. An inventory of *P. senegalus* in Indonesia was conducted by contacting ornamental fish hobbyists, fish sellers, the Regional Fisheries Agency and the Fish Quarantine Agency in Indonesia via telephone and WhatsApp. Findings indicating the species' presence were confirmed by data, photographs, and personal interviews with residents and fishers. Certain selected localities in Java and Sumatra were sampled incidentally between 15 July and 30 September 2021 by fishermen using nets (in Yogyakarta) and angling (hooks baited with pellets and earthworms). All activities were carried out in compliance with Indonesian laws and ethical rules and warranted by Indonesian academic staff from the IPB University. Data on domestic production and trade, export and import were obtained from the Fish Quarantine and Inspection Agency and the Ministry of Marine Affairs & Fisheries of the Republic of Indonesia. The trade amounts of *P. senegalus* in Indonesia were obtained from 2 e-commerce platforms, Shopee (www.shopee.co.id) and Tokopedia (www.tokopedia.com). Facebook (www.facebook.com) and YouTube (www.youtube.com) have created platforms with potentially valuable information about fish invasion introduction pathways that were surveyed for potential records of *Polypterus* spp. in Indonesia (using Indonesian language).

### 2.2. Climatic similarity

Contemporary (1970–2000) climate data were downloaded at a spatial resolution of 10 arc-minutes from the WorldClim dataset. Environmental layers of future climate data (CSIRO A1B) were obtained from the CliMond database (v.1.2, https://www.climond.org/) at a spatial resolution of 10 arc-minutes. We calculated 19 bioclimatic variables for *P. senegalus* (Table 1). These represented the average, extreme and variation of temperature and precipitation and are widely used in ecological niche modelling. Both datasets were assembled in QGIS 3.14.16-π 'Pi' (https://qgis.org/en/site/) to ASCII format for use with the MaxEnt algorithm. The MaxEnt tool was chosen because it is one of the best performing algorithms for presence-only data. The model assesses the continued likelihood of habitat relevance within the target area. Bioclimatic

Table 1. Bioclimatic variables used in the variable selection strategy to build a climate similarity model for *Polypterus senegalus* in Indonesia

| Code | Bioclimatic variables |
|---|---|
| BIO1 | Annual mean temperature |
| BIO2 | Monthly mean diurnal range (max. temperature minus min. temperature) |
| BIO3 | Isothermality (BIO2/BIO7) (×100) |
| BIO4 | Temperature seasonality (SD ×100) |
| BIO5 | Max. temperature of warmest month |
| BIO6 | Min. temperature of coldest month |
| BIO7 | Temperature annual range (BIO5–BIO6) |
| BIO8 | Mean temperature of wettest quarter |
| BIO9 | Mean temperature of driest quarter |
| BIO10 | Mean temperature of warmest quarter |
| BIO11 | Mean temperature of coldest quarter |
| BIO12 | Annual precipitation |
| BIO13 | Precipitation of wettest month |
| BIO14 | Precipitation of driest month |
| BIO15 | Precipitation seasonality (coefficient of variation) |
| BIO16 | Precipitation of wettest quarter |
| BIO17 | Precipitation of driest quarter |
| BIO18 | Precipitation of warmest quarter |
| BIO19 | Precipitation of coldest quarter |

variables provide a statistical summary of the climate within a set of static spatial variables that are appropriate for bioclimatic modelling. Climatic similarity based on temperature characteristics was modelled from a dataset of environmental layers and the native range of *P. senegalus* using the MaxEnt program (v.3.4.1; https://biodiversityinformatics.amnh.org/open_source/maxent) in order to test its environmental suitability. As a cumulative result, a continuous map was created and visualised in QGIS 3.14.16-π 'Pi'. If the climate suitability value reached or exceeded a certain threshold value, this was interpreted as an absence of climate constraint on the survival of the species and was indicated by a red area on the map. MaxEnt was trained using all 19 bioclimatic variables with default features and regularisation multipliers (default model), which were based on empirical tuning studies (Phillips & Dudík 2008).

## 3. RESULTS

The production of *Polypterus senegalus* in Indonesia has rapidly increased in recent years. The vast majority of *P. senegalus* is pet-traded on the domestic market, while a minor part is exported (Fig. 1) (e.g. to the Czech Republic). Exports started to increase towards the end of the survey period (Feb 2021). Only a few hundred individuals are imported annually to improve the quality of broodstock (Fig. 1). *P. senegalus* was found to be advertised for sale across Indonesia in Bali, Bangka Belitung islands, Java, Kalimantan, Lombok (West Nusa Tenggara), Papua, Riau Islands, Sulawesi and Sumatra (Table S1 in the Supplement at www.int-res.com/articles/suppl/q014p127_supp.pdf). The sellers included wholesalers, retailers, large-scale and small-scale producers, and

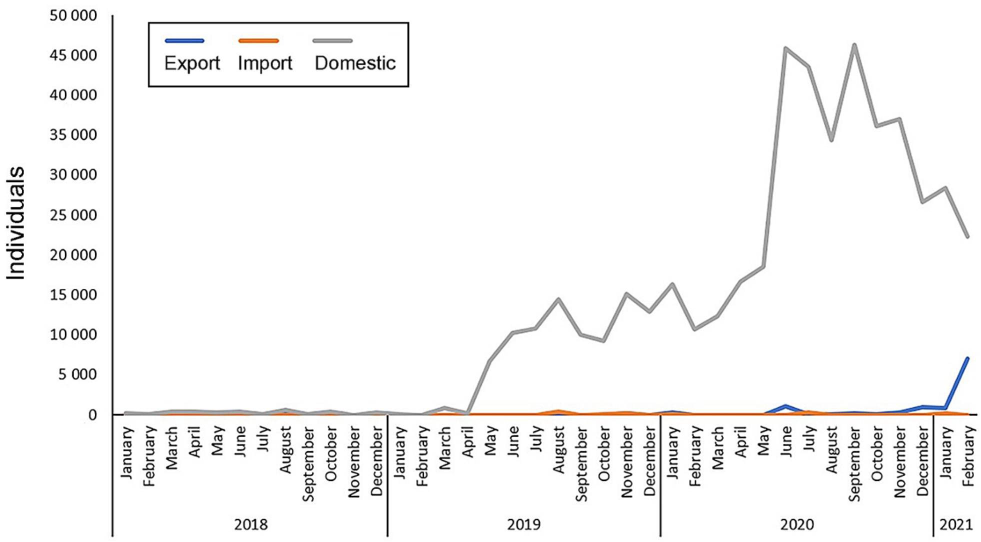


Fig. 1. *Polypterus senegalus* trade trend lines in Indonesia: individuals traded via export, import and domestic market per month from January 2018 to February 2021

the quantity of *P. senegalus* traded varied depending on the type of seller. Wholesale, retail and large-scale producers sell fish in large amounts (>50 individuals per sale), while small-scale producers average <5 individuals per sale. In ornamental aquaculture in Indonesia, the species are mostly produced and stocked in earthen ponds and concrete tanks which are connected via outflow drainages with streams in the vicinity.

Based on climate matching, the probability of establishing feral populations of *P. senegalus* in new localities was high given the vast suitable territory in Indonesia (Fig. 2a). This estimation was confirmed by 3 records of potentially established populations of this species in the wild in the Bugisan and Code Rivers in Yogyakarta, Java, and the Gedong Tataan River and in one unnamed river in Pesawaran, Lampung Province at the southern tip of Sumatra (Fig. 2b,c, Table S1). Since various size classes of *P. senegalus* were recorded, the populations found in these rivers were considered to be potentially prospering. Both wild and albino phenotypes were recorded (Fig. 2d) except in the Bugisan River, where only the wild type was recorded (Table S2). Based on personal information from local fishermen, there were 3 more potentially established populations in rivers in Central Kalimantan (East Kotawaringin: GPS –2.344630, 112.884996; Katingan Regency: GPS –2.424426, 113.314176; South Barito Regency: GPS –2.022376, 114.906431), 2 in rivers in Java (West Java: GPS –6.185917, 107.442926; Yogyakarta: GPS –7.781657, 110.419273), and 1 in a creek in Lombok (Keruak, East Lombok Regency, West Nusa Tenggara: GPS –8.743616, 116.460930; Fig. 2b,c). Additional *P. senegalus* were reported via social media in Java (see e.g. https://www.facebook.com/groups/pasiraner/permalink/1844727202217504/?_rdc=1&_rdr; https://mobile.facebook.com/groups/pasiraner/permalink/1516380868385474/?sfnsn=wiwspwa&_rdc=1&_rdr; https://www.youtube.com/watch?v=qiPqGZ1Txbs, all links accessed on 25 March 2022) and identified by visual inspection (both wild and albino phenotypes). The statuses of all mentioned records need to be verified and further monitored via future field trips.

## 4. DISCUSSION

Based on the survey, we found *Polypterus senegalus* to be widely traded in Indonesia in huge quantities. Even though the environmental risks and probability of establishment are high, no local or national regulations are applicable, and this species can be owned, cultured and released everywhere legally. Central policies (PermenKP/19/2020, previously PermenKP/41/2014) regulating 'banned' aquatic species in Indonesia have never included *P. senegalus* or any species of the genus *Polypterus.* Indonesian policymakers consider *P. senegalus* not to be a dangerous predator and do not plan to ban or restrict its spread in the country. This situation is exacerbated by the increasing volume of domestic trade and export of this species. Indonesian climatic conditions are eminently suitable for *P. senegalus*, so it is not surprising that the first potentially established populations were recorded there. It is predicted that more records from the wild will appear soon, and this conclusion is supported by as yet unverified personal information from local fishers and reports on social media in Java, Kalimantan and Lombok islands.

Even though there is only one species with the name 'palmas' (*P. palmas*), all *Polypterus* spp. have been traded in Indonesia using the market name 'palmas'. This creates confusion, and correct identification of the species is difficult or impossible in many cases. This inaccurate naming is suspected to have occurred because the first fish were imported using the *P. palmas* species name, after which all species in the genus *Polypterus* were generalised as 'palmas'. For this reason, previously published reports on production and trade of 'palmas' are misleading, including that of the albino morph (Sobariah & Wiryati 2013). *P. senegalus* is very popular in Indonesia, and it is likely that the majority of these albino fishes belonged to this species.

*P. senegalus* invasion can cause losses to ecological diversity mainly because of its predatory behaviour. This nocturnal ambush predator preys on many types of aquatic invertebrates and vertebrates (Ayoade et al. 2018); thus, there is the potential for them to negatively affect native faunal assemblages. Since Indonesia incorporates 3 biodiversity hotspots with many endemic species, the introduction of a new predator could have devastating consequences. Moreover, *P. senegalus* serves as a host of several monogenean fish parasites of the genera *Diplogyrodactylus* and *Macrogyrodactylus* (Přikrylová & Gelnar 2008). These parasitic flatworms attach to skin and gills and can easily be overlooked and transported via their host fish into the ornamental aquaculture trade. In Indonesia, the domestic trade in ornamental aquatic creatures is well-developed, and infested species could be rapidly spread over the territory through numerous routes (Yuliana et al. 2021). Since production and trade volumes have rapidly increased in recent years in Indonesia, the probability

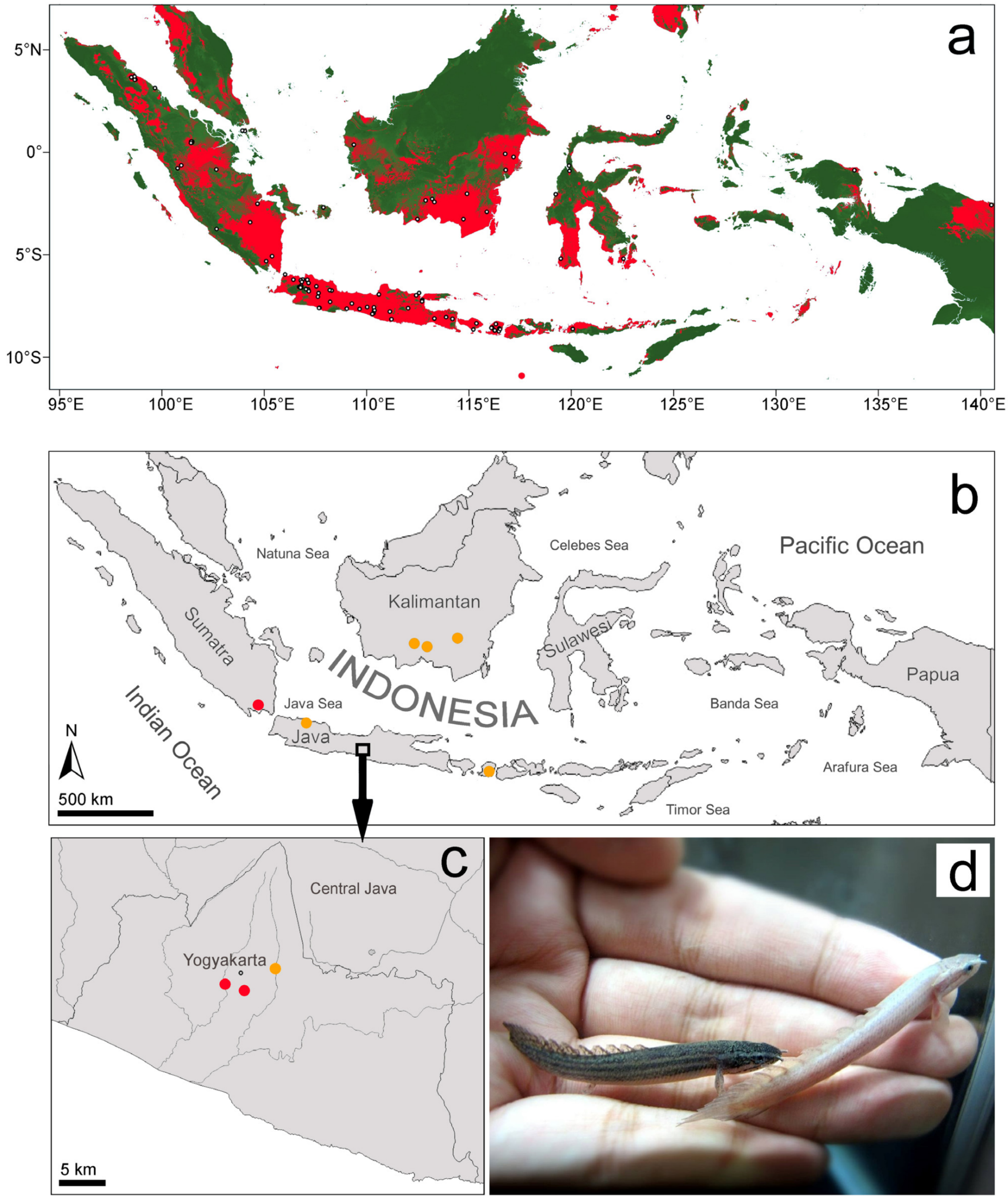


Fig. 2. (a) Map derived from the MaxEnt model for the possible establishment of *Polypterus senegalus* in Indonesia. Red: areas suitable for establishment; white dots: locations used for model training. (b,c) Red dots: first potentially established population in Indonesia; orange dots: unconfirmed populations. (d) Wild and albino phenotypes captured in the same locality in the Gedong Tataan River (Sumatra)

of both intentional release of unwanted *P. senegalus* and unintentional escape of fishes has accordingly become higher. In comparison with other *Polypterus* species recorded as being traded as pets in Indonesia, the price of *P. senegalus* is much cheaper, and owners are more likely to release these fish than more expensive species.

Considering the potential risks and consequences, a total ban on this fish in Indonesia seems a reasonable solution at first sight. Nevertheless, the increasing volume of intra- and international trade suggest that the aquaculture of *P. senegalus* is too popular and economically valuable for local producers to agree to such a restriction in Indonesia. It follows that any restrictions without effective education of the general public about possible risks would be ineffective and result in failure (Patoka et al. 2018). Similar to what has been tried with other high-risk species (Putra et al. 2018), one feasible solution would be to switch production exclusively to the potentially less-invasive albino variety. The albino *P. senegalus* is popular in Indonesia, and its culture is well-established and profitable (Rohmy et al. 2010, Sobariah & Wiryati 2013) with both online and offline markets in Indonesia, especially in Java and Sumatra. In comparison to pigmented individuals, albino fishes can be easily detected by predators (Ellegren et al. 1997), their social behaviour is abnormal (Slavík et al. 2015), and they are more susceptible to diseases (Miyamoto 2016). It can be hypothesized that physiological and behavioural limitations resulting in reduced reproductive potential may represent a lower risk for the native environment compared to that of pigmented conspecifics.

In light of research on the consequences of albinism in fish, it follows that the impact of albino *P. senegalus* on the environment could be significantly less than that of normally pigmented conspecifics. This hypothesis has to be tested experimentally before establishing mandatory regulations leading to the banning of the wild phenotype in preference to albinos in aquaculture in Indonesia. Albino *P. senegalus* is still a non-native species, but there has not been a unique albino population found in Indonesia, and the reproduction/establishment of *P. senegalus*, if it is to occur, is more likely via the wild phenotype. If the invasiveness of this species can be significantly reduced by the suggested regulation, it should have a positive effect on wildlife conservation and less of a negative socio-economic impact on local communities. For *P. senegalus*, this seems to be the most feasible and effective strategy.

*Acknowledgements*. S.G.A., O.S., and J.P. were supported by the European Regional Development Fund; the submitted article was supported within the frame of the comprehensive project named 'Centre for the investigation of synthesis and transformation of nutritional substances in the food chain in interaction with potentially harmful substances of anthropogenic origin: comprehensive assessment of soil contamination risks for quality of agricultural products' (No. CZ.02.1.01/0.0/16_091/0000845). J.P. and L.K. were supported by the Technology Agency of the Czech Republic within the project 'DivLand' (No. SS02030018). R.J. acknowledges the 'Ichthys-Alien Indonesia' project.

## LITERATURE CITED

Akmal SG, Zámečníková-Wanma BPD, Prabowo RE, Khatami AM and others (2020) Marine ornamental trade in Indonesia. Aquat Living Resour 33:25

Arnoult J (1964) Comportement et reproduction en captivité de *Polypterus senegalus* Cuvier. Acta Zool 45:191–199

Ayoade AA, Adeyemi SA, Ayedun AS (2018) Food and feeding habits of *Hepsetus odoe* and *Polypterus senegalus* in Eleyele Lake, Southwestern Nigeria. Trop Freshw Biol 27:43–53

Diatin I, Larasati R, Ellanda RE (2015) Analisis marjin keuntungan usaha budi daya ikan hias skala mikro di Bogor. In: Prosiding Seminar Nasional Ikan ke 8. Masyarakat Iktiologi Indonesia, Bogor, p 79–86

Du TY, Standen EM (2020) Terrestrial acclimation and exercise lead to bone functional response in *Polypterus* pectoral fins. J Exp Biol 223:1–9

Ellegren H, Lindgren G, Primmer CR, Møller AP (1997) Fitness loss and germline mutations in barn swallows breeding in Chernobyl. Nature 389:593–596

Haubrock PJ, Cuthbert RN, Hudgins EJ, Crystal-Ornelas R and others (2022) Geographic and taxonomic trends of rising biological invasion costs. Sci Total Environ 817: 52948

Magid AMA (1966) Breathing and function of the spiracles in *Polypterus senegalus*. Anim Behav 14:530–533

Marková J, Jerikho R, Wardiatno Y, Kamal MM and others (2020) Conservation paradox of giant arapaima *Arapaima gigas* (Schinz, 1822) (Pisces: Arapaimidae): endangered in its native range in Brazil and invasive in Indonesia. Knowl Manag Aquat Ecosyst 421:47

Miyamoto K (2016) Effects of body color luminance and behavioral characteristics on predation risk in salmonid fishes. Hydrobiologia 783:249–256

Novák J, Kalous L, Patoka J (2020) Modern ornamental aquaculture in Europe: early history of freshwater fish imports. Rev Aquacult 12:2042–2060

Parenti LR, Soeroto B (2004) *Adrianichthys roseni* and *Oryzias nebulosus*, two new ricefishes (Atherinomorpha: Beloniformes: Adrianichthyidae) from Lake Poso, Sulawesi, Indonesia. Ichthyol Res 51:10–19

Patoka J, Magalhães ALB, Kouba A, Faulkes Z, Jerikho R, Vitule JRS (2018) Invasive aquatic pets: failed policies increase risks of harmful invasions. Biodivers Conserv 27:3037–3046

Phillips SJ, Dudík M (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31:161–175

Přikrylová I, Gelnar M (2008) The first record of *Macrogyrodactylus* species (Monogenea, Gyrodactylidae) on freshwater fishes in Senegal with the description of *Macrogyrodactylus simentiensis* sp. nov., a parasite of *Polypterus senegalus* Cuvier. Acta Parasitol 53:1−8

Putra MD, Bláha M, Wardiatno Y, Krisanti M and others (2018) *Procambarus clarkii* (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. Aquat Conserv 28:1434−1440

Pyšek P, Richardson DM (2010) Invasive species, environmental change and management, and health. Annu Rev Environ Resour 35:25−55

Rohmy S, Permana A, Subamia IW, Nur B (2010) Pengamatan pemijahan ikan palmas albino (*Polypterus senegalus* var.) dengan stimulasi hormon gonadotropin. In: Prosiding Forum Inovasi Teknologi Akuakultur Ministry of Marine Affairs and Fisheries, Jakarta, p 453−459

Schäfer F (2004) *Polypterus* – Flösselhechte Bichirs. Aqualog Animalbook, Rodgau

Slavík O, Horký P, Maciak M (2015) Ostracism of an albino individual by a group of pigmented catfish. PLOS ONE 10:e0128279

Sobariah S, Wiryati G (2013) Analisis margin pemasaran dari saluran pemasaran ikan hias di enam pasar Bogor (survei di Kota/Kab. Bogor Provinsi Jawa Barat). Jurnal Penyuluhan Perikanan dan Kelautan 7:52−62

Yonvitner Y, Patoka J, Yuliana E, Bohatá L and others (2020) Enigmatic hotspot of crayfish diversity at risk: invasive potential of non-indigenous crayfish if introduced to New Guinea. Aquat Conserv 30:219−294

Yuliana E, Yonvitner, Akmal SG, Subing RA and others (2021) Import, trade and culture of non-native ornamental crayfish in Java, Indonesia. Manag Biol Invasions 12: 846−857

*Editorial responsibility: Ian Fleming,*
*St. John's, Newfoundland and Labrador, Canada*
*Reviewed by: 2 anonymous referees*

*Submitted: January 11, 2022*
*Accepted: April 19, 2022*
*Proofs received from author(s): June 17, 2022*

## 6.6 The native range of *Xenophthalmus pinnotheroides* White, 1846 (Decapoda: Brachyura) predicted by climate matching with the first record for Vietnam

Patoka J, Prokin A, Dinh CN, Tsvetkov A, **Akmal SG**, Petrtýl M, Bláha M. 2022. The native range of *Xenophthalmus pinnotheroides* White, 1846 (Decapoda: Brachyura) predicted by climate matching with the first record for Vietnam. *Biologia*. 78:829–836. https://doi.org/10.1007/s11756-022-01287-1

*Xenophthalmus pinnotheroides* is a tiny subtidal marine crab found in the West Pacific and Northern Indian Oceans. Its native range is poorly understood, but it is known to occur from southeastern India to Japan and Southeast Asia. The first record of this species in Vietnam has been reported. The native range of *Xenophthalmus pinnotheroides* has been predicted by climate matching with the first record for Vietnam. There are numerous fragmented localities with the largest area in the shoreline of continental East Asia. Also, in Vietnam, where this crab was recorded for the first time, a significant part of the territory seems to be suitable for its existence. Moreover, various islands and islets such as the Indonesian Jamdena and Trangan Islands close to New Guinea, the Indian Andaman and Nicobar Islands and the Japanese Yaeyama Islands perfectly match in climatic conditions and thus it is probable that populations of *X. pinnotheroides* will be found there. However, all this modelled distribution should be verified by future.

The first record of the species in Vietnamese waters and prediction of its native range based on climate matching analysis have highlighted the areas of its potential occurrence. The confirmation of the species' presence in Vietnam through field surveys is recommended. Although *Xenophthalmus pinnotheroides* is not exploited by humans, degradation of suitable habitats by anthropogenic activities can significantly threaten this species. Therefore, the first record of this species in Vietnam is important for conservation efforts and understanding the distribution of this species in Asia, especially in Indonesia.

Biologia (2023) 78:829–836
https://doi.org/10.1007/s11756-022-01287-1

ORIGINAL ARTICLE

# The native range of *Xenophthalmus pinnotheroides* White, 1846 (Decapoda: Brachyura) predicted by climate matching with the first record for Vietnam

**Jiří Patoka[1] · Alexandr Prokin[2] · Cu Nguyen Dinh[3] · Alexander Tsvetkov[2] · Surya Gentha Akmal[1,4] · Miloslav Petrtýl[1] · Martin Bláha[5]**

Received: 25 May 2022 / Accepted: 1 December 2022 / Published online: 12 December 2022


**Abstract**

*Xenophthalmus pinnotheroides* is a tiny subtidal marine crab from the West Pacific and Northern Indian Oceans. Its native range is poorly documented, with few records from the wild. Although it is not exploited by humans, degradation of suitable habitats by anthropogenic activities can significantly threaten this species. Here we bring the first record of the species in Vietnamese waters and prediction of its native range based on climate matching analysis. The areas of its potential occurrence are highlighted and future confirmation through field survey is recommended. The present findings indicate the range extension of *X. pinnotheroides* in Asia.

**Keywords** Asia · Crab · Macrozoobenthos · Mekong Delta · Occurrence · *Xenophthalmidae*

## Introduction

The genus *Xenophthalmus* White, 1846 represents two formally described species of tiny subtidal marine crabs: *Xenophthalmus pinnotheroides* White, 1846 and *X. wolffi* Takeda and Miyake, 1970. Other previously included species are protonyms (see World Register of Marine Species, WoRMS, www.marinespecies.org): *X. garthii* renamed as *Neoxenophthalmus garthii* (Sankarankutty, 1969); *X. latifrons* renamed as *Arcotheres latifrons* (Bürger, 1895); and *X. obscurus* renamed as *Neoxenophthalmus obscurus* (Henderson, 1893); *X. duplociliatus* Sluiter, 1881 is *nomen dubium*. The genus *Xenophthalmus* was considered previously in the family Pinnotheridae, in the subfamily Xenophthalminae, and that molecular (Palacios-Theil et al. 2009) and morphological studies (Ng et al. 2008) proposed to move it to the present location in the superfamily Ocypodoidea in its own family Xenophthalmidae. *Xenophthalmus wolffi* is native in the Persian Gulf with the coast of Pakistan in the Northern Indian Ocean as the most eastward range extension; while *X. pinnotheroides* ranges from the Japanese Archipelago through the Philippine Islands, Indonesia, China, Hongkong, Gulf of Thailand, Gulf of Martaban, and Gulf of Manaar in the West Pacific and Northern Indian Ocean as the most westward range extension (White 1846; Takeda and Miyake 1968; Naderloo 2017; Yan et al. 2017). Both valid species of the genus *Xenophthalmus* are tiny in size and inhabit intertidal zones with a muddy substrate. At the present time, very little is known about the biology, ecology and life requirements of these crab species, with some anecdotal details such as serving as host for the commensal bivalve *Arthritica japonica* Lützen et Takahashi, 2003 (Goto et al. 2012).

✉ Jiří Patoka
patoka@af.czu.cz

1 Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, 16500 Prague – Suchdol, Czech Republic

2 Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences, 152742 Borok, Russia

3 Vietnam – Russia Tropical Center, Southern Branch, 72509 Ho Chi Minh City, Vietnam

4 Centre for Coastal and Marine Resources Studies, The Institute for Research and Community Service, IPB University, 166 80 Bogor, Indonesia

5 South Bohemian Research Center of Aquaculture and Biodiversity of Hydrocenoses, Faculty of Fisheries and Protection of Waters, University of South Bohemia in České Budějovice, 38925 Vodňany, Czech Republic

Tiny crabs are usually not exploited by humans with few exceptions of ornamental purpose as in the case of *Limnopilos naiyanetri* Chuang and Ng, 1991 and related species (Patoka et al. 2019). Even if there is no evidence about the exploitation of crabs of genus *Xenophthalmus*, it cannot be excluded in the future, especially in the marine ornamental trade whose aquaculture sector is increasing in popularity globally (Pouil et al. 2020; Akmal et al. 2020). In the case of potential intensive capture, the wild populations can be at risk of decline or extinction.

Therefore, the details filling the expected gaps in the native range are crucial at this stage of our background information related to these enigmatic crabs. It was decided to survey selected localities in Vietnam where these crabs are not known to occur and, based also on previously published data, to prepare a climate matching analysis to predict their distribution in Asia.

## Material and methods

### Study locality

Two localities in the South-western region in Vietnam were surveyed in April 2019: the Mekong River tributary of Song Cua Tieu in the Mekong Delta (GPS coordinates: 10.268325, 106.750452) and the mouth of Bassac River (GPS 9.500353, 106.221717; Fig. 1). In both localities, floating invasive water hyacinths (*Pontederia crassipes* Mart) and a dense colony of nipa palm (*Nypa fruticans* Wurmb) were observed (Fig. 2).

### Data collecting

Macrozoobenthos was sampled with a "Petit Poinar Grab, All 316" (capture area 0.023 $m^2$; two collections of sediments). Sediments were filtered through a sieve with a mesh size of $200 \times 200$ µm and all macroinvertebrates were preserved in 96% alcohol immediately for later determination. The material has been deposited in the aquatic invertebrate collection of the Papanin Institute for Biology of Inland Waters of the Russian Academy of Sciences (Borok, Yaroslavl Oblast, Russia) and the crustacean collection of the Department of Zoology and Fisheries at the Czech University of Life Sciences Prague (Czech Republic).

### Morphological analysis

Relevant morphological characteristics of the tiny crabs were compared with the formal description (White 1846) and with a recent handbook (Dai and Yang 1991). Crab species identification was also discussed with Professor Peter Kee Lin Ng from the National University of Singapore.


**Fig. 1** Map of Vietnam, with two localities with the occurrence of *Xenophthalmus pinnotheroides* in Mekong and Bassac rivers indicated by red dots

For imaging of the analysed specimen diffusible iodine-based contrast-enhanced computed tomography (diceCT) was used, following (Metscher 2009) and (Gignac et al. 2016). The specimen was fixed and preserved in 70% ethanol. Thereafter, the specimen was placed in a solution of 1% iodine (I2) in 70% ethanol for 18 h and it was rinsed gently in 70% ethanol prior the CT scan. To keep the specimen in the sample holder, it was enclosed within a disposable tip for adjustable pipettes with flame-sealed tip filled with 70% ethanol. Scans were performed using a XT H 225 industrial (Nikon Metrology). The scanning parameters were as

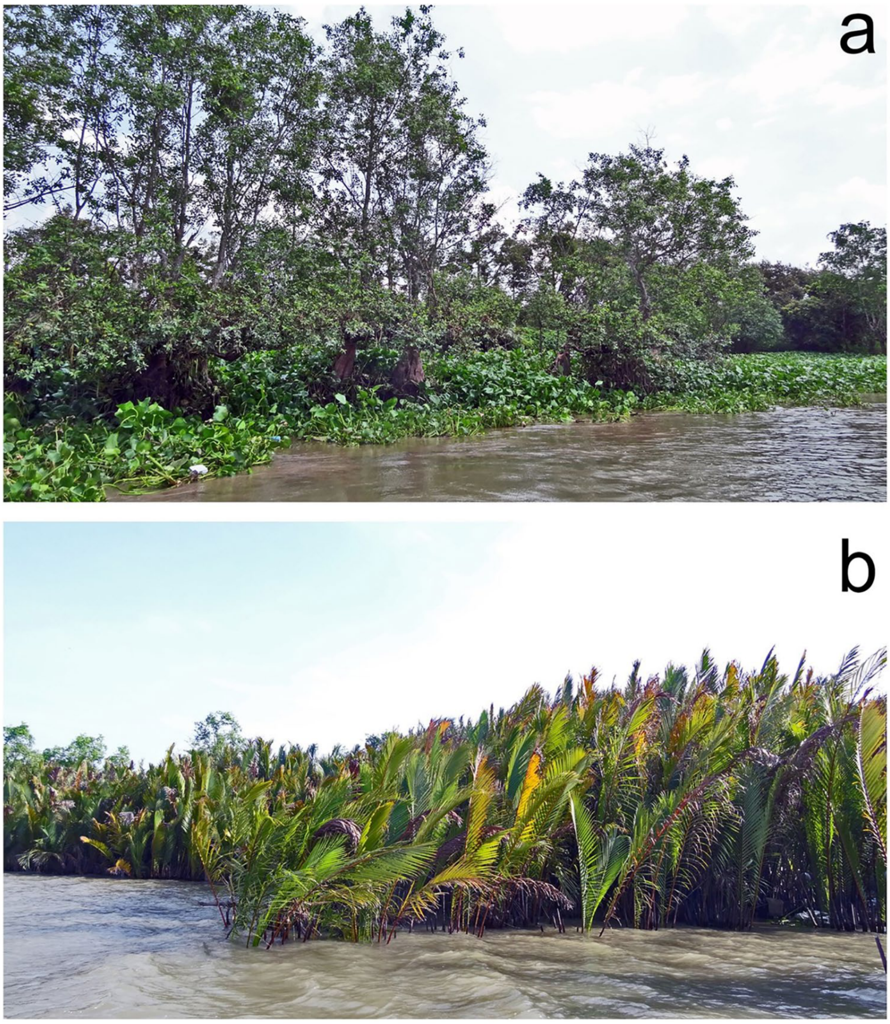


**Fig. 2** Surveyed habitats in Mekong Delta and Bassac River: **a** floating invasive water hyacinths (*Pontederia crassipes*); **b** dense colony of nipa palm (*Nypa fruticans*)

follows: isotropic voxel size of 5.2 µm, energy 60 kV, current 142 uA, power 8.5 W, exposure 0.707 fps, 360° rotation scan with 720 projections (8 frames per projection). Reconstruction was performed using Nikon CT Pro 3D (Nikon Metrology NV). Postprocess and final visualization of CT images was performed using VG studio MAX 3.3 (Volume Graphics, Heidelberg, Germany).

## DNA analysis

DNA was extracted using E.Z.N.A.® Tissue DNA Mini Kits (Peqlab, Erlangen, Germany). A fragment of mitochondrial gene Cytochrome c oxidase subunit I (COI), 12S and 16S rRNA were amplified using newly designed primers (Table 1) applying protocol from Bláha et al. (2021) except annealing temperatures. In addition, part of 16S rRNA was amplified with primers 16S-L6 and NADH1 (Schubart 2009; Palacios-Theil et al. 2009, and protocols adapted from Palacios-Theil et al. 2016). Nuclear marker histone H3 and 28S rDNA were amplified using universal primers H3af and H3ar (Svenson and Whiting 2004) and 28Srd1a and 28Srd4b

**Table 1** Primer sequences used for amplification with annealing temperatures

| Primer | Sequence (5' – 3') | Annealing temperature |
|---|---|---|
| COI-64 | GCTTGAGCAGGAATAGTAGGAA | 53 |
| COI-574 | AGATTGCGGTAATGAACACAGA | |
| COI-553 | TCTGTGTTCATTACCGCAATCT | 53 |
| COI-937 | GCACGGCAATAATCATAGTAGC | |
| 12S-13,417 | TGAAAGCGACGGGCGATA | 53 |
| 12S-13,891 | GGTGAAATTAGGTTGCTACTGT | |
| 16S-12,126 | ATTCAACATCGAGGTCGCAAT | 53 |
| 16S-12,582 | TTGTGGTTATAGAGAGTCTGGC | |

(Edgecombe and Giribet 2006). PCR products were purified with NucleoSpin® (Macherey-Nagel, Düren, Germany) and sequenced on an ABI automatic capillary sequencer (series 373; Macrogen, Seoul, Korea), using amplification primers. Nucleotide BLAST web service (NCBI Resource Coordinators 2016) was used to match particular sequences to the crab species.

## Climate matching analysis

Contemporary climate data were downloaded at a 10 arc-minutes spatial resolution from the WorldClim dataset (Fick and Hijmans 2017) and environmental layers of future climate data (CSIRO A1B) were obtained from the CliMond database (v.1.2, https://www.climond.org/; Kriticos et al. 2012) at a 10 arc-minutes spatial resolution. We calculated 19 bioclimatic variables (Table 2); these represent the average, extreme and variation of temperature and precipitation and are widely used in ecological niche modelling. Both datasets were assembled in QGIS 3.22.2 'Białowieża' and were released on 17.12.2021 (https://qgis.org/en/site/) to ASCII format for use with the MaxEnt algorithm (Phillips 2005). MaxEnt was chosen because it is one of the best performing algorithms with presence-only data (Elith et al. 2010). The model describes an area of the continued likelihood of habitat relevance in the target area. Bioclimatic variables provide a statistical summary of the climate within a set of static spatial variables that are appropriate for bioclimatic modelling. Climatic similarity based on temperature characteristics was modelled from a dataset of environmental layers and the native range of *X. pinnotheroides* using the MaxEnt program (v.3.4.1; https://biodiversityinformatics.amnh.org/open_source/maxent) to test its environmental suitability. As a cumulative result, a continuous map was created and visualized in QGIS 3.22.2 'Białowieża'. If the climate suitability value reaches or exceeds a certain threshold value, this is interpreted as no evidence of a climate constraint on the survival of the species and is indicated by a red area on the map within the expected native range of the species. MaxEnt was trained using all 19 bioclimatic variables with default features and regularization multipliers (Default model), which are based on empirical tuning studies (Phillips and Dudík 2008).

**Table 2** Bioclimatic variables used in the variable selection strategy to build a climate matching model

| Bioclimatic variables | |
|---|---|
| BIO1 | Annual Mean Temperature |
| BIO2 | Mean Diurnal Range (Mean of monthly max temp - min temp) |
| BIO3 | Isothermality (BIO2/BIO7) (×100) |
| BIO4 | Temperature Seasonality (standard deviation ×100) |
| BIO5 | Max Temperature of Warmest Month |
| BIO6 | Min Temperature of Coldest Month |
| BIO7 | Temperature Annual Range (BIO5-BIO6) |
| BIO8 | Mean Temperature of Wettest Quarter |
| BIO9 | Mean Temperature of Driest Quarter |
| BIO10 | Mean Temperature of Warmest Quarter |
| BIO11 | Mean Temperature of Coldest Quarter |
| BIO12 | Annual Precipitation |
| BIO13 | Precipitation of Wettest Month |
| BIO14 | Precipitation of Driest Month |
| BIO15 | Precipitation Seasonality (Coefficient of Variation) |
| BIO16 | Precipitation of Wettest Quarter |
| BIO17 | Precipitation of Driest Quarter |
| BIO18 | Precipitation of Warmest Quarter |
| BIO19 | Precipitation of Coldest Quarter |

For the distribution of *X. pinnotheroides*, all known GPS coordinates were added (Online resource: Table S1). No exact locality with GPS coordinates could be identified in the Philippines, whereas in Indonesia, there are two previously published localities in which exact locations were identified and added to the analysis: Jangkar (Situbondo, East Java), and Sape Bay (Sumbawa, West Nusa Tenggara) (Tesch 1918).

# Results

There were 307 crabs collected at the locality in Mekong Delta and 28 crabs in the Bassac River. Selected individuals were analysed both morphologically and genetically.

The genetic analysis resulted in successful amplification of all markers resulting in final length of COI fragment 817 bp, 16S rRNA fragment 617 bp, 12S rRNA fragment 452 bp, H3 fragment 372 bp, and 28S rDNA fragment 750 bp. Based on the DNA analysis, the species was identified as *Xenophthalmus pinnotheroides* which was supported by morphological characteristics (Fig. 3). Haplotypes of particular genes were submitted to the GenBank database under the accession numbers OP600577 (COI), OP603228 (16S rRNA), OP603030 (12S rRNA), OP615944 (Histone H3) and OM348529 (28 S). The nuclear marker 28S being the first for this species, therefore Blast analysis did not match our sequences with any sequence of *X. pinnotheroides*, while the Histone H3 fragment was the same as the sequence of *X. pinnotheroides* ON379803. The mitochondrial gene fragments COI, 16S rRNA and 12S rRNA matched with existing sequences of *X. pinnotheroides* with 93% (COI NC063601), 94% (NC063601, EU934951), and 96% (NC063601, ON379416) of similarity, respectively.

The density of crabs in the Mekong site was 6,643.5 ind. $m^{-2}$ with biomass 84.4 g $m^{-2}$, and in the Bassac site 86.6 ind. $m^{-2}$ and 2.21 g $m^{-2}$. Discrepancy in these densities

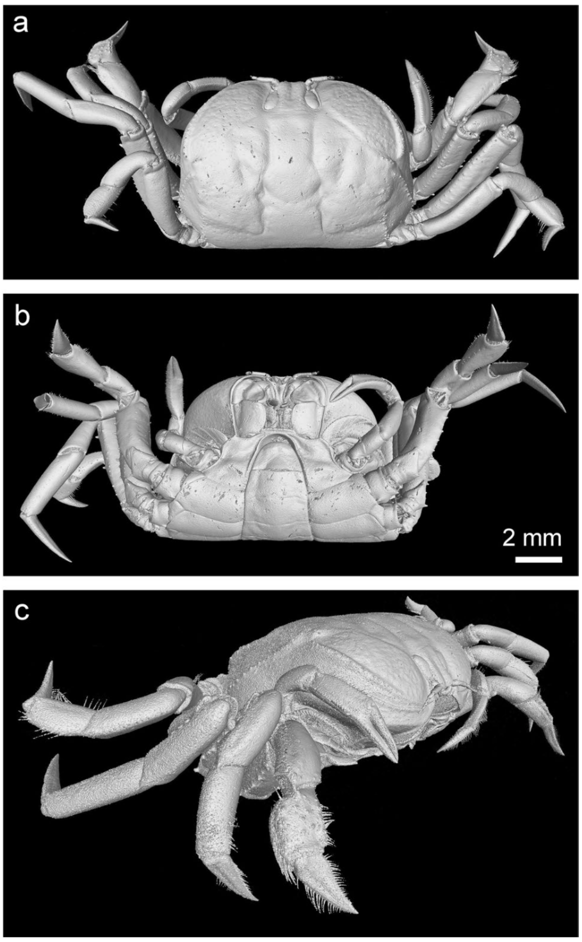


**Fig. 3** Collected *Xenophthalmus pinnotheroides* (male): dorsal view (**a**), ventral view (**b**), lateral view (**c**)

and a very high value from the first mentioned site can be caused by limited numbers of samplings and because the crabs may form an aggregation from unknown reason. Further monitoring is recommended in this regard. Some other invertebrates were also collected at the same sites; in the Mekong, the gastropod *Tomlinia frausseni* Thach, 2014, undetermined gastropod species from the family Muricidae, and the namanereid polychaete worm *Namanereis* sp.; and in the Bassac, a polychaete worm from the family Capitellidae, and an amphipod crustacean *Grandidierella* sp.

Based on the climate matching analysis, we presumed the native range of *X. pinnotheroides* (Fig. 4). There are numerous fragmented localities with the largest area in the shoreline of continental East Asia. Also, in Vietnam, where this crab was recorded for the first time, a significant part of the territory seems to be suitable for its existence. Moreover, various islands and islets such as the Indonesian Jamdena and Trangan Islands close to New Guinea, the Indian Andaman and Nicobar Islands and the Japanese Yaeyama Islands perfectly match in climatic conditions and thus it is probable that populations of *X. pinnotheroides* will be found there. However, all this modelled distribution should be verified by future fieldwork and lab taxonomic work.

## Discussion

We recorded *X. pinnotheroides* for the first time in two sites in Vietnam, which is the first record of the mentioned species in this country. These populations filled a gap in the distribution of this species in Southeastern Asia. Within recent years, the Mekong delta and its surroundings, where these crabs were recorded, have been heavily impacted by anthropogenic stresses, such as upstream dam construction and sand mining, leading to riverbank and shoreline erosion, progradation and sediment deposition (Besset et al. 2019; Nardin et al. 2021), and microplastic pollution (Hằng et al. 2021). Therefore, increasing our knowledge about faunal assemblages native to this region has merit, allowing possible overlapping to conservation practices.

Correct identification of this tiny crab species is crucial for its monitoring in the wild and despite the morphological analysis, one of the most suitable methods is genetic analysis. The species in the present study was identified by morphological analysis and reference sequences of mtDNA and nuDNA genes (COI, 16S rRNA, 12S rRNA, H3 and 28S rDNA) were obtained and shared for later use by other authors using these methods including detection by metabarcoding environmental DNA (eDNA; Komai et al. 2019).

Since this tiny crab is easily overlooked in the local fauna in many sites, climate suitability can suggest where its occurrence can be expected. This method is commonly used in such predictions (Yonvitner et al. 2020; Kuljanishvili et al. 2021). Based on our output, the vast majority of suitable habitats in the West Pacific and Northern Indian Ocean were highlighted as habitable by *X. pinnotheroides*. Tropical shorelines, the suitable habitat as documented by our records in Vietnam, are usually colonized by mangroves (Fagherazzi et al. 2017).

The effect of climate shift on this crab distribution is expected with expansion of its range especially in the southern Yellow Sea and the northern East China Sea (Xu et al. 2022). It should be noted that based on the analysis of climatic conditions, certain localities, where this crab was previously recorded at the turn of the 19th and 20th centuries in Indonesia and within the 1960-1970s and a single record from 2003 in Australia, were evaluated as not currently suitable for its occurrence most probably due to climatic shift. These localities and the presence of the crab therefore should be verified and monitored via future field trips.

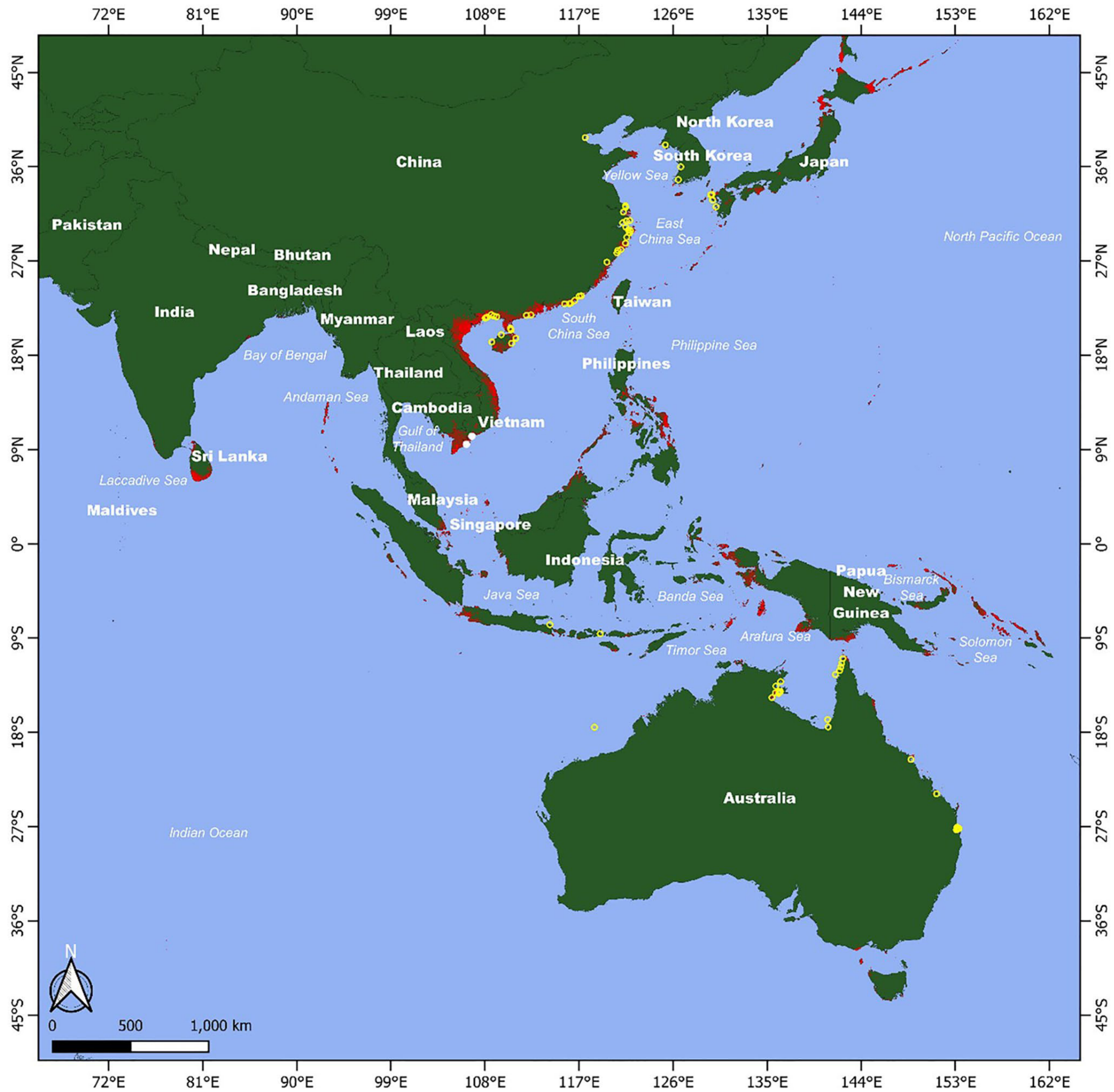


**Fig. 4** Map of the native range of *Xenophthalmus pinnotheroides* with predicted areas of its occurrence: red colour indicates areas where *X. pinnotheroides* is expected; white dots show presence locations used for training, while yellow dots indicate locations of "presence-only"/non-quantitative observations

Even if there is currently no evidence of exploitation of this species for ornamental purposes, it is worth mentioning that tiny marine animals or their specific life stages can be transported via this pathway also as "hitchhikers" (Patoka et al. 2020). The vast majority of marine organisms used for ornamental purposes are collected from the wild (Akmal et al. 2020). Therefore, some individuals of *X. pinnotheroides* could be harvested unintentionally together with fish and invertebrates traded as ornamentals and transported internationally over geographic boundaries in marine aquaria.

Since new regions of the potential existence of *X. pinnotheroides* were suggested by climate matching analysis, the native range should be redefined after future detailed monitoring which is recommended in this regard. Inasmuch as this xenophthalmid crab is not listed in The IUCN Red List of Threatened Species www.iucnredlist.org, and its population structure, stability and trends still remain poorly studied, further investigation and evaluation are required.

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1007/s11756-022-01287-1.

**Acknowledgements** We thank Prof. Peter K.L. Ng for his help with the preliminary crab identification and Marisa Giorgi from Queensland Museum for data providing. The authors express their sincere gratitude to the Joint Vietnamese-Russian Tropical Research and Technological Centre for financial support and organization of scientific and expedition work on the topic Ecolan E-3.4. AP was partly supported by the Ministry of Education and Science of the Russian Federation (project no. 121051100109-1). SGA was supported by the European Regional Development Fund: This submitted article was supported within the frame of the comprehensive project “Centre for the investigation of synthesis and transformation of nutritional substances in the food chain in interaction with potentially harmful substances of anthropogenic origin: comprehensive assessment of soil contamination risks for the quality of agricultural products” (No. CZ.02.1.01/0.0/16_091/0000845). JP was supported by the Technology Agency of the Czech Republic within the project “DivLand” (No. SS02030018). The English was proofread by Julian D. Reynolds.

**Author contributions** All authors cited in the title page meet the criteria for authorship. All authors certify that they have participated to assume public responsibility for the content in all stages of work reported in the manuscript.

**Data availability** The datasets generated during and/or analysed during the current study are included in the main manuscript, additional data available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Akmal SG, Zámečníková-Wanma BPD, Prabowo RE et al (2020) Marine ornamental trade in Indonesia. Aquat Living Resour 33:1–8. https://doi.org/10.1051/alr/2020026

Besset M, Gratiot N, Anthony EJ et al (2019) Mangroves and shoreline erosion in the Mekong River delta, Viet Nam. Estuar Coast Shelf S 226. https://doi.org/10.1016/j.ecss.2019.106263

Bláha M, Patoka J, Japoshvili B et al (2021) Genetic diversity, phylogenetic position and morphometric analysis of *Astacus colchicus* (Decapoda, Astacidae): a new insight into eastern european crayfish fauna. Integr Zool 16:368–378. https://doi.org/10.1111/1749-4877.12493

Bürger O (1895) Ein Beitrag zur Kenntnis der Pinnotherinen. Zoologische Jahrbücher Abteilung für Systematik. Geographie und Biologie der Tiere 8:361–390

Chuang CTN, Ng PKL (1991) Preliminary descriptions of one new genus and three new species of hymenosomatid crabs from southeast Asia (Crustacea: Decapoda: Barchyura). Raffles B Zool 39:363–368

Dai A, Yang S (1991) Crabs of the China Seas. Springer-Verlag, New York

Edgecombe GD, Giribet G (2006) A century later - a total evidence re-evaluation of the phylogeny of scutigeromorph centipedes (Myriapoda: Chilopoda). Invertebr Syst 20:503–525. https://doi.org/10.1071/IS05044

Elith J, Kearney M, Phillips S (2010) The art of modelling range-shifting species. Methods Ecol Evol 1:330–342. https://doi.org/10.1111/j.2041-210X.2010.00036.x

Fagherazzi S, Bryan K, Nardin W (2017) Buried live or washed away: the challenging life of mangroves in the Mekong Delta. Oceanography 30:48–59. https://doi.org/10.5670/oceanog.2017.313

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315. https://doi.org/10.1002/joc.5086

Gignac PM, Kley NJ, Clarke JA et al (2016) Diffusible iodine-based contrast-enhanced computed tomography (diceCT): an emerging tool for rapid, high-resolution, 3-D imaging of metazoan soft tissues. J Anat 228:889–909. https://doi.org/10.1111/joa.12449

Goto R, Kawakita A, Ishikawa H et al (2012) Molecular phylogeny of the bivalve superfamily Galeommatoidea (Heterodonta, Veneroida) reveals dynamic evolution of symbiotic lifestyle and interphylum host switching. BMC Evol Biol 12:1–13. https://doi.org/10.1186/1471-2148-12-172

Hằng NTG, Do NTK, Nguyen MTTT et al (2021) Microplastic pollution in clam (*Meretrix lyrata* Sowerby, 1851) at Mekong Delta river, Vietnam. Sci Technol Dev J-Nat Sci 5:1443–1454. https://doi.org/10.32508/stdjns.v5i3.949

Henderson JR (1893) A contribution to indian carcinology. Zool J Linn Soc-Lond 5:325–458. https://doi.org/10.1111/j.1096-3642.1893.tb00653.x

Komai T, Gotoh RO, Sado T, Miya M (2019) Development of a new set of PCR primers for eDNA metabarcoding decapod crustaceans. Metabarcoding Metagenom 3:1–19. https://doi.org/10.3897/mbmg.3.33835

Kriticos DJ, Webber BL, Leriche A et al (2012) CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. Meth Ecol Evol 3:53–64. https://doi.org/10.1111/j.2041-210X.2011.00134.x

Kuljanishvili T, Patoka J, Bohatá L et al (2021) Evaluation of the potential establishment of black-striped pipefish transferred by cultural drivers. Inland Waters 11:278–285. https://doi.org/10.1080/20442041.2021.1909374

Lützen J, Takahashi D (2003) *Arthritica japonica*, sp. nov. (Bivalvia: Galeommatoidea: Leptonidae), a commensal with the pinnotherid crab *Xenophthalmus pinnotheroides* White, 1846. Yuriyagai 9:11–19

Metscher BD (2009) MicroCT for comparative morphology: simple staining methods allow high-contrast 3D imaging of diverse non-mineralized animal tissues. BMC Physiol 9:1–14. https://doi.org/10.1186/1472-6793-9-11

Naderloo R (2017) Atlas of Crabs of the Persian Gulf. Springer International Publishing, Cham, Germany

Nardin W, Vona I, Fagherazzi S (2021) Sediment deposition affects mangrove forests in the Mekong delta, Vietnam. Cont Shelf Res 213:104319. https://doi.org/10.1016/j.csr.2020.104319

NCBI Resource Coordinators (2016) Database resources of the National Center for Biotechnology Information. Nucleic Acids Res 44:D7–D19. https://doi.org/10.1093/nar/gkv1290

Ng PKL, Guinot D, Davie PJF (2008) Systema brachyurorum: part I. An annotated checklist of extant brachyuran crabs of the world. Raffles B Zool 17:1–286. https://doi.org/10.1163/15685403-00003947

Palacios-Theil EP, Cuesta JA, Campos E, Felder DL (2009) Molecular genetic re-examination of subfamilies and polyphyly in the family Pinnotheridae (Crustacea). In: Martin JW, Crandall KA, Felder DL (eds) Decapod crustacean phylogenetics. CRC Press, Boca Raton, pp 457–474

Palacios-Theil EP, Cuesta JA, Felder DL (2016) Molecular evidence for non-monophyly of the pinnotheroid crabs (Crustacea: Brachyura:

Pinnotheroidea), warranting taxonomic reappraisal. Invertebr Syst 30:1–27. https://doi.org/10.1071/IS15023
Patoka J, Bohatá L, Karella T et al (2019) Invasive potential of pet-traded pill-box crabs from genus *Limnopilos* Diversity 11:91. https://doi.org/10.3390/d11060091
Patoka J, Prabowo RE, Petrtýl M et al (2020) Marine hitchhikers: a preliminary study on invertebrates unintentionally transported via the international pet trade. NeoBiota 61:33–46. https://doi.org/10.3897/neobiota.61.57682
Phillips SJ (2005) A brief tutorial on Maxent. AT&T Research 190:231–259
Phillips SJ, Dudík M (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31:161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x
Pouil S, Tlusty MF, Rhyne AL, Metian M (2020) Aquaculture of marine ornamental fish: overview of the production trends and the role of academia in research progress. Rev Aquacult 12:1217–1230. https://doi.org/10.1111/raq.12381
Sankarankutty C (1969) On a new species of *Xenophthalmus* White, (Crustacea, Brachyura, Pinnotheridae) from Cochin. J Bombay Nat History Soc 66:92–98
Schubart CD (2009) Mitochondrial DNA and decapod phylogenies: the importance of pseudogenes and primer optimization. In: Martin JW, Crandall KA, Felder DL (eds) Decapod Crustacean Phylogenetics. CRC Press, Boca Raton, pp 47–65
Sluiter CP (1881) Bijdrage tot de kennis der Crustaceën Fauna van Java's noordkust. Natuurk Tijdschr Ned-Indië 1:159–164
Svenson GJ, Whiting MF (2004) Phylogeny of Mantodea based on molecular data: evolution of a charismatic predator. Syst Entomol 29:359–370. https://doi.org/10.1111/j.0307-6970.2004.00240.x
Takeda M, Miyake S (1968) Crabs from the East China Sea, I.: Corystoidea and Brachygnatha Brachyrhyncha. J Fac Agr Kyushu U 14:541–582. https://doi.org/10.5109/22780
Takeda M, Miyake S (1970) A new free-living pinnotherid crab (Crustacea, Brachyura) from the Iranian Gulf. OHMU, Occasional Papers of the Zoological Laboratory, Faculty of Agriculture, Kyushu University, vol 3, pp 11–18
Tesch JJ (1918) The Decapoda Brachyura of the Siboga-Expedition. II. Goneplacidae and Pinnotheridae. Brill, Siboga Expeditie, Leiden
Thach NN (2014) A new Tomlinia (Gastropoda: Buccinidae) from Vietnam. Gloria Maris 53:1–5
White A (1846) Notes on four new genera of Crustacea. Ann Mag Nat Hist 18:176–178. https://doi.org/10.1080/037454809494406
Xu Y, Ma L, Sui J et al (2022) Potential effects of climate change on the habitat suitability of macrobenthos in the Yellow Sea and East China Sea. Mar Pollut Bull 174:113238. https://doi.org/10.1016/j.marpolbul.2021.113238
Yan J, Xu Y, Sui J et al (2017) Long-term variation of the macrobenthic community and its relationship with environmental factors in the Yangtze River estuary and its adjacent area. Mar Pollut Bull 123:339–348. https://doi.org/10.1016/j.marpolbul.2017.09.023
Yonvitner, Patoka J, Yuliana E et al (2020) Enigmatic hotspot of crayfish diversity at risk: invasive potential of non-indigenous crayfish if introduced to New Guinea. Aquat Conserv 30:219–224. https://doi.org/10.1002/aqc.3276

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## 6.7 Foreign stingers: South American freshwater river stingrays *Potamotrygon* spp. established in Indonesia

Jerikho R, **Akmal SG**, Hasan V, Yonvitner, Novák J, Magalhães ALB, Maceda-Veiga A, Tlusty MF, Rhyne AL, Slavík O, Patoka J. 2023. Foreign stingers: South American freshwater river stingrays *Potamotrygon* spp. established in Indonesia. *Scientific Reports* 13, 7255 (2023). https://doi.org/10.1038/s41598-023-34356-9

A recent study published in 'Scientific Reports' reports that South American freshwater river stingrays, *Potamotrygon* spp., have been established in Indonesia since the 1980s. The culture of these stingrays is unregulated in Indonesia, and there is a risk of their establishment and potential spread. Potamotrygonidae is a family of Neotropical freshwater fishes that are found in rivers in tropical and subtropical South America. The family includes river stingrays or freshwater stingrays, which are cartilaginous fishes related to sharks. Potamotrygonidae is different from the family Dasyatidae, which includes freshwater stingrays in Africa, Asia, and Australia.

The establishment of *Potamotrygon* spp. in Indonesia can have potential ecological impacts, as the culture of these stingrays is unregulated in Indonesia, and there is a risk of their establishment and potential spread. The first case of envenomation caused by *Potamotrygon* spp. in the wild outside of South America was recorded, which is alarming for wildlife. The Brantas River in Java, where an established, self-sustaining population of non-native Potamotrygon spp. was found, also recorded a South American giant arapaima (Marková et al., 2020). This is a Biodiversity Conservation Paradox because both mentioned taxa are present in the same river. The pet trade is known to be one of the most important pathways of aquatic non-native species introduction, and Indonesia is a significant trade partner. The culture of potamotrygonid stingrays is unregulated in Indonesia, and the risk of the establishment of this predator and its potential spread is alarming for wildlife. Non-native fish species may exert negative ecological impacts.

www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

# Foreign stingers: South American freshwater river stingrays *Potamotrygon* spp. established in Indonesia

Rikho Jerikho[1], Surya Gentha Akmal[1,2], Veryl Hasan[3], Yonvitner[2], Jindřich Novák[1], André Lincoln Barroso Magalhães[4], Alberto Maceda-Veiga[5], Michael F. Tlusty[6], Andrew L. Rhyne[7], Ondřej Slavík[1] & Jiří Patoka[1]✉

**The pet trade is known to be one of the most important pathways of aquatic non-native species introduction and Indonesia is a significant trade partner. Popular ornamental South American river stingrays (*Potamotrygon* spp.) were introduced to Indonesia in the 1980s and the culture was established. Here we present a detailed Indonesian market and aquaculture survey, the volume of trade between January 2020 and June 2022, and the list of customer countries with the total amount of imported stingrays. Climate similarities between the native range of *P. motoro* and *P. jabuti* and Indonesia were analysed. A significant number of areas of Indonesian islands were identified as suitable for the establishment of this species. This was confirmed by the first record of probably established populations in the Brantas River (Java). In total 13 individuals including newborns were captured. The culture of potamotrygonid stingrays is unregulated in Indonesia, and the risk of the establishment of this predator and its potential spread is alarming for wildlife. Moreover, the first case of envenomation caused by *Potamotrygon* spp. in the wild outside of South America was recorded. The current condition is predicted as the 'tip of the iceberg' and continuous monitoring and mitigation of risks are strongly recommended.**

Biological invasions cause extensive environmental and socio-economic losses worldwide[1–3]. The invasive species tend to have wide adaptability to different environmental conditions (e.g. wide temperature adaptability and oxygen requirement)[4]. Ornamental aquaculture and the related pet-trade industry are important sources of non-native species given the quantity and diversity of species cultured and transported across the globe[5–9]. The producers, traders, garden pond vendors and aquarium owners have been responsible for many introductions of ornamental creatures, some of which have established self-sustaining populations as invasive species[10–13]. Even if policymakers aim to mitigate biological invasion risks by regulating the pet trade, there are examples of failure[14,15] including up to seven years after the species was banned for sale[16].

Since most of the species exploited in ornamental aquaculture are thermophilous (i.e., warmth-loving species)[5], the most vulnerable regions threatened by putative invasions are the tropics (documented by several examples of introduced ornamentals)[2,17–20]. These introductions may also lead to the "Biodiversity Conservation Paradox" which occurs when aquarium species that are endangered in their native range will behave as invaders when introduced elsewhere such as the giant arapaima or pirarucu (*Arapaima gigas*) in Indonesia[21].

[1]Department of Zoology and Fisheries, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Science Prague, Kamýcká 129, 16500 Prague–Suchdol, Czech Republic. [2]Centre for Coastal and Marine Resources Studies, The Institute for Research and Community Service, IPB University, Bogor 16680, Indonesia. [3]Department of Aquaculture, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya 60115, Indonesia. [4]Programa de Pós-Graduação em Ecologia de Biomas Tropicais, Universidade Federal de Ouro Preto, Rua Diogo de Vasconcelos 122, Ouro Preto, Minas Gerais 35400-000, Brazil. [5]Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals, Institut de Recerca de la Biodiversitat (IRBio), Universitat de Barcelona, 08028 Barcelona, Spain. [6]School for the Environment, University of Massachusetts Boston, Boston, MA 02125, USA. [7]Department of Biology, Marine Biology, and Environmental Science, Roger Williams University, One Old Ferry Road, Bristol, RI 02809, USA. ✉email: patoka@af.czu.cz

Another popular large aquarium fishes are the South American freshwater stingrays from the genus *Potamotrygon* (family Potamotrygonidae, subfamily Potamotrygoninae)[22–24]. Despite the high price, these stingrays are sold as ornamentals because they are attractive and easy to keep in captivity[25,26]. Ornamental fishing for more than four decades in Amazon catches these stingrays[27]. The genus *Potamotrygon* is the most diverse[28,29]. The popularity of *Potamotrygon* spp. also stems from being the only elasmobranchs completely adapted for living in a freshwater environment as well as their reproductive mode, described as matrotrophic viviparity[30,31]. The first record of an established introduced potamotrygonid population elsewhere out of the native range was in Singapore where the ocellate river stingray (*Potamotrygon motoro* (Müller & Henle, 1841)) was recorded in 2009[25]. From all potamotrygonids, *P. motoro* is the most widespread species occurring in most freshwaters in South America, including the Amazon, Mearim, Orinoco, Paraná-Paraguay, and Uruguay basins including most regions of Brazil[32].

Potamotrygonins represent an important part of the Neotropical freshwater ichthyofauna and are collected in the wild and overharvested in some regions in South America such as Brazil, Peru, Colombia, Venezuela[24,33–35]. From about 42 species of the family Potamotrygonidae[35], only seven species are newly fully protected by CITES Convention. Following amendments implementation of CITES CoP 19, *Potamotrygon albimaculata*, bigtooth river stingray *P. henlei*, *P. jabuti*, white-blotched river stingray *P. leopoldi*, *P. marquesi*, Parnaiba river stingray *P. signata* and *P. wallacei* were included in Appendix II of the Convention, valid from 23 February 2023 (NOTIFICATION TO THE PARTIES, Secretariat of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), No. 2023/015, Geneva, 10 February 2023, cites.org). Moreover, followed populations are classified in Appendix III: The Colombian populations of discus ray *Paratrygon aiereba*, thorny river stingray *Potamotrygon constellata*, Magdalena river stingray *P. magdalenae*, ocellate river stingray *P. motoro*, smooth back river stingray *P. orbignyi*, rosette river stingray *P. schroederi*, raspy river stingray *P. scobina*, and Maracaibo river stingray *P. yepezi*, and the Brazilian populations of *Potamotrygon* spp. not included in Appendix II. Certain local populations of selected species from Colombia (*Paratrygon aiereba, Potamotrygon constellata*, *P. magdalenae*, *P. motoro*, *P. orbignyi*, *P. schroederi*, *P. scobina*, and *P. yepezi*), and Brazil (*Potamotrygon* spp.) are listed in CITES Appendix C in European Union (Commission Regulation (EU) No. 2021/2280 of 16 December 2021 amending Council Regulation (EC) No. 338/97 on the protection of species of wild fauna and flora by regulating trade therein, and Commission Regulation (EC) No. 865/2006 laying down detailed rules concerning the implementation of Council Regulation (EC) No. 338/97). The amendment of the European Annexes to Council Regulation (EC) 338/97 is currently in process. In total, many of formally described species of five genera of Neotropical freshwater stingrays still remain not protected by the Convention and their proposals to CITES were rejected due to insufficient trade and population status data[22].

Unfortunately, the regulations and restrictions are ineffective in many cases (in part also for the aforementioned reasons) and these stingrays are traded illegally[36]. Since they are economically valuable fishes (more than 68,000 of wild-collected individuals were exported from Brazil in 2003–2016; WCS Position Statement CITES CoP17—Johannesburg, South Africa 2016), their commercial culture was established in many countries in Asia[25]. One of the leading producers and exporters of ornamental aquatic species is Indonesia[6,37,38]. Regarding the tropical climate in this region, numerous non-native ornamental aquarium species have established new populations there after accidental or deliberate introduction[11,17,19,21,39]. Despite the exported shipments, ornamental animals are also traded in huge quantities via domestic markets[19,40]. While regulations for the management of non-native fish species and their associated trade exist[41], the current legislative framework is mostly ineffective in this regard[14]. Thus, there is a pressing need to predict the most vulnerable habitats to invasions by ornamental aquarium species.

The goal of this study is to inform the invasion potential of the very popular South American freshwater stingray *Potamotrygon* spp. in tropical regions such as Indonesia. Given that the spread of invasive species of ornamental origin in Indonesia is likely, we surveyed the trade evidence and screened the online market for the presence of stingrays for sale and natural waters through local fishermen for the location of potentially already established invasive populations to address the risks they pose for the native environment, biota, and humans. Since the climate is among the major factors explaining the successful establishment of invasive ornamental fish species[42,43], we used species distribution models with climatic variables to predict the regions of Indonesia potentially vulnerable to this invasion.

## Results

**Domestic trade.** In total, 66 online sale offers of *Potamotrygon* spp. (advertised as *P. motoro*) were recorded in Indonesia (Java, Sumatra and Bali) within January 2022. Fish were offered for 700,000–20,000,000 IDR (47.8–1365.9 USD) per individual in quantity 1–100 individuals. The stores are located on the islands of Java, Sumatra and Bali. The price depends on the colouration patterns and size of the offered individual (10–36 cm in disc diameter). The albino phenotype has never been recorded in Indonesia. The local name in Bahasa Indonesia is 'Pari Motoro'. Moreover, there are also other species of the genus *Potamotrygon* offered via pet trade in this country such as the white-blotched river stingray (*P. leopoldi*). These stingrays are produced in local farms in Indonesia (Fig. 1).

**Climate matching.** Climate matching analysis showed a high probability especially for *P. motoro* and *P. jabuti* to become established in Indonesia when introduced to new localities (Fig. 2a,b). Individuals that were found were observed to fit perfectly with the predicted suitable areas. Populations of *P. motoro* and *P. jabuti* can

**Figure 1.** Local farm in Cirebon City (West Java) where ornamental fish including *Potamotrygon motoro* and *P. leopoldi* are produced in huge quantities.

be expected as potentially well-established in Java, Bali, and Nusa Tenggara, and some in Sumatra, Kalimantan, Sulawesi, Maluku Islands and Papua.

**Records in the wild.** In total, 13 individuals of *Potamotrygon* spp. (three morphologically identified as *P. motoro*, six as *P. jabuti*) were captured by local fishermen using 'Ayap' (traditional fishing gear which is similar to big bottom barless dipnet but made from bamboo; the mesh size ranged from 2 to 8 cm; the fisherman use the Ayap from riverbank when the water level is high or during flood, holding it in the water and waiting for fish drifting into the Ayap; when fish where stuck in the net, fisherman lift the Ayap and the fish are caught), angling, castnet, and gillnet in the Brantas River, East Java Province (Fig. 2c, 3, Table 1). Also, newborns and a gravid female of *P. jabuti* were recorded and thus, reproduction is occurring. The furthest distance between findings was more than 40 km. The voucher specimen was identified as *Potamotrygon motoro*.

The voucher specimen (*P. motoro*, adult male, total body length 370 mm, disc width 230 mm) was caught on 28 November 2021 using Ayap and kept in an aquarium by a local angler (Fig. 4a). In concordance with previously published morphological analysis[44], disc was sub-circular with small tips on the anterior margin. Eyes bulging dorsally and relatively large (4% DW). Dorsally covered with tricolour ocelli (Fig. 4d), evenly distributed. The central region of the dorsal disc presents large irregular shapes due to unidentified derm disease (Fig. 4a,b). Pelvic fins are present over the posterior margin of the disc. The tail is relatively short, thick, and punctured on the posterior margin of the sting. One row of curved tail spines with a large base (Fig. 4c). Dermal denticles are present on the dorsal region of the disc and tail, various sizes covered on the disc, but larger denticles present on the central region of the disc, star-shaped denticles with dichotomous ridges present in large denticles, small denticles often with monochotomous ridges or 'x' mark-shaped denticles. The ventral disc is whitish with a black and grey irregular shape across the central region, outer margin covered with dark-grey colouration. This voucher specimen is deposited in Museum Zoologicum Bogoriense (MZB), Java, Indonesia, under the coll. No. MZB.26608.

Type habitats of *P. motoro* and *P. jabuti* in the Brantas River system consist of three areas as the main stream (Brantas River), floodplain, and irrigation canals connected to Brantas River. Water discharges of the main river correlated with dam activity in the upper stream. The connectivity of the floodplain and the main river will be greatly increasing if the water level of the main river was increased. The water discharge in irrigation canals fluctuated following the water level on the reservoir at Njegu Dam and Serut Dam.

We have conducted a rapid qualitative assessment of the habitats in the Brantas River. The Brantas River considers resembling native habitats based on qualitative descriptions of climate (tropic), substrates, and type habitats. The presence of a floodplain and connectivity between the main river and floodplain provides diverse habitat ranges. Muddy and sandy substrates provide similar niches for foraging and burying activities[45]. The habitats in the main river consisted of lacustrine (reservoir) and riverine region (river). Individuals in the lacustrine region (upper stream of Njegu Dam and Serut Dam) were found in areas with mud substrate sporadically covered with leaf litter. Records in the riverine region were found in boulder, pebble, sand, and mud substrates. The voucher specimen was collected on the shore of the riverine region with sand and mud substrates (depth of approximately 0.5–1.5 m). The depth of the main river varies and the observed water clarity range between 0 and 15 cm (wet season). In several sections of the main river, there were observed submerged deposits of sand and pebbles.

The floodplain habitats are located near the main river in the Brantas River system. The gravid female of *P. jabuti* with four neonate individuals and one adult male were caught in floodplain habitats. Water depth tends to be shallower (0.5–1.0 m) than the main river and mud dominate the type of substrates. Submerged aquatic plants dominate the edges of the floodplain.

Irrigation canals are connected to the reservoir in the upper stream of the Brantas River. Water clarity tends to fluctuate following reservoir activity (water level, drifted substrates, flood, and dam activity). The majority of

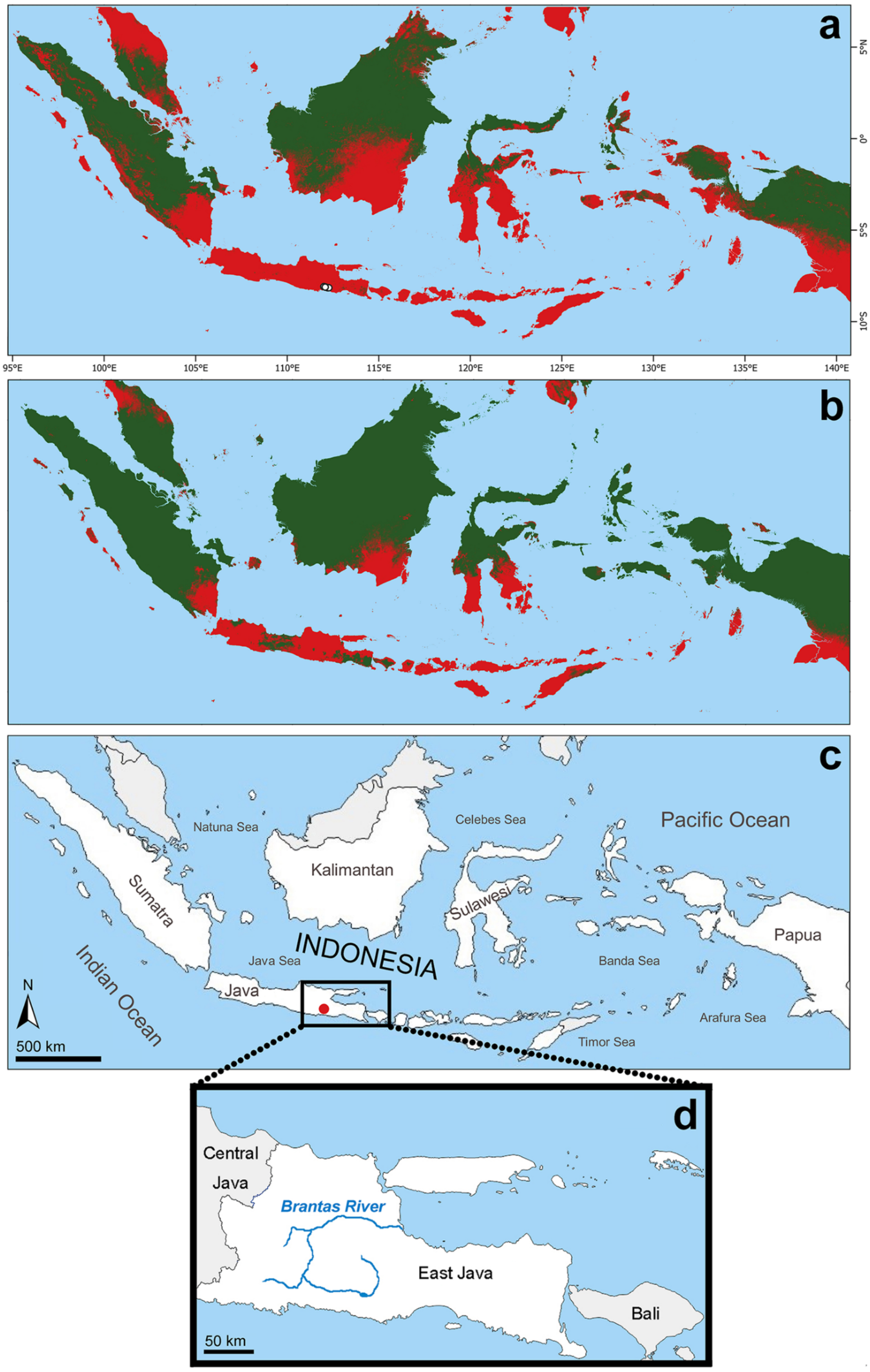


**Figure 2.** Map derived from the MaxEnt model (v. 3.4.4, https://biodiversityinformatics.amnh.org/open_source/maxent/) for the possible establishment of *Potamotrygon motoro* (**a**) and *P. jabuti* (**b**) in Indonesia. The red colour indicates areas suitable for establishment due to climatic similarity with the native range. The white dots show locations used for model training (**a**); the red dot indicates the Brantas River where the first potentially established population in Indonesia was found (**c**); detail of East Java Province with the Brantas River (**d**).

**Figure 3.** The Brantas River, the locality of a potentially established population of non-native *Potamotrygon* spp. in Java, Indonesia.

| Species | Individual(s) | Date | GPS | Sex | Size | Personal inspection |
|---|---|---|---|---|---|---|
| *Potamotrygon* sp. | 1 | 07 Nov 2021 | − 8.153374, 112.204180 | Male | Subadult | Yes |
| *Potamotrygon* sp. | 1 | 15 Nov 2021 | − 8.153284, 112.217016 | Female | Adult | Yes |
| *Potamotrygon* sp. | 1 | 22 Nov 2021 | − 8.110967, 112.095229 | Male | Subadult | Yes |
| *Potamotrygon motoro* | 1* | 28 Nov 2021 | − 8.1177073, 112.0732019 | Male | Subadult | Yes |
| *Potamotrygon* sp. | 1 | 29 Nov 2021 | − 8.145205, 112.252589 | Female | Subadult | Yes |
| *Potamotrygon motoro* | 1 | 30 Nov 2021 | − 8.1522527, 112.2709947 | Female | Adult | Yes |
| *Potamotrygon* sp. | 1 | 2 Dec 2021 | Uncertain | Female | Subadult | No |
| *Potamotrygon jabuti* | 1 | 8 Dec 2021 | − 8.0890841, 111.9960106 | Female | Adult | Yes |
| *Potamotrygon jabuti* | 4 | 8 Dec 2021 | − 8.0890841, 111.9960106 | Unknown | Neonate | Yes |
| *Potamotrygon jabuti* | 1 | 31 Dec 2021 | − 8.1176183, 112.0728518 | Female | Subadult | Yes |
| *Potamotrygon motoro* | 1 | 17 March 2022 | − 8.1176183, 112.0728518 | Female | Subadult | Yes |

**Table 1.** Records of *Potamotrygon* spp. in Java, Indonesia: species (all of them traded as *P. motoro*), quantity (individuals(s)); date (D/M/Y); GPS coordinates; sex (male/female/unknown); size (neonate/subadult/adult); personal inspection (yes/no). The voucher specimen is indicated by an asterisk.

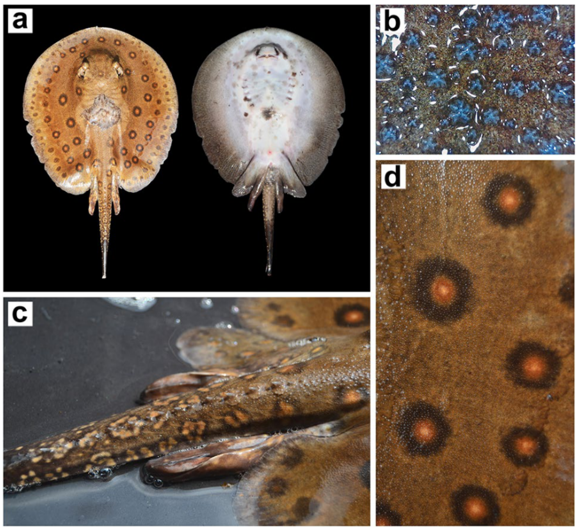


**Figure 4.** (**a**) *Potamotrygon motoro* captured in Java, Indonesia: Voucher specimen TL 370 mm, DW 230 mm, left (dorsal view) and right (ventral view); (**b**) irregular shape of dermal denticles on voucher specimen (60 ×); (**c**) tricolour ocelli on voucher specimen; (**d**) curved tail spines on voucher specimen.

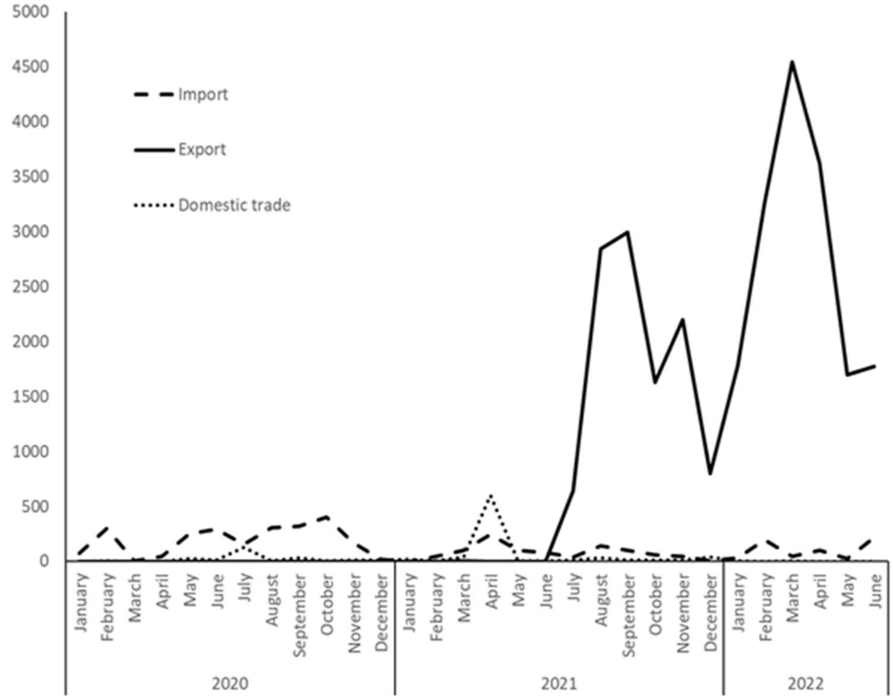


**Figure 5.** Trade with advertised *Potamotrygon motoro* in Indonesia: import, export, and domestic trade within the period from January 2020 to June 2022.

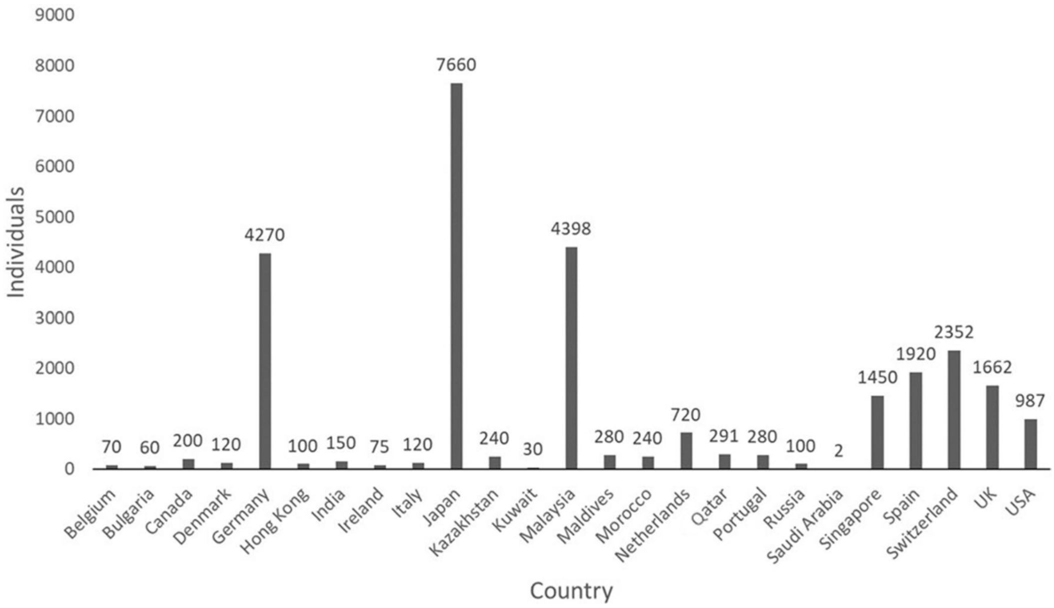


**Figure 6.** Export of 27,777 individuals traded as *Potamotrygon motoro* from Indonesia within the period from January 2020 to June 2022 with the indicated number of individuals delivered to each customer country.

substrates are covered by mud and some others are covered by plants and rock. The canal edges were engineered with concrete and rock. There were no confirmed records of *Potamotrygon* spp. in this habitat. On the other hand, local fishermen stated that 'plenty of small stingrays' are often seen in the irrigation canals (Lodagung canals). Align with a precautionary approach, we considered this type of habitat as potentially invaded.

| Year | Month | Import | Export | Domestic trade |
|---|---|---|---|---|
| 2020 | January | 74 | 0 | 0 |
| | February | 298 | 0 | 2 |
| | March | 1 | 0 | 0 |
| | April | 47 | 0 | 0 |
| | May | 251 | 0 | 25 |
| | June | 294 | 0 | 10 |
| | July | 152 | 0 | 124 |
| | August | 304 | 0 | 1 |
| | September | 316 | 0 | 29 |
| | October | 402 | 0 | 3 |
| | November | 165 | 0 | 8 |
| | December | 16 | 0 | 13 |
| 2021 | January | 0 | 0 | 16 |
| | February | 47 | 0 | 3 |
| | March | 101 | 1 | 41 |
| | April | 246 | 0 | 602 |
| | May | 101 | 0 | 3 |
| | June | 81 | 0 | 5 |
| | July | 35 | 640 | 9 |
| | August | 143 | 2845 | 31 |
| | September | 102 | 2995 | 8 |
| | October | 61 | 1627 | 12 |
| | November | 47 | 2195 | 9 |
| | December | 1 | 800 | 40 |
| 2022 | January | 30 | 1780 | 3 |
| | February | 199 | 3262 | 0 |
| | March | 42 | 4545 | 4 |
| | April | 102 | 3617 | 0 |
| | May | 27 | 1695 | 0 |
| | June | 218 | 1775 | 0 |
| Sum | | 3903 | 27,777 | 1001 |

**Table 2.** Indonesian trade in *Potamotrygon motoro* (probably more species are traded under the same name) within the period from January 2020 to June 2022 (based on the statistical evidence of Fish Quarantine and Inspection Agency, Ministry of Marine Affairs and Fisheries Republic of Indonesia).

Brantas River basin is a national strategic river basin playing a vital role in driving Indonesia's economy. The Brantas River is the second-longest river (320 km) on the island of Java and crosses the province of East Java. The upper stream of the Brantas River originates from several mountains and springs around the highlands in East Java. The Brantas River flows through various plantation lands, and paddy fields, and is one of the sources of raw material for drinking water in most areas in East Java. Connectivity between main rivers and irrigation canals is located upstream, middle, and downstream. *Potamotrygon* spp. were recorded in the middle (Blitar Regency and Tulungagung Regency) of the Brantas River.

The diets of non-native *Potamotrygon* spp. in the Brantas River are only known from an interview from local anglers. Several anglers use worm bait (*Lumbricus* spp.) and shrimps (*Macrobrachium* spp.) for fishing the *Potamotrygon* spp. The voucher individual was kept in indoor aquarium for several days and had been fed by shrimps and fish (meat-pieces of *Barbonymus* spp. and *Oreochromis* spp.).

Anthropogenic activities in the surveyed area were observed to be diverse and intense. The activities of fishermen, recreational fishing and sand mining were observed in the central part of the Brantas River. These activities are associated with the direct use of water bodies and overlap with the localities of *Potamotrygon* spp. records. Sand mining activities have been carried out in the main river with shallow sand substrates, where *Potamotrygon* spp. were commonly found (for example, locality from confirmed individuals on 22 November 2021 and 31 December 2021 are approximately 50 m from the sand mining site). During the survey of this locality, one fisherman who was stung by a captured *P. jabuti* was found. The fisherman was hospitalized for two days after being stung two times (in the left and right forearms). The fisherman described the pain as 'worse than being stabbed by a dagger'.

**International trade.** Of all *P. motoro* traded globally, Indonesia imported 2,717 individuals (5.4%), while 122 of them (2.0%) were exported (based on Importer/Exporter-reported quantity of CITES data). Indonesia does not report any trade in *P. motoro* to CITES, hence the need to shift focus from exporter to importer-reported data. Between 2017 and 2021, across the globe, all globally reported 5998 *P. motoro* were traded, while exporters reported 50,401 were traded. This discrepancy carries through to all *Potamotrygon* species where importers reported 14,868 were traded (2017–2021) while exporters reported 127,489 individuals in the trade (based on data from Fish Quarantine and Inspection Agency (FQIA), Ministry of Marine Affairs and Fisheries Republic of Indonesia).

Data from the Indonesian trade analysis based on data from the Fish Quarantine and Inspection Agency, Ministry of Marine Affairs and Fisheries Republic of Indonesia present a different scenario. In total, 3903 individuals of *P. motoro* were imported within the period of January 2020 to June 2022 from Thailand, Taiwan, China, Malaysia, India, and Colombia (the majority of 3525 individuals were from Thailand) and 27,777 individuals were exported to 25 countries (with 7660 individuals delivered to Japan; Figs. 5, 6). Furthermore, 1001 individuals were traded domestically. The first *P. motoro* were imported to Indonesia via trade routes from South America by fish entrepreneurs in the 1980s. The first exported individual was delivered to Qatar in March 2021, the largest export was recorded in March 2022 when 4,545 individuals were shipped to 12 countries (Table 2).

## Discussion

In Indonesia, an established, self-sustaining population of non-native *Potamotrygon* spp. was found in the Brantas River, Java. This same river also recorded a South American giant arapaima[21]. Obviously, this is what is called a Biodiversity Conservation Paradox[46] because both mentioned taxa are endangered in their native ranges, but are becoming invasive.

Indonesia has broad ranges of freshwaters from peat water to blackwater (similar to Negro River in low acidity and a huge river system[47]) in Sumatra and Kalimantan (Indonesian part of Borneo) to white-transparent water in three zoogeography areas[48]. The rivers in Borneo and Sumatra are also habitats of native freshwater stingrays (*Fluvitrygon* spp. and *Urogymnus polylepis*)[49,50]. The occurrences of freshwater stingrays (despite different genera and families, potentially similar in their physiology) indicate the potential suitability of natural habitats for to be invaded in the future.

Besides escapes from home aquaria and farms, "Fang Sheng" rite, and pest control[17,21], a new pathway of non-native species introduction is worth mentioning: affluent people intentionally release expensive animals to demonstrate their wealth and power. There is no clear evidence about the *Potamotrygon* spp. introduction pathway in the Brantas River. Humans value non-natives for a wide range of reasons-aesthetic, culinary, or diverse cultural reasons, among them, financial/social status[51]. With globalization, the trend is that the number of rich Indonesians will increase in the future and thus, maintain the cultural tradition of releasing expensive non-native animals.

Even if climate matching analysis is a preliminary estimation, it showed that the vast majority of Indonesian territory is suitable for further establishment of *P. motoro*, *P. jabuti*, and other potamotrygonin species. Since aquatic ornamental creatures are known to be transported across the Indonesian territory in huge quantities[40], it is not surprising that *P. motoro* and *P. jabuti* are becoming established. The Brantas River resembles native stingray habitats based on qualitative descriptions of climate (tropic), substrates, habitat types, and food resources. Muddy and sandy substrates provide similar niches for foraging and burying activities[45]. The presence of a floodplain and connectivity between the main river and floodplain provides diverse habitat ranges. The record of gravid female at the floodplain confirmed that *Potamotrygon* spp. can use this habitat as nursery ground in the Brantas River. The distribution of *Potamotrygon* spp. was recorded across the floodplain and main river. This stingray is able to overcome artificial barriers (found in three locations separated by artificial barriers such as Upperstream Njegu Dam, Downstream Njegu Dam-Upperstream Serut Dam, and Downstream Serut Dam). It is likely that stingrays crossed the barriers during flood events. A similar situation occurred with introduced *P. motoro* and *P. falkneri* in Jupiá Dam, Upper Paraná River basin, Southeastern Brazil, attesting to the ability of stingrays to overcome artificial barriers such as hydro power plants[52].

*Potamotrygon* spp. are a nocturnal predatory fish[53]. The interview-based evidence of broad range of food preferences of recorded non-native *Potamotrygon* spp. have slight similarity with the stomach content of *P. motoro* in Negro River[54]. It is known that younger individuals inhabit mostly sandy bottoms of depth no more than four meters while bigger ones migrate between deeper waters during the day and shallow areas at night[45] but we have no exact data confirming or denying this behaviour also in Indonesia. Because the pigmented and well-camouflaged wild phenotype only is traded in Indonesia and because of burrowing activity, detection of *Potamotrygon* spp. by fishermen and collectors could be difficult. Simply, this species, for having a cryptic colouring, can be easily neglected by locals at least until its abundance will be high. On the other hand, once detected, it can be targeted according to its high price.

There are no native species in Indonesia which can be able to mate with this non-native stingray. On the other hand, negative impacts on native biota and also the local community can be expected. They are regarded by native people in the Amazonia as venomous fishes[55] and responsible for frequent stings and the envenomation has also occasionally been reported by aquarium traders and owners[56–58]. Especially venomous species can threaten naïve animals and can easily hurt fishermen and all laypersons who will handle these stingrays which is supported by the record of envenomation. For instance, stingray accidents are considered a public health problem in Brazil [59]. Most of the injuries caused by fish in the country involved freshwater stingrays, especially from the Potamotrygonidae family, and the most affected people are fishermen, who are handling these animals daily, and bathers (children and adults), especially during the dry season in Amazonia, Paraguay and Lower Paraná river basins (i.e., native range)[60,61]. Moreover, accident data in these regions is underestimated because most fishermen do not report or even go to the hospital; some fishermen get used to be frequently sting. In the non-native range (i.e., Upper Paraná River basin), stingray envenomation appeared over the past 20 years. An important natural barrier—the Seven Falls of Guaíra (Paraná State, Southern Brazil)—served as a natural barrier preventing species of the Lower Paraná River to colonize regions of the Upper Paraná River. However, with the creation of the Itaipu hydroelectric dam in 1982, these falls were submerged, allowing the movement of several fish species upstream, including freshwater stingrays that are taking advantage of locks installed at the dam to expand their distribution area[62]. In the Upper course of the Paraná River, injuries are reported by inhabitants and also tourists in municipalities of Mato Grosso do Sul, Paraná and São Paulo states, who are often unaware of the presence of these non-native animals in the area[63]. As is our knowledge, this is the first case of envenomation caused by *Potamotrygon* spp. in the wild outside of their native and non-native locations in South America. Such a situation is alarming because *Potamotrygon* spp. can reach populated areas, where most inhabitants are unaware of how to prevent accidents and to treat wounds they may cause. If we consider the existence of numerous properties by hotels and the intense practice of fishing/tourism activity in the region of Brantas River and throughout the country, it is expected that the negative interaction between humans and *Potamotrygon* spp. will be more intense, causing important changes in epidemiological profiles of envenomation in Indonesia. Further potential encounters between *Potamotrygon* spp. and humans are highly probable and imminent also due to sand mining and fishing in the reported localities in the Brantas River.

Moreover, harmful consequences can be expected due to the predatory feeding behaviour of *Potamotrygon* spp. Diet analysis showed that aquatic invertebrates such as molluscs (both gastropods and bivalves), crustaceans (mainly shrimps from family Palaemonidae), insects (mainly Ephemeroptera and Diptera) and vertebrates such as fish are consumed[64,65]. Also, the foraging behaviour of *Potamotrygon* spp. can impact the native fauna. Several species of rays forage disturb the substrate, also known as bioturbation[66,67], with the use of a tactic we termed "undulate the disc and stir substrate" to uncover insect larvae, crabs, snails and small fish[68]. This activity stirs the substrate particles and discrete sediment clouds are formed near the foraging ray[69]. These clouds can catch the attention of nearby rare *Akysis variegatus*, endangered *Rasbora lateristriata*, protected *Notopterus notopterus* and tadpoles of the vulnerables *Microhyla orientalis* and *Gonocephalus kuhlii* that approach the ray to feed and thus, it can prey on them[70,71]. Freshwater stingrays can also change the diet preferences according to the prey availability in different hydrological seasons. Indeed, this easy adjustment for the available resources can be the main advantage in competition for food with native aquatic organisms. Furthermore, competition for utilizing food and space with native benthic organisms (such as *Hemibagrus* sp. and *Mastacembelus* sp.) is predicted if the populations of *Potamotrygon* spp. explode. Thus, it is obvious that this invader can negatively affect rich Indonesian aquatic biota in general and native, rare, protected, endemic, endangered, and vulnerable species in particular. In line with no predators of potamotrygonin species in their native range[66], it is also a main problem for these invasive organisms in Indonesia because the control of their populations by native predators is really difficult.

Several parasites such as Digenea, Nematoda and Cestoda are known in *Potamotrygon* spp.[72,73]. Also, branchiuran fish lice *Argulus juparanaensis* was found to infest *P. motoro* in its native range[74–76]. Therefore, the parasitic infection of native/endemic species cannot be excluded in the case of *Potamotrygon* spp. spread in Indonesia.

The popularity of various species of *Potamotrygon* as an ornamental fish in Indonesia is obvious because it is produced in significant quantities. In the early part of this species' history in Indonesia, some individuals were imported from Malaysia and India. The current list of customer countries is wide with Japan, Malaysia and Germany as leaders. No individuals were delivered to the Czech Republic even if this country is perceived as one of the leading producers and traders of ornamental fish globally[37,77,78]. This is probably caused by the significant production of *Potamotrygon* spp. by domestic breeders in the Czech Republic (Dařbujan, H., 2022 pers. comm.). It is obvious that the formal evidence of traded *P. motoro* in Indonesia is undervalued by CITES and the real volume of the trade is much higher. This discrepancy in trade evidence increases the potential for *P. motoro* and similar species to be invasive in Indonesia.

What is alarming, the current Indonesian legislative framework is ineffective in preventing the future introductions of this freshwater stingray to new localities and islands across the Indonesian territory[14]. Thus, without significant improvement in the management and regulations, the spread of *Potamotrygon* spp. in Indonesia can be expected to be unlimited for ongoing years. As Reynolds et al.[22] mentioned, detailed surveys of the trade with potamotrygonids are required for future proposals for CITES listing and we believe that the presented findings can be helpful in this regard.

Presented records align with the habitat use of native potamotrygonids at the Paraná River Basin[45]. Generally, potamotrygonids can adapt to broad ranges of physiochemical parameters[79] and we assume that this ability is crucial in case of invasion in the Brantas River. Further spread of these species is thus expected and the locality has to be monitored continuously and complemented by physical–chemical parameters measurements. The current condition is predicted as the 'tip of the iceberg' invasion event. Thus, continuous monitoring is recommended for this species. Therefore, we emphasize the importance of training health professionals near risk areas, as well as reporting accidents through a kind of "Information System for Notifiable Diseases" as it is carried out in Brazil[61]. According to Brazilian experience, it is recommended to remove fragments, wound cleaning, and immersion of the injured limb in hot water for pain relief (approximately 60 °C—due to the heat-labile properties of some of the toxins in the venom and the vasodilation caused by the hot water helps to counter the intense vasoconstriction and resulting ischemia induced by the venom), antibiotics to prevent bacterial septicemia, gangrene, tetanus, local anaesthetic, and systemic analgesics. Prevention of introductions is the first and most cost-effective management option for the Indonesian aquarium trade. Intensive awareness of importers, wholesalers, retailers, aquarium hobbyists and the general public about why releasing non-native freshwater stingrays is risky for native biota, and why releasing in wild could become a public health problem is crucial. Pamphlets combined with lectures, as well as the dissemination of information through the media, social networks like Facebook, Twitter, Instagram, and WhatsApp and warning signs in places of intense tourism/agglomeration of people showing that it is necessary to drag the feet or use a stick or paddle to grope the substrate in order to blows away any freshwater rays are measures that can be effective in preventing the number of accidents by rays in different parts of Indonesia.

Last but not least is to focus on other species of the genus *Potamotrygon* which are offered for sale as ornamental creatures in Indonesia and evaluate their invasion potential and their ability to cause harm to people's health. Additional effort should be placed on the other tropical countries that produce *Potamotrygon* species.

## Methods

Data collection was carried out after the first author received non-formal information from social media regarding the presence of stingrays in the Brantas River, Java (Fig. 2d). An in-depth online desk study was conducted following[21] in several mass-media and social media outlets (Facebook®, www.facebook.com; Instagram®, www.instagram.com). A survey including direct observations was carried out in December 2021 by inventorying stingray findings in the Brantas River (Blitar and Tulungagung Regency). Interviews with locals were conducted using the snowball method to qualitatively identify the impact of the invasion on human activities around the Brantas River. In total, 75 people (local non-fishermen who live near the river/locality: such as farmers, 'tambangan' people, i.e. person who utilized/organized traditional boat-bridge, local shop keepers; local fishermen: anglers, fishermen) were asked about the occurrence/locality of *Potamotrygon*/freshwater stingray, and only less than 10 providing the specific information about freshwater stingray. Informed consent was obtained from all interviewed people. If possible, individuals observed during the survey were documented and preserved using 96% alcohol. Authors complied with the ARRIVE guidelines. All methods were performed in accordance with the relevant guidelines and regulations. All methods, experiments, protocols, and survey were approved by the ethics committee of Centre for Coastal and Marine Resources Studies at the Bogor Agricultural University (IPB; No. 17/IT3/PL/2012).

Trade information was based on an online survey obtained from two e-commerce platforms (Tokopedia®, www.tokopedia.com; Shopee®, www.shopee.co.id). Keywords in Bahasa Indonesia and English (pari, pari air tawar, motoro, pari motoro, pari hias, pari black diamond, stingray, stingray motoro, pari marble) were generated and applied to search engines in each platform. The result from each keyword was screened based on the quality of photographs, stock availability, reliability and track record of the stores. The filtered result was synthesized into data and qualitatively described.

The MaxEnt model (v. 3.4.4, https://biodiversityinformatics.amnh.org/open_source/maxent/), a maximum entropy model that is ideally suited to mapping species distributions is commonly used to predict alien species dispersion[80] since it represents a continuous probability surface of habitat suitability in the target region[19,21,81,82]. This model consists of bioclimatic variables that are characteristics derived from monthly temperatures and rainfall data that reflect yearly patterns, seasonality, and extremes that are crucial for species survival. Bioclimatic factors from the WorldClim database were used to simulate species distribution (v.2.0; https://www.worldclim.org)[83] with a spatial resolution of 30 s ($\sim 1$ km$^2$). The distribution pattern of aquatic species and environmental factors, particularly temperature, have been discovered to be related[9,84]. These environmental layers were assembled in QGIS 3.24 'Tisler' and released on 13 May 2022 (https://qgis.org/en/site/) to ASCII format for use with the MaxEnt algorithm[85]. We calculated nine bioclimatic variables for both *P. motoro* and *P. jabuti* (Table 3), these represented the average, extreme and variation of temperature and precipitation and were widely used in ecological niche modelling. MaxEnt was trained using all nine bioclimatic variables with default features and regularization multipliers (Default model), which was based on empirical tuning studies[80]. As the cumulative output, a continuous map was generated and visualized in QGIS 3.24 'Tisler'. The MaxEnt model output a threshold value for *P. motoro* = 12.74 and *P. jabuti* = 16.32. If the value of the climate match reached or exceeded this threshold, this was interpreted as no evidence of climatic constraints to the survival of the species and was shown in red on the map. The value for the area under the receiver operator curve (AUC) for *P. motoro* was 0.981 and for *P. jabuti*, was 0.982 which means there was a 98% probability for both species that a random selection from presence records had a model score greater than a random selection from the absence records[82].

The trade analysis includes a detailed survey of evidence of the domestic market in Indonesia and main customer regions such as Europe with the Czech Republic as a hub[37,77]. Data from the Czech Environmental Inspectorate, (www.cizp.cz), CITES (https://trade.cites.org/) and Fish Quarantine and Inspection Agency (FQIA), Ministry of Marine Affairs and Fisheries Republic of Indonesia were obtained for this purpose and further interpreted.

| Bioclimatic variables | |
|---|---|
| BIO1 | Annual mean temperature |
| BIO2 | Mean diurnal range (Mean of monthly (max temp – min temp)) |
| BIO3 | Isothermality (BIO2/BIO7) (× 100) |
| BIO4 | Temperature seasonality (standard deviation × 100) |
| BIO5 | Max temperature of warmest month |
| BIO6 | Min temperature of coldest month |
| BIO7 | Temperature annual range (BIO5–BIO6) |
| BIO9 | Mean temperature of driest quarter |
| BIO10 | Mean temperature of warmest quarter |
| BIO11 | Mean temperature of coldest quarter |

**Table 3.** Bioclimatic variables used in the variable selection strategy to build a climate similarity model for *Potamotrygon motoro* and *P. jabuti* introduced in Indonesia.

The species identification of captured individuals was based on morphological analysis and comparison with the latest morphological study[32,86]. Morphological characteristics were measured using a calliper (accuracy 0.1 mm) and microscope images (Dino-lite AM2111). All captured individuals were exploited by the local community as ornamentals or for human consumption with the exception of a voucher specimen.

## Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Received: 3 November 2022; Accepted: 28 April 2023
Published online: 04 May 2023

## References

1. Simberloff, D. *et al.* Impacts of biological invasions: What's what and the way forward. *Trends. Ecol. Evol.* **28**, 58–66. https://doi.org/10.1016/j.tree.2012.07.013 (2013).
2. Pelicice, F. M. *et al.* Neotropical freshwater fishes imperilled by unsustainable policies. *Fish Fish.* **18**, 1119–1133 (2017).
3. Hulme, P. E. Unwelcome exchange: International trade as a direct and indirect driver of biological invasions worldwide. *One Earth* **4**, 666–679. https://doi.org/10.1016/j.oneear.2021.04.015 (2021).
4. Vilizzi, L. *et al.* A global-scale screening of non-native aquatic organisms to identify potentially invasive species under current and future climate conditions. *Sci. Total. Environ.* https://doi.org/10.1016/j.scitotenv.2021.147868 (2021).
5. Novák, J., Kalous, L. & Patoka, J. Modern ornamental aquaculture in Europe: Early history of freshwater fish imports. *Rev. Aquacult.* **12**, 2042–2060. https://doi.org/10.1111/raq.12421 (2020).
6. Akmal, S. G. *et al.* Marine ornamental trade in Indonesia. *Aquat. Living Resour.* **33**, 25 (2020).
7. Tapkir, S. D. *et al.* Far from home: Tracking the global ornamental fish trade in endangered zebra loach, *Botia striata*, from freshwater ecoregion and biodiversity hotspot in India. *J. Nat. Conserv.* **61**, 126007. https://doi.org/10.1016/j.jnc.2021.126007 (2021).
8. Lockwood, J. L. *et al.* When pets become pests: The role of the exotic pet trade in producing invasive vertebrate animals. *Front. Ecol. Environ.* **17**, 323–330. https://doi.org/10.1002/fee.2059 (2019).
9. Magalhães, A. L. B. *et al.* Biotic differentiation in headwater creeks after the massive introduction of non-native freshwater aquarium fish in the Paraíba do Sul River basin, Brazil. *Neotrop. Ichtyol.* **19** (2021).
10. Patoka, J., Bláha, M., Kalous, L. & Kouba, A. Irresponsible vendors: non-native, invasive and threatened animals offered for stocking garden ponds. *Aquat. Conserv.* **27**, 692–697. https://doi.org/10.1002/aqc.2719 (2017).
11. Putra, M. D. *et al.* *Procambarus clarkii* (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. *Aquat. Conserv.* **28**, 1434–1440 (2018).
12. Akmal, S. G. *et al.* Culture, trade and establishment of *Polypterus senegalus* in Indonesia with first record of wild populations. *Aquacult. Env. Interact.* **14**, 127–133. https://doi.org/10.3354/aei00433 (2022).
13. Bueno, M. L. *et al.* Alien fish fauna of southeastern Brazil: Species status, introduction pathways, distribution and impacts. *Biol. Invasions* **23**, 3021–3034 (2021).
14. Patoka, J. *et al.* Invasive aquatic pets: Failed policies increase risks of harmful invasions. *Biodivers. Conserv.* **27**, 3037–3046. https://doi.org/10.1007/s10531-018-1581-3 (2018).
15. Magalhães, A. Presence of prohibited fishes in the Brazilian aquarium trade: Effectiveness of laws, management options and future prospects. *J. Appl. Ichthyol.* **31**, 170–172. https://doi.org/10.1111/jai.12491 (2015).
16. Maceda-Veiga, A., Escribano-Alacid, J., Martínez-Silvestre, A., Verdaguer, I. & Mac Nally, R. What's next? The release of exotic pets continues virtually unabated 7 years after enforcement of new legislation for managing invasive species. *Biol. Invasions* **21**, 2933–2947. https://doi.org/10.1007/s10530-019-02023-8 (2019).
17. Patoka, J. *et al.* Two species of illegal South American sailfin catfish of the genus *Pterygoplichthys* well-established in Indonesia. *Knowl. Manag. Aquat. Ecosyst.* https://doi.org/10.1051/kmae/2020021 (2020).
18. Herder, F. *et al.* Alien invasion in Wallace's Dreamponds: Records of the hybridogenic "flowerhorn" cichlid in Lake Matano, with an annotated checklist of fish species introduced to the Malili Lakes system in Sulawesi. *Aquat. Invasions* **7**, 521–535. https://doi.org/10.3391/ai.2012.7.4.009 (2012).
19. Akmal, S. G. *et al.* Culture, trade and establishment of *Polypterus senegalus* in Indonesia with first record of wild population. *Aquacult. Env. Interact.* **14**, 127–133. https://doi.org/10.3354/aei00433 (2022).
20. Magalhães, A. L. B. & Vitule, J. R. S. Aquarium industry threatens biodiversity. *Science* **341**, 457. https://doi.org/10.1126/science.341.6145.457-a (2013).
21. Marková, J. *et al.* Conservation paradox of giant arapaima *Arapaima gigas* (Schinz, 1822) (Pisces: Arapaimidae): Endangered in its native range in Brazil and invasive in Indonesia. *Knowl. Manag. Aquat. Ecosyst.* **421**, 47. https://doi.org/10.1051/kmae/2020039 (2020).
22. Reynolds, J., Hornbrook, E., Stettner, G. & Terrell, R. in *The Elasmobranch Husbandry Manual II: Recent Advances in the Care of Sharks, Rays and their Relatives* Vol. 99 (eds Willson, K. *et al.*) Ch. 11, 99–112 (Ohio Biological Survey, 2017).
23. Carvalho, M. D., Loboda, T. S. & Silva, J. A new subfamily, Styracurinae, and new genus, *Styracura*, for *Himantura schmardae* (Werner, 1904) and *Himantura pacifica* (Beebe & Tee-Van, 1941) (Chondrichthyes: Myliobatiformes). *Zootaxa* **4175**, 201–221. https://doi.org/10.11646/zootaxa.4175.3.1 (2016).
24. Lucifora, L. O., Scarabotti, P. A. & Barbini, S. A. Predicting and contextualizing sensitivity to overfishing in Neotropical freshwater stingrays (Chondrichthyes: Potamotrygonidae). *Rev. Fish. Biol. Fisher.* **32**, 669–686. https://doi.org/10.1007/s11160-021-09696-2 (2022).
25. Ng, H. H., Tan, H. H., Yeo, D. C. & Ng, P. K. Stingers in a strange land: South American freshwater stingrays (Potamotrygonidae) in Singapore. *Biol. Invasions* **12**, 2385–2388. https://doi.org/10.1007/s10530-009-9663-5 (2010).
26. Magalhães, A. L. *et al.* Small size today, aquarium dumping tomorrow: sales of juvenile non-native large fish as an important threat in Brazil. *Neotrop. Ichtyol.* **15** (2017).
27. Araújo, M., Charvet-Almeida, P., Almeida, M. P. & Pereira, H. Freshwater stingrays (Potamotrygonidae): Status, conservation and management challenges. *Cites Org. Doc. AC20* **8**, 1–6 (2004).
28. De Carvalho, M. R. & Lovejoy, N. R. Morphology and phylogenetic relationships of a remarkable new genus and two new species of Neotropical freshwater stingrays from the Amazon basin (Chondrichthyes: Potamotrygonidae). *Zootaxa* **2776**, 13–48 (2011).
29. Fontenelle, J. P., Lovejoy, N. R., Kolmann, M. A. & Marques, F. P. Molecular phylogeny for the Neotropical freshwater stingrays (Myliobatiformes: Potamotrygoninae) reveals limitations of traditional taxonomy. *Biol. J. Linn. Soc.* **134**, 381–401. https://doi.org/10.1093/biolinnean/blab090 (2021).
30. Thorson, T. B., Langhammer, J. K. & Oetinger, M. I. Reproduction and development of the South American freshwater stingrays, *Potamotrygon circularis* and *P. motoro*. *Environ. Biol. Fish.* **9**, 3–24. https://doi.org/10.1007/BF00001055 (1983).

31. Charvet-Almeida, P., Araújo, M. L. G. & Almeida, M. P. Reproductive aspects of freshwater stingrays (Chondrichthyes: Potamotrygonidae) in the Brazilian Amazon Basin. *J. Northwest Atl. Fish.* **35**, 165–171. https://doi.org/10.2960/J.v35.m502 (2005).
32. Loboda, T. S. & Carvalho, M. R. Systematic revision of the *Potamotrygon motoro* (Müller & Henle, 1841) species complex in the Paraná-Paraguay basin, with description of two new ocellated species (Chondrichthyes: Myliobatiformes: Potamotrygonidae). *Neotrop. Ichtyol.* **11**, 693–737 (2013).
33. van den Boog, T. *Non-Timber Forest Products: Indigenous Ethnobotanical Knowledge and Livelihood Security in West Suriname*. Master thesis (University of British Columbia, 2017).
34. de Oliveira, A. T. *et al.* Relação entre as populações naturais de arraias de água doce (Myliobatiformes: Potamotrygonidae) e pescadores no baixo rio Juruá, Estado do Amazonas, Brasil. *Biota Amazôn.* **5**, 108–111 (2015).
35. Fricke, R., Eschmeyer, W. & Van der Laan, R. Eschmeyer's catalog of fishes: Genera, species, references, http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp (2023).
36. Camacho-Oliveira, R. B. *et al.* DNA barcode reveals the illegal trade of rays commercialized in fishmongers in Brazil. *Forensic Sci. Int. Synergy* **2**, 95–97. https://doi.org/10.1016/j.fsisyn.2020.02.002 (2020).
37. Kalous, L., Patoka, J. & Kopecký, O. European hub for invaders: Risk assessment of freshwater ornamental fish exported from the Czech Republic. *Acta Ichthyol. Piscat.* **45**, 239–245. https://doi.org/10.3750/AIP2015.45.3.03 (2015).
38. Patoka, J., Kalous, L. & Kopecký, O. Imports of ornamental crayfish: the first decade from the Czech Republic's perspective. *Knowl. Manag. Aquat. Ecosyst.* **416**, 4. https://doi.org/10.1051/kmae/2014040 (2015).
39. Akmal, S. G., Santoso, A., Yuliana, E. & Patoka, J. Redclaw crayfish (*Cherax quadricarinatus*): Spatial distribution and dispersal pattern in Java, Indonesia. *Knowl. Manag. Aquat. Ecosyst.* **422**, 16. https://doi.org/10.1051/kmae/2021015 (2021).
40. Yuliana, E. *et al.* Import, trade and culture of non-native ornamental crayfish in Java. *Indonesia. Manag. Biol. Invasions* **12**, 846–857. https://doi.org/10.3391/mbi.2021.12.4.05 (2021).
41. Akmal, S. G. *et al.* Ornamental aquaculture: Regulation and implementation of digital platforms to support fish trade pathways in Indonesia. *Workshop Biodivers. Jevany* **13**, 93–98 (2021).
42. Bomford, M., Barry, S. C. & Lawrence, E. Predicting establishment success for introduced freshwater fishes: A role for climate matching. *Biol. Invasions* **12**, 2559–2571. https://doi.org/10.1007/s10530-009-9665-3 (2010).
43. Magalhães, A. L. B. & Jacobi, C. M. Invasion risks posed by ornamental freshwater fish trade to southeastern Brazilian rivers. *Neotrop. Ichtyol.* **11**, 433–441. https://doi.org/10.1590/S1679-62252013005000003 (2013).
44. Loboda, T. S. *Revisão Taxonômica e Morfológica de Potamotrygon Motoro (Müller & Henle, 1841) na Bacia Amazônica (Chondrichthyes: Myliobatiformes: Potamotrygonidae)* Master thesis (Universidade de São Paulo, 2010).
45. Garrone-Neto, D. & Uieda, V. S. Activity and habitat use of two species of stingrays (Myliobatiformes: Potamotrygonidae) in the upper Paraná River basin, Southeastern Brazil. *Neotrop. Ichtyol.* **10**, 81–88. https://doi.org/10.1590/S1679-62252012000100008 (2012).
46. Vellend, M. The biodiversity conservation paradox. *Am. Sci.* **105**, 94–101 (2017).
47. Duncan, W. P. & Fernandes, M. N. Physicochemical characterization of the white, black, and clearwater rivers of the Amazon Basin and its implications on the distribution of freshwater stingrays (Chondrichthyes, Potamotrygonidae). *Pan-Am. J. Aquat. Sci.* **5**, 454–464 (2010).
48. MacKinnon, K., Hatta, G., Halim, H. & Mangalik, A. *The Ecology of Kalimantan* Vol. 3 (Oxford University Press, 1996).
49. Iqbal, M., Zulkifli, H. & Yustian, I. The valid species and distribution of stingrays (Myliobatiformes: Dasyatidae) in south Sumatera waters, Indonesia. *Biovalentia* **4**, 12–20. https://doi.org/10.24233/BIOV.4.1.2018.98 (2018).
50. Windusari, Y., Iqbal, M., Hanum, L., Zulkifli, H. & Yustian, I. Contemporary distribution records of the giant freshwater stingray *Urogymnus polylepis* in Borneo (Chondrichthyes: Dasyatidae). *Ichthyol. Explor. Fres.* **IEF-1089**, 1–6. https://doi.org/10.23788/IEF-1089 (2019).
51. Spee, L. B., Hazel, S. J., Dal Grande, E., Boardman, W. S. & Chaber, A.-L. Endangered exotic pets on social media in the Middle East: Presence and impact. *Animals* **9**, 480 (2019).
52. Júlio Júnior, H. F., Tós, C. D., Agostinho, Â. A. & Pavanelli, C. S. A massive invasion of fish species after eliminating a natural barrier in the upper rio Paraná basin. *Neotrop. Ichtyol.* **7**, 709–718. https://doi.org/10.1590/S1679-62252009000400021 (2009).
53. Garrone-Neto, D. *et al.* Uma área de vida restrita aumenta a vulnerabilidade da raia-de-fogo, *Potamotrygon motoro*, a pesca em um hotspot de biodiversidade da região neotropical. *Biota Amazôn.* **11**, 38–42 (2021).
54. Shibuya, A., Araújo, M. L. G. D. & Zuanon, J. A. S. Analysis of stomach contents of freshwater stingrays (Elasmobranchii, Potamotrygonidae) from the middle Negro River, Amazonas, Brazil. *Pan-Am. J. Aquat. Sci.* **4**, 466–475 (2009).
55. Abati, P. A. M. *et al.* Injuries caused by freshwater stingrays in the Tapajós River Basin: A clinical and sociodemographic study. *Rev. Soc. Bras. Med. Trop.* **50**, 374–378 (2017).
56. Brisset, I. B., Schaper, A., Pommier, P. & De Haro, L. Envenomation by Amazonian freshwater stingray *Potamotrygon motoro*: 2 cases reported in Europe. *Toxicon* **47**, 32–34. https://doi.org/10.1016/j.toxicon.2005.09.005 (2006).
57. Choa, M. H. *et al.* A case report of envenomation and injury by a poisonous spine of a marble motoro (*Potamotrygon motoro*). *J. Korean Soc. Clin. Toxicol.* **11**, 46–48 (2013).
58. Schiera, A., Battifoglio, M. L., Scarabelli, G. & Crippa, D. Stingray injury in a domestic aquarium. *Int. J. Dermatol.* **41**, 50–51 (2002).
59. Haddad Junior, V., Cardoso, J. L. C. & Garrone-Neto, D. Injuries by marine and freshwater stingrays: History, clinical aspects of the envenomations and current status of a neglected problem in Brazil. *J. Venom. Anim. Toxins Incl. Trop. Dis.* **19**, 1–11 (2013).
60. Haddad Junior, V., Garrone-Neto, D., de Paula Neto, J. B., de Luna Marques, F. P. & Barbaro, K. C. Freshwater stingrays: study of epidemiologic, clinic and therapeutic aspects based on 84 envenomings in humans and some enzymatic activities of the venom. *Toxicon* **43**, 287–294 (2004).
61. Reckziegel, G. C., Dourado, F. S., Garrone Neto, D. & Haddad, V. Jr. Lesões causadas por animais aquáticos no Brasil: Uma análise dos dados presentes no sistema de informação para doenças de notificação obrigatória. *Rev. Soc. Bras. Med. Trop.* **48**, 460–467. https://doi.org/10.1590/0037-8682-0133-2015 (2015).
62. Garrone-Neto, D., Haddad Junior, V., Vilela, M. J. A. & Uieda, V. S. Registro de ocorrência de duas espécies de potamotrigonídeos na região do Alto Rio Paraná e algumas considerações sobre sua biologia. *Biota Neotrop.* **7**, 0–0 (2007).
63. Garrone-Neto, D. & Haddad Junior, V. Arraias em rios da região Sudeste do Brasil: Locais de ocorrência e impactos sobre a população. *Rev. Soc. Bras. Med. Trop.* **43**, 82–88 (2010).
64. Silva, T. B. & Uieda, V. S. Preliminary data on the feeding habits of the freshwater stingrays *Potamotrygon falkneri* and *Potamotrygon motoro* (Potamotrygonidae) from the Upper Paraná River basin, Brazil. *Biota Neotrop.* **7**, 221–226 (2007).
65. Almeida, M. P. D., Lins, P. M. D. O., Charvet-Almeida, P. & Barthem, R. B. Diet of the freshwater stingray *Potamotrygon motoro* (Chondrichthyes: Potamotrygonidae) on Marajó Island (Pará, Brazil). *Braz. J. Biol.* **70**, 155–162. https://doi.org/10.1590/S1519-69842010000100022 (2010).
66. Shibuya, A. A review of the ecological role of the Neotropical freshwater stingrays (Chondrichthyes: Potamotryoninae). *Food Webs* **32**, e00244. https://doi.org/10.1016/j.fooweb.2022.e00244 (2022).
67. Shibuya, A., Zuanon, J. & Tanaka, S. Feeding behavior of the Neotropical freshwater stingray *Potamotrygon motoro* (Elasmobranchii: Potamotrygonidae). *Neotrop. Ichtyol.* **10**, 189–196. https://doi.org/10.1590/S1679-62252012000100018 (2012).
68. Garrone-Neto, D. & Sazima, I. Stirring, charging, and picking: hunting tactics of potamotrygonid rays in the upper Paraná River. *Neotrop. Ichtyol.* **7**, 113–116 (2009).

69. Garrone-Neto, D. & Sazima, I. The more stirring the better: cichlid fishes associate with foraging potamotrygonid rays. *Neotrop. Ichtyol.* **7**, 499–501 (2009).
70. Rohman, F. *et al.* Revealing herpetofauna diversity at Brantas River, East Java Indonesia: Evidence of decreasing populations. *Biodiversitas* **23** (2022).
71. Hasan, V. *et al.* A checklist of native freshwater fish from Brantas River, East Java, Indonesia. *Biodiversitas* **23**, 6031–6039. https://doi.org/10.13057/biodiv/d23115 (2022).
72. Lacerda, A. C., Takemoto, R. M. & Pavanelli, G. C. Digenea, Nematoda, Cestoda, and Acanthocephala, parasites in Potamotrygonidae (Chondrichthyes) from the upper Paraná River floodplain, states of Paraná and Mato Grosso do Sul, Brazil. *Check List* **4**, 115–122. https://doi.org/10.15560/4.2.115 (2008).
73. Brooks, D. R. & Amato, J. F. Cestode parasites in *Potamotrygon motoro* (Natterer) (Chondrichthyes: Potamotrygonidae) from southwestern Brazil, including *Rhinebothroides mclennanae* n. sp. (Tetraphyllidea: Phyllobothriidae), and a revised host-parasite checklist for helminths inhabiting neotropical freshwater stingrays. *J. Parasitol. Res.* **78**, 393–398. https://doi.org/10.2307/3283633 (1992).
74. Ivanov, V. A. A new species of *Acanthobothrium* (Cestoda: Tetraphyllidea: Onchobothriidae) from the ocellate river stingray, *Potamotrygon motoro* (Chondrichthyes: Potamotrygonidae), in Argentina. *J. Parasitol.* **91**, 390–396 (2005).
75. Souza, A. C. F., Gama, C. S., da Costa, A. L. P., Costa, J. F. & Viana, D. C. Índices parasitários de *Brevimulticaecum* sp. (Nematoda: Heterocheilidae) em *Potamotrygon motoro* (Chondrichthyes: Potamotrygonidae) capturados no Arquipélago do Bailique, Macapá. *Ens. Ciênc.* **24**, 511–515 (2020).
76. Oliveira, M. S. B., Corrêa, L. L., Oliveira Ferreira, D., Neves, L. R. & Tavares-Dias, M. Records of new localities and hosts for crustacean parasites in fish from the eastern Amazon in northern Brazil. *J. Parasit. Dis.* **41**, 565–570 (2017).
77. Novák, J. *et al.* Ornamental aquaculture significantly affected by the "Czech aquarium phenomenon". *Aquaculture* **555**, 738259. https://doi.org/10.1016/j.aquaculture.2022.738259 (2022).
78. Evers, H. G., Pinnegar, J. K. & Taylor, M. I. Where are they all from?–Sources and sustainability in the ornamental freshwater fish trade. *J. Fish Biol.* https://doi.org/10.1111/jfb.13930 (2019).
79. Duncan, W. P., Machado, R. N. & Fernandes, M. N. Environmentally-induced osmoregulation in Neotropical freshwater stingrays (Myliobatiformes: Potamotrygoninae) after controlling for phylogeny. *Comp. Biochem. Phys. A* **262**, 111076. https://doi.org/10.1016/j.cbpa.2021.111076 (2021).
80. Phillips, S. J. & Dudík, M. Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography* **31**, 161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x (2008).
81. Yonvitner, Y. *et al.* Enigmatic hotspot of crayfish diversity at risk: Invasive potential of non-indigenous crayfish if introduced to New Guinea. *Aquat. Conserv.* **30**, 219–224. https://doi.org/10.1002/aqc.3276 (2020).
82. Ward, D. F. Modelling the potential geographic distribution of invasive ant species in New Zealand. *Biol. Invasions* **9**, 723–735. https://doi.org/10.1007/s10530-006-9072-y (2007).
83. Fick, S. E. & Hijmans, R. J. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* **37**, 4302–4315. https://doi.org/10.1002/joc.5086 (2017).
84. Gallardo, B., Errea, M. P. & Aldridge, D. C. Application of bioclimatic models coupled with network analysis for risk assessment of the killer shrimp, *Dikerogammarus villosus* in Great Britain. *Biol. Invasions* **14**, 1265–1278. https://doi.org/10.1007/s10530-011-0154-0 (2012).
85. Phillips, S. J. *A Brief Tutorial on Maxent* (AT&T Research, 2005).
86. van der Sleen, P. & Albert, J. S. *Field Guide to the Fishes of the Amazon, Orinoco, and Guianas* Vol. 115 (Princeton University Press, 2017).

## Acknowledgements

RJ acknowledged the 'Ichthys-Alien Indonesia' project. JP was supported by the Technology Agency of the Czech Republic within the project, "DivLand" (No. SS02030018). SGA, OS, and JP were supported by the European Regional Development Fund: Submitted article was supported within the frame of the comprehensive project named "Centre for the investigation of synthesis and transformation of nutritional substances in the food chain in interaction with potentially harmful substances of anthropogenic origin: comprehensive assessment of soil contamination risks for the quality of agricultural products" (No. CZ.02.1.01/0.0/16_091/0000845). The trade statistic evidence was provided by Fish Quarantine and Inspection Agency (FQIA), Ministry of Marine Affairs and Fisheries Republic of Indonesia. Special thanks to Wild Water Indonesia (Mike and Salim Alimi) for providing crucial information. We thank two anonymous reviewers for their constructive comments.

## Author contributions

J.P. idea of the paper, and wrote the main manuscript text, R.J. and S.G.A. collected data, R.J. identified the species, J.P., R.J. and S.G.A. analysed data, and prepared figures. All authors reviewed the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

**Correspondence** and requests for materials should be addressed to J.P.

# 7. SUMMARY DISCUSSION

The presented findings revealed the increasing numbers of non-native and invasive aquatic species in Indonesia which are introduced via various pathways. Many of them have a high invasion potential and pose a serious threat to native biota and human communities. Human activities have largely impacted the environment and its biota to extend that biodiversity declines can be seen worldwide. The trade of marine ornamental fish in Indonesia began in the 1960s, and more than 280 types of marine ornamental fish are traded for export purposes (Sinansari and Priono, 2019). The trade gate is centralized at Jakarta and Bali, probably because both places have access to the United States and Europe, thus becoming shelters center for exporters. The value of the world's marine ornamental fish trade from year to year continues to increase, and Indonesia's rank as one of the exporting countries of ornamental fish increases as well (Sinansari and Priono, 2019). However, there are challenges in the development of the marine ornamental fish business, such as community behavior in marine ornamental fish catching that damages the ecosystem (Syafei and Sudinno, 2018).

Further details about the most important finding on the vulnerability status of the coral ecosystem in Kepulauan Seribu Marine National Park, Indonesia is that based on the findings, islands were classified as high-vulnerable (64%), moderate vulnerable (19.6%), and low vulnerable (16.07%). This information is crucial for the management and conservation of the coral ecosystem in the park. The study provides baseline coral disease data in the Kepulauan Seribu Marine National Park, and previously only one type of disease (White Syndrome, WS) has been reported. The vulnerability assessment of ecological conditions in Seribu Islands, Indonesia, is important to identify the factors that contribute to the vulnerability of the coral ecosystem, such as human activities, climate change, and natural disasters. The study highlights the need for effective management and conservation strategies to protect the coral ecosystem in the park and maintain its ecological functions and services.

Why is it important to study marine ornamental fish sales and coral vulnerability? Because of the interconnectedness of the spread of alien species through unforeseen pathways, they can become hitchhikers to reach areas outside their native range, and of course human intervention is one of the main reasons (Nijman et al., 2022b). Invasive alien species can enter Indonesian waters through international trade, such as the import of ornamental fish, or they can be accidentally introduced into Indonesian waters through ballast water discharge, hull fouling, and other human activities, and can also enter Indonesian waters through natural dispersal, such as ocean currents and migration (Ascensão and Capinha, 2017; Giovos et al., 2019; Patoka et al., 2016a; Patoka and Patoková, 2021; Rothlisberger et al., 2010). To prevent the introduction of harmful alien species into Indonesian waters, the government has implemented regulations to restrict the import of certain species. The Ministry of Marine Affairs and Fisheries is also working to control and manage invasive alien species in Indonesian waters.

Biological invasions significantly contribute to these processes. The introduction of many aquatic species into new habitats has been recorded to be invasive and later threatened the native species present in that habitat (Patoka et al., 2016c; Yanuarita et al., 2020). In Indonesia, local/native fishes are threatened by the increasing number of alien species introduced, mostly for aquaculture and aquarium purposes (Akmal et al., 2020; Kennedy et al., 2020; Palmtag, 2017). The introduction of non-native species in Indonesia has been facilitated by the government in the development of aquaculture that was carried out before the 1900s (Handayani et al., 2021). The most successful invasive alien species in Indonesia are ornamental cichlids and sailfin catfish, which frequently inhabit lakes and rivers (Fig. 2).


Figure 2 The sailfin catfish that successfully invaded a river in Yogyakarta, Indonesia. A) The habitat introduced by sailfin catfish. B) Sailfin catfish that was captured from the river.

There is limited information on whether the number of invasive species in Indonesia is increasing or not. However, some sources suggest that invasive species are a growing concern in the country. In 2014, at least 2,809 foreign animals, plants, and microorganisms were introduced into Indonesia, according to the Ministry of Environment and Forestry (Satriastanti, 2015). The spread of invasive, non-native mynas is partially or largely driven by the massive trade in these species as songbirds (Pyšek et al., 2020).

Despite the growing concern, Indonesia has taken some actions to control the introduction of alien flora and fauna. National regulations to control the introduction of alien flora and fauna include Act No. 5/1990 on conservation of biological diversity and its ecosystems. The government has also published a guidebook to invasive species in Indonesia. Additionally, there are ongoing efforts to raise awareness and develop capacity for the management of invasive alien species in the country.

Indonesia is facing issues related to invasive non-native species that are adversely affecting its biodiversity. However, the education of the general public about the risks related to the release of non-native species is poor in Indonesia. The legal framework on aquatic alien species in Indonesia should be developed as a basic role to the risk analysis and certification system. Here are some relevant points from the research:

a. The introduction of non-native species in various parts of the world negatively impacts biodiversity and the existence of native and endemic species.
b. Invasive species can cause great economic and environmental harm to the new area.
c. Invasive species are almost always spread by human activity, such as tourism and trade.
d. The increase in activities like tourism and trade have meant people and goods can move all over the planet, and they often take invasive species with them, accidentally or intentionally.
e. Invasive species can cause the extinction of endemic bird species and put coral reef ecosystems at risk.

f. The education of the general public about the risks related to the release of non-native species is poor in Indonesia.

To address this issue, Indonesia should focus on developing a legal framework on aquatic alien species and increasing public awareness about the risks associated with the release of non-native species. This can be achieved through various means such as public campaigns, educational programs, and workshops. It is important to note that the introduction of non-native species can have severe consequences on the environment and the economy, and it is crucial to take necessary measures to prevent their spread.

# 8. CONCLUSIONS

This dissertation is a collection of publications focusing on the above-discussed risks associated with aquatic invasive species, including the results of prediction models, and can therefore serve as a basis for the development and implementation of measures to minimize these risks. The results contained in this dissertation may assist in the compilation of a list of non-native invasive species that significantly impact Indonesia, on the basis that the listed species should be prioritized for monitoring and their trade and import into Indonesia should be restricted or prohibited. The challenges in implementing potential solutions for controlling the spread of Aquatic invasive species in Indonesia include:

a. Lack of effective regulations: There are no effective regulations of introductions and exploitation of this aquatic invasive species in Indonesia, which can lead to its further spread to new localities.
b. High invasive potential: aquatic invasive species is considered an intruder with high invasive potential, capable of causing biodiversity homogenization, at least at a local level. This makes it difficult to control its spread and manage its impact on native biota.
c. Culture and trade: Aquatic invasive species is considered valuable for producers and traders, and its culture and release to inland waters in Java and Sulawesi is undesirable and risky to biodiversity. The pet trade and aquaculture industry can also contribute to the spread of this species.
d. Limited research: 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. This limits the understanding of the species' behavior and the development of effective management strategies.
e. Lack of public awareness: Public awareness of the risks associated with the introduction and spread of invasive species is limited in Indonesia, which can hinder the implementation of effective prevention and management measures.

Addressing these challenges will require a collaborative effort among government agencies, researchers, industry stakeholders, and the public to develop and implement effective regulations, management strategies, and public education programs. The authors and team also established a robust cooperation with government, stakeholders, university colleagues, and NGOs to continuously disseminate our research findings. Cooperation with senators in the Regional Representative Council of the Republic of Indonesia, Ratu Hemas of Yogyakarta, the Sulawesi Keepers, the Indonesian Crayfish Research Group, and others is our starting point for long-term sustainability.

## 9. NON-IMPACTED OUTPUTS OF THE AUTHOR

The following are some of the author's works that were successfully produced before and during PhD studies:

Books:

a. Lesser Sunda and Bismarck Solomon Seascape. Section 17-*Potential Development of Fisheries Industry Based on Fisheries Raw Materials in Eastern Indonesia*. (2018)
   Authors: Yonvitner, Surya Gentha Akmal, Ki Agus Abdul Aziz, Nandi Syukri.
   ISBN: 978-602-440-517-5
   Published by: IPB Press Publisher

b. Fisheries Biology (2019) – in Bahasa
   Authors: Yonvitner, Isdradjad Setyobudiandi, Yunizar Ernawati, Zairion, Ali Mashar, **Surya Gentha Akmal**.
   ISBN: 978-602-440-273-0
   Published by: IPB Press Publisher

c. Fisheries Biology and Management (2020) – in Bahasa
   Authors: Yonvitner, Isdradjad Setyobudiandi, Yunizar Ernawati, Zairion, Ali Mashar, Ahmad Muhtadi, **Surya Gentha Akmal**.
   ISBN: 978-602-440-629-5
   Published by: IPB Press Publisher

d. A collection of ideas from Indonesian students around the world.
   Series 11: Maritime, Chapter 8. *Sustainable Fisheries Management Model Based on Fisheries Management Areas of the Republic of Indonesia* (2021) – in Bahasa
   Authors: **Surya Gentha Akmal**.
   ISBN: 978-602-496-231-9
   Published by: LIPI Press Publisher

Papers in the scientific journal:

a. Yonvitner, Yuliana E, Yani DE, Setijorini LE, Nurhasanah, Santoso A, Boer M, Kurnia R, **Akmal SG**. 2020. Fishing gear productivity related fishing intensity and potency of stock vulnerability in Sunda strait. *IOP Conf. Ser.: Earth Environ. Sci. 404 012066*. doi:10.1088/1755-1315/404/1/012066
b. **Akmal SG**, Adrianto L, Yonvitner. 2020. The spatial vulnerability of fisheries resources for sustainable management. *IOP Conf. Ser.: Earth Environ. Sci. 420 012002*. doi:10.1088/1755-1315/420/1/012002
c. Yonvitner, Lloret J, Boer M, Kurnia R, **Akmal SG**, Yuliana E, Yani DE, Gómez S, Setijorini LE. 2020. Vulnerability of marine resources to small-scale fishing in a tropical area: The example of Sunda Strait in Indonesia. *Fish Manag Ecol*. 2020;00:1- https://doi.org/10.1111/fme.12428
d. Yonvitner, Perdinan, Agus SB, Rusrita G, Ramadhani RA, **Akmal SG**. 2020. Mangrove governance: Establish a new paradigm of mangrove management "from village to the world". *IOP Conf. Ser.: Earth Environ. Sci. 550 012012*. doi:10.1088/1755-1315/550/1/012012
e. Yonvitner, Boer M, Akbar H, **Akmal SG**. 2020. Kerentanan Bycatch Tuna Dari Perikanan Handline di Selatan Samudera Hindia: Pencatatan Pelabuhan Sendang Biru-Malang. *Tropical Fisheries Management Journal*. 4(2):66-78. https://doi.org/10.29244/jppt.v4i2.32945
f. Sulistiono, Affandi R, Wildan DM, Jusadi D, Samson S, Akmal SG, Yonvitner, Patoka J. 2022. Artificial feeding of *Birgus latro* (L., 1767) (Anomura: Coenobitidae) as an alternative to natural diet: perspective for conservation breeding. Scientia Agriculturae Bohemica. 53:33-39. doi: 10.7160/sab.2022.530203

Contribution in the Proceedings:

a. Yonvitner, Yuliana E, Yani DE, Setijorini LE, Nurhasanah, Santoso A, Boer M, Kurnia R, Perdinan, Agus SB, **Akmal SG**. 2021. Effect of silent tsunami sunda strait to fisheries activity: Record from Labuan Landing Port, Pandeglang. AIP Conference Proceedings 2320, 040027. https://doi.org/10.1063/5.0037561

b. **Akmal SG**, Yonvitner, Patoka J. 2022. Ornamental aquaculture: Regulation and implementation of digital platforms to support fish trade pathways in Indonesia. Kubík S & Barták M (eds), 13$^{th}$ Workshop on Biodiversity, Jevany, Czech University of Life Sciences Prague, pp. 5-11. ISBN: 978-80-213-3157-0.

c. **Akmal SG**, Yonvitner, Yuliana E, Patoková B, Patoka J. 2022. Bifurcation of left long antenna in *Cherax* cf. *boesemani* (Decapoda: Parastacidae). Kubík S & Barták M (eds), 14$^{th}$ Workshop on Biodiversity, Jevany, Czech University of Life Sciences Prague, pp. 5-11. ISBN: 978-80-213-3241-6.

# 10. REFERENCES


Akmal, S.G., Santoso, A., Yonvitner, Yuliana, E., Patoka, J., 2021. Redclaw crayfish (Cherax quadricarinatus): spatial distribution and dispersal pattern in Java, Indonesia. Knowl Manag Aquat Ecosyst 422, 16. https://doi.org/10.1051/kmae/2021015

Akmal, S.G., Zámečníková-Wanma, B.P.D., Prabowo, R.E., Khatami, A.M., Novák, J., Petrtýl, M., Kalous, L., Patoka, J., 2020. Marine ornamental trade in Indonesia. Aquat Living Resour 33, 25. https://doi.org/10.1051/alr/2020026

Alidoost Salimi, P., Creed, J.C., Esch, M.M., Fenner, D., Jaafar, Z., Levesque, J.C., Montgomery, A.D., Alidoost Salimi, M., Edward, J.K.P., Raj, K.D., Sweet, M., 2021. A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. Mar Biodivers Rec 14, 11. https://doi.org/10.1186/s41200-021-00206-8

Ascensão, F., Capinha, C., 2017. Aliens on the Move: Transportation Networks and Non-native Species, in: Railway Ecology. Springer International Publishing, Cham, pp. 65–80. https://doi.org/10.1007/978-3-319-57496-7_5

Astegiano, J., Guimarães, P.R., Cheptou, P.-O., Vidal, M.M., Mandai, C.Y., Ashworth, L., Massol, F., 2015. Persistence of Plants and Pollinators in the Face of Habitat Loss. pp. 201–257. https://doi.org/10.1016/bs.aecr.2015.09.005

Baker, R.E., Mahmud, A.S., Miller, I.F., Rajeev, M., Rasambainarivo, F., Rice, B.L., Takahashi, S., Tatem, A.J., Wagner, C.E., Wang, L.-F., Wesolowski, A., Metcalf, C.J.E., 2022. Infectious disease in an era of global change. Nat Rev Microbiol 20, 193–205. https://doi.org/10.1038/s41579-021-00639-z

Boedhihartono, A., 2017. Can Community Forests Be Compatible With Biodiversity Conservation in Indonesia? Land (Basel) 6, 21. https://doi.org/10.3390/land6010021

Brewer, G., 2022. Indonesia: A treasure trove of biodiversity [WWW Document]. KEW, Royal Botanic Gardens. URL https://www.kew.org/read-and-watch/Indonesia-biodiversity (accessed 5.26.23).

Cambray, J.A., 2003. Impact on indigenous species biodiversity caused by the globalisation of alien recreational freshwater fisheries. Hydrobiologia 500, 217–230. https://doi.org/10.1023/A:1024648719995

Capps, K.A., Flecker, A.S., 2013. Invasive Fishes Generate Biogeochemical Hotspots in a Nutrient-Limited System. PLoS One 8, e54093. https://doi.org/10.1371/journal.pone.0054093

Cleeland, J.B., Pardo, D., Raymond, B., Terauds, A., Alderman, R., McMahon, C.R., Phillips, R.A., Lea, M.-A., Hindell, M.A., 2020. Introduced species and extreme weather as key drivers of reproductive output in three sympatric albatrosses. Sci Rep 10, 8199. https://doi.org/10.1038/s41598-020-64662-5

Cuthbert, R.N., Pattison, Z., Taylor, N.G., Verbrugge, L., Diagne, C., Ahmed, D.A., Leroy, B., Angulo, E., Briski, E., Capinha, C., Catford, J.A., Dalu, T., Essl, F., Gozlan, R.E., Haubrock, P.J., Kourantidou, M., Kramer, A.M., Renault, D., Wasserman, R.J., Courchamp, F., 2021. Global economic costs of aquatic invasive alien species. Science of The Total Environment 775, 145238. https://doi.org/10.1016/j.scitotenv.2021.145238

Davis, A.J.S., Darling, J.A., 2017. Recreational freshwater fishing drives non-native aquatic species richness patterns at a continental scale. Divers Distrib 23, 692–702. https://doi.org/10.1111/ddi.12557

Deacon, A.E., Ramnarine, I.W., Magurran, A.E., 2011. How Reproductive Ecology Contributes to the Spread of a Globally Invasive Fish. PLoS One 6, e24416. https://doi.org/10.1371/journal.pone.0024416

Decena, S.C.P., Avorque, C.A., Decena, I.C.P., Asis, P.D., Pacle, B., 2020. Impact of habitat alteration on amphibian diversity and species composition in a lowland tropical rainforest in Northeastern Leyte, Philippines. Sci Rep 10, 10547. https://doi.org/10.1038/s41598-020-67512-6

Dennis, R.L.H., 2018. A Decade of the Resource-Based Habitat Paradigm: The Semantics of Habitat Loss, in: Encyclopedia of the Anthropocene. Elsevier, pp. 85–96. https://doi.org/10.1016/B978-0-12-809665-9.09209-0

Doherty, T.S., Glen, A.S., Nimmo, D.G., Ritchie, E.G., Dickman, C.R., 2016. Invasive predators and global biodiversity loss. Proceedings of the National

Academy of Sciences 113, 11261–11265. https://doi.org/10.1073/pnas.1602480113

Drew, G.C., Stevens, E.J., King, K.C., 2021. Microbial evolution and transitions along the parasite–mutualist continuum. Nat Rev Microbiol 19, 623–638. https://doi.org/10.1038/s41579-021-00550-7

Durante, L., Wing, S., Ingram, T., Sabadel, A., Shima, J., 2022. Changes in trophic structure of an exploited fish community at the centennial scale are linked to fisheries and climate forces. Sci Rep 12, 4309. https://doi.org/10.1038/s41598-022-08391-x

Elith, J., Kearney, M., Phillips, S., 2010. The art of modelling range-shifting species. Methods Ecol Evol 1, 330–342. https://doi.org/10.1111/j.2041-210X.2010.00036.x

Ewel, J.J., O'Dowd, D.J., Bergelson, J., Daehler, C.C., D'Antonio, C.M., Gómez, L.D., Gordon, D.R., Hobbs, R.J., Holt, A., Hopper, K.R., Hughes, C.E., LaHart, M., Leakey, R.R.B., Lee, W.G., Loope, L.L., Lorence, D.H., Louda, S.M., Lugo, A.E., McEvoy, P.B., Richardson, D.M., Vitousek, P.M., 1999. Deliberate Introductions of Species: Research Needs. Bioscience 49, 619–630. https://doi.org/10.2307/1313438

FAO, 2019. Revitalizing Integrated Pest Management in Indonesia - TCP/INS/3403 and TCP/INS/3601. Rome, Italy.

Fèvre, E.M., Bronsvoort, B.M. de C., Hamilton, K.A., Cleaveland, S., 2006. Animal movements and the spread of infectious diseases. Trends Microbiol 14, 125–131. https://doi.org/10.1016/j.tim.2006.01.004

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37, 4302–4315. https://doi.org/10.1002/joc.5086

Foster, R., Peeler, E., Bojko, J., Clark, P.F., Morritt, D., Roy, H.E., Stebbing, P., Tidbury, H.J., Wood, L.E., Bass, D., 2021. Pathogens co-transported with invasive non-native aquatic species: implications for risk analysis and legislation. NeoBiota 69, 79–102. https://doi.org/10.3897/neobiota.69.71358

Gallardo, B., Clavero, M., Sánchez, M.I., Vilà, M., 2016. Global ecological impacts of invasive species in aquatic ecosystems. Glob Chang Biol 22, 151–163. https://doi.org/10.1111/gcb.13004

García-Berthou, E., Alcaraz, C., Pou-Rovira, Q., Zamora, L., Coenders, G., Feo, C., 2005. Introduction pathways and establishment rates of invasive aquatic species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 62, 453–463. https://doi.org/10.1139/f05-017

Giovos, I., Katsanevakis, S., Coll, M., Piroddi, C., Steenbeek, J., Lasram, F.B.R., Zenetos, A., Cardoso, A.C., 2019. Human Activities Help Alien Species to Invade the Mediterranean Sea. Front Young Minds 7. https://doi.org/10.3389/frym.2019.00097

Handayani, I., Saad, H., Ratnakomala, S., Lisdiyanti, P., Kusharyoto, W., Krause, J., Kulik, A., Wohlleben, W., Aziz, S., Gross, H., Gavriilidou, A., Ziemert, N., Mast, Y., 2021. Mining Indonesian Microbial Biodiversity for Novel Natural Compounds by a Combined Genome Mining and Molecular Networking Approach. Mar Drugs 19, 316. https://doi.org/10.3390/md19060316

Hanley, N., Roberts, M., 2019. The economic benefits of invasive species management. People and Nature 1, 124–137. https://doi.org/10.1002/pan3.31

Hassan, A., Nawchoo, I.A., 2020a. Impact of Invasive Plants in Aquatic Ecosystems, in: Bioremediation and Biotechnology. Springer International Publishing, Cham, pp. 55–73. https://doi.org/10.1007/978-3-030-35691-0_3

Hassan, A., Nawchoo, I.A., 2020b. Impact of Invasive Plants in Aquatic Ecosystems, in: Bioremediation and Biotechnology. Springer International Publishing, Cham, pp. 55–73. https://doi.org/10.1007/978-3-030-35691-0_3

Haubrock, P.J., Bernery, C., Cuthbert, R.N., Liu, C., Kourantidou, M., Leroy, B., Turbelin, A.J., Kramer, A.M., Verbrugge, L.N.H., Diagne, C., Courchamp, F., Gozlan, R.E., 2022. Knowledge gaps in economic costs of invasive alien fish worldwide. Science of The Total Environment 803, 149875. https://doi.org/10.1016/j.scitotenv.2021.149875

Havel, J.E., Kovalenko, K.E., Thomaz, S.M., Amalfitano, S., Kats, L.B., 2015. Aquatic invasive species: challenges for the future. Hydrobiologia 750, 147–170. https://doi.org/10.1007/s10750-014-2166-0

He, Y., Zhao, K., Zhang, H., He, L., Niu, Y., Zhang, M., Xu, J., 2021. Linking macrophyte community structure with food chain length: A case study in the largest freshwater lake in China and ecological restoration implications. Ecol Indic 123, 107363. https://doi.org/10.1016/j.ecolind.2021.107363

Heilman, M., 2014. Aquatic Invasive Species Prevention and Policies [WWW Document]. SOLitude Lake Management. URL https://www.solitudelakemanagement.com/blog/aquatic-invasive-species-prevention-and-policies/ (accessed 5.26.23).

Hejda, M., Pyšek, P., Jarošík, V., 2009. Impact of invasive plants on the species richness, diversity and composition of invaded communities. Journal of Ecology 97, 393–403. https://doi.org/10.1111/j.1365-2745.2009.01480.x

Hulme, P.E., 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. Journal of Applied Ecology 46, 10–18. https://doi.org/10.1111/j.1365-2664.2008.01600.x

IUCN, 2021. Invasive alien species and climate change [WWW Document]. International Union for Conservation of Nature and Natural Resources. URL https://www.iucn.org/resources/issues-brief/invasive-alien-species-and-climate-change (accessed 5.26.23).

Jackson, H.B., Fahrig, L., 2013. Habitat Loss and Fragmentation, in: Encyclopedia of Biodiversity. Elsevier, pp. 50–58. https://doi.org/10.1016/B978-0-12-384719-5.00399-3

Jo, I., Fridley, J.D., Frank, D.A., 2017. Invasive plants accelerate nitrogen cycling: evidence from experimental woody monocultures. Journal of Ecology 105, 1105–1110. https://doi.org/10.1111/1365-2745.12732

Jones, P.E., Tummers, J.S., Galib, S.M., Woodford, D.J., Hume, J.B., Silva, L.G.M., Braga, R.R., Garcia de Leaniz, C., Vitule, J.R.S., Herder, J.E., Lucas, M.C., 2021. The Use of Barriers to Limit the Spread of Aquatic Invasive Animal Species: A Global Review. Front Ecol Evol 9. https://doi.org/10.3389/fevo.2021.611631

Ju, R., Li, X., Jiang, J., Wu, J., Liu, J., Strong, D.R., Li, B., 2020. Emerging risks of non-native species escapes from aquaculture: Call for policy improvements in China and other developing countries. Journal of Applied Ecology 57, 85–90. https://doi.org/10.1111/1365-2664.13521

Katsanevakis, S., Wallentinus, I., Zenetos, A., Leppäkoski, E., Çinar, M.E., Oztürk, B., Grabowski, M., Golani, D., Cardoso, A.C., 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. Aquat Invasions 9, 391–423. https://doi.org/10.3391/ai.2014.9.4.01

Kennedy, E. V, Vercelloni, J., Neal, B.P., Ambariyanto, Bryant, D.E.P., Ganase, A., Gartrell, P., Brown, K., Kim, C.J.S., Hudatwi, M., Hadi, A., Prabowo, A., Prihatinningsih, P., Haryanta, S., Markey, K., Green, S., Dalton, P., Lopez-Marcano, S., Rodriguez-Ramirez, A., Gonzalez-Rivero, M., Hoegh-Guldberg, O., 2020. Coral Reef Community Changes in Karimunjawa National Park, Indonesia: Assessing the Efficacy of Management in the Face of Local and Global Stressors. J Mar Sci Eng 8, 760. https://doi.org/10.3390/jmse8100760

Kovalenko, K.E., Pelicice, F.M., Kats, L.B., Kotta, J., Thomaz, S.M., 2021a. Aquatic invasive species: introduction to the Special Issue and dynamics of public interest. Hydrobiologia 848, 1939–1953. https://doi.org/10.1007/s10750-021-04585-y

Kovalenko, K.E., Pelicice, F.M., Kats, L.B., Kotta, J., Thomaz, S.M., 2021b. Aquatic invasive species: introduction to the Special Issue and dynamics of public interest. Hydrobiologia 848, 1939–1953. https://doi.org/10.1007/s10750-021-04585-y

Lauber, T.B., Stedman, R.C., Connelly, N.A., Ready, R.C., Rudstam, L.G., Poe, G.L., 2020. The effects of aquatic invasive species on recreational fishing participation and value in the Great Lakes: Possible future scenarios. J Great Lakes Res 46, 656–665. https://doi.org/10.1016/j.jglr.2020.04.003

Lin, L., Yang, H., Xu, X., 2022. Effects of Water Pollution on Human Health and Disease Heterogeneity: A Review. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.880246

Linders, T.E.W., Schaffner, U., Eschen, R., Abebe, A., Choge, S.K., Nigatu, L., Mbaabu, P.R., Shiferaw, H., Allan, E., 2019. Direct and indirect effects of invasive species: Biodiversity loss is a major mechanism by which an invasive tree affects ecosystem functioning. Journal of Ecology 107, 2660–2672. https://doi.org/10.1111/1365-2745.13268

Lodge, D.M., Williams, S., MacIsaac, H.J., Hayes, K.R., Leung, B., Reichard, S., Mack, R.N., Moyle, P.B., Smith, M., Andow, D.A., Carlton, J.T., McMichael, A., 2006. Biological invasions: recommendations for U.S. Policy and Management. Ecological Applications 16, 2035–2054.

Manchester, S.J., Bullock, J.M., 2000. The impacts of non-native species on UK biodiversity and the effectiveness of control. Journal of Applied Ecology 37, 845–864. https://doi.org/10.1046/j.1365-2664.2000.00538.x

Marková, J., Jerikho, R., Wardiatno, Y., Kamal, M.M., Magalhães, A.L.B., Bohatá, L., Kalous, L., Patoka, J., 2020. Conservation paradox of giant arapaima Arapaima gigas (Schinz, 1822) (Pisces: Arapaimidae): endangered in its native range in Brazil and invasive in Indonesia. Knowl Manag Aquat Ecosyst 421, 1–10. https://doi.org/10.1051/kmae/2020039

Marwoto, R.M., Isnaningsih, N.R., Joshi, R.C., 2018. The invasive apple snail (Pomacea spp.) in Indonesia. Agriculture for Development 35, 41–48.

Maskun, Assidiq, H., Mukarramah, N.H. Al, Bachril, S.N., 2021. Threats to the sustainability of biodiversity in Indonesia by the utilization of forest areas for national strategic projects: A normative review. IOP Conf Ser Earth Environ Sci 886, 012071. https://doi.org/10.1088/1755-1315/886/1/012071

Mayfield, A.E., Seybold, S.J., Haag, W.R., Johnson, M.T., Kerns, B.K., Kilgo, J.C., Larkin, D.J., Lucardi, R.D., Moltzan, B.D., Pearson, D.E., Rothlisberger, J.D., Schardt, J.D., Schwartz, M.K., Young, M.K., 2021. Impacts of Invasive Species in Terrestrial and Aquatic Systems in the United States, in: Invasive Species in Forests and Rangelands of the United States. Springer International Publishing, Cham, pp. 5–39. https://doi.org/10.1007/978-3-030-45367-1_2

McNeely, J., 2001. Invasive species: a costly catastrophe for native biodiversity. Land Use and Water Resources Reseach2 1, 1–10. https://doi.org/10.22004/ag.econ.47850

Mehta, S. V, Haight, R.G., Homans, F.R., Polasky, S., Venette, R.C., 2007. Optimal detection and control strategies for invasive species management. Ecological Economics 61, 237–245. https://doi.org/10.1016/j.ecolecon.2006.10.024

Meyerson, L.A., Mooney, H.A., 2007. Invasive alien species in an era of globalization. Front Ecol Environ 5, 199–208. https://doi.org/https://doi.org/10.1890/1540-9295(2007)5[199:IASIAE]2.0.CO;2

Minamoto, T., Yamanaka, H., Takahara, T., Honjo, M.N., Kawabata, Z., 2012. Surveillance of fish species composition using environmental DNA. Limnology (Tokyo) 13, 193–197. https://doi.org/10.1007/s10201-011-0362-4

Mooney, H.A., Cleland, E.E., 2001. The evolutionary impact of invasive species. Proceedings of the National Academy of Sciences 98, 5446–5451. https://doi.org/10.1073/pnas.091093398

Muchlisin, Z., 2012. First report on introduced freshwater fishes in the waters of Aceh, Indonesia. Archives of Polish Fisheries 20. https://doi.org/10.2478/v10086-012-0015-1

Nijman, V., Ardiansyah, A., Siriwat, P., Birot, H., Winnasis, S., Damianou, E., Imron, M.A., Langgeng, A., Lewis, B., Nekaris, K.A.-I., 2022a. Wildlife trade and the establishment of invasive alien species in Indonesia: management, policy, and regulation of the commercial sale of songbirds. Biol Invasions 24, 2905–2916. https://doi.org/10.1007/s10530-022-02831-5

Nijman, V., Ardiansyah, A., Siriwat, P., Birot, H., Winnasis, S., Damianou, E., Imron, M.A., Langgeng, A., Lewis, B., Nekaris, K.A.-I., 2022b. Wildlife trade and the establishment of invasive alien species in Indonesia: management, policy, and regulation of the commercial sale of songbirds. Biol Invasions 24, 2905–2916. https://doi.org/10.1007/s10530-022-02831-5

Nijman, V., Campera, M., Imron, M.A., Ardiansyah, A., Langgeng, A., Dewi, T., Hedger, K., Hendrik, R., Nekaris, K.A.-I., 2021. The Role of the Songbird Trade as an Anthropogenic Vector in the Spread of Invasive Non-Native Mynas in Indonesia. Life 11, 814. https://doi.org/10.3390/life11080814

NISAW, 2021. Climate Change and Invasive Species [WWW Document]. webinar on Climate Change and The RISCC Network, National Invasive Species Awareness Week. URL https://www.nisaw.org/climatechange/ (accessed 5.26.23).

Palmtag, M.R., 2017. The Marine Ornamental Species Trade, in: Marine Ornamental Species Aquaculture. Wiley, pp. 3–14. https://doi.org/10.1002/9781119169147.ch1

Patoka, J., Bláha, M., Devetter, M., Rylková, K., Čadková, Z., Kalous, L., 2016a. Aquarium hitchhikers: attached commensals imported with freshwater shrimps via the pet trade. Biol Invasions 18, 457–461. https://doi.org/10.1007/s10530-015-1018-9

Patoka, J., Magalháes, A.L.B., Kouba, A., Faulkes, Z., Jerikho, R., Vitule, J.R.S., 2018. Invasive aquatic pets: failed policies increase risks of harmful invasions. Biodivers Conserv 27, 3037–3046. https://doi.org/https://doi.org/10.1007/s10531-018-1581-3

Patoka, J., Patoková, B., 2021. Hitchhiking Exotic Clam: Dreissena polymorpha (Pallas, 1771) Transported via the Ornamental Plant Trade. Diversity (Basel) 13, 410. https://doi.org/10.3390/d13090410

Patoka, J., Takdir, M., Yonvitner, Aryadi, H., Jerikho, R., Nilawati, J., Tantu, F.Y., Bohatá, L., Aulia, A., Kamal, M.M., Wardiatno, Y., Petrtýl, M., 2020. Two species of illegal South American sailfin catfish of the genus Pterygoplichthys well-established in Indonesia. Knowl Manag Aquat Ecosyst 28, 1–5. https://doi.org/https://doi.org/10.1051/kmae/2020021

Patoka, J., Wardiatno, Y., Yonvitner, Kuříková, P., Petrtýl, M., Kalous, L., 2016b. Cherax quadricarinatus (von Martens) has invaded Indonesian territory west of the Wallace Line: evidences from Java. Knowl Manag Aquat Ecosyst 517, 1–6. https://doi.org/https://doi.org/10.1051/kmae/2016026

Patoka, J., Wardiatno, Y., Yonvitner, Kuříková, P., Petrtýl, M., Kalous, L., 2016c. *Cherax quadricarinatus* (von Martens) has invaded Indonesian territory west of the Wallace Line: evidences from Java. Knowl Manag Aquat Ecosyst 39. https://doi.org/10.1051/kmae/2016026

Peeler, E.J., Taylor, N.G., 2011. The application of epidemiology in aquatic animal health -opportunities and challenges. Vet Res 42, 94. https://doi.org/10.1186/1297-9716-42-94

Phillips, S.J., 2005. A brief tutorial on Maxent. AT&T Research 190, 231–259.

Phillips, S.J., Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31, 161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x

Pimentel, D., 2011. Biological invasions. economic and environmental costs of alien plant, animal, and microbe species. CRC Press, Florida.

Pinho, B.X., Peres, C.A., Leal, I.R., Tabarelli, M., 2020. Critical role and collapse of tropical mega-trees: A key global resource. pp. 253–294. https://doi.org/10.1016/bs.aecr.2020.01.009

Prior, K.M., Robinson, J.M., Meadley Dunphy, S.A., Frederickson, M.E., 2015. Mutualism between co-introduced species facilitates invasion and alters plant community structure. Proceedings of the Royal Society B: Biological Sciences 282, 20142846. https://doi.org/10.1098/rspb.2014.2846

Putra, M.D., Bláha, M., Wardiatno, Y., Krisanti, M., Yonvitner, Jerikho, R., Kamal, M.M., Mojžišvá, M., Bystřický, P.K., Kouba, A., Kalous, L., Petrusek, A., Patoka, J., 2018. Procambarus clarkii (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. Aquatic Conservation: Marine and Freshwater Ecosystem 28, 1434–1440. https://doi.org/DOI: 10.1002/aqc.2970

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T., Dawson, W., Essl, F., Foxcroft, L.C., Genovesi, P., Jeschke, J.M., Kühn, I., Liebhold, A.M., Mandrak, N.E., Meyerson, L.A., Pauchard, A., Pergl, J., Roy, H.E., Seebens, H., Kleunen, M., Vilà, M., Wingfield, M.J., Richardson, D.M., 2020. Scientists' warning on invasive alien species. Biological Reviews 95, 1511–1534. https://doi.org/10.1111/brv.12627

Rafferty, J.P., 2023. Invasive Species [WWW Document]. Encyclopedia Britannica. URL https://www.britannica.com/science/invasive-species (accessed 5.20.23).

Rothlisberger, J.D., Chadderton, W.L., McNulty, J., Lodge, D.M., 2010. Aquatic Invasive Species Transport via Trailered Boats: What is Being Moved, Who is Moving it, and What Can Be Done. Fisheries (Bethesda) 35, 121–132. https://doi.org/10.1577/1548-8446-35.3.121

Sanka, I., Kusuma, A.B., Martha, F., Hendrawan, A., Pramanda, I.T., Wicaksono, A., Jati, A.P., Mazaya, M., Dwijayanti, A., Izzati, N., Maulana, M.F., Widyaningrum, A.R., 2023. Synthetic biology in Indonesia: Potential and projection in a country with mega biodiversity. Biotechnology Notes 4, 41–48. https://doi.org/10.1016/j.biotno.2023.02.002

Santas, A.J., Persaud, T., Wolfe, B.A., Bauman, J.M., 2013. Noninvasive Method for a Statewide Survey of Eastern Hellbenders Cryptobranchus alleganiensis Using Environmental DNA. Int J Zool 2013, 1–6. https://doi.org/10.1155/2013/174056

Satriastanti, F.E., 2015. After two decades, Indonesia publishes plan for tackling invasive species [WWW Document]. Mongabay. URL https://news.mongabay.com/2015/06/after-two-decades-indonesia-publishes-plan-for-tackling-invasive-species/ (accessed 5.26.23).

Sinansari, S., Priono, B., 2019. Opportunity and business challenge of marine ornamental fishes in Indonesia as a potential commodity of fisheries. IOP Conf Ser Earth Environ Sci 230, 012067. https://doi.org/10.1088/1755-1315/230/1/012067

Smith, E.R.C., Bennion, H., Sayer, C.D., Aldridge, D.C., Owen, M., 2020. Recreational angling as a pathway for invasive non-native species spread: awareness of biosecurity and the risk of long distance movement into Great Britain. Biol Invasions 22, 1135–1159. https://doi.org/10.1007/s10530-019-02169-5

Strauss, A., White, A., Boots, M., 2012. Invading with biological weapons: the importance of disease-mediated invasions. Funct Ecol 26, 1249–1261. https://doi.org/10.1111/1365-2435.12011

Sulpizio, J., 2020. Slow the Spread of Aquatic Invasive Species [WWW Document]. College of Agricultural Sciences, The Pennsylvania State University. URL https://extension.psu.edu/slow-the-spread-of-aquatic-invasive-species (accessed 5.20.23).

Syafei, L.S., Sudinno, D., 2018. Ikan Asing Invasif, Tantangan Keberlanjutan Biodiversitas Perairan. Jurnal Penyuluhan Perikanan dan Kelautan 12, 149–165. https://doi.org/10.33378/jppik.v12i3.106

Tarkan, A.S., Yoğurtçuoğlu, B., Karachle, P.K., Kalogianni, E., Top Karakuş, N., Tricarico, E., 2021. Editorial: Understanding the Impact and Invasion Success of Aquatic Non-native Species: How They Interact With Novel Environments and Native Biota. Front Ecol Evol 9. https://doi.org/10.3389/fevo.2021.790540

Thomaz, S.M., Kovalenko, K.E., Havel, J.E., Kats, L.B., 2015. Aquatic invasive species: general trends in the literature and introduction to the special issue. Hydrobiologia 746, 1–12. https://doi.org/10.1007/s10750-014-2150-8

Thorburn, C., 2015. The Rise and Demise of Integrated Pest Management in Rice in Indonesia. Insects 6, 381–408. https://doi.org/10.3390/insects6020381

Tiebre, M.-S., Vanderhoeven, S., Saad, L., Mahy, G., 2007. Hybridization and Sexual Reproduction in the Invasive Alien Fallopia (Polygonaceae) Complex in Belgium. Ann Bot 99, 193–203. https://doi.org/10.1093/aob/mcl242

Torchin, M.E., Lafferty, K.D., Dobson, A.P., McKenzie, V.J., Kuris, A.M., 2003. Introduced species and their missing parasites. Nature 421, 628–630. https://doi.org/10.1038/nature01346

Tricarico, E., 2022. 'Many eyes on the water': The role of citizen science in freshwater conservation. Aquat Conserv 32, 1867–1871. https://doi.org/10.1002/aqc.3891

USDA, n.d. Control Mechanisms [WWW Document]. National Invasive Species Information Center, U.S. Department of Agriculture. URL https://www.invasivespeciesinfo.gov/subject/control-mechanisms (accessed 5.26.23).

Vander Zanden, M.J., Olden, J.D., 2008. A management framework for preventing the secondary spread of aquatic invasive species. Canadian Journal of Fisheries and Aquatic Sciences 65, 1512–1522. https://doi.org/10.1139/F08-099

Vanni, M.J., 2021. Invasive mussels regulate nutrient cycling in the largest freshwater ecosystem on Earth. Proceedings of the National Academy of Sciences 118. https://doi.org/10.1073/pnas.2100275118

Whitney, K.D., Gabler, C.A., 2008. Rapid evolution in introduced species, 'invasive traits' and recipient communities: challenges for predicting invasive potential. Divers Distrib 14, 569–580. https://doi.org/10.1111/j.1472-4642.2008.00473.x

Williams-Subiza, E.A., Epele, L.B., 2021. Drivers of biodiversity loss in freshwater environments: A bibliometric analysis of the recent literature. Aquat Conserv 31, 2469–2480. https://doi.org/10.1002/aqc.3627

Wilson, M.E., 2010. Geography of infectious diseases, in: Infectious Diseases. Elsevier, pp. 1055–1064. https://doi.org/10.1016/B978-0-323-04579-7.00101-5

Wiyono, S., 2020. Building new phase of IPM in Indonesia. IOP Conf Ser Earth Environ Sci 468, 011003. https://doi.org/10.1088/1755-1315/468/1/011003

Yanuarita, D., Inaku, D.F., Nurdin, N., Rahim, S.W., Kudsiah, H., Parawansa, B.S., Rukminasari, N., Irmawati, Moka, W., 2020. Aquatic invasive species distribution within Wallace region: a preliminary review. IOP Conf Ser Earth Environ Sci 564, 012038. https://doi.org/10.1088/1755-1315/564/1/012038

Yonvitner, Patoka, J., Yuliana, E., Bohatá, L., Tricarico, E., Karella, T., 2020a. Enigmatic hotspot of crayfish diversity at risk: Invasive potential of non-indigenous crayfish if introduced to New Guinea. Aquatic Conservation: Marine and Freshwater Ecosystem 30, 219–224. https://doi.org/https://doi.org/10.1002/aqc.3276

Yonvitner, Patoka, J., Yuliana, E., Bohatá, L., Tricarico, E., Karella, T., Kouba, A., Reynolds, J.D., 2020b. Enigmatic hotspot of crayfish diversity at risk: Invasive potential of non-indigenous crayfish if introduced to New Guinea. Aquat Conserv 30, 219–224. https://doi.org/10.1002/aqc.3276

Yuan, Y., Li, J., 2022. Effects of Parasitism on the Competitive Ability of Invasive and Native Species. Life 12, 1800. https://doi.org/10.3390/life12111800

Yuliana, E., Yonvitner, Akmal, S.G., Subing, R., Ritonga, S., Santoso, A., Kouba, A., Patoka, J., 2021. Import, trade and culture of non-native ornamental crayfish in Java, Indonesia. Management of Biological Invasions 12, 846–857. https://doi.org/10.3391/mbi.2021.12.4.05

Yuliana, E., Yonvitner, Bláha, M., Patoka, J., 2019. Unusual rostral deformity in Cherax quadricarinatus (von Martens, 1868). Workshop on Biodiversity, Jevany, Czech Republic. 11: 201-206.