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Research Article

Growth and competitions of the Australian red-claw crayfish, *Cherax quadricarinatus* (von Martens, 1868) in Thailand: the experimental approaches

Tuantong Jutagate[1], Wachira Kwangkhwang[2], Samnao Saowakoon[3]

1 Faculty of Agriculture, Ubon Ratchathani University, Warin Chamrab, Ubon Ratchathani, 34190 Thailand

2 Department of Fisheries, Chatuchak, Bangkok, 10900 Thailand

3 Faculty of Agriculture and Technology, Rajamangala University of Technology Isan: Surin Campus, Muang, Surin, 32000 Thailand

Corresponding author: Samnao Saowakoon (samnao.sa@rmuti.ac.th)

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Abstract

The Australian red-claw crayfish (RCC) *Cherax quadricarinatus* (von Martens 1868) (Crustacea: Decapoda: Parastacidae) has been introduced and promoted for freshwater aquaculture in many countries including Thailand. This study i) evaluates the growth performance of RCC in near-natural conditions relative to captive conditions and ii) investigates how successfully RCC can compete with a trophically and functionally analogous native species. Growth of RCC was compared among two aquaculture systems (concrete tank and earthen pond) and a treatment with simulated natural conditions. After 12 months of rearing, total length and weight were greatest in the earthen pond and poorest in the near-natural treatment, with significant differences in total length between the near-natural treatment and the two culture systems. Length-weight relationships showed that the RCC had positive allometry in the culture systems but negative allometry in the near-natural treatment. Competition was evaluated by means of a biotic resistance test and an additive–substitutive experiment between RCC and the native freshwater crab *Esanthelphusa dugasti* (Rathbun, 1902) (Crustacea: Decapoda: Gecarcinucidae). Specific growth rates after 90 days of the experiments suggest that the crab inhibited growth of RCC. This implies that the invasion of RCC in Thai waters could be limited by competition from resident freshwater crabs.

Key words: Parastacidae; length-weight relationship; biotic resistance test; additive–substitutive experiment; freshwater crab; specific growth rate

Introduction

The revenue from fisheries and aquaculture in Thailand accounts for 10% of all agricultural sectors and 1% of the country's GDP (Fishery Economics Group 2019). The projection in growth of aquaculture in Thailand from 2016 to 2030 is estimated at 36% (FAO 2018), indicating the continued expansion of this sector in the near future. Thai aquaculture relies not only on finfish species, but also shellfish, of which the introduced Pacific white shrimp, *Penaeus vannamei* Boone, 1931, and black tiger shrimp, *Penaeus monodon* Fabricius, 1798, dominate coastal aquaculture (Boyd et al. 2017), while the giant freshwater prawn *Macrobrachium rosenbergii* (De Man, 1879) is raised in inland farms (Kwangkhang et al. 2019). In addition, the Australian redclaw crayfish (RCC) *Cherax quadricarinatus* (von Martens, 1868) was introduced for culture in Thailand around the year 2000 for the aquarium trade, domestic consumption and export (Soowannayan et al. 2015; Chaichana and Wanjit 2018).

Other non-indigenous crayfish species, e.g., *Procambarus clarkii* (Girard 1852) and *Cherax destructor* (Clarke 1936), have previously been introduced to Thailand for ornamental purposes, but their presence in the natural environment has never been reported. However, RCC has been found extensively in some rivers and reservoirs in recent years, although the reports haven't yet suggested any established populations (Chaichana and Wanjit 2018; Musikasinthorn 2020). A high proportion of introduced crayfish species have shown the ability to thrive and develop self-sustaining populations in new environments, including RCC (Gherardi 2012; Haubrock et al. 2021; Yonvitner et al. 2020). The characteristics of RCC as a large and physically robust omnivorous species with moderate fecundity and broad tolerance to environmental conditions also imply that this crayfish can invade and become established in natural habitats of Southeast Asia, as has occurred already in Singapore and in Indonesia, where RCC has dispersed throughout the country (Ahyong and Yeo 2007; Patoka et al. 2018; Zeng and Yeo 2018; Akmal et al. 2021). Haubrock et al. (2021) reported that RCC has established wild populations in 6 out of 9 countries where it has been introduced in Africa, 7 out of 16 countries in the Americas, and 2 out of 18 countries in Europe. Snovsky and Galil (2011) note that RCC can wander into nearby ponds and drainage canals if there is no appropriate barrier to contain them. Concerns over escaped RCC include their impacts on native species, in particular via predation, alteration of community structure and spread of pathogens; these outcomes already been experienced in many countries (e.g., Ahyong and Yeo 2007; Marufu et al. 2014; Hsieh et al. 2016; Tapia-Varela et al. 2020). Studies of other introduced crayfish species revealed that once they establish in new environments, they may disperse rapidly, which makes their eradication or control extremely difficult and expensive (Gherardi 2012; Patoka et al. 2018).

The potential of an introduced species to become invasive depends on how well it grows and survives in the new environment. If environmental conditions are suitable, biotic resistance may still provide a means to inhibit establishment or spread of the introduced species. Biotic resistance can be either from the biodiversity of the ecosystem (i.e., the higher the biodiversity, the more the resistance against non-native species), or from predators or strong competitors of the introduced species (Britton 2012; South et al. 2020). The presence of predators can result in sub-lethal, long-term effects on the invasive species such as reduction in growth, reproduction and survival (Gherardi 2012). A successful invasive species must further outcompete trophically and functionally analogous native species for limited resources. . Competition between the invader and native species, as well as interspecific competition among invaders, can be examined by additive and substitutive experiments with different density combinations (Britton et al. 2011).

Lynas et al. (2007) hypothesized that RCC could outcompete *Macrobrachium* prawns, which are both ecologically and economically important, in inland water bodies in Thailand. Moreover, the negative effects of RCC on paddy fields are a serious concern in Thailand, in particular due to its ability to damage developing seedlings and consequently reduce production (Anastácio et al. 2015). Ngamniyom et al. (2019) reported that RCC that inhabit natural freshwaters in Thailand may harbor endoparasites such as metacercaria of the trematode *Pseudolevinseniella anenteron*, and ecto- and endosymbionts, such as temnocephalans *Diceratocephala boschmai* and *Temnosewellia* sp. Moreover, laboratory results in Thailand showed that RCC is susceptible to yellow head virus and white spot syndrome virus, which can be transmitted to native shrimp species such as the black tiger shrimp, one of country's most valuable coastal aquaculture products (Soowannayan et al. 2015). Chaichana and Wanjit (2018) reported that Thai farmers who raised RCC had a basic knowledge of its biology and culture practices, but little awareness or understanding of the impacts of this crayfish once escaped into natural waters. As a precautionary approach, the Department of Fisheries of Thailand implemented zoning and registration of all RCC farmers in October 2015 to restrict the culture of this crayfish.

Haubrock et al. (2021) reviewed the invasive potential of RCC in tropical and subtropical biodiversity hotspots and pointed out the need for empirical studies to address the potential impacts of this crayfish. Although predicting the potential impacts of an exotic species is quite complicated (Larson and Olden 2012), knowledge of its growth performance and feeding competition is instrumental in understanding how successful they might be in a novel environment (Gherardi 2012). Understanding the risks of RCC is quite important in Thailand, where at least 23 exotic aquatic animal species have already become established in natural habitats (Musikasinthorn 2020). Given that several non-indigenous crayfish species are known to have established populations in a variety of habitats and geographical locations, this work aims to (a) evaluate the growth performance of RCC in near-natural conditions relative to RCC raised in captive conditions, and (b) investigate how successfully escaped RCC can compete with native species present in the limited area and *vice versa*, using a biotic resistance test and an additive–substitutive experiment, respectively.

Materials and methods

All experiments were conducted at the fish farm of Ubon Ratchathani University, Ubon Ratchathani Province, Thailand. Ubon Ratchathani has a tropical wet and dry climate and consists of 3 seasons, namely summer (from March to June), rainy season (from July to October) and winter (from November to February). The annual mean maximum and minimum temperatures are around 35 °C and 20 °C, respectively (Lebel et al. 2020).

Growth performance

Newly hatched RCC with average size and weight of 0.9 ± 0.2 cm in total length (TL) and 0.02 ± 0.02 g were acquired from a hatchery for the study. The animals were grown out in three treatments: concrete tanks, earthen ponds and community pond (natural conditions). The concrete tanks and earthen ponds were 2 × 2 m and represented two aquaculture conditions; both styles had three replicates. Water level was maintained at 60 cm, and 25% of the volume was exchanged every two weeks with tap water, which was vigorously aerated overnight. Pipe stacks were provided as shelter throughout the rearing areas. Three pen enclosures (2 × 2 m) constructed of bamboo poles and fine mesh net, without top or bottom, were set in a community pond to simulate natural conditions (Suppl. material 1). To prevent crayfish from escaping the pens, the netting was dug approximately 1 m into the pond bottom and reached 2 m above the water surface. A tree branch was set into each enclosure as shelter. The stocking density in all treatments was 5 RCC per square meter. For the crayfish in captive conditions, commercial feed (Brand "CP-Turbo" with > 38% crude protein, CPF - Charoen Pokphand Foods, Thailand) was provided every day at dusk. The feeding rate increased with crayfish growth: 1 pellet per individual in the first month, 2 pellets in months two to six, and 4 pellets in the last six months. For the near-natural treatment, chopped red worms were fed every two days, simulating limited food resource, at the same weight as commercial feed. Additionally, duckweed (*Lemna minor* L.) was raised in each enclosure. Every month, five (5) RCC individuals were randomly selected from each replicate for measurements of total length (cm TL) and weight (g), and then returned to the system. This experiment was conducted for 12 months.

Competition

Two experiments were used to evaluate potential competition between RCC and a resident native species: (a) a test of biotic resistance (Britton 2012) and (b) an additive–substitutive design (Britton et al. 2011). The freshwater crab *Esanthelphusa dugasti* (Rathbun, 1902) was used in both experiments to represent native species. This crab was selected because it is trophically and functionally analogous to crayfish (Zeng et al. 2019; South et al. 2020).

Experiments were conducted in 2 × 2 m concrete tanks with water level maintained at 60 cm, with six replicates for each treatment. Three replicates were assigned for data collection, whereas animals in the remaining three tanks were kept to replace any dead individuals in the data collection tanks. Sex ratio of RCC in each treatment was 3 females: 2 males. In both experiments, the initial mean length and weight of RCC were 2.49 ± 0.10 cm and 0.32 ± 0.04 g, respectively. Initial mean carapace width and weight of crabs were 3.09 ± 0.14 cm and 2.05 ± 0.05 g.

For the biotic resistance test, growth performance of RCC was compared against native residents (i.e., freshwater crab). The first phase of the experiment lasted 30 days, and included five treatments (Table 1): (i) the control, with no resident animals; (ii, iii) treatments to examine the resistance of crabs (at 2 densities) to the introduced RCC; and (iv, v) treatments to examine the resistance of established RCC (at 2 densities) to the introduced RCC. First, the residents (crabs or RCC) were reared in their designated tanks for 30 days. Then, five (5) RCC, reared in different tanks to serve as invaders, were transferred to each replicate described above and reared with the resident animals for 60 days. Meanwhile, the additive–substitutive experiment was also designed with five treatments (including a control) to test the strength of intra- and inter- specific competition among the native crabs and the invaders. First, five (5) crabs were raised in each replicate for 30 days, then the invaders were introduced to the tank according to the designed treatments (Table 2): (i) the control with no added animals; (ii, iii) the additive treatments (at 2 densities); and (iv, v) the substitutive treatments (at 2 densities). After introduction of the invaders, the experiment was continued for 60 days. In both experiments, chopped red worms were offered every day at 10 AM and left

Table 1. Treatments for biotic resistance test to Australian red-claw crayfish.

Treatment	Resident animals at start (Day 1)	Introduced animals (Day 31)
Control	No animals	5 red-claw crayfish
Treatment 1	5 freshwater crabs (medium density)	5 red-claw crayfish
Treatment 2	10 freshwater crabs (high density)	5 red-claw crayfish
Treatment 3	5 red-claw crayfish (medium density)	5 red-claw crayfish
Treatment 4	10 red-claw crayfish (high density)	5 red-claw crayfish

Note: each introduced RCC was labeled with a sticker.

Table 2. Treatments for the additive–substitutive experiment with freshwater crab.

Treatment	Resident animals at start (Day 1)	Introduced animals (Day 31)
Control	5 freshwater crabs	No animal
Treatment 1	5 freshwater crabs	3 red-claw crayfish (Additive, low density)
Treatment 2	5 freshwater crabs	10 red-claw crayfish (Additive, high density)
Treatment 3	5 freshwater crabs	3 freshwater crabs (Substitutive, low density)
Treatment 4	5 freshwater crabs	10 freshwater crabs (Substitutive, high density)

Note: each resident crab was labeled with a sticker.

for 6 h; any remaining feed was then removed. For the intra-specific competition treatments, small lab stickers were used to mark introduced RCC (biotic resistance test) and resident crab (additive–substitutive experiment). Labels were monitored every 12 h and replaced if necessary (from loss or moulting).

Data analysis

For the growth performance study, the length-weight relationship (LWR) of RCC in each grow-out system was expressed by the exponential equation $W = aL^b$, where W is the body weight (g); L is the total length (cm); a and b are the regression coefficients. Coefficient b can be used to indicate growth (Froese et al. 2011), as isometric ($b = 3$), positive allometric ($b > 3$), or negative allometric ($b < 3$). Analysis of covariance (ANCOVA) was used to determine if the average length differed among the grow-out systems, with month as a covariate. The Bonferroni post-test was applied if significant difference was found among systems at $\alpha = 0.05$.

For the two competition trials, specific growth rates (%SGR) were calculated at two time intervals (day 1–30, day 31–90) for the introduced RCC (biotic resistance test) and resident crabs (additive–substitutive experiment), using the formula

$$\%SGR = \left(\frac{ln(W_{end}) - ln(W_{start})}{d} \right)$$

where W is the body weight (g) and d is days. A significant difference in average %SGR among treatments in each experiment was tested by ANOVA. The assumptions for ANOVA test, i.e. normality and homoscedasticity, were met ($P > 0.05$). Differences were considered significant at $\alpha = 0.05$. Dunn's post hoc tests were performed in cases where the ANOVA found a significant difference. The orthogonal contrast procedure was applied to four comparisons in each experiment: (i) control *vs* other treatments; (ii) interspecific treatments *vs* intraspecific treatments; (iii) between different densities of the same species and; (iv) between different densities of different species. All statistical analyses were performed using R (R Core Team 2021).

Results

At the end of the growth experiment, mean length and weight of RCC (Figure 1) from the earthen pond treatment were greatest (15.4 ± 0.8 cm and 97.3 ± 4.8 g), followed by the concrete tank (13.8 ± 0.6 cm and 65.4 ± 3.6 g) and the natural treatment (10.9 ± 1.5 cm and 32.4 ± 4.5 g). The estimated LWRs (Figure 2) for all RCC groups all had high coefficients of determination ($R^2 > 0.90$). The *"b"* coefficients of LWRs for RCC grown in culture treatments (pond, tank) were greater than 3, indicating positive allometric growth. In contrast, negative allometric growth was found for the natural system ($b < 3$). ANCOVA was based on length

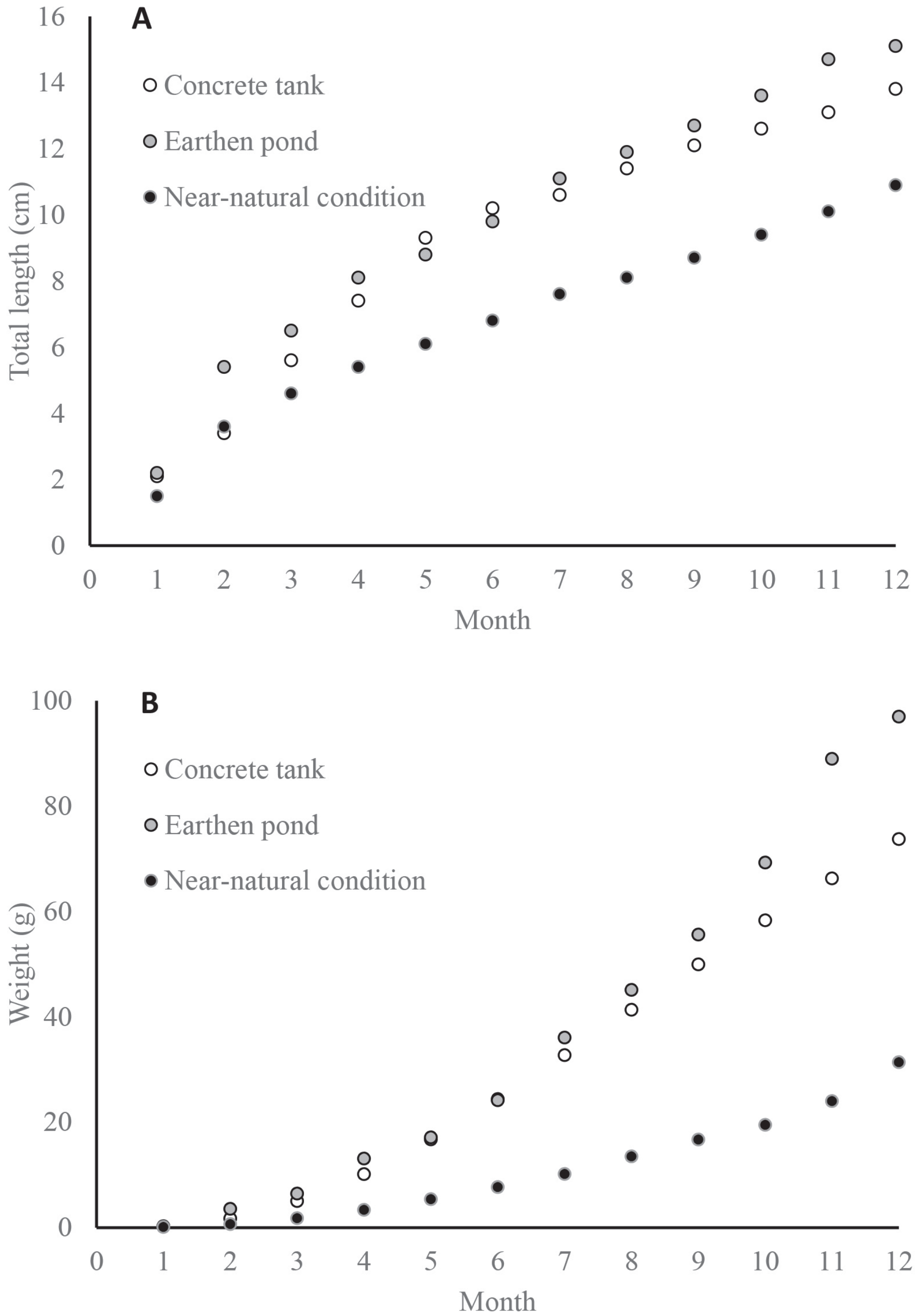

Figure 1. Growth in (**A**) length and (**B**) weight of Australian red-claw crayfish in three experimental grow-out systems.

because this parameter showed less variation than weight in each month, and the assumptions of ANCOVA were met. Regressions between month and length for all three treatments showed homogeneity of regression slope ($P = 0.054$) and variance ($P = 0.072$). The ANCOVA results revealed significant difference in length among the three RCC groups ($P < 0.001$). The Bonferroni post-test showed no statistical difference between the samples from concrete tank and earthen pond treatments ($P = 0.080$), but the natural treatment differed from the two culture systems, i.e., concrete tank ($P < 0.001$) and earthen pond ($P < 0.001$).

There was no significant difference in the initial weight of RCC reared as invaders at 30 days (before introduction) in each treatment ($F_{4,10} = 1.355$, $P = 0.316$). There was also no statistical difference in %SGR of these RCC among treatments

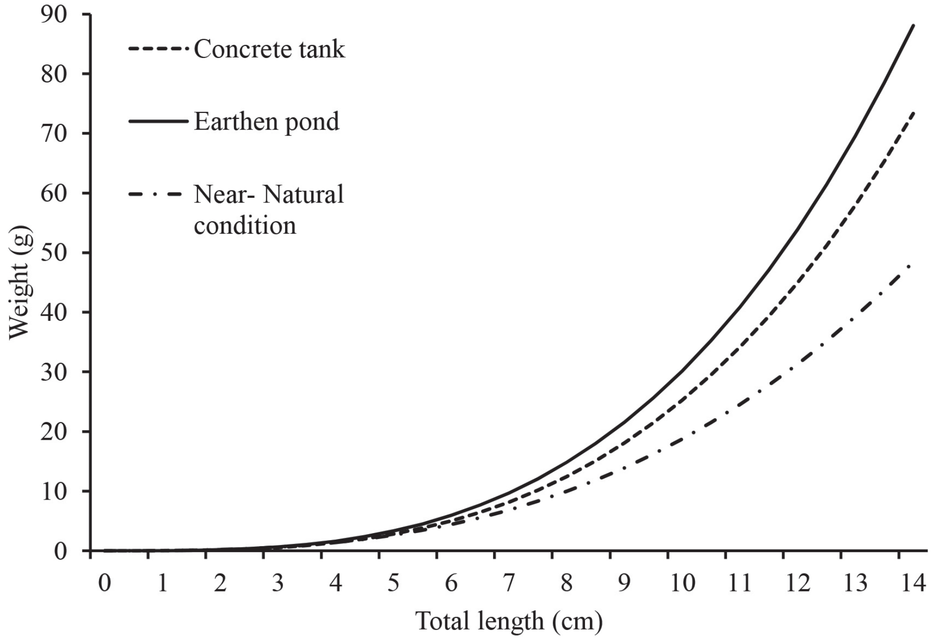

Figure 2. Length-weight relationships of Australian red-claw crayfish in three grow-out systems.

($F_{4,10}$ = 0.896, P = 0.501; Figure 3A) at 30 days, with the overall average %SGR of 3.84 ± 3.11%. These RCC were then introduced according to their assigned treatment and raised for 60 more days. The %SGRs of the introduced RCC differed significantly among treatments at the end of the experiment (Figure 3B; $F_{4,10}$ = 49.758; P < 0.001) and ranged from 2.06 ± 0.25% (interspecific competition at high density) to 3.40 ± 0.09% (control). Three of the four orthogonal contrasts in this experiment (Table 3) showed significant differences in %SGR. The interspecific treatments showed significantly lower %SGR of introduced RCC than intraspecific treatments (Figure 3B; Table 3; $F_{1,10}$ = 48.13; P < 0.001). Significant difference in %SGR of introduced RCC between high and low densities was found in interspecific treatments but not in intraspecific treatments (Figure 3B; Table 3).

For the additive–substitutive experiment, there was no statistical difference among treatments, either in terms of weight of crabs at start (average weight of 2.05 ± 0.05 g [$F_{4,10}$ = 1.223, P = 0.361]) or %SGR after 30 days of initial rearing (average %SGR of 2.91 ± 0.14% [$F_{4,10}$ = 2.433, P = 0.116; Figure 4A]). The %SGR of the crabs differed significantly among treatments at the end of the experiment (Figure 4B; $F_{4,10}$ = 30.442; P < 0.001) and ranged from 0.72 ± 0.01% (intraspecific competition at high density) to 1.58 ± 0.01% (control). Specific growth rate of crabs in the control was significantly higher than the in other treatments ($F_{1,10}$ = 58.33, P = < 0.001; Figure 4B; Table 4). The difference in %SGR between interspecific and intraspecific competition was significant, with slower growth when

Table 3. Orthogonal comparison of %SGRs of introduced Australian red-claw crayfish in biotic resistance test.

Comparison	$F_{1,10}$-value	P-value
Control vs other treatments	96.92	< 0.001
Interspecific vs Intraspecific competition	48.13	< 0.001
Interspecific competition: low vs high density	52.56	< 0.001
Intraspecific competition: low vs high density	1.40	0.264

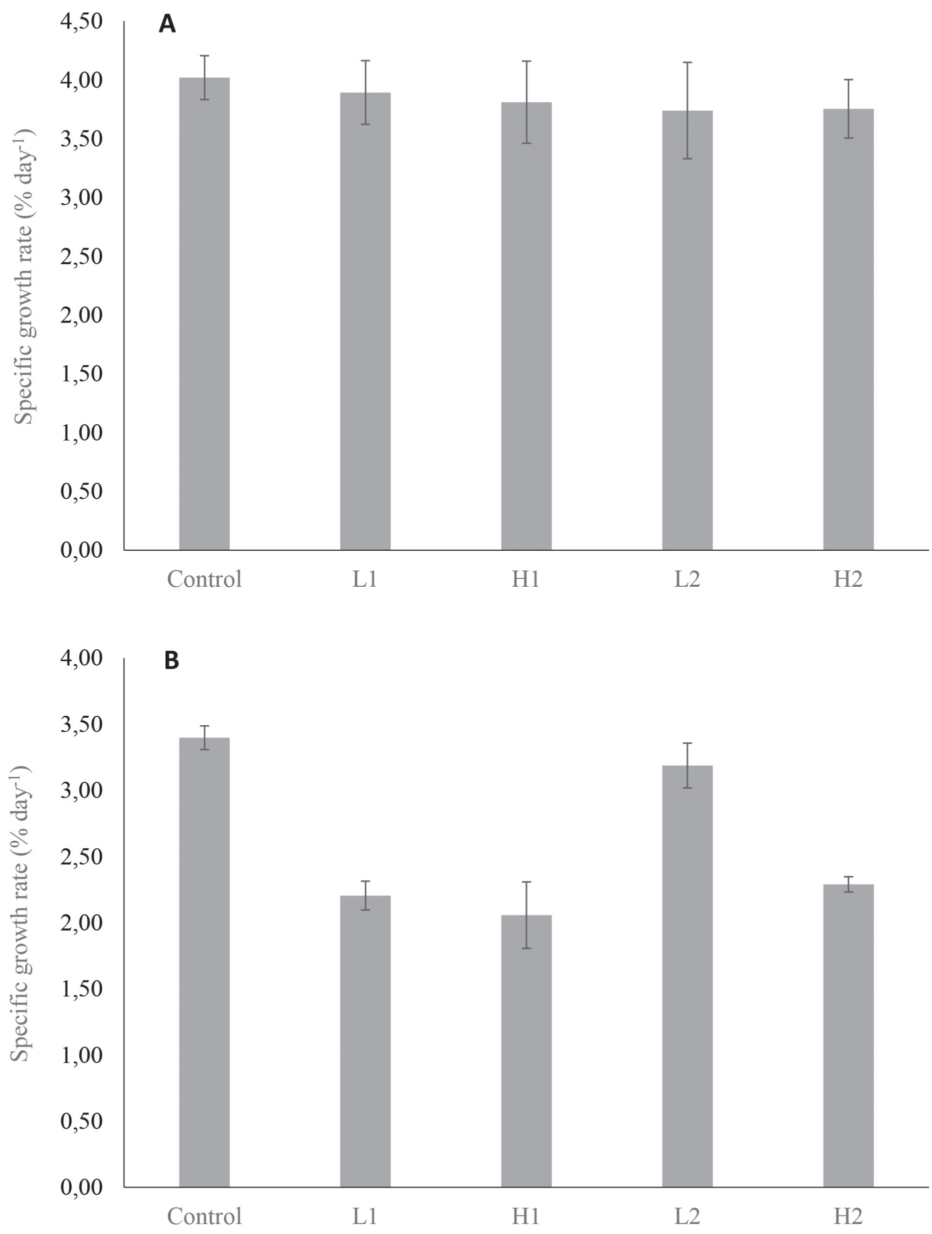

Figure 3. Specific growth rates of Australian red-claw crayfish raised in the biotic resistance test after (**A**) 30 days and (**B**) 90 days. Different letters in each graph indicate significant differences (Dunn's post hoc test, $P < 0.05$). L1 = interspecific competition at low density, H1 = interspecific competition at high density, L2 = intraspecific competition at low density, and H2 = intraspecific competition at high density.

competition was with the same species. Results also showed that %SGR was lower at higher density, both for interspecific and intraspecific competition ($P < 0.05$; Figure 4B; Table 4).

Table 4. Orthogonal comparison of %SGRs of freshwater crab in additive–substitutive experiment.

Comparison	$F_{1,10}$-value	P-value
Control vs other treatments	58.33	< 0.001
Interspecific vs Intraspecific competition	47.86	< 0.001
Interspecific competition: low vs high density	10.01	0.01
Intraspecific competition: low vs high density	5.41	0.042

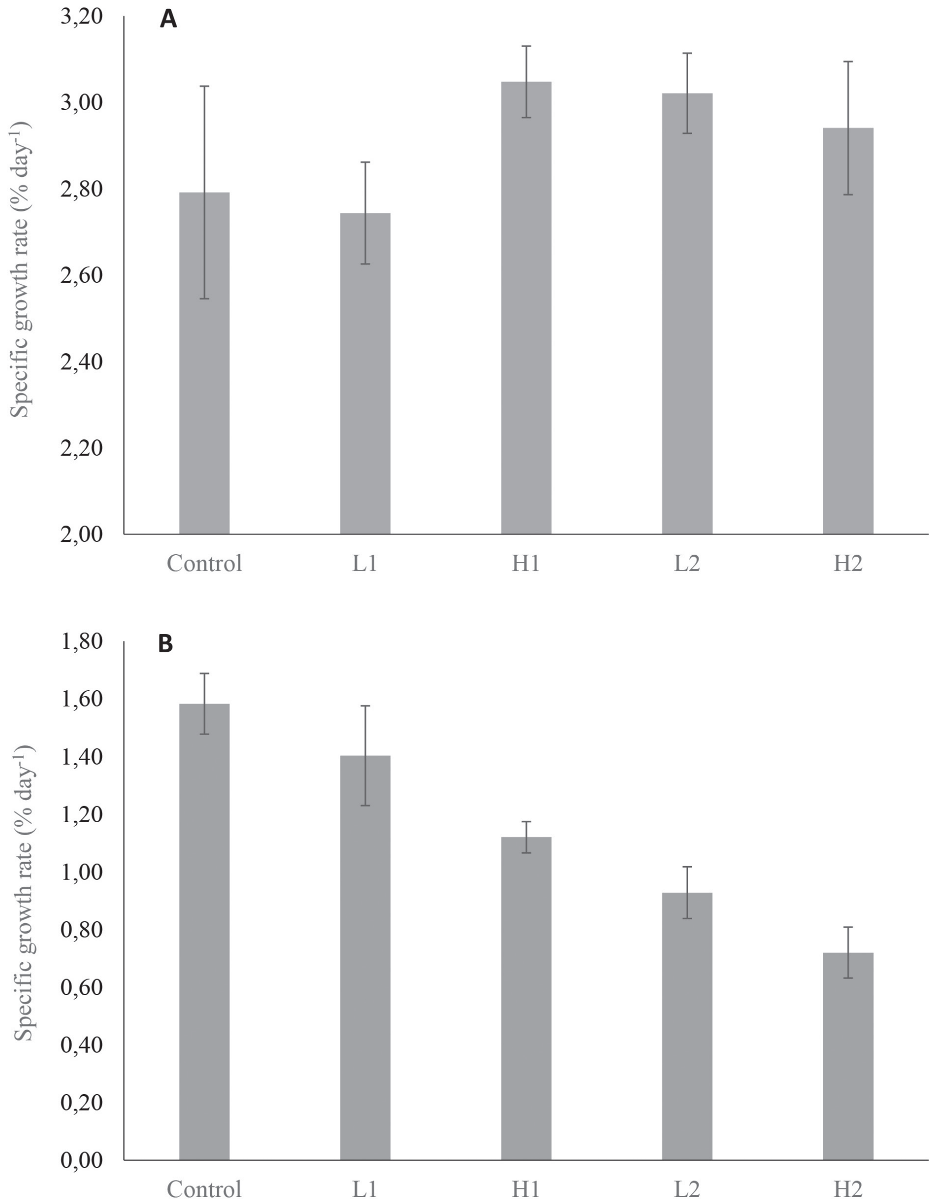

Figure 4. Specific growth rate of freshwater crab in the additive–substitutive experiment after (**A**) 30 days and (**B**) 90 days. Different letters in each graph indicate significant differences (Dunn's post hoc test, $P < 0.05$). L1 = interspecific competition at low density, H1 = interspecific competition at high density, L2 = intraspecific competition at low density, and H2 = intraspecific competition at high density.

Discussion

Certain crayfish species including RCC are ranked among the top invasive aquatic animals globally, and are capable of negative impacts to native residents, habitats and ecosystems due to their plasticity in feeding and other behaviours. Although RCC has become popular as a farmed freshwater crustacean in many countries, Larson and Olden (2012) revealed the high potential of this species to establish populations beyond its native range, particularly in the tropical belt zone (Haubrock et al. 2021). This study, therefore, demonstrates the growth performance of RCC and its potential for competition, as well as likely impacts to native animals that share the same niche (i.e., freshwater crab).

Female and male RCC have similar relative growth, and differences between the sexes are more in body shape than size (Rodríguez et al. 2014; Purnamasari et al. 2018). RCC can grow to marketable size (~30 g) within four months, and males and females can reach 100 g and 70 g within 12 months, respectively, under suitable pond conditions and best farming practices (Jones and Ruscoe 2000). This study reveals that the grow-out system using earthen ponds was most suitable for RCC, which is consistent with the common practice in commercial operations, where broodstock adults are always raised in earthen ponds (Ghanawi and Saoud 2012). Jones (1990) reported that concrete tanks may also be an option for rearing RCC, which is supported by our results, demonstrating no significant difference in growth of RCC between earthen pond and concrete tanks. In contrast, growth of the RCC in the near-natural system was very poor, which could be due to the different availability and quality of food and shelter. The commercial feed used in the culture systems is formulated to be suitable to each stage of RCC growth (Saoud et al. 2013), while the food provided in the near-natural treatment was limited in availability and of possibly lower quality. Growth of RCC observed in the near-natural treatment of this study implies that most of the RCC that have been found in the natural waters in Thailand and Indonesia were about one year old, since their typical sizes were around 10 cm TL (Patoka et al. 2016; Chaichana and Wanjit 2018). The low stocking density treatment in this study shows that crowding may not be the factor limiting growth in the near-natural conditions. Nonetheless, many studies reported that stocking density significantly affected growth of RCC, with higher stocking densities resulting in lower average weight of individuals (Jones 1990; Jones and Ruscoe 2000). Morrissy (2002) mentioned that poor growth of RCC in the wild or intensive outdoor systems could be attributed to the lack of available natural food and/or inadequate artificial feeds. As a consequence of moulting during the early months of life, inappropriate habitat complexity and shelter could hinder the growth of RCC, because social interactions would make them more stressed and vulnerable (Aiken and Waddy 1992; Barki et al. 2006). This idea is supported by the slow increase in length of RCC in the near-natural system of this study compared to the two culture systems.

The regression coefficient *"b"* from the LWR for RCC in the natural treatment indicates negative allometry ($b < 3$), unlike the culture systems, which both show positive allometry (Austin 1995; Rodríguez et al. 2002). Negative allometry generally implies that the bodies of large individuals have changed in shape to become more elongated, or that the animals are thinner due to less available food resources or habitat (Damchoo et al. 2021). Purnamasari et al. (2018) showed that RCC from a lake in West Sumatra, Indonesia, also had negative allometry, and that there was no significant difference in LWR between males and females from all stations and all periods of study. Weya et al. (2017) reported that of the four *Cherax* crayfishes in Papua, Indonesia, only *C. snowden* had negatively allometric growth, while the remaining three species (*C. monticola*, *C. albertisii* and *C. communis*) showed positive allometry. The authors concluded that the differences were caused by food supply and suitability of the habitat.

Successful invasion of non-indigenous crayfish into a new territory is common because they are often more aggressive and grow faster than the native residents (Hossain et al. 2019; Lopez et al. 2019; Kouba et al. 2021). Studies have shown that many non-indigenous crayfish species have greater resource holding potential and the ability to win agonistic interactions with native residents, with consequent negative effects on the feeding and survival of the native species (e.g., Fořt et al. 2019; Hossain et al. 2019). The resistance of freshwater crabs toward crayfish invasions varies according to geographical area and species involved (South 2020). In this study, the experiments with *E. dugasti* crabs and RCC showed that the presence of the crabs retarded growth of RCC when reared together, although agonistic interactions between the two species were not clearly observed. This may be due to the less aggressive behavior of these two species compared to other crabs and crayfish (Ng 2017). It is also noteworthy that the RCC occupied the provided shelter more often than the crabs during feeding, which suggests a greater opportunity of the crabs to approach the food. The outcome of agonistic contests between freshwater crabs and crayfish can be predicted by the resource holding potential of each species, which is related to chelae strength (South et al. 2020). Potamiid crabs showed more aggressive and higher resource holding potential than the invasive crayfish *P. clarkii* in Europe (Mazza et al. 2017), and similar results were found for pseudothelphusid crabs and the invasive RCC in Latin America (Bortolini et al. 2007). South et al (2020) examined the chelae closing force of the potamiid crab and two crayfish species (RCC and *P. clarkii*) and found that the crab showed significantly stronger maximum chela closing force than the crayfishes.

Higher resource holding potential of native crabs than crayfish might help to control the invasion of RCC in Thai inland waters. However, Zeng et al. (2019) pointed out the matter of body size, in which larger crabs can outcompete smaller RCC and *vice versa*. They also showed that the competition success of RCC could be predicted by the relative aggressiveness and size difference between the RCC and native crab residents. Potential risk of pathogen transmission from host crayfish to crabs may also reduce the competitiveness of native crab residents (Putra et al. 2018). Besides freshwater crabs, a number of native freshwater fishes in Thailand such as *Osphronemus goramy* and *Anabas testudineus* may prey on RCC, which may limit the invasiveness of RCC (Chaichana and Wanjit 2018).

Conclusion

Invasive potential of the RCC is of concern worldwide, as it is now the second-most economically important crayfish after *P. clarkii*, and has been widely translocated (Haubrock et al. 2021). Besides its culture for human consumption, RCC is also popular in the ornamental pet trade in many countries including Thailand (Chaichana and Wanjit 2018; Putra et al. 2018; Musikasinthorn 2020). This study revealed that RCC can grow in natural conditions, though at a significantly reduced rate compared to RCC raised in aquaculture systems. However, the freshwater crab, used as a representative native resident, was able to outcompete the RCC in terms of growth, and could limit the spread of RCC in Thai waters. Acknowledging the importance of food production and income of crayfish farmers, strict controls are imperative to prevent escapes and invasions of RCC. Preventative measures such as limiting the number of farms and traceability regulations are desired to protect the aquatic biodiversity and integrity of local ecosystems.

Author contribution

Research conceptualization: T. Jutagtae and S. Saowakoon; sample design and methodology: T. Jutagtae; investigation and data collection: T. Jutagtae and W. Kwangkhang; data analysis and interpretation: T. Jutagtae and S. Saowakoon; draft manuscript preparation: T. Jutagtae. All authors reviewed the results and approved the final version of the manuscript.

Ethics and permits

The study was followed the Ethics statements Animal care and all experimental procedures (Animal use license number: U1-03817-2559).

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References

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

Ahyong ST, Yeo DCJ (2007) Feral populations of the Australian red-claw crayfish (*Cherax quadricarinatus* von Martens) in water supply catchments of Singapore. Biological Invasions 9: 943–946. https://doi.org/10.1007/s10530-007-9094-0

Aiken DE, Waddy SL (1992) The growth process in crayfish. Reviews in Aquatic Science 6: 335–381.

Anastácio PM, Banha F, Capinha C, Bernardo JM, Costa AM, Teixeira A, Bruxelas S (2015) Indicators of movement and space use for two co-occurring invasive crayfish species. Ecological Indicators 53: 171–181. https://doi.org/10.1016/j.ecolind.2015.01.019

Austin MC (1995) Length-weight relationship of cultured species of Australian freshwater crayfish of the genus *Cherax*. Freshwater Crayfish 10(4): 410–418.

Barki A, Karplus I, Manor R, Parnes S, Aflalo ED, Sagi A (2006) Growth of redclaw crayfish (*Cherax quadricarinatus*) in a three-dimensional compartments system: Does a neighbor matter? Aquaculture 252(2–4): 348–355. https://doi.org/10.1016/j.aquaculture.2005.07.012

Bortolini JL, Alvarez F, Rodríguez-Almaraz G (2007) On the presence of the Australian redclaw crayfish, *Cherax quadricarinatus*, in Mexico. Biological Invasions 9(5): 615–620. https://doi.org/10.1007/s10530-006-9054-0

Boyd CE, McNevin AA, Racine P, Tinh HQ, Minh HN, Viriyatum R, Paungkaew D, Engle C (2017) Resource use assessment of shrimp, *Litopenaeus vannamei* and *Penaeus monodon*, production in Thailand and Vietnam. Journal of the World Aquaculture Society 48(2): 201–226. https://doi.org/10.1111/jwas.12423

Britton JR (2012) Testing strength of biotic resistance against an introduced fish: inter-specific competition or predation through facultative piscivory? PLoS ONE 7(2): e31707. https://doi.org/10.1371/journal.pone.0031707.t001

Britton JR, Cucherousset J, Grey J, Gozlan RE (2011) Determining the strength of exploitative competition from an introduced fish: roles of density, biomass and body size. Ecology of Freshwater Fish 20(1): 74–79. https://doi.org/10.1111/j.1600-0633.2010.00460.x

Chaichana R, Wanjit C (2018) Impacts, control and perception of introduced Crayfish in Thailand. Aquatic Ecosystem Health & Management 21(1): 60–69. https://doi.org/10.1080/14634988.2017.1407204

Damchoo S, Grudpan C, Jutagate A, Grudpan J, Jutagate T (2021) Morphological investigation and length-weight relationships of long snouted pipefish *Doryichthys boaja* (Syngnathidae) from two different environments. Agriculture and Natural Resources 55(4): 664–673. https://doi.org/10.34044/j.anres.2021.55.4.17

FAO (2018) The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goal. FAO, Rome, Italy, 210 pp.

Fishery Economics Group (2019) The situation of fishery economic in 2019. Fishery Economics Group, Division of Planning and Policy, Department of Fisheries, Bangkok, Thailand, 7 pp. [In Thai]

Fořt M, Hossain MS, Kouba A, Buřič M, Kozák P (2019) Agonistic interactions and dominance establishment in three crayfish species non-native to Europe. Limnologica 74: 73–79. https://doi.org/10.1016/j.limno.2018.11.003

Froese R, Tsikliras AC, Stergiou KI (2011) Editorial note on weight–length relations of fishes. Acta Ichthyologica et Piscatoria 41(4): 261–263. https://doi.org/10.3750/AIP2011.41.4.01

Ghanawi J, Saoud IP (2012) Molting, reproductive biology, and hatchery management of redclaw crayfish *Cherax quadricarinatus* (von Martens 1868). Aquaculture 358: 183–195. https://doi.org/10.1016/j.aquaculture.2012.06.019

Gherardi F (2012) Control and management of non-indigenous crayfish. In: Reynolds J, Souty-Grosset C (Eds) Management of Freshwater Biodiversity Crayfish as Bioindicators. Cambridge University Press, Cambridge, England, 197–218. https://doi.org/10.1017/CBO9781139031790.013

Haubrock PJ, Oficialdegui FJ, Zeng Y, Patoka J, Yeo DC, Kouba A (2021) The redclaw crayfish: A prominent aquaculture species with invasive potential in tropical and subtropical biodiversity hotspots. Reviews in Aquaculture 13(3): 1488–1530. https://doi.org/10.1111/raq.12531

Hossain MS, Kubec J, Kouba A, Kozák P, Buřič M (2019) Still waters run deep: marbled crayfish dominates over red swamp crayfish in agonistic interactions. Aquatic Ecology 53(1): 97–107. https://doi.org/10.1007/s10452-019-09675-7

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 CM (1990) The biology and aquaculture potential of the tropical freshwater crayfish, *Cherax quadricarinatus*. Queensland Department of Primary Industries, Report of Project QDPI/8860, 116 pp.

Jones CM, Ruscoe IM (2000) Assessment of stocking size and density in the production of redclaw crayfish, *Cherax quadricarinatus* (von Martens) (Decapoda: Parastacidae), cultured under earthen pond conditions. Aquaculture 189: 63–71. https://doi.org/10.1016/S0044-8486(00)00359-8

Kouba A, Lipták B, Kubec J, Bláha M, Veselý L, Haubrock PJ, Oficialdegui FJ, Niksirat H, Patoka J, Buřič M (2021) Survival, growth, and reproduction: comparison of marbled crayfish with four prominent crayfish invaders. Biology 10(5): 422. https://doi.org/10.3390/biology10050422

Kwangkhang W, Jutagate A, Saowakoon S, Jutagate T (2019) Food web structure and ecosystem analysis in culture-based fisheries, with emphasis on giant freshwater prawn *Macrobrachium rosenbergii*. Agriculture and Natural Resources 53: 274–282. https://doi.org/10.34044/j.anres.2019.53.3.09

Larson ER, Olden JD (2012) Using avatar species to model the potential distribution of emerging invaders. Global Ecology and Biogeography 21(11): 1114–1125. https://doi.org/10.1111/j.1466-8238.2012.00758.x

Lebel L, Lebel P, Soe KM, Phuong NT, Navy H, Phousavanh P, Jutagate T, Akester M, Lebel B (2020) Aquaculture farmers' perceptions of climate-related risks in the Mekong Region. Regional Environmental Change 20(3): 1–14. https://doi.org/10.1007/s10113-020-01688-5

Lopez LK, Hendry K, Wong MY, Davis AR (2019) Insight into invasion: Interactions between a critically endangered and invasive crayfish. Austral Ecology 44(1): 78–85. https://doi.org/10.1111/aec.12654

Lynas J, Storey A, Knott B (2007) Introduction and spread of crayfish (Parastacidae) in Western Australia and their potential to displace indigenous species. In: Gherardi F (Ed.) Biological invaders in inland waters: profiles, distribution and threats. Springer, Dordrecht, The Netherlands, 577–596. https://doi.org/10.1007/978-1-4020-6029-8_31

Marufu LT, Phiri C, Nhiwatiwa T (2014) Invasive Australian crayfish *Cherax quadricarinatus* in the Sanyati Basin of Lake Kariba: a preliminary survey. African Journal of Aquatic Science 39(2): 233–236. https://doi.org/10.2989/16085914.2014.922457

Mazza G, Tricarico E, Cianferoni F, Stasolla G, Inghilesi AF, Zoccola A, Innocenti G (2017) Native crab and crayfish co-occurrence: First evidence in Europe. Biologia 72(7): 790–795. https://doi.org/10.1515/biolog-2017-0086

Morrissy NM (2002) Culturing the marvelous marron in Western Australia: 1967–1997. Freshwater Crayfish 13: 13–38.

Musikasinthorn P (2020) "Alien fish problems in Thailand - How can we live together with alien fishes?" An academic conference for people. Natural History Bulletin of Siam Society 64(1): 3–10.

Ng PK (2017) Collecting and processing freshwater shrimps and crabs. The Journal of Crustacean Biology 37(1): 115–122. https://doi.org/10.1093/jcbiol/ruw004

Ngamniyom A, Sriyapai T, Sriyapai P, Panyarachun B (2019) Contributions to the knowledge of *Pseudolevinseniella* (Trematoda: Digenea) and temnocephalans from alien crayfish in natural freshwaters of Thailand. Heliyon 5(12): e02990. https://doi.org/10.1016/j.heliyon.2019.e02990

Patoka J, Wardiatno Y, Mashar A., Yonvitner Y, Wowor D, Jerikho R, Takdir M, Purnamasari L, Petrtýl M, Kalous L, Kouba A, Bláha M (2018) Redclaw crayfish, *Cherax quadricarinatus* (von Martens, 1868), widespread throughout Indonesia. BioInvasions Records 7(2): 185–189. https://doi.org/10.3391/bir.2018.7.2.11

Purnamasari L, Kasmeri R, Amin MHF, Soegianto A (2018) Morphometric characteristics of alien crayfish *Cherax quadricarinatus* from Maninjau lake (West Sumatra, Indonesia). Polish Journal 33(3): 369–384.

Putra MD, Bláha M, Wardiatno Y, Krisanti M, Jerikho R, Kamal MM, Mojžišová M, Bystřický PK, Kouba A, Kalous L, Petrusek A (2018) *Procambarus clarkii* (Girard, 1852) and crayfish plague as new threats for biodiversity in Indonesia. Aquatic Conservation: Marine and Freshwater Ecosystems 28(6): 1434–1440. https://doi.org/10.1002/aqc.2970

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org

Rodríguez A, Arredondo CJL, Ponce FJT, Rouse PDB (2002) Growth characteristics of the Australian redclaw crayfish. *Cherax quadricarinatus*, cultured in an indoor recirculating system. Journal of Applied Aquaculture 12(3): 59–64. https://doi.org/10.1300/J028v12n03_06

Rodríguez AC, Alvarez SH, Ibáñez AL (2014) Comparative morphometrics and relative growth of *Cherax quadricarinatus* (Von Martens, 1868) males and females. Crustaceana 87(6): 674–685. https://doi.org/10.1163/15685403-00003312

Saoud IP, Ghanawi J, Thompson KR, Webster CD (2013) A review of the culture and diseases of redclaw crayfish *Cherax quadricarinatus* (von Martens 1868). Journal of the World Aquaculture Society 44(1): 1–29. https://doi.org/10.1111/jwas.12011

Snovsky G, Galil BS (2011) The Australian redclaw crayfish *Cherax quadricarinatus* (von Martens, 1868) (Crustacea: Decapoda: Parastactidae) in the Sea of Galilee, Israel. Aquatic Invasions 6(Suppl 1): S29–S31. https://doi.org/10.3391/ai.2011.6.S1.007

Soowannayan C, Nguyen GT, Pham LN, Phanthura M, Nakthong N (2015) Australian red claw crayfish (*Cherax quadricarinatus*) is susceptible to yellow head virus (YHV) infection and can transmit it to the black tiger shrimp (*Penaeus monodon*). Aquaculture 445: 63–69. https://doi.org/10.1016/j.aquaculture.2015.04.015

South J, Madzivanzira TC, Tshali N, Measey J, Weyl OL (2020) In a pinch: mechanisms behind potential biotic resistance toward two invasive crayfish by native African freshwater crabs. Frontiers in Ecology and Evolution 8: 72. https://doi.org/10.3389/fevo.2020.00072

Tapia-Varela JR, Ponce-Palafox JT, Palacios-Salgado DS, Romero-Bañuelos CA, Nieto-Navarro JT, Aguiar-García P (2020) Establishment of the exotic invasive redclaw crayfish *Cherax quadricarinatus* (Von Martens, 1868) in the Coastal Plain of San Blas, Nayarit, SE Gulf of California, Mexico. BioInvasions Records 9(2): 357–366. https://doi.org/10.3391/bir.2020.9.2.21

Weya JM, Rumbiak, NS, Hariyanto S, Irawan B, Soegianto A (2017) Length-weight relationship and condition factor of crayfish from South Sorong and Jayawijaya, Papua, Indonesia. Croatian Journal of Fisheries 75(1): 18–24. https://doi.org/10.1515/cjf-2017-0004

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(2): 219–224. https://doi.org/10.1002/aqc.3276

Zeng Y, Yeo DCJ (2018) Assessing the aggregated risk of invasive crayfish and climate change to freshwater crabs: A Southeast Asian case study. Biological Conservation 223: 58–67. https://doi.org/10.1016/j.biocon.2018.04.033

Zeng Y, Shakir KK, Yeo DCJ (2019) Competition between a native freshwater crab and an invasive crayfish in tropical Southeast Asia. Biological Invasions 21: 2653–2663. https://doi.org/10.1007/s10530-019-02009-6

Supplementary material 1

Photographs from growth performance experiment

Authors: Tuantong Jutagate, Wachira Kwangkhwang, Samnao Saowakoon

Data type: figure (docx. file)

Explanation note: Photographs from growth performance experiment (A) experiment in the community pond (natural conditions), (B) preparing for measurement, (C) total length measurement and (D) weight measurement.

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