RESEARCH ARTICLE

Freshwater Crayfish 26(1):1–8, 2021
ISSN: 2076-4324 (Print), 2076-4332 (Online)
https://doi.org/10.5869/fc.2021.v26-1.1

Evaluation of Four Practical Diets on the Growth and Survival of Juvenile Redclaw, *Cherax quadricarinatus* (von Martens, 1868)

Damian P. Rigg,[1] Robert L. Courtney,[1] Jamie E. Seymour[1] and Clive M. Jones[1,*]

[1] James Cook University, P.O. Box 6811, Cairns, Queensland, 4870 Australia.
*Corresponding Author.— *clive.jones@jcu.edu.au*

ABSTRACT

Redclaw, *Cherax quadricariatus* (von Martens) has shown promise as an aquaculture species but commercial development has been constrained by variability of production, perhaps due to poor survival and growth of early craylings. Diet contributes to survival and growth and previous studies have determined requirements for larger redclaw, but little research exists for the early craylings. An experiment was performed to evaluate survival and growth of early instar redclaw using four diets; Frippak (commercial shrimp diet), CSIRO compound diet, bloodworms, and on-grown *Artemia*. Bloodworms and *Artemia* produced significantly higher survival of craylings over two weeks than the two other diets. Artemia diet had a significantly higher weight increase than bloodworms or the CSIRO diet, but not Frippak, which did not differ from bloodworms or CSIRO. Biomass was significantly higher when fed *Artemia*. High mortality in the Frippak and CSIRO diet treatments were not wholly attributable to nutritional deficiencies as the manufactured diets became less physically accessible, potentially reducing intake, leading to difficulties completing ecdysis and eventually death. This study concluded that *Artemia* and bloodworms promoted highest survival, and *Artemia* and Frippak the highest weight gain. The best combination of survival, weight gain and biomass was with the *Artemia* diet.

ARTICLE INFO

Article History:
Submitted: 15 JUN 2020
Accepted: 14 DEC 2020
Published Online: 23 DEC 2020
Published Print: 15 APR 2021

Keywords:
aquaculture;
Cherax quadricarinatus;
crayling;
hatchery;
juvenile;
redclaw;

Additional Author E-mails:
damian.rigg@jcu.edu.au
robert.courtney@jcu.edu.au
jamie.seymour@jcu.edu.au

INTRODUCTION

Redclaw, *Cherax quadricarinatus* (von Martens, 1868) is a large and commercially attractive freshwater crayfish aquaculture species, endemic to the Gulf of Carpentaria catchment of northern Australia, and southern Papua New Guinea (Jones 1990b; Jones and Ruscoe 2002; Webster et al. 2004; Bugnot and Lopez Greco 2009; Ghanawi and Saoud 2012; Saoud et al. 2013; Zhu et al. 2013; Stumpf et al. 2014). The genus *Cherax* includes several species endemic to and of commercial interest in Australia including *Cherax destructor* Clark, 1936 and *Cherax albidus* Clarke, 1936, collectively referred to as yabbies, *Cherax tenuimanus* (Smith, 1912) and *Cherax cainii* Austin, 2002, collectively referred to as marron, and *C. quadricarinatus* referred to as redclaw (Masser and Rouse 1997). Although long known to locals of the remote areas where it is endemic and highly valued as a food resource, redclaw was first introduced to the broader public in the late 1980's in southeast Queensland as an exciting new aquaculture species (Jones 1990b).

From the initial attempts to farm this species through to the present, redclaw has shown potential and great promise to be a significant aquaculture candidate (Jones 1990a). It is considered a generally robust species with beneficial physical, biological and commercial properties that translate well to farming in sub-tropical and tropical areas worldwide (Jones and Ruscoe 1996). Its physical robustness, comparatively simple life cycle and production technology, combined with low protein food requirement (Jones and Ruscoe 1996), suggest it is economically viable to produce (FAO 2017).

Despite these positive credentials, commercial aquaculture production of redclaw in Australia peaked in 2005/06 at 105 t with an average of only 66 t per annum since 1995 (Queensland Government 2016). In 2017/18, production was only 48.8 t (Queensland Government 2018). Part of the reason for the relatively low level of production and lack of industry growth is the high variability of production from grow-out operations, which has constrained new investment. Such production variability has been attributed to high mortality of the craylings when first stocked to grow-out ponds due to their small size and vulnerability to predation. Exacerbating this, there is a lack of knowledge about the specific requirements for the earliest juvenile stages in regard to diet, temperature, habitat and stocking density. Variability in survival and growth rates in the grow-out of redclaw may also be due to the extensive / semi-intensive nature of production practices used in the redclaw farming industry, in contrast with more intensive, managed approaches of well-established aquaculture industries such as shrimp and finfish aquaculture. Intensification has been a key factor in reducing variability of survival and growth rate of commercial aquaculture species, leading to enhanced stability, investment and growth of the industry. Redclaw aquaculture will likely benefit from such intensification of farming practices, and the recent development of a redclaw hatchery system to mass-produce crayling seedstock for grow-out is a positive sign (Jones et al. 2018; Jones and Valverde 2020).

Current redclaw aquaculture industry practice is to purchase the hatchery produced crayling stage (2 moults post egg hatch) (Parnes and Sagi 2002) and stock them directly into earthen ponds for ongrowing for approximately six to nine months to reach marketable size of minimum 30 g but ideally around 75 g (Stevenson 2013). This results in high variability of production, with survival ranging from < 10% to greater than 70%. Inconsistency is the greatest threat to the farmer, and industry consensus is that the crayling stage may be too small and vulnerable for direct pond stocking.

The crayling is the first independent, post-larval stage when exogenous feeding begins. Typical grow-out ponds of 1,000 to 2,000 m^2, are stocked at a density of 10 per m^2 (Jones 1995b, c, d). Each crayling is around 0.02 g in size, therefore, a 1000 m^2 grow-out pond would be stocked with 200 g of craylings. This relatively small biomass in such a large area is an inefficient use of farm resources and subject to the vagaries of the environment. This has highlighted the lack of knowledge about the requirements of craylings in terms of diet, temperature, habitat/shelter and predation immediately after their release into grow-out ponds (Manor et al. 2002). The study reported here examined the effect of different diets on crayling-stage redclaw with a view toward defining optimal feeding practices and developing specific nursery protocols to enable high survival and acceptable growth rates through to a more advanced juvenile stage. The study assessed the effect of four diets; Frippak PL + 300 Ultra (a commercially-available post-larval shrimp diet), a compound diet with formulation and production by CSIRO (Commonwealth Scientific and Industrial Research Organisation) (RC-16-2) and two natural feeds, frozen bloodworms (Chironomidae) and frozen on-grown *Artemia*, on redclaw crayling survival, weight change and biomass.

MATERIALS AND METHODS

Craylings

A breeding facility consisting of four 2000 L tanks, was stocked with nine mature male and 16 mature female redclaw divided between the four tanks, sourced from Aquaverde Redclaw Farm and hatchery (17.3090°S, 145.4593°E, aquaverde.com.au) each provided with individual 90 mm diameter pvc tubes of c. 200 mm length for shelter/habitat. To stimulate the redclaw to reproduce outside the natural spring/summer breeding period from September to April, the thermal and photoperiod regimes were managed to enable the anticipated need to supply craylings for experiments after April and on-going throughout the year. Water temperature was stabilized at 27°C ± 1°C from ambient water temperature (air temperature daily average 23 – 30°C) using a heat pump, and the photoperiod was set to 14L:10D, using timer adjustable lighting as per methods applied for *C. quadricarinatus* by Parnes and Sagi (2002). This protocol was successful in producing berried females, and one female redclaw crayfish (Occipital Carapace Length, OCL = 49 mm, 76.10 g) with post-larval, stage 2 juveniles attached (Levi et al. 1999; García-Guerrero et al. 2003), was chosen for the study. The female with attached stage 2 juveniles was moved to the experimental laboratory, placed in a 300 mm × 300 mm × 300 mm aquarium and held for five days until the juveniles had completed a further moult to stage 3 craylings, and began making forays away from the maternal pleopods. These craylings were examined to confirm they were all stage 3 craylings and were isolated from the female. Excess water was removed from the craylings by placing them on absorbent paper for three seconds and each crayling was weighed to the nearest tenth of a milligram prior to being placed in the individual experimental baskets. At the conclusion of the experiment this weighing procedure was repeated. The diet experiment was performed over two weeks to allow for at least one moult. Offspring from a single female were used in order to avoid the possible confounding effects of multiple genetic sources (Austin 1986; Jones 1995a).

Water Quality

Tap water which had been heavily aerated for 48 hours to remove free chlorine was used to initially fill the systems, and to perform water exchanges of 34 L per system per day (~70%). Ammonia and nitrite readings were taken daily throughout the experiment using an API Freshwater Master Test Kit. Temperature, pH and dissolved oxygen readings were taken on days 2 and 9 with a YSI Professional Plus water quality meter (Yellow Springs Instrument Company, Ohio, USA). All readings were taken in the sump of each discrete system.

Diet Treatments

The shrimp aquaculture industry commonly uses commercial, manufactured feeds for post-larval stages, and these may be suited to early stage juvenile redclaw. The commercial diet Frippak PL+ 300 (specified for shrimp stages PL4 to PL8), was chosen as one of the diet treatments as it had been previously used successfully for early instar redclaw (Meade and Watts 1995). An experimental compound diet formulated by CSIRO (RC-16-2) was the second diet chosen for the experiment. Its formulation was based on a review of redclaw nutrition literature and designed specifically for early stage juvenile redclaw (Pavasovic 2008; Kobayashi et al. 2015; Pirozzi et al. 2016), and prepared as an extruded diet in crumble form (300 to 500 µm). For the third and fourth diet treatments, two whole organism foods were chosen on the basis that such food had proved successful in other redclaw studies (Jones 1995b; Parnes and Sagi 2002). These two diets consisted of on-grown *Artemia* and whole Chironomid worms. The *Artemia* were frozen and supplied from Aqua One, and bloodworms (Chironomidae) supplied from Aquarium Industries, in Australia. Both feeds are commonly used by redclaw farmers to feed craylings (North Queensland Redclaw Farmer's Association, personal communication). The proximate composition of the diets are presented in Table 1.

Replicated Experimental Recirculating Systems

Each of the four diet treatments were assigned to one of four replicated recirculating aquarium systems, each system consisting of five tanks (8 L) with a flow rate of 120 $L \cdot h^{-1}$ (three exchanges per hour) and one sump (10 L) with a total system water volume of 50 L. Of the five tanks in each system, only three were used for the experiment (i.e., three replicates). Water temperature was controlled using 50 W in-line heaters to achieve a constant 26°C ± 1°C consistent with existing industry protocols. The fourth and fifth tanks of each system had no experimental baskets but did hold system water, to increase system volume and buffering capacity. Mechanical filtration was via a filter sock (pore size 200 µm, 130 × 180 mm) fitted over the sump inlet, which was removed and cleaned daily. Biological filtration was achieved via a mixture of 20 mm and 30 mm bio-balls that were preconditioned prior to the experiment with nitrogen-fixing bacteria. These bio-balls were held in a plastic drainage basket beneath the filter sock. Three of the experimental tanks in each experimental system contained a stainless-steel rack holding 30 slotted plastic baskets of 50 mL capacity (50 × 35 mm top dimension, depth = 60 mm, 20 × 35 mm bottom dimension). Each basket was modified by the addition of sealant to the bottom 10 mm of slots to prevent food loss. Each treatment had a total of 90 craylings which were each held individually in baskets. The water was delivered to each tank via a spray bar under the water surface, which was designed to push water across the tanks and through the baskets to assist in the flushing of waste and excess food, and to increase water and oxygen exchange within the baskets. A weighted foam pad covered all 30 baskets to prevent craylings moving between baskets, prevent cannibalism, and to allow for the tracking of individual craylings over the course of the experiment. The crayfish were kept in darkness by keeping an opaque lid on each tank. The lids were lifted daily for cleaning (each rack lifted and swirled to remove remaining food items from the previous day) and feeding. The craylings were fed according to the following protocol and mortalities were counted daily.

There were two different preparation protocols for the feed types. The frozen bloodworms and frozen *Artemia* were defrosted and mixed with dechlorinated tap water at the ratio of 10 g water: 1 g bloodworms or *Artemia*, the Frippak diet was mixed with dechlorinated tap water at the ratio of 10 g water: 1 g Frippak. All diet mixtures were weighed on a four-point balance prior to mixing. The CSIRO diet was presented as a crumble of 300 to 500 µm size. The crumble was mixed with dechlorinated tap water at the ratio of 10 g water: 1 g CSIRO diet. This step was applied to reduce potential physical handling effects as reported by Meade and Watts (1995). Each crayling was fed once per day via a 6 mL pipette at the quantity of 1 droplet (~ 0.03 mL) per individual animal. The prepared feed was placed directly into the bottom of each experimental basket, which allowed for each crayling to feed to satiation daily.

Statistical Analyses

The mean weight of the different diet treatment portions fed to individual craylings were calculated by preparing ten replicates of each diet and weighing on a four-point balance prior to initiation of the study. Data were recorded and analysed via a One-Way Analysis of Variance for the independent variable diet treatment weight, with *post hoc* least significant difference (LSD) tests (diet treatment weight = dependent variable, diet [4 levels] = independent variable).

Table 1. Proximate composition of diets used for *Cherax quadricarinatus* craylings. Data as supplied by the manufacturer.

Diet	**Crude Protein** (% dry weight)	**Crude Lipid** (% dry weight)
Frippak PL + 300	51.9%	8.6%
CSIRO Diet	37.1%	4.9%
Artemia	57.0%	8.4%
Bloodworms	90.0%	4.0%

Weight gain was calculated as a percentage of the starting weight for each crayling in each diet treatment, arcsine√ transformed and analysed for the independent variable, diet treatment, via a One-Way Analysis of Variance, with *post hoc* LSD tests (percent weight gain = dependent variable, diet [4 levels] = independent variable). These data were similarly analysed for the independent variable tank [3 levels].

The daily crayling mortality data were analysed via a Kaplan-Meier survivorship curve with a comparison of survival functions for diet treatment, analysed via a log rank (Mantel-Cox) Chi –Square analysis, as per Jelkić et al. (2014). Survival time was defined as the elapsed number of days from the beginning of the experiment.

The survival of *C. quadricarinatus* craylings data was analysed as a percentage of the starting density, arcsine√ transformed, and survival of craylings over the two week trial period was compared via a One-Way Analysis of Variance, with *post hoc* LSD tests, the critical level for α was 0.05 (percent survival = dependent variable, diet [4 levels] = independent variable). These data were similarly analysed for the independent variable tank [3 levels].

To quantify the starting biomass of the craylings, the mean weight of craylings in each tank (n = 3) per diet treatment was compared via a One-Way Analysis of variance with *post hoc* LSD tests (crayling weight = dependent variable, diet [4 levels] = independent variable). Biomass at the completion of the experiment was similarly analysed. Statistical analyses were conducted using IBM SPSS Statistics Version 24.

RESULTS

Water quality parameters over the course of the experiment were: Ammonia (NH_3) $\bar{x}$ = 0.0417 ppm, S.E. = 0.1373, range 0 – 0.25 ppm; Nitrite (NO_2) $\bar{x}$ = 0.0052 ppm, S.E. = 0.0052, range 0 – 0.25 ppm; Temperature $\bar{x}$ = 25.5°C, S.E. = 0.1373, range = 25°C – 26.2°C pH $\bar{x}$ = 8.74, S.E. = 0.1072, range 8.36 – 9.20, Dissolved Oxygen $\bar{x}$ = 78.5%, S.E. = 1.2101, range 73% – 85%.

The mean weight of the food for each diet provided to individual craylings varied between diet types. The mean weights

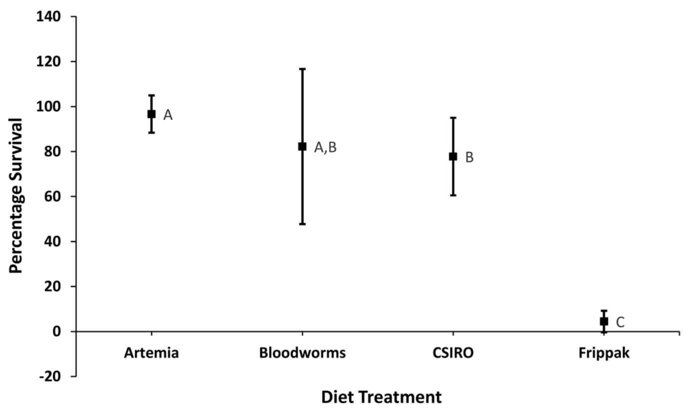

Figure 1. Average survival of *Cherax quadricarinatus* craylings fed four different diet types over a two-week period. Values presented as means, whiskers represent ± 95% confidence limits. Treatments with the same letter are not significantly different.

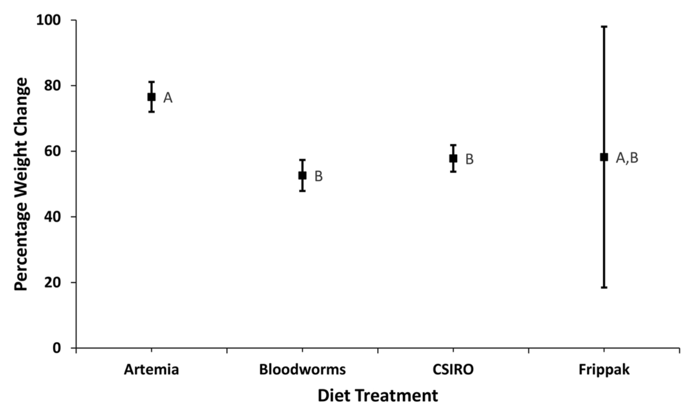

Figure 2. Kaplan-Meier survival function curves for *Cherax quadricarinatus* craylings reared with different diets over a two-week period. Y-axis denotes the cumulative proportion of craylings surviving at the time.

for bloodworms and *Artemia* fed to the craylings were not significantly different from each other (*Artemia* $\bar{x}$ = 0.0477 g, *SD* = 0.0058 g, *n* = 10; bloodworms $\bar{x}$ = 0.0532 g, *SD* = 0.0096 g, *n* = 10) although they were significantly greater than the Frippak and CSIRO diets (Frippak $\bar{x}$ = 0.0329 g, *SD* = 0.0054g, *n* =10, CSIRO $\bar{x}$ = 0.0338 g, *SD* = 0.0083 g, *n* = 10), which were not different from one another ($F_{3,\,39}$ = 18.384, $P < 0.001$). However, for all food types, there was always uneaten food found in the individual baskets of all craylings when they were cleaned, indicating the crayfish were fed beyond satiation.

Craylings had a significantly higher survival rate when fed *Artemia* (97%) or bloodworms (84%), compared to the lower survival of craylings fed the CSIRO diet (79%), and lower again when fed Frippak diet (4%) ($F_{3,\,11}$ = 80.308, $P < 0.001$)(Figure 1). Mortality in three of the food treatments was low (less than 2% per day)(Figure 2). However, there was significant mortality (> 50%) for Frippak-fed craylings on day 8 (Log-Rank [Mantel-Cox] $\chi^2_{3,\,n=4353}$ = 748.396, $P < 0.001$) (Figure 2).

Craylings had a significantly higher weight gain when fed *Artemia* (77%) than when fed bloodworms (53%) or the CSIRO diet (58%)(Figure 3). Craylings fed the Frippak diet were not significantly different to any of the other diets (58%) ($F_{3,\,230}$ = 24.399, $P < 0.001$) (Figure 3).

There was no significant effect of tank on the survivorship of craylings at the end of the experiment, however there was a statistically significant effect of tank on percentage weight gain $F_{2,\,231}$ = 4.579, P = 0.011, whereby one individual tank was significantly higher overall than the other tanks, which did not differ.

There was no statistically significant difference in the mean biomass ($\bar{x}$ = 0.4366 g, *SD* = 0.0111 g, *n* = 12) for craylings assigned to each of the four diet treatments at the start of the experiment ($F_{3,\,11}$ = 0.392, P = 0.762). At the conclusion of the experiment, craylings fed *Artemia* ($\bar{x}$ = 0.7495 g, *SD* = 0.0370 g, *n* = 3) had a significantly higher biomass ($F_{3,\,11}$ = 91.226, $P < 0.001$) than craylings fed bloodworms ($\bar{x}$ = 0.5490 g, *SD* = 0.0953 g, *n* = 3) and the CSIRO diet ($\bar{x}$ = 0.5382 g, *SD* = 0.0467 g, *n* = 3), which were not significantly different from each other (Figure 4). The biomass for Frippak-fed craylings ($\bar{x}$ = 0.0236 g, *SD* = 0.0120 g, *n* = 3) was significantly lower than the other three diet treatments, ($F_{3,\,11}$ = 91.226, $P < 0.001$) (Figure 4).

DISCUSSION

Of the four diets trailed, the on-grown *Artemia* diet was the most favourable in terms of growth and survival, and would be a suitable candidate for a nursery phase based on its ready availability and low cost. The survival and weight gain of craylings fed on-grown *Artemia* combined to produce the greatest biomass at the end of the experiment. High biomass and a relatively consistent size of animals are common production goals for producers of many aquacultured species. In both respects, the *Artemia* diet amongst the four diets trailed shows promise for a nursey phase.

There was an observed tank effect whereby the percentage weight gain was significantly higher in one particular tank. This effect was driven predominantly by craylings in that particular tank in the *Artemia* treatment where there were eight craylings which had more than doubled in mass over the course of the experiment (weight gain of 100.64% to 146.1%). There was only one other crayling in the experiment with over 100% weight gain which was a crayling in the CSIRO treatment (103.08%). The *Artemia* treatment had the highest mean percentage weight gain over the course of the experiment by tank, with an exception for one tank in the Frippak treatment system which had only a single surviving crayling. Excluding the eight *Artemia*-fed craylings from the analysis of tank effect removes the significance of the tank effect ($F_{2,223}$ = 0.742, P = 0.477) and lowers the mean weight by very little (0.001463 g). There are many reasons for why the craylings in the particular *Artemia* treatment tank grew at a higher rate than all the other tanks, for example a study by Speare et al. (1995) showed a tank effect where feed conversion rate was lower despite higher feed intake, caused by disruptions due to foot traffic or tank location. The colour of the tank can also have an effect on survivorship (Yasharian et al. 2005), as can many other factors in which the tanks themselves are in some way a different treatment. In this case, the tanks were duplicated in size, shape and colour, noise and disruptions appeared similar for all tanks, and proximity to ambient light was negated by the cover over the baskets. It may be that food retention in the baskets differed due to flow dynamics in the tanks, which effectively altered the ration size, or that by pure coincidence these were strong, healthy craylings in the same tank. This does introduce a good point, however, whereby grading at this stage for size may improve the stock resulting from the nursery phase by eliminating the smallest craylings.

The ability of the craylings to access the nutrients in the diet may help explain the high levels of mortality in some of the treatments. If the craylings were physically unable to ingest the diets offered (Jones 1995b), they may have struggled to absorb and assimilate the available proteins and lipids efficiently or effectively. This may be the case for the Frippak diet, which was of such a small particle size (300 µm, which is optimal for larval shrimp) that it might require a filter feeding capacity to enable ingestion. Juveniles of some freshwater crayfish may be capable of filter feeding as reported by Budd et al. (1978, 1979), however, such capability has not been confirmed for redclaw. The poor performance of both the Frippak and CSIRO diets may also be attributable to their tendency to settle as a compounded amalgam on the bottom of the baskets, rendering them less accessible. This amalgam appeared to form soon after feeding and may have prevented the craylings from filter feeding or otherwise ingesting. In addition, the food amalgam appeared to stick to the craylings appendages, impairing their ability to move and feed, and leaving them moribund. This was most acute for the Frippak diet and less so for the CSIRO diet.

The highest mortalities were recorded for craylings in the Frippak diet treatment, and there was a marked mortality spike between days six and nine (Figure 4). The timing of this mortality spike is of interest as it coincides with expected moulting of the craylings to the next juvenile stage. Ecdysis is known to be a metabolically expensive and physiologically stressful process in which undernourished crayfish can become moribund during the moult, referred to as 'moult-death syndrome' (Bowser and Rosemark 1981; Meade and Watts 1995; Anson and Rouse 1996; Thompson et al. 2003). The Frippak diet may not have fulfilled the nutritional requirements, either by nutritional deficiency or inaccessibility, and the physiological stress of ecdysis caused the mortality. Frippak diets are well known as being suitable for post-larval shrimp, but may not be for redclaw craylings. The external dentition of juvenile redclaw mouthparts is more raptorial than that of shrimp, and substantially different to that of adult redclaw. Such morphology is more suited to the capture and mastication of relatively large food particles such as zooplankton (copepods, ostracods, conchostracans, etc.) which are known prey of redclaw craylings (Jones 1995b), rather than fine, particulate diets.

The protein level in the diet is of importance to this discussion as redclaw craylings are known to be highly carnivorous (Loya-Javellana et al. 1994; Jones 1995c). According to Cortés-Jacinto et al. (2009), juvenile redclaw (mean starting weight 1.04 ± 0.3 g) require 31 to 34% protein, which complements the findings of Jones (1995b), which demonstrated a predilection for zooplankton. The craylings in the present experiment were smaller and at an earlier life stage than the juveniles in both earlier reported studies with a starting weight of $\bar{x}$ = 0.0143 to 0.0147 g. Saoud et al.

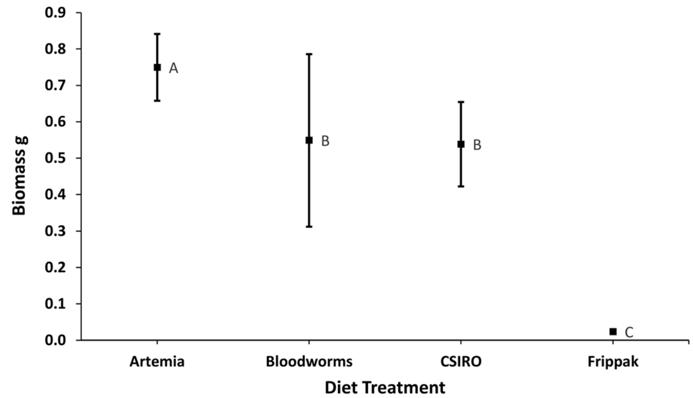

Figure 3. Average weight change of *Cherax quadricarinatus* craylings fed different diets over a two-week period. Values presented as means, whiskers represent ± 95% confidence limits. Treatments with the same letter are not significantly different.

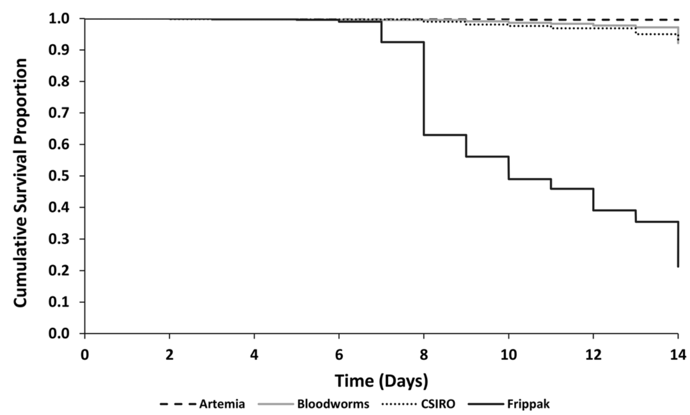

Figure 4. Mean biomass of *Cherax quadricarinatus* craylings fed different diet types at the end of a two-week period. Values presented as means, whiskers represent ± 95% confidence limits. Treatments with the same letter are not significantly different.

(2012) suggested an ontogenetic dietary shift in redclaw, whereby craylings have a much higher protein requirement than adults. This is supported by the present results in terms of survival and growth. Craylings fed the Frippak diet and CSIRO formulated diet performed poorly against the craylings fed the higher protein content whole-animal feeds (bloodworms and *Artemia*, Figures 1 to 3). It would appear that protein levels in excess of those suggested by Cortés-Jacinto et al. (2009) have had a positive effect, however, the highest protein level of 90% in the bloodworms did not produce the best results. It may be that the high level of protein combined with the high level of lipids in the *Artemia* diet conveyed additional benefits. This however is not conclusive as the physical form of the manufactured diets appeared to have an adverse impact that may have masked the adequacy of the nutrient content.

The implications from the results are that a diet of on-grown *Artemia* shows promise as a food for a nursery phase in the aquaculture of juvenile redclaw. *Artemia* supported high survival, individual growth rate and overall biomass increase in comparison to the other diets trailed. Nevertheless, more research in respect of a nursery diet is warranted. Based on the physical morphology and nutritional requirements of *C. quadricarinatus*, future diet trials examining the enrichment of on-grown *Artemia* are advisable. There are many commercial products available to enrich *Artemia* and this could be an effective way to introduce additional beneficial nutrients into the juvenile redclaw diet, to improve health, resilience to disease and increased growth rate. In regard to manufactured diets for juvenile redclaw, further research is warranted to account for the observed preference for relatively large food particles that mimic the size and shape of the bloodworms and *Artemia*, in the form of a water-stable, semi-moist pellet.

The prospect of developing a nursery phase for redclaw aquaculture that takes the craylings now being produced in hatchery systems (Jones and Valverde 2020), to an advanced juvenile stage, best suited for grow-out pond stocking, is strongly justified. Whether such a nursery phase is managed in a tank system or pond environment is not clear, but in either system, knowledge of the nutrient requirements and feeding husbandry are critical to support high survival and production of robust craylings, likely to thrive in the subsequent growout phase. Redclaw craylings are small, and even when on-grown to an advanced stage of 5 g, the biomass involved in a mass production nursery system will be relatively low. Consequently, the amount of food required will also be relatively small, and conducive to a high specification diet, although the cost of feed in a nursery phase is still worthy of consideration. At the time of writing, frozen on-grown *Artemia* were priced at A$4.99 per 100 g, frozen bloodworms were A$6.99 and Frippak was A$12.46 per 100 g (available in 1.25 kg). The CSIRO formulation was not in production and pricing was not available. On-grown *Artemia,* therefore, also have a competitive cost benefit, and should be used in further trials as a reference diet to compare against, based on the results of this study. A high-specification compound diet, however, with form and delivery appropriate to juvenile redclaw morphology and behaviour, remains a worthy subject for further investigation.

ACKNOWLEDGMENTS

Funding for this study was provided by the Australian Government through its agency AgriFutures, formerly Rural Industries Research and Development Corporation, Project PRJ-009388: Eliminate factors inhibiting redclaw farming from reaching its full potential. Sub-Project B: Investigate and implement methods to maximise the transition survival from hatchery to pond and to formulate best practice for the hatchery operator and farmer. Broodstock were held and maintained in breeding condition at the Cairns James Cook University Aquarium facility, the authors thank and acknowledge the important input into this project by Aquarium Curator Jessica Sleeman, Aquarist / Research Assistant Sally Browning, and numerous volunteers. The research was supported by the Queensland Crayfish Farmer's Association and Aquaverde Redclaw Crayfish Hatchery and Farm (www.aquaverde.com.au). Grateful thanks to Colin and Ursula Valverde. Experimental diet RC-16-2 was prepared and supplied by CSIRO Bribie Island, grateful thanks to Simon Irvin. We thank the Freshwater Crayfish editor and the two anonymous reviewers for their useful comments and suggestions.

LITERATURE CITED

Anson KJ and Rouse DB (1996). Evaluation of several commercial feeds and Crustacean Reference Diet for juvenile Australian Red Claw crayfish, *Cherax quadricarinatus*. *Journal of Applied Aquaculture* 6(1):65–76. **doi:** 10.1300/J028v06n01_06

Austin C (1986). Genetic considerations in freshwater crayfish farming. Pp. 73–80 *In:* Owen P and Bowden J (eds.). Aquaculture in Australia. Fish Farming for Profit. Rural Press Qld., Brisbane, Australia.

Bowser PR and Rosemark R (1981). Mortalities of cultured lobsters, *Homarus*, associated with a moult death syndrome. *Aquaculture* 23(1-4):11–18. **doi:** 10.1016/0044-8486(81)90003-X

Budd T, Lewis J and Tracey M (1978). The filter-feeding apparatus in crayfish. *Canadian Journal of Zoology* 56(4):695–707. **doi:** 10.1139/z78-097

Budd T, Lewis J and Tracey M (1979). Filtration feeding in *Orconectes propinquus* and *Cambarus robustus* (Decapoda, Cambaridae). *Crustaceana, Supplement* 5:131–134. **doi:** www.jstor.org/stable/25027494

Bugnot AB and López Greco LS (2009). Structural alterations in the male reproductive system of the freshwater crayfish, *Cherax quadricarinatus* (Decapoda, Parastacidae). *Journal of Invertebrate Pathology* 102(2):160–166. **doi:** 10.1016/j.jip.2009.08.004

Cortés-Jacinto E, Campa-Córdova ÁI, Ascencio F, Villarreal-Colmenares H and Holguín-Peña RJ (2009). The effect of protein and energy levels in diet on the antioxidant activity of juvenile redclaw *Cherax quadricarinatus* (von Martens, 1868) Efecto del nivel de proteína y energía en la actividad antioxidante de juveniles de langosta de agua dulce *Cherax quadricarinatus* (von Martens, 1868). *Hidrobiológica* 19(2):77–83.

FAO (2017). *Cherax quadricarinatus* (von Martens, 1868). Cultured species information program. *In:* FAO Fisheries and Aquaculture Department [online] http://www.fao.org/fishery/culturedspecies/Cherax_quadricarinatus/en [accessed 16 January 2018].

García-Guerrero M, Hendrickx ME and Villarreal H (2003). Description of the embryonic development of *Cherax quadricarinatus* (Von Martens, 1868) (Decapoda, Parastacidae), based on the staging method. Crustaceana 76(3):269–280. **doi:** 10.1163/156854003765911676

Ghanawi J and Saoud IP (2012). Molting, reproductive biology, and hatchery management of redclaw crayfish *Cherax quadricarinatus* (von Martens 1868). *Aquaculture* 358–359:183-195. **doi:** 10.1016/j.aquaculture.2012.06.019

Jelkić D, Opačak A, Horvat D and Safner R (2014). Common carp fry survival during salinity stress test: effect of feeding regime-short communication. *Veterinarski Arhiv* 84(4):429–438.

Jones CM (1990a). The biology and aquaculture potential of the tropical freshwater crayfish *Cherax quadricarinatus*.

Queensland Department of Primary Industries Information Series (qi-90028):I-XV. Pp. 1–109.

JONES CM (1990b). Biology and aquaculture potential of the tropical Australian freshwater crayfish (*Cherax quadricarinatus*). Pp. 19. Abstracts, Eighth International Symposium of the International Association of Astacology, Baton Rouge, USA, April 22–26, 1990. International Association of Astacology, Baton Rouge.

JONES CM (1995a). Effect of temperature on growth and survival of the tropical freshwater crayfish *Cherax quadricarinatus* (von Martens)(Decapoda, Parastacidae). *Freshwater Crayfish* 8:391–398.

JONES CM (1995b). Production of juvenile redclaw crayfish, *Cherax quadricarinatus* (von Martens)(Decapoda, Parastacidae) I. Development of hatchery and nursery procedures. *Aquaculture* 138(1995):221–238. **doi:** 10.1016/0044-8486(95)00068-2

JONES CM (1995c). Production of juvenile redclaw crayfish, *Cherax quadricarinatus* (von Martens)(Decapoda, Parastacidae) II. Juvenile nutrition and habitat. *Aquaculture* 138(1995):239–245. **doi:** 10.1016/0044-8486(95)00069-0

JONES CM (1995d). Production of juvenile redclaw crayfish, *Cherax quadricarinatus* (von Martens)(Decapoda, Parastacidae) III. Managed pond production trials. *Aquaculture* 138(1995):247–255. **doi:** 10.1016/0044-8486(95)00067-4

JONES CM AND RUSCOE I (1996). Production Technology for Redclaw Crayfish (*Cherax quadricarinatus*). Final Report FRDC Project 92/119. Fisheries Research and Development Corporation, Canberra, Australia.

JONES CM AND RUSCOE IM (2002). Biological and aquaculture characteristics of five stocks of redclaw, *Cherax quadricarinatus* (von Martens) (Decapoda: Parastacidae) from northern Queensland, Australia. *Freshwater Crayfish* 13: 115–135.

JONES CM AND VALVERDE C (2020). Development of Mass Production Hatchery Technology for the Redclaw Crayfish, *Cherax quadricarinatus*. *Freshwater Crayfish* 25(1):1–6. **doi:** 10.5869/fc.2020.v25-1.001

JONES CM, VALVERDE C AND RIGG D (2018). Redclaw Crayfish Hatchery. Development of Mass Production Hatchery for *Cherax quadricarinatus*. The International Association of Astacology's Twenty-Second International Symposium on Freshwater Crayfish. International Association of Astacology, Carnegie Museum of Natural History, Pittsburgh, Pennsylvania, USA.

KOBAYASHI Y, WEBSTER CD, THOMPSON KR, CUMMINS JR VC, GANNAM AL, TWIBELL RG, HYDE NM AND ALBERS KOCH JF (2015). Effects on growth, survival, body composition, processing traits and water quality when feeding a diet without vitamin and mineral supplements to Australian red claw crayfish (*Cherax quadricarinatus*) grown in ponds. *Aquaculture Research* 46(11):2716–2727. **doi:** 10.1111/are.12427

LEVI T, BARKI A, HULATA G AND KARPLUS I (1999). Mother-offspring relationships in the red-claw crayfish *Cherax quadricarinatus*. Journal of Crustacean Biology 19(3):477–484. **doi:** 10.2307/1549256

LOYA-JAVELLANA GN, FIELDER DR AND THORNE MJ (1994). Ontogeny of foregut in the tropical freshwater crayfish, *Cherax quadricarinatus* von Martens, 1868 (Parastacidae: Decapoda). *Invertebrate Reproduction and Development* 25(1):49–58. **doi:** 10.1080/07924259.1994.9672368

MANOR R, SEGEV R, LEIBOVITZ MP, AFLALO ED AND SAGI A (2002). Intensification of redclaw crayfish *Cherax quadricarinatus* culture: II. Growout in a separate cell system. *Aquacultural Engineering* 26(4):263–276. **doi:** 10.1016/S0144-8609(02)00035-3

MASSER MP AND ROUSE BD (1997). Australian Red Claw Crayfish. SRAC Publication No.244. The Alabama Cooperative Extension Service, USA.

MEADE ME AND WATTS SA (1995). Weight gain and survival of juvenile Australian crayfish *Cherax quadricarinatus* fed formulated feeds. *Journal of the World Aquaculture Society* 26(4):469–474. **doi:** 10.1111/j.1749-7345.1995.tb00845.x

PARNES S AND SAGI A (2002). Intensification of redclaw crayfish *Cherax quadricarinatus* culture: I. Hatchery and nursery system. *Aquacultural Engineering* 26(4):251–262. **doi:** 10.1016/S0144-8609(02)00034-1

PAVASOVIC A (2008). Evaluation of the nutritional requirements of redclaw crayfish, *Cherax quadricarinatus*. PhD Dissertation. Queensland University of Technology, Queensland, Australia.

PIROZZI I, JOYCE M, CLAY S, OWENS L, CONRADO DV, LE HH, NGUYEN MC, PICHETTE A AND STRIGHT T (2016). Boosting redclaw industry productivity with improved nutrition and feed management. Rural Industries Research and Development Corporation, Project No. PRJ-008536, Final Report #13, Canberra.

QUEENSLAND GOVERNMENT (2016). Ross Lobegeiger Report to Farmers. Aquaculture production summary for Queensland 2015–2016.

QUEENSLAND GOVERNMENT (2018). Ross Lobegeiger report to farmers. Aquaculture production summary for Queensland 2017–2018.

SAOUD IP, GARZA DE YTA A AND GHANAWI J (2012). A review of nutritional biology and dietary requirements of redclaw crayfish *Cherax quadricarinatus* (von Martens 1868). *Aquaculture Nutrition* 18(4):349–368. **doi:** 10.1111/j.1365-2095.2011.00925.x

SAOUD IP, GHANAWI J, THOMPSON KR AND 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. **doi:** 10.1111/jwas.12011

SPEARE DJ, MACNAIR N AND HAMMELL KL (1995). Demonstration of tank effect on growth indices of juvenile rainbow trout (*Oncorhynchus mykiss*) during an ad libitum feeding trial. *Americal Jounral of Veterinary Research* 56(10):1372–1379.

STEVENSON J (2013). Redclaw selective breeding project *In:* Australian Government Rural Industries Research and

Development Corporation, RIRDC Project No. PRJ – 0003274800, No.13/007.

Stumpf L, Tropea C and López Greco LS (2014). Recovery growth of *Cherax quadricarinatus* juveniles fed on two high-protein diets: Effect of daily feeding following a cyclic feeding period on growth, biochemical composition and activity of digestive enzymes. *Aquaculture* 433:404–410. **doi:** 10.1016/j.aquaculture.2014.06.037

Thompson K, Muzinic L, Christian T, Webster C, Manomaitis L and Rouse D (2003). Lecithin requirements of juvenile Australian red claw crayfish *Cherax quadricarinatus. Aquaculture Nutrition* 9(4):223–230. **doi:** 10.1046/j.1365-2095.2003.00246.x

Webster CD, Thompson KR, Muzinic LA, Yancey DH, Dasgupta S, Xiong YL, Rouse DB and Manomaitis L (2004). A preliminary assessment of growth, survival, yield, and economic return of Australian red claw crayfish, *Cherax quadricarinatus*, stocked at three densities in earthen ponds in a cool, temperate climate. *Journal of Applied Aquaculture* 15(3-4):37–50. **doi:** 10.1300/J028v15n03_03

Yasharian D, Coyle SD, Tidwell JH and Stilwell WE (2005). The effect of tank colouration on survival, metamorphosis rate, growth and time to metamorphosis freshwater prawn (*Macrobrachium rosenbergii*) rearing. *Aquaculture Research* 36(3):278–283. **doi:** 10.1111/j.1365-2109.2005.01242.x

Zhu H, Jiang Q, Wang Q, Yang J, Dong S and Yang J (2013). Effect of dietary carbohydrate-to-lipid ratios on growth performance, body composition, hepatic enzyme activities, and digestive enzyme activities of juvenile Australian Redclaw Crayfish, *Cherax quadricarinatus* (von Martens). *Journal of the World Aquaculture Society* 44(2):173–186. **doi:** 10.1111/jwas.12024