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Morphometric relationship of length–weight and chelae length–width of eastern white river crayfish (*Procambarus acutus acutus*, Girard, 1852), under culture conditions

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Summary

Length–weight (TL vs WWT) and chelae length–width (ChL vs ChW) relationships were described for juveniles, males and females, and for form I and form II males of *Procambarus acutus acutus*. The length–weight relationships for juveniles, form I, form II males, and females could be described as: WWT = 5×10^{-3} TL$^{3.09}$, WWT = 6×10^{-3} TL$^{3.61}$, WWT = 6×10^{-9} TL$^{3.26}$, and WWT = 6×10^{-4} TL$^{3.5}$, respectively. In all forms, growth was allometric ($P < 0.05$). The ANCOVA test indicated that slopes and intercepts of the length–weight regressions were significantly different between sex and sexual stages. The regressions for chelae length–width relationships for form I and form II males, and females were: ChW = −0.81 + 0.27CL, ChW = −0.33 + 0.25CL, and ChW = −0.82 + 0.32CL, respectively. Although the slope and intercepts of regressions for ChL and ChW were similar for those of form I and form II males, the slopes and intercepts of regressions of females were significantly different from form I and form II males. No statistical difference was observed in mean ChL between form II males and females ($P > 0.05$), but a significant difference was detected in mean ChL between form I and form II males ($P < 0.05$) and form I and females ($P < 0.05$). Form I males had longer ChL than form II males and females. The same trend was observed in mean ChW for form I and form II males, but a significant difference was detected between form II males and females ($P < 0.05$). In addition, results indicated that chelae lengths and widths increased allometrically with total length (TL) for both sex and sexual stages.

Introduction

Length–weight relationship is a useful tool for estimation of the crustacean population as well as an important characteristic of species to describe growth and size at sexual maturity (Lindqvist and Lathi, 1983). Measuring growth is complicated because of molting, and the growth increment can vary in different ontogenetic stages in crustaceans (Lindqvist and Lathi, 1983; Aiken and Waddy, 1987). In addition, length–weight data are more easily measured and standardized in field sampling, and thus not subject to wide variations. For *Procambarus acutus acutus* crayfish, as for the other crustaceans, the molting process is an essential event for growth. In preparation for molting, crayfish cease to feed and activity decreases. Many cambarid crayfish have different body conformations in different ontogenetic stages. Primavera et al. (1998) found that the life stage was the most striking difference for both length–length and length–weight relationships in cultured crustaceans.

Molting allows adult male crayfish to alternate from form I (sexually mature) to form II (sexually inactive) during the reproductive stage (Guiasu, 2001). It is generally assumed that form II males revert back to the form I state with the following molt, although some empirical evidence indicates that form II males may go through two or more molts before reverting back to the form I state. Mazlum and Eversole (2005) indicated that the largest change in the relative proportion of crayfish stages occurred from April to May when Young-of-the Year (YOY) crayfish averaged 53.4 mm. They also observed that the proportion increased when growing juveniles exceeded the 50 mm TL minimum used for sexing and staging crayfish.

Chelae length–weight relationships are important factors for determining aggressive behavior and competitive outcomes. Because crayfish species compete for limited resources such as food and shelter, space was significant in determining the competitive outcome (Söderbäck, 1991; Garvey and Stein, 1993; Nakata and Goshima, 2003; Mazlum and Eversole, 2005).

Several authors have provided length–weight relationships for *Astacus astacus*, *Cherax* sp., *Procambarus alleni* (Acosta and Perry, 2000), and *P. clarkii* (Girard, 1852) (Clark, 1973; Huner, 1975; Huner et al., 1990; Austin, 1992; Gutierrez-Yurrita et al., 1997), and a few studies relate to chelae length–width (Garvey and Stein, 1993; Eversole et al., 2006). There is no detailed information on length–weight and chelae length–width relationships for the eastern white river crayfish, *Procambarus acutus acutus* (Girard, 1852). Therefore the objectives of this study were to determine the length–weight relationships between juveniles and sexual stages, and chelae length–width relationships among sexes and sexual stages for eastern white river *P. a. acutus* under culture conditions.

Materials and methods

The study was conducted in four, 0.1-ha crayfish culture ponds located at the Calhoun Field Station, Clemson University, Clemson, South Carolina. All experimental ponds were slowly drained over a 2-week period in July 2002. The pond bottoms were fertilized with a 16–4–8 granular formulation of N–P–K and treated with 100 kg lime^{-1} ha^{-1}. Then, rice seeds (*Oryza sativa*) were planted at a rate of 90 kg ha^{-1} in 15 August 2002 to provide forage and substrate for crayfish. Forage was fertilized (34–0–0, N–P–K) at a rate of 30 kg ha^{-1} after planting because of poor rice germination. The crayfish ponds were reflooded on 22 October 2002. Water depth was maintained by routinely adding water. The ponds had surface areas of 625 m^2, and averaged 0.55 m in depth when filled. All ponds had well-established populations of *Procambarus acutus acutus;* no crayfish were added during the study period.

Water temperatures (°C) and dissolved oxygen (DO, mg L^{-1}) were measured with a YSI oxygen meter (Yellow Spring Instruments Inc., Yellow Springs, OH) in the early morning. Water was flushed (upwelling type aerators) through the ponds when DO levels fell below 3 mg L^{-1}.

Crayfish were sampled monthly from November 2002 through July 2003. In total, 722 crayfish were collected with a D-shaped dip net (1.6 cm^2, 0.1 cm mesh size) and three funnel (19 mm mesh size) plastic pyramid traps (Huner and Barr, 1991) baited with commercial crayfish bait (Crayfish Bait-Jumbo, Purina Mills, Inc., St Louis, MO).

Specimens with complete sets of appendages were frozen for morphological measurements for each sampling period. They were later thawed and put on filter paper for several minutes to removed excess water, and weighed (wet weight, WWT) to the nearest 0.01 g. For total length (from tip of rostrum to telson, TL), we measured the right chelae length (tip of propodus to carpal joint, ChL), and chelae width (greatest palm width, ChW) to the nearest 0.01 mm. Damaged and regenerated chelae were not used. Each crayfish was externally identified according to sex and reproductive state. Crayfish < 50 mm TL were not sexed, as identifying male gonopodia was not possible (Hobbs, 1989). Males were classified as reproductively active (form I) or inactive (form II). Form I males are sexually mature adults and in a non-growth phase, identified by the presence of chelae and cornified gonadopods and distinct hooks on the ischial segment of the third and fourth pereiopods. Form II males are adults that are not sexually active and that are in a growth phase.

Regression analyses were performed for the relationship between total length (TL in mm) and wet weight (WWT in g), and chelae length (ChL in mm) and chelae width (ChW in mm) for each sex and sexual stages expressed by the equation: $\mathrm{WWT} = a\mathrm{TL}^b$ and log base 10 equation $\log \mathrm{WWT} = \log a + b \log \mathrm{TL}$, where WWT is the wet weight, TL is the total length, and a and b are constants.

Data were analyzed with the analysis of variance (ANOVA), analysis of covariance (ANCOVA), and linear regression using Micro-SAS Statistical Software Version 8 (SAS, Institute, 1999). A general linear model for two-way ANOVA was used to compare sex and sexual stages differences in TL, WWT, ChW and ChL. Regression analysis was used to determine the length–weight and chelae length–width relationships. Analysis of covariance (ANCOVA) was used to compare length–weight and chelae length–width regression slopes and intercepts among juveniles, form I and form II males, and females. Differences in means were detected with the least significant difference (LSD) test.

Results

Water temperatures ranging from 1°C in winter to a maximum 26°C in summer, averaged 17.5°C and DO 6.32 mg L^{-1} (2.4–7.6). Levels of DO below the 3 mg L^{-1} recommended for supplemental aeration (Huner and Barr, 1991) occurred infrequently (5.8%) during the sampling period; most low DO levels were observed later in the season when the water temperature was elevated. In total, 722 specimens (juveniles = 212, form I = 147, form II = 112 and females = 249) were examined for total length and weight measurement (Fig. 1). Mean total length (TL ± SD), mean wet weight (WWT ± SD), and their range were 71.55 ± 29.50 mm (range = 17–130), 16.40 ± 16.54 g (range = 0.07–76.82 g), respectively (Table 1). Mean total length (TL ± SD), mean wet weight (WWT ± SD), and their range were calculated for males and females, respectively as: TL = 85.64 ± 16.51 (range = 51–130 mm), WWT = 22.03 ± 16.63 (range = 2.91–76.82 g), and TL = 78.55 ± 18.82 (range = 51–125 mm), WWT = 17.80 ± 16.54 (range = 3.0–61.17 g). Male crayfish were found to be larger in size than females. TL increased allometrically (positive growth) with weight for juveniles, form I and form II males, females, and the entire population. ANCOVA tests showed that length–weight regression slopes and intercepts were significantly different among sexes and sexual stages ($P < 0.0001$). In addition, our results indicated that form I males were 1.2

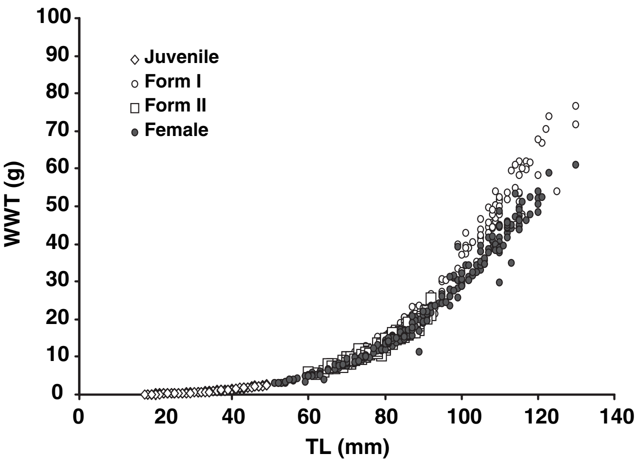

Fig. 1. Length–weight relationship for *Procambarus acutus acutus* sexual stages. Open circles (form I males), closed circles (females), triangles (juveniles), and boxes (form II males)

Table 1
Descriptive statistics, estimated parameters and growth type of length–weight relationships for 722 crayfish from culture ponds

	Length (mm)				Parameters of the relationships					
Sex and sexual form	N	Mean (SD)	Min	max	a	b	SE	CL (**b**)	R^2	Type of Growth
Juvenile	212	31.23 (9.44)	17	49	5×10^{-3}	3.09	0.018	3.05–3.13	0.99	+(A)
form I	147	97.33 (13.95)	72	130	6×10^{-3}	3.61	0.05	3.51–3.71	0.97	+(A)
form II	114	78.55 (7.26)	60	92	6×10^{-9}	3.26	0.067	3.13–3.40	0.95	+(A)
Female	249	88.48 (22.70)	51	130	6×10^{-4}	3.5	0.024	3.45–3.55	0.98	+(A)
Total	722	71.55 (29.50)	17	130	6×10^{-8}	3.3	0.008	3.28–3.31	0.99	+(A)

SE, standard errors of **b**; CL, confidence limits of b; N, number of crayfish; +A, positive allometric growth.

times heavier and 20.6 mm larger than form II males. Mean total length and weight did not differ between males and females ($P > 0.060$); the only significant differences were detected among sexual stages ($P < 0.0001$).

Of 722 crayfish, 246 selected at random were used to determine chelae length and width measurements of the population. Mean chelae length (ChL ± SD), mean chelae width (ChW ± SD), and their range were calculated for form I, form II, and females, respectively, as: ChL = 50.69 ± 14.22 (25.6–71.2 mm), ChW = 13.06 ± 4.10 (6.7–20.2 g), ChL = 31.75 ± 12.90 (10.7–54.6 mm), ChW = 7.84 ± 3.37 (2.4–13.7 g), and ChL = 33.30 ± 11.70 (9.7–57.2 mm), ChW = 10.07 ± 3.91 (1.8–18.8 g).

No statistical difference was observed in mean ChL between form II and females ($P > 0.05$), but significant differences were detected in mean ChL form I and form II males ($P < 0.05$) and form I males and females ($P < 0.05$). Form I males were thus found to have longer ChL than form II males and females. The same trend was observed in mean ChW for form I and form II males, but a significant difference was observed between form II males and females ($P < 0.05$). Chela lengths and widths increased allometrically with TL for both sexes and sexual stages (Table 2). In addition, chelae length–width relationships were positively correlated with sex and sexual stages (Table 2). Although the slope and intercepts of regressions for ChL and ChW were similar for those form I and form II males, the slope and intercepts of regression of females were significantly different from form I and form II (Table 2).

Discussion

The growth potential of *Procambarus acutus acutus* is well established; maximum size recorded for this species was 80 g (Mazlum, 2003; Mazlum and Eversole, 2005). This study confirms that *P. a. acutus* can be grown to significant size under aquaculture conditions, with males apparently growing to larger sizes than females. Streissl and Hödl (2002) analyses of the weight–length relationship of *Austropotamobius torrentium* revealed that males gained weight with increasing length faster than females. Similar relationships were found in *Pacifastacus leniusculus* Dana by Mason (1974). Positive allometric growth relating to TL was found in both sexes. Therefore, an increase in the abdomen width in relation to TL could be the reason for their length–weight regression coefficient exceeding three. Form I males were heavier than either females or form II males of the same length. This disparity is due primarily to the accelerated development of the chelae in males with sexual maturity, whereas chelae of females remain isometric throughout life.

Length–weight relationships vary among crayfish species according to their sex, sexual stages, and ecological conditions (Lindqvist and Lathi, 1983). Such a large difference may be a reflection of a number of factors including photoperiod, population density, food abundance, water level fluctuations, water temperature, and water quality (Huner and Romaire, 1978; Chien, 1980; Huner and Barr, 1991). Growth of *P. a. acutus* was fastest in autumn and spring, and lowest in winter and during harvest season in our culture ponds. The November and April, May and June sampling date water temperatures averaged 17.5°C, whereas the December to January sampling date water averaged 7.3°C at the research facility (Mazlum and Eversole, 2004). Warmer water temperatures are more favorable for *P. a. acutus* growth (Seals et al., 1997). Although the water temperatures were appropriate for rapid growth from May to June, the shortage of forage more than likely limited crayfish growth potential (Romaire and Lutz, 1989; Mazlum and Eversole, 2005). The faster-growing more frequently molting crayfish are more vulnerable to cannibalism and predation (Lutz, 1983). It could be argued that burrowing and harvesting activities in spring effectively reduced crayfish density (Mazlum and Eversole, 2000), therefore it is unlikely that much of the crayfish population density decreased at this time. Juvenile, form I, form II males, and females naturally differ in body conformation in many cambarid crayfish (Lutz, 1983; Craig and Wolters, 1988; Lutz and Wolter, 1990) . For example, Acosta and Perry (2000) found that *P. alleni* grown on artificial diets had a significantly different length–weight relationship from those of wild crayfish.

While many studies focused on length–weight relationships in crayfish ponds, sexual dimorphism appears common in freshwater crayfish (Rhodes and Holdich, 1984; Köksal, 1988), which appears to be due largely to the disproportionately rapid growth of chelae in males compared with females. Differences in body size between sex and sexual stages were consistent with those reported in other studies (Stein, 1976). Our study showed that juvenile crayfish rapidly grow to adult size, becoming form II males, which change into form I adults by molting.

Variations in morphometric traits may also be largely affected by environmental factors such as feeding behavior, foraging efficiency, and the availability and quality of food resources (Momot and Gowing, 1977; Lindqvist and Lathi, 1983; France, 1985). Environmental conditions influence crustacean growth by affecting molt intervals and incremental increases in length and weight. It is also possible that the length–weight relationship may vary in relation to physiological cycles associated with molting and reproduction. The influence of temperature on the length–weight relationship of *P. a. acutus* juveniles showed a high correlation between the relative increments in both measurements with temperature, but the effect on weight was stronger when compared to length (Lindqvist and Lathi, 1983). The environment changes not only growth, but also the shape of crayfish (Stewart et al.,

Table 2
Mean and standard deviation (SD) for chelae length (ChL) and chelae width (ChW) characteristics and parameters of the relationship between ChL and ChW of each sex and sexual forms

Sex and sexual form	N	Length characteristic mean (SD)	Width characteristic mean (SD)	Parameters of the relationships				
				a	b	SE (b)	CL (b)	R^2
Form I	35	50.69 (14.21) (25.6–71.2)	13.06 (4.1) (6.7–0.2)	0.81	0.27	0.015	0.24–0.30	0.90
Form II	38	31.75 (12.90) (10.7–4.6)	7.84 (3.37) (2.4–3.7)	0.33	0.25	0.007	0.24–0.27	0.96
Female	173	33.30 (11.70) (9.7–7.2)	10.07 (3.91) (1.8–8.8)	0.82	0.32	0.327	0.31–0.33	0.95

SE, standard errors of b; CL, confidence limits of b; N, number of crayfish; R^2, coefficient of determination.

1967). Under our culture conditions, differences in morphometrics among culture phases may also reflect variatons in environmental variables (e.g. temperature, feeding, and stocking) in such a way that most growth occurs during the flood season, the duration of which impacts the time available for foraging and foraging returns in terms of resource availability and quality. In April and May a lower crayfish density was observed, which corresponded to a period of depleted vegetation and substrate; larger crayfish also burrow in at this time. Cannibalism frequently occurs in crayfish populations when food sources are limited (Nystrom, 2002); reduced cover also increases predation losses (Jordan et al., 1996). Most crayfish biomass decreases in our ponds was between March and May, when vegetation was in short supply and water temperatures increased.

Length–weight and chelae length–width relationships of form I, form II males, and females showed positive allometric growth ($b > 3.0$). Similar results were found for *Procambarus zonangulus* (Romaire et al., 1977), *P. clarkii* (Correia, 1990) and *P. alleni* (Acosta and Perry, 2000). In addition, *Cherax quadricarinatus*, *C. destructor*, and *P. clarkii* showed allometric growths of 3.04, 3.18, and 3.22, respectively. In *P. clarkii*, there is an isometry in total length–chelae length relationships for juveniles of both sexes (Correia, unpublished). Form I and form II males, and females showed a positive allometry, being more positive in form I males than in females and form II males (Correia, 1990).

Females do not have chelae lengths as large as form I males, but their chelae are larger than form II males. Form I males have chelae that are larger than form II males (Suko, 1953; Szaniawska et al., 2005; Eversole et al., 2006). Therefore, isometric growth for juveniles and allometric growth for sexual stages were expected because of faster growth and molting, respectively. This situation appears to be dependent on the season and year and on other factors such as temperature, food (quantity, quality and size), breeding time and maturity stage (Pauly, 1984). For the length–weight relationships we showed that form I males were heavier than either females or form II males of the same length; 50 mm was the minimum size at maturity. As stated above, this difference was largely due to a secondary characteristic of form I males in which chelae are larger than those of form II males.

Differences between male and female chelae lengths have been well documented in the crayfish literature since the work of Huxley (1880). In our study, males had longer and wider chelae than equal-size females. The more robust nature of male crayfish imparts a distinct advantage in activities related to sexual reproduction (Stein, 1976). The difference in chelae size between males and females increased as individuals increased in body size and reached maturity. Rhodes and Holdich (1979) identified diphasic chelae growth in male and female *Austropotamobius pallipes* (Lereboullet); male chelae grew significantly faster than female chelae after sexual maturity. A commercial consequence of differential chelae growth is that male crayfish yield relatively less abdominal meat than processed female crayfish (Huner et al., 1988; Huner, 1993; Harlioğlu and Holdich, 2001). Female chelae lengths and widths increased allometrically in *Procambarus clarkii* and *P. a. acutus*. Although the change of b values depends primarily on the shape and fatness of the species, various factors may be responsible for the difference in parameters of the length and weight relationships among seasons, food, sex, time of year, and sexual stages (Suko, 1953; Lindqvist and Lathi, 1983).

In summary, for all life stages (form I, form II males) and all sexes (juveniles, males, and females), length increased allometrically (positive growth) with weight. In addition, chelae lengths and widths increased allometrically in total length for sex and sexual stages. Form I males had longer ChL than form II males and females. Systematic and taxonomic studies have shown that crustaceans display a high degree of variation, which includes variability in size and proportion of major body parts.

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