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ORIGINAL ARTICLE

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Geometric morphometric analysis of the freshwater prawn *Macrobrachium borellii* (Decapoda: Palaemonidae) at a microgeographical scale in a floodplain system

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Abstract Morphometric studies are useful for delineating the shapes of various populations and species over geographical ranges and as evidence of regional differences in crustaceans. Hydrological fluctuations in a floodplain system modulate the dispersal and presence of decapods among habitats and constitute an important macrofactor that regulate other environmental variables and which could explain the richness, distribution and abundance of organisms that live in these systems. Morphological variations among populations of the freshwater prawn *Macrobrachium borellii* in a floodplain system at a microgeographical scale were studied using geometric morphometrics. Carapace structure was represented using 16 digitised landmarks. Allometry and sexual dimorphism was tested. Variation in shape was explored via Principal Component Analysis. Canonical Variate Analyses was applied to compare the differences in shape between species' populations. The correlations and covariations among shapes and hydrometric level, current velocity, geographical location and hydrologic distances were analysed. The average carapace shape was different between sexes in all sites. Populations that were near each other in terms of hydrological distance had similar shapes, but all of the populations differed in shape from the farthest population. The environmental variables were not good predictors of the carapace shape. Instead, the shape was strongly related to the hydrologic distance and geographical location. The swimming characteristics of these prawns and their passive movements, together with the dynamics of a floodplain system, explain the low morphological variation between populations in this study. The dynamic characteristics of the system influence the dispersal of the prawns and allow populations to remain connected.

Keywords Morphological variation · Geometric morphometric · Freshwater prawn · Populations · Floodplain system · *Macrobrachium*

Introduction

Throughout the history of biology various perspectives in the analysis of forms have been developed, e.g. biometric morphology (Huxley 1932), functional morphology (Bock 1999), structural morphology (Seilacher 1970), and theoretical morphology (McGhee 1999). Geometric morphometrics (GM) have emerged as method for comparing organisms' shapes, providing a powerful technique in the quantitative biologists' repertoire for the study of shape variation and the identification of its causes (Corti 1993; Rohlf and Marcus 1993). This method generates a set of shape variables that can be used to test statistical hypotheses and to provide a means of visually describing patterns of shape differences in the data (Adams et al. 2013; Klingenberg 2013). Particularly, morphometric studies are useful for delineating the shapes of various populations and species over geographical ranges and as evidence of regional differences in crustaceans (Rufino et al. 2006; Konan et al. 2010; Silva et al. 2010; Srijaya et al. 2010). Thus, GM could be a good tool for comparing populations of crustacean decapods. Previous studies have used GM to compare populations of several species of freshwater decapods (Giri and Collins 2004; Giri and Loy 2008; Barría et al. 2011; Idaszkin et al. 2013). However, the use of GM to study prawns is still rare (Bissaro et al. 2012; Zimmermann et al. 2012).

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For freshwater decapods that live in a floodplain system, populations move continually within each aquatic environment of the system. These movements can be induced by both biotic and abiotic factors in a dynamic system, and they occur over different spatial and temporal scales (Williner et al. 2010). For example, hydrological fluctuations in a floodplain system have a modulating effect on the dispersal and presence of decapods in a particular habitat (Fernandez and Collins 2002; Collins et al. 2007; Williner et al. 2009). The regular movements of floodplain-living decapods can be characterised as displacements within lakes, ponds or rivers that can occur in either a passive or active manner (Williner et al. 2009). This is the case for the freshwater prawn *Macrobrachium borellii* (Nobili 1896) (Family Palaemonidae), which is widely distributed in the La Plata Basin of northern Argentina, Paraguay and southern Brazil (Morrone and Lopretto 1995).

Natural river landscapes are often characterised by extensive floodplains that influence the system's spatial and biological dynamics (Ward et al. 2002; Winemiller 2004). These are characterised by a high diversity of environments and by the particular hydrological regime. The distinctiveness of these macrosystems affects the dynamics and the relationships among populations (Williner et al. 2010).

The movements of some species are related to the spatial and temporal dynamics of the environment in the context of a floodplain system. Dispersal is related to the movements of organisms, and it is defined as a movement of a specified distance or from one predefined patch to another (Bennetts et al. 2003). The hydrologic regime of a floodplain system tends to homogenise populations between water bodies in high water periods, decreasing the differences between the populations of nearby sites (Gomes et al. 2012). Therefore, hydrological fluctuations constitute an important macrofactor that regulate environmental variables and can explain the richness, distribution and abundance of organisms that live in these systems (Neiff et al. 2001; Winemiller 2004; Rossi et al. 2007; Mayora et al. 2013). Moreover, the flow of the water current acquires a relative importance in systems with floodplains because currents have an effect on faunal distribution and the movement of aquatic invertebrates (Olden et al. 2004).

In the present study we analyse the geometric shape variation of populations of the freshwater prawn *M. borellii* with the aim to infer and explain the morphological variations at a microgeographical scale in the context of a floodplain system.

Materials and methods

Sampling

Individuals of the freshwater prawn *Macrobrachium borellii* were collected between October and November of 2011 with hand nets at sites on the Saladillo Stream (SS: 30°17′46.26″S; 60°05′17.58″W), Paraná River (San Javier River (SJR: 30°34′12.66″S; 59°35′39.45″W), Santa Fe River (SFR: 31°36′33.28″S; 60°40′48.40″W), Salado River (SR: 31°37′30.11″S; 60°45′42.32″W) and Coronda River (CR: 31°43′32.93″S; 60°45′22.47″W).

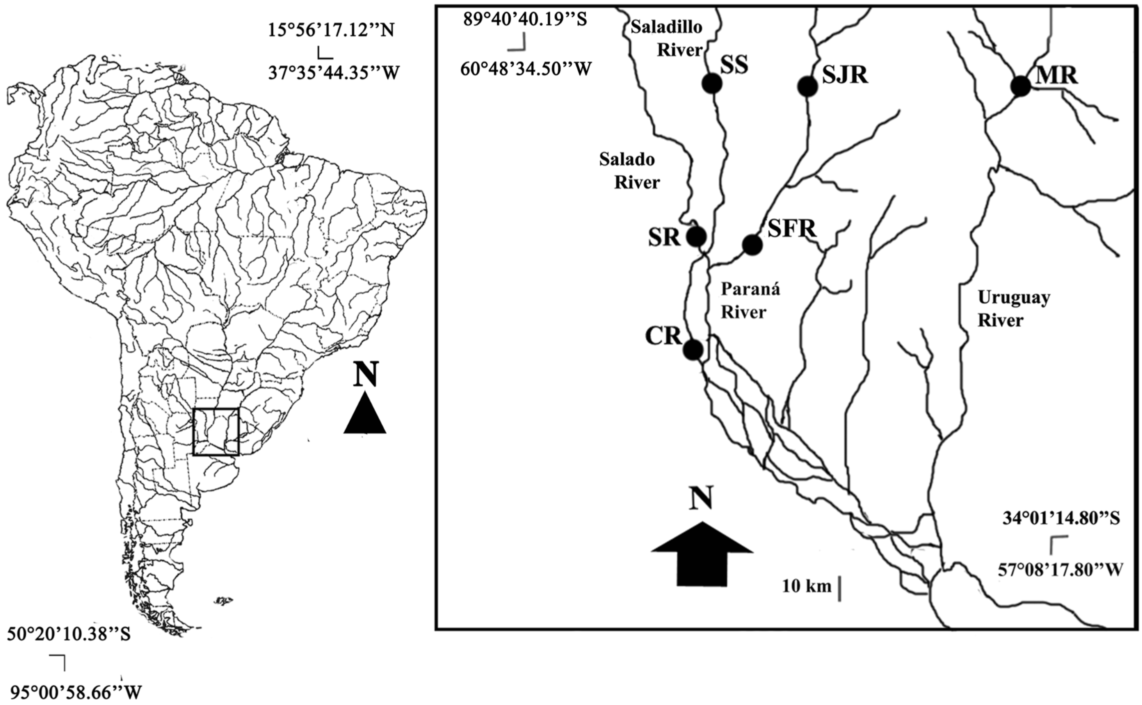

Fig. 1 Sample sites: *SS* Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Table 1 Hydrologic distances (km) between the sample sites

Sites	SS	SJR	RS	SR	CR	MR
SS	–	350	150	160	180	1,180
SJR	350	–	200	240	230	1,230
SFR	150	200	–	10	30	1,030
SR	160	240	10	–	20	1,020
CR	180	230	30	20	–	1,000
MR	1,180	1,230	1,030	1,020	1,000	–

SS Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Additionally, prawns were sampled from the Miriñay River (MR: 30°10′38.39″S; 57°35′59.37″W), a tributary of the Uruguay River (Fig. 1). The hydrologic distances were measured with Google Earth, taking into account the nearest road by river connectivity (Table 1). To characterise each site, the pH and conductivity were measured with a digital sensor (HANNA 198130). Data on the hydrometric level and current velocity were obtained from the local ports, Facultad de Ingeniería Hídrica (Universidad Nacional del Litoral) and the Prefectura Naval.

A total of 147 prawns were sampled and analysed, of which 24 prawns (14 females and 10 males) were collected from SS, 8 (4 females and 4 males) were collected from SJR, 22 (8 females and 14 males) were collected from SFR, 25 (16 females and 9 males) were collected from SR and 43 (28 females and 15 males) were collected from CR. The Miriñay site was represented by 25 prawns (8 females and 17 males).

Data acquisition

Digital images of the left side of the carapace of the sampled prawns were taken using a Sony Cyber-shot digital camera with a 12.1 mp resolution. Configurations of landmarks were digitised with the tpsDig 2.17 program (Rohlf 2013). The carapace structure was represented using 16 digitised landmarks (Type I: LMs #1–10) (Bookstein 1991) and curvature maxima (Type II: LMs #11–16) (Fig. 2). A representation of the overall rostrum shape was obtained by placing landmarks on the teeth of the rostrum, and homologies were evaluated by counting the minimum number of teeth of each sampled prawn, starting with the postorbital teeth. The rostral formula for the sampled prawns was $\frac{6\text{–}12}{2\text{–}4}$ (6–12 spines of superior margin; 2–4 spines of inferior margin), similar to that found by Boschi (1981).

Geometric morphometric analysis

Geometric morphometrics analyse the relative positions of anatomical landmarks and sets of points used to approximate curves (outlines) and surfaces to quantify an object's size and shape (Adams et al. 2004). For this analysis, shape components associated with position, rotation, translation and size were removed by a Procrustes fit in the MorphoJ program (Klingenberg 2011). Variation in shape was explored via a Principal Component Analysis (PCA) applied to the Procrustes coordinates. Allometry was tested with a multivariate regression using the log of the centroid size as the independent variable and the Procrustes coordinate as dependent variable. Sexual dimorphism was tested with discriminant analysis using the Procrustes coordinates. Permutations were used to establish the significance of each test statistic: 10,000 permutations for the multivariate regression and 1,000 permutations for the discriminant analysis (Klingenberg 2011).

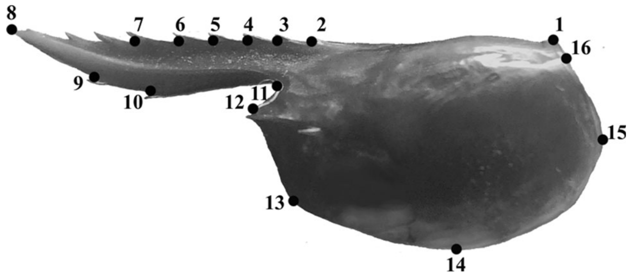

Fig. 2 Left side of the carapace of the prawn *M. borellii* with the configuration of the 16 landmarks

To compare the differences in shape between populations in a pairwise manner, Procrustes pairwise permutation tests (using Procrustes distances test) with Canonical Variate Analyses (CVA) were applied using the programme MorphoJ with 10,000 permutations. It is used to separate known groups in the data and provides an ordination that maximizes the separation of the group means relative to the variation within groups. Group membership is assumed to be known a priori (Darlington et al. 1973).

The dissimilarity analysis (UPGMA) using the matrix of pairwise Procrustes distances between the mean shape of each population is also presented. The software programme tpsRegr was used to obtain the mean shape of the overall shape (Rohlf 2007).

The differences in the environmental variables (pH, conductivity), hydrometric level and current velocity between sites were evaluated with a non-parametric Chi squared test. The correlations and covariations among shapes and hydrometric level, current velocity and geographical location (altitude and longitude) were ana-

Table 2 Intrapopulation multivariate regression (shape–log centroid size) with the carapace shape

Sites	Carapace shape	
	p value	% Predicted
SS	0.8993	1.1706
SJR	–	–
SFR	0.4033	4.2552
SR	0.1779	6.4101
CR	0.1296	4.1548
MR	0.0654	9.2353

SJR site was n < 10 prawns

SS Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Table 3 Intrapopulation discriminant analysis of the carapace shape between sexes (shape–sex)

Sites	Carapace shape	
	p value	*T* square
SS	< 0.0001	1,028.9901
SJR	–	–
SFR	0.0020	491.3487
SR	0.0380	283.2380
CR	0.0620	178.9161
MR	< 0.0001	930.3243

Site SJR had n < 10 prawns

SS Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

lysed with the software tpsPLS (Rohlf 2006) using a permutation test with 99 randomisations. tpsPLS applies the two-block partial least-squares analysis, analysing the covariation between shape and a set of variables (Rohlf 2006). In this analysis, the two sets of variables are treated symmetrically rather than using one set of variables (independent variables) to predict variation in the other set of variables (dependent variables) (Rohlf and Corti 2000). We used this type of analysis to examine whether the shape variations of the populations were related to hydrometric level, current velocity and geographical location of each river.

Morphological divergence among populations was related to hydrologic distances. Non-Euclidean distances between populations in the carapace shape (Procrustes distances) were compared with the corresponding matrices of pairwise hydrologic distances between sampling sites using Mantel tests.

Results

All populations exhibited non-allometric relationships between the carapace shape and the log centroid, and none had a statistically significant relationship (Table 2). The shape of the carapace was significantly different between females and males in most sites, though there was no difference between sexes in the CR site (Table 3).

The shape of the carapace was more variable on the first axis (PC1) in female (57.04 %) and male (53.85 %) prawns. The individuals were ordered along two axes, PC1 and PC2 (10.69 % for females and 16.80 % for males) by site. In this analysis, the populations had a high degree of overlap with respect to the carapace shape, except the Miriñay River population, which differed more in shape from the others. The differences in shape between females and males are shown on the rostrum (Fig. 3). Male prawns had finer (LMs #2 and 11) and longer rostrum than females (LMs #2–7) in relation to the carapace. The carapace was smaller in males than females, with a taller posterior region (LMs #1, 14 and 16) and longer carapace (LMs #1 and 2) in females. A difference in the length and the orientation of the rostrum (LMs #7 and 8) was observed between the individuals from different sites, with individuals from site MR having a slightly longer rostrum that was oriented more upward (LM #7 and LM #6) than the other sampled individuals. These differences were more pronounced in males (Fig. 3). In this manner, the shape of the prawns from MR differed from the other populations (SS, SJR, SFR, SR and CR). The carapace shape was more compressed in the MR population in females and males (LMs #12, 13 and 14). Moreover, the variation in shape among populations showed that the carapace of females was more similar among the sites than the carapace of males (Fig. 3).

The Procrustes distances tests among groups with CVA showed that the populations that were closest to one another (SS, SJR, SFR, SR and CR) in terms of hydrological distances (Table 4; Fig. 4) were not statistically significantly different in carapace shape but that all of those populations were different from the population at the Miriñay River, the site farthest from the others (Table 4; Fig. 4). This pattern was generally observed for females and males, but there were some exceptions. There were no statistically significant differences in shape between the MR and SFR sites for females and between the MR and SJR sites for males. Males also presented differences in shape between the SFR and SR sites and the CR and SS sites (Table 4). For females and males, the highest Procrustes distance values corresponded to the comparisons of the MR site with the other sites (Table 4). The UPGMA over the Procrustes distances of each carapace shape between sites presented similar patterns for females and males. The populations that were closest together were more similar in shape to one another than to the population from the site farthest away (Fig. 5).

The environmental variables measured at each site are shown in Table 5. The conductivity was significantly different between the sites ($\chi^2 = 3{,}227.2125$, $p < 0.00001$). The Salado River site and the Saladillo Stream site exhibited a higher conductivity than the sites along the Paraná and Uruguay Rivers (Table 5). However, the other variables were not significantly different between the sites (pH: $\chi^2 = 0.4354$, $p = 0.99$; hydro-

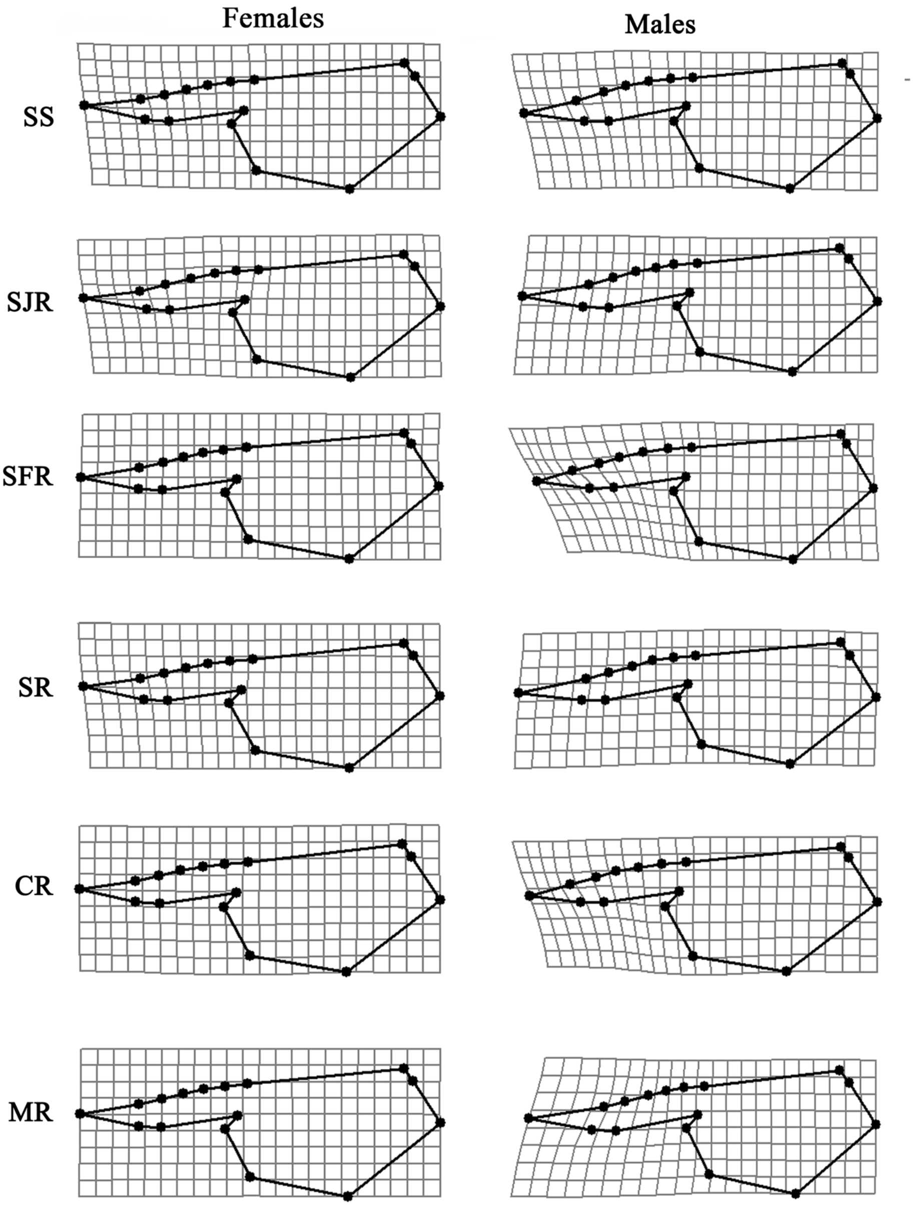

Fig. 3 Grids representing the variation in the mean shape of the carapace. These data include the variation in the shapes of the carapace of both female and male prawns. *SS* Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

metric level: $\chi^2 = 1.0194$, $p = 0.96$; current velocity: $\chi^2 = 1.879$, $p = 0.86$).

The carapace shape of female prawns showed small and non significant correlations between hydrometric level, current velocity and geographical location of sites along the first and second dimensions (Table 6). Moreover, the male prawns showed higher significant correlations in dimension 1 than females and weak and non-significant correlations in dimension 2. On the other hand, the covariance revealed high values for females and males in dimension 1, but these shape variations did not have significant linear relationships with hydrometric level, current velocity or geographical location (Table 6). Despite the weak correlations and lack of significant covariation, the driver of the variation in shape between the MR site and other sites was the geographical location (latitude and longitude) (Fig. 6). The hydrometric level and current velocity had little influence on the shape. On the other hand, despite the similarities in shape between nearby sites, geographical location was the variable that most influenced the shape in both dimensions 1 and 2 (Fig. 6).

The correlation between the hydrologic distance and carapace shape for females was highly positive and near the level of significance (Mantel test, r = 0.8981,

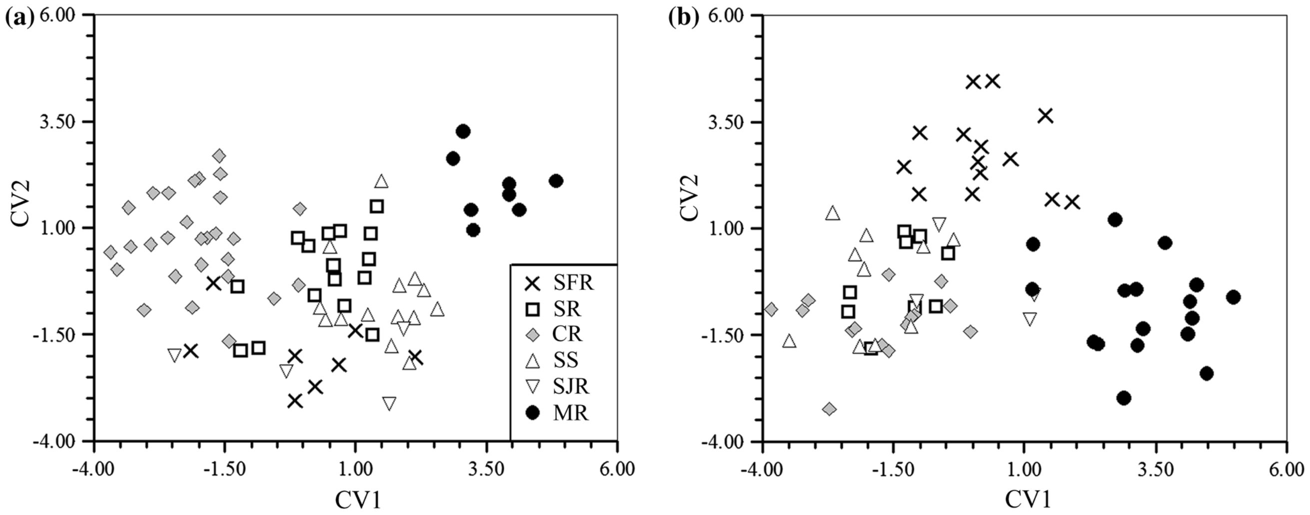

Fig. 4 Graphics of canonical variate analyses (CVA) with procrustes pairwise permutation tests between carapace shapes of populations. CV1 (canonical variate of axis 1), CV2 (canonical variate of axis 2). **a** Females and **b** males. *SS* Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Table 4 Procrustes pairwise permutation tests with canonical variate analyses (CVA) between carapace shapes of populations

Sites	Carapace shape (females)					
	SS	SJR	SFR	SR	CR	MR
SS	–	0.0234	0.0271	0.0113	0.0208	0.0518
SJR	0.3330	–	0.0368	0.0296	0.0296	0.0586
SFR	0.1885	0.1718	–	0.0230	0.0218	0.0315
SR	0.9443	0.8694	0.4751	–	0.0177	0.0467
CR	0.2832	0.3588	0.3327	0.3877	–	0.0445
MR	0.0174	0.0008	0.0796	0.0363	0.0074	–
	Carapace shape (males)					
	SS	SJR	SFR	SR	CR	MR
SS	–	0.0304	0.0434	0.0381	0.0411	0.0572
SJR	0.5309	–	0.0344	0.0247	0.0232	0.0397
SFR	0.0839	0.4178	–	0.0461	0.0287	0.0577
SR	0.0818	0.6175	0.0360	–	0.0304	0.0391
CR	0.0421	0.7265	0.1720	0.0947	–	0.0384
MR	0.0049	0.2558	0.0038	0.0439	0.0291	–

The upper right triangle gives the procrustes distances among sites and the lower left triangle gives the p values from permutation tests for procrustes distances among population shapes

SS Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

$p = 0.0586$), whereas for males, the correlation was weaker and non-significant (Mantel test, $r = 0.6497$, $p = 0.1284$). Overall, the carapace shape was strongly related to the hydrologic distance.

Discussion

The shape of the carapace was different between males and females in most of the populations. This sexual dimorphism in the carapace has been found in many geometric morphometric studies in decapods, in which authors have reported a wider posterior carapace region in females of freshwater crab species of the genus *Aegla* (Leach 1820), which is most likely linked to the wider pleon required by females to carry eggs (Giri and Collins 2004; Giri and Loy 2008; Barría et al. 2011). In this study, females had a taller and longer carapace than males which should result in a greater relative volume for gonad development within the carapace (Hartnoll 1985). These differences on carapace length between males and females were also observed on the shrimp *Xiphopenaeus kroyeri* (Heller 1862) by Bissaro et al. (2012) and on *Palaemonetes antennarius* (Anastasiadou et al. 2009).

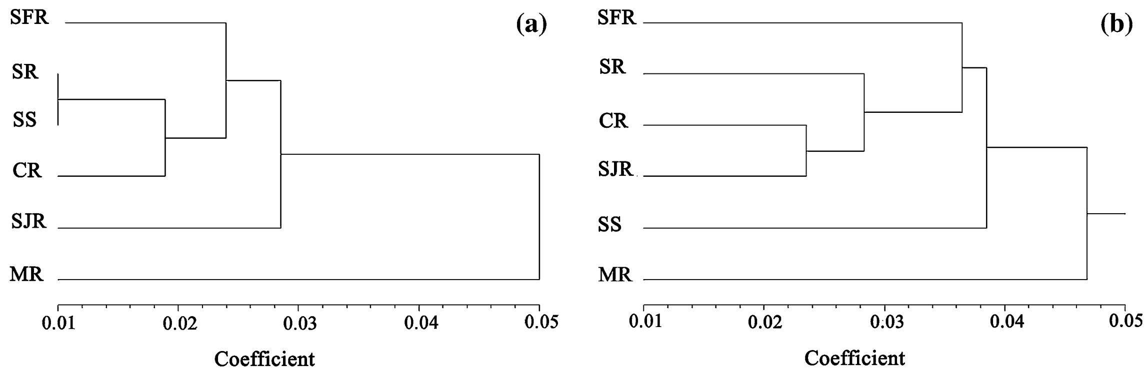

Fig. 5 Unweighted pair group method with arithmetic mean (UPGMA) over the procrustes distances of each carapace shape between sites: **a** females and **b** males. *SS* Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Table 5 Environmental variables measured in each sample site

Sites	pH	Conductivity (µs cm^{-1})	Hydrometric level (m)	Current velocity (m s^{-1})
SS	8.02	760	1.69	0.28
SJR	8.29	130	3.92	0.40
SFR	8.02	90	3.55	0.26
SR	7.87	1,470	3.98	0.29
CR	7.94	390	3.86	0.29
MR	5.80	30	3.87	0.36

SS Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River

Table 6 Correlations and covariations between the carapace shapes of the sites and hydrometric level, current velocity, geographical location

Hydrometric level, current velocity, geographical location	Carapace shape			
	Females		Males	
	Correlation value	*p* value	Correlation value	*p* value
Dimension 1	0.3413	0.0500	0.5796	0.0100
Dimension 2	0.3546	0.0900	0.3438	0.1400
	% Covariance	*p* value	% Covariance	*p* value
Dimension 1	0.6996	0.6500	0.7320	0.3600
Dimension 2	0.2732	0.2100	0.2376	0.4700

Moreover, the high degree of variation in shape of *Macrobrachium borellii* was represented by the displacement of the upper teeth to the left or the right in the rostrum. This displacement was affected by the variable number of spines on the upper and lower margins of the rostrum in this species. The variation in the number of teeth in the rostrum of freshwater prawns, including *M. borellii*, has been reported by Ringuelet (1949). Additionally, García-Dávila et al. (2005) showed high intrapopulation variability in the number of teeth in populations of *Palaemonetes* spp. The rostrum of *M. borellii* differed in shape and size between females and males in most populations. The longer and finer rostrum of males is explained by the sex difference in decapods, which is related to territorial defence, combat, display and courtship (Boschi 1981; Collins 2001). Nevertheless, the role of the rostrum in the general behavioural pattern is discussed. In shrimp, the rostrum is known to be related to sexual segregation, sexual maturity and size, habitat, mating behaviour, swimming behaviour and feeding (Kapiris and Thessalou-Legaki 2001).

The flow of water currents becomes particularly important in systems with floodplains because the flow regime organises the river ecosystem. In rivers, the physical structure of the environment and thus the habitat is influenced largely by physical processes,

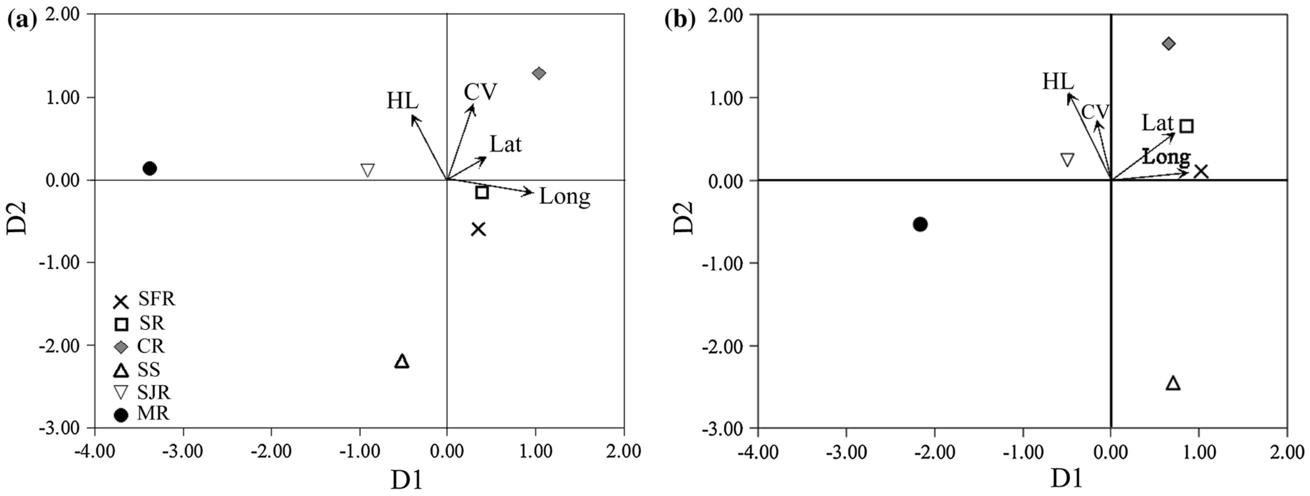

Fig. 6 Graphic of results of the 2B-PLS analysis. D1 (dimension 1) and D2 (dimension 2). **a** Females and **b** males. *SS* Saladillo Stream, *SJR* San Javier River, *SFR* Santa Fe River (Paraná River), *SR* Salado River, *CR* Coronda River, *MR* Miriñay River. HL (hydrometric level), CV (current velocity), Lat (latitude), Long (longitude)

especially the flow of water and sediment within the channel and between the channel and the floodplain (Poff et al. 1997). The flow and the magnitude of water currents can reflect forces experienced by the organisms in the current (Poff and Ward 1992). These factors have an effect on faunal distributions and the movement of aquatic invertebrates (Olden et al. 2004). Thus, while hydrological distances and geographical location explained the differences in shape between more distant populations, the connectivity and flow of the rivers and the dispersal of *M. borellii* within the floodplain system explained the generally low variation in shape between nearby populations. For example, fluctuations in water levels determine the level of connectivity between lentic and lotic environments as well the time of water residence, which determines the rates of exchange of nutrients and organisms (José de Paggi and Paggi 2007). Hydrological connectivity provides a corridor for biota and materials to move among patches, and it is often assumed that the presence of water acts as a bridge between habitats for organisms (Jenkins and Boulton 2003). Therefore, relationships between populations, for example, gene flow, depend on fluctuations of the system among other variables of the hydrological cycle (Williner et al. 2010). Studies of morphological character variation are therefore important to elucidate patterns observed in phenotypic and genetic character variation among populations (O'Reilly and Horn 2004). It has been observed in the decapod crab *Pachygrapsus marmoratus* (Fabricius 1787) that the low morphological geographical differentiation is attributable to the gene flux and consequent homogenisation that results from the continuous distribution of this species and its free dispersal (Silva et al. 2009).

The similarity in shape between the closest populations can also be understood in light of the mode of locomotion (mobility) of the prawn morphotype. The movements of freshwater decapods are either passive or active. In passive flux, an individual's movement is facilitated directly by the river current or mediated by a substratum that moves along the water surface or within the water column. The association of prawns of the genus *Macrobrachium* Bate 1868 with macrophytes was also examined by Montoya (2003), who found that prawns of this genus are associated with the roots of *Echiornnia crassipes* in the Orinoco Delta. Additionally, the water movement of the flow hydrological regime is one of the primary factors regulating the growth and distribution of aquatic plants in streams and rivers (Chambers et al. 1991) affecting this, the passive movements of prawns. Moreover, with respect to the dispersal of *M. borellii*, although this species is not an estuary species, there are species of the genus *Macrobrachium* that have migratory responses to changes in water salinity and migrate downstream to reproduce in more saline environments (Anger 2013). Therefore, it is possible that the swimming ability of these prawns combined with the dynamics of the floodplain system explain the low morphological variation between populations in this study.

The prawns belonging to the more distant population differed in shape from the prawns of the other (nearer) populations, and this difference could be explained by the hydrological distance. Similar observations have been reported in a study of the prawn *M. vollenhovenii* (Herklots 1851), in which the morphological variations between populations depended on the distances between four rivers in Côte d'Ivoire (Konan et al. 2010) such that the greater the distance between sites, the greater the phenotypic differences in the prawns (Konan et al. 2010). In addition, Tzeng et al. (2001) showed that there has been considerable morphological divergence between different geographical groups of the red-spot prawn *Metapenaeopsis barbata* (Miers 1878) from

Taiwan. Furthermore, morphometric variables were also found effective for comparing populations of the shrimp *Atyaephyra desmarestii* (Millet 1831) from freshwater habitats in north-western Greece (Anastasiadou and Leonardos 2008).

Despite the differences in the conductivity among sites, prawns were similar in shape. Most studies performed in aquatic systems with floodplains have shown that regardless of the environmental variables, the hydrological fluctuations constitute an important temporal and spatial macrofactor (Neiff et al. 2001; Arrington et al. 2005; Rossi et al. 2007; Montoya et al. 2006; Winemiller 2004; Mayora et al. 2013). These fluctuations regulate the environmental variables and explain the richness, distribution and abundance of the organisms that live in these systems (Neiff et al. 2001; Rossi et al. 2007; Mayora et al. 2013). Thus, hydrological fluctuations strongly affect movements and population dynamics. Accordingly, the increase in the populations of the prawn *M. amazonicum* (Heller 1862) in the Amazon River was associated with prawn migrations during floods (Walker and Ferreira 1985). In yet another study, four different stages in the densities of palemonids and trichodactilids in the Middle Paraná River were recognised, coinciding with events in the hydrological cycle (Collins et al. 2007; Williner et al. 2010).

Our results document the variations in body shape within and between populations of the freshwater prawn *M. borellii* in a floodplain system utilising geometric morphometrics. The variation in the carapace shape between populations of *M. borellii* is related to the population dynamic modulated by the characteristics of the floodplain system, which allow populations to remain connected influencing the dispersal of the prawns. The sexual dimorphism in shape is of interest in understanding the processes that influence differences in this species of freshwater prawn. This work considers the importance of dynamics aquatic systems as a macrofactor that modulates the faunal distribution and the movement of aquatic invertebrates. In a freshwater floodplain system, the populations are modulated by the dynamics of the hydrological cycle, and when studies of geometric morphometrics are conducted, it is important to take into account the effect of past hydrological fluctuations as a macrofactor, in addition to the hydrological distances between populations. Finally, genetic analyses are required to better understand the processes of dispersal involved in the variation in body shape among populations of the freshwater prawn *M. borellii* in a floodplain system.

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References

Adams DC, Rohlf FJ, Slice DE (2004) Geometric morphometrics: ten years of progress following the "revolution". Ital J Zool 71:5–16

Adams DC, Rohlf FJ, Slice DE (2013) A field comes of age: geometric morphometrics in the 21st century. Hystrix 24:7–14

Anastasiadou Ch, Leonardos ID (2008) Morphological variation among populations of *Atyaephyra desmarestii* (Millet, 1831) (Decapoda, Natantia, Atyidae) from freshwater habitats of north-western Greece. J Crustac Biol 28:240–247

Anastasiadou Ch, Liasko R, Leonardos ID (2009) Biometric analysis of lacustrine and riverine populations of *Palaemonetes antennarius* (H-Milne Edwards, 1837) (Crustacea, Decapoda, Palaemonidae) from north-western Greece. Limnologica 39:244–254

Anger K (2013) Neotropical *Macrobrachium* (Caridea: Palaemonidae): on the biology, origin, and radiation of freshwater-invading shrimp. J Crustac Biol 33:151–183

Arrington DA, Winemiller KO, Layman CA (2005) Community assembly at the patch scale in a species-rich tropical river. Oecologia 144:157–167

Barría EM, Sepúlveda RD, Jara CG (2011) Morphologic variation *in Aegla* Leach (Decapoda: Reptantia: Aeglidae) from central-southern Chile: interspecific differences, sexual dimorphism, and spatial segregation. J Crustac Biol 31:231–239

Bennetts RE, Nichols JD, Lebreton JD (2003) Methods for estimating dispersal probabilities and related parameters using marked animals. In: Clobert J, Danchin E, Dhondt AA, Nichols JD (eds) dispersal. Oxford University Press, Oxford, pp 3–17

Bissaro FG, Gomes JL, Madeira Di Beneditto AP (2012) Morphometric variation in the shape of the carapace of shrimp *Xiphopenaeus kroyeri* on the east coast of Brazil. J Mar Biol Assoc UK 93(03):683–691

Bock W (1999) Functional and evolutionary explanations in morphology. Neth J Zool 49(1):45–65

Bookstein FL (1991) Morphometric tools for landmark data. Cambridge University Press, Cambridge

Boschi EE (1981) Decapoda Natantia. Fauna de Agua Dulce de la República Argentina. FECIC 26:1–61

Chambers PA, Prepas EE, Hamilton HR, Bothwell ML (1991) Current velocity and its effect on aquatic macrophytes in flowing waters. Ecol Appl 1:249–257

Collins P (2001) Relative growth of the freshwater prawn *Macrobrachium borellii* (Nobili 1896) (Decapoda: Palaemonidae). Nauplius 9:53–60

Collins PA, Williner V, Giri F (2007) Littoral communities: Macrocrustaceans. In: Iriondo MH, Paggi JC, Parma MJ (eds) The middle Parana River, limnology of a subtropical wetland. Springer-Verlag, Berlin, pp 277–302

Corti M (1993) Geometric morphometrics: an extension of the revolution. Trends Ecol Evol 8:302–303

Darlington RB, Weinberg SL, Walberg HJ (1973) Canonical variate analysis and related techniques. Rev Educ Res 43:443–454

Fernandez D, Collins P (2002) Supervivencia de cangrejos en ambientes dulceacuícolas inestables. Nat Neotrop 33:81–84

García-Dávila CR, Magalhães C, Guerrero JCH (2005) Morphometric variability in populations of *Palaemonetes* spp. (Crustacea, Decapoda, Palaemonidae) from the Peruvian and Brazilian Amazon Basin. Iheringia Sér Zool 95:327–334

Giri F, Collins PA (2004) A geometric morphometric analysis of two sympatric species of the family Aeglidae (Crustacea, Decapoda, Anomura) from the La Plata basin. Ital J Zool 71:85–88

Giri F, Loy A (2008) Size and shape variation of two freshwater crabs in Argentinean Patagonia: the influence of sexual dimorphism, habitat, and species interactions. J Crustac Biol 28:37–45

Gomes LC, Bulla CK, Agostinho AA, Vasconcelos LP, Miranda LE (2012) Fish assemblage dynamics in a neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. Hydrobiologia 685:97–107

Hartnoll AL (1985) Growth, sexual maturity and reproductive output. In: Wenner AM (ed) Crustacean: factors in adult growth. Rotterdam AA, Balkema, pp 101–128

Huxley JS (1932) Problems of relative growth. The John Hopkins University Press, Baltimore (276 pp)

Idaszkin YL, Márquez F, Nocera AC (2013) Habitat-specific shape variation in the carapace of the crab *Cyrtograpsus angulatus*. J Zool 290:117–126

Jenkins KM, Boulton AJ (2003) Connectivity in a dryland river: short-term aquatic microinvertebrate recruitment following floodplain inundation. Ecology 84:2708–2723

José de Paggi S, Paggi JC (2007) Zooplancton. In: Iriondo MH, Paggi JC, Parma MJ (eds) The middle Parana River, limnology of a subtropical wetland. Springer-Verlag, Berlin, pp 229–245

Kapiris K, Thessalou-Legaki M (2001) Sex-related variability of rostrum morphometry of *Aristeus antennatus* (Decapoda: Aristeidae) from the Ionian Sea (Eastern Mediterranean, Greece). Hydrobiologia 449:123–130

Klingenberg CP (2011) MorphoJ: an integrated software package for geometric morphometrics. Mol Ecol Resour 11:353–357

Klingenberg CP (2013) Visualizations in geometric morphometrics: how to read and how to make graphs showing shape changes. Associazione Teriologica Italiana Hystrix. Ital J Mammal 24:15–24

Konan KM, Adépo-Gourène AB, Ouattaraa A, Nyingy WD, Gourène G (2010) Morphometric variation among male populations of freshwater shrimp *Macrobrachium vollenhovenii* Herklots, 1851 from Côte d'Ivoire Rivers. Fish Res 103:1–8

Mayora G, Devercelli M, Giri F (2013) Spatial variability of chlorophyll-*a* and abiotic variables in a river–floodplain system during different hydrological phases. Hydrobiologia 717:51–63

McGhee Jr GR (1999) Theoretical morphology: the concepts and its applications. Columbia University Press, New York (316 pp)

Montoya JV (2003) Freshwater shrimps of the genus *Macrobrachium* associated with roots of *Eichhornia crassipes* (Water Hyacinth) in the Orinoco Delta (Venezuela). Carib J Sci 39:155–159

Montoya JV, Roelke DL, Winemiller KO, Cotner JB, Snider JA (2006) Hydrological seasonality and benthic algal biomass in a neotropical floodplain river. J N Am Benthol Soc 25(1):157–170

Morrone JJ, Lopretto EC (1995) Parsimony analysis of endemicity of freshwater Decapoda (Crustacea: Maclacostraca) from southern South America. Neotropica 41:3–8

Neiff JJ, Poi de Neiff A, Casco S (2001) The effect of prolonged floods on *Eichhornia crassipes* growth in Paraná River floodplain lakes. Acta Limnol Bras 3:51–60

O'Reilly KM, Horn MH (2004) Phenotypic variation among populations of *Atherinops affinis* (Atherinopsidae) with insights from a geometric morphometric analysis. J Fish Biol 64:1117–1135

Olden JD, Hoffman AL, Monroe JB, Poff NL (2004) Movement behaviour and dynamics of an aquatic insect larva in a stream benthic landscape. Can J Zool 82:1135–1146

Poff NL, Ward JV (1992) Heterogeneous currents and algal resources mediate in situ foraging activity of a mobile stream grazer. Oikos 65:465–478

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime. BioSience 47:769–784

Ringuelet RA (1949) Camarones y cangrejos de la zona de Goya (Sergéstidos, Palamonidae y Trichodactylidae). Notas Mus La Plata Zool 14:79–109

Rohlf FJ (2006, 2007, 2013) Tps series. Department of Ecology and Evolution, State University of New York at Stony Brook, New York. http://life.bio.sunysb.edu/morph/

Rohlf FJ, Corti M (2000) The use of two-block partial least-squares to study covariation in shape. Syst Biol 49:740–753

Rohlf FJ, Marcus LF (1993) A revolution in morphometrics. Trends Ecol Evol 8:129–132

Rossi L, Cordoviola E, Parma MJ (2007) Fishes. In: Iriondo MH, Paggi JC, Parma MJ (eds) The middle Parana River, limnology of a subtropical wetland. Springer-Verlag, Berlin, pp 305–325

Rufino M, Abelló P, Yule AB (2006) Geographic and gender shape differences in the carapace of *Liocarcinus depurator* (Brachyura: Portunidae) using geometric morphometrics and the influence of a digitizing method. J Zool 269:458–465

Seilacher A (1970) Arbeitskonzept zur Konstruktionsmorphologie. Lethaia Oslo 3:393–396

Silva IC, Hawkins SJ, Paula J (2009) A comparison of population differentiation in two shore crab species with contrasting distribution along the Portuguese coast, using two morphological methodologies. Mar Freshw Res 60:833–844

Silva IC, Alves MJ, Paula J, Hawkins SJ (2010) Population differentiation of the shore crab *Carcinus maenas* (Brachyura: Portunidae) on the southwest English coast based on genetic and morphometric analyses. Sci Mar 74:435–444

Srijaya TC, Pradeep PJ, Mithun S, Hassan A, Shaharom F, Chatterji A (2010) A new record on the morphometric variations in the populations of Horseshoe Crab (*Carcinoscorpius rotundicauda* Latreille) obtained from two different ecological habitats of Peninsular Malaysia. Our Nat 8:204–211

Tzeng TD, Chiu CS, Yeh SY (2001) Morphometric variation in red-spot prawn (*Metapenaeopsis barbata*) in different geographic waters of Taiwan. Fish Res 53:211–217

Walker I, Ferreira MJN (1985) On the populations dynamics and ecology of the shrimp species (Crustacea, Decapoda, Natantia) in the Central Amazonian river Taruma-Mirim. Oecologia 66:264–270

Ward JV, Tockner K, Arscott DB, Claret C (2002) Riverine landscape diversity. Freshw Biol 47:517–539

Williner V, Giri F, Collins PA (2009) Los crustáceos decápodos dulceacuícolas en Argentina. FABICIB 13:107–125

Williner V, Giri F, Collins PA (2010) Metapopulations of Decapods in the floodplain of Parana River, South America. In: Alvarez MA (ed) Floodplains: physical geography, ecology and societal interactions. Nova Science Publication, New York, pp 179–199

Winemiller KO (2004) Floodplain river food webs: generalizations and implications for fisheries management. In: Welcomme RL, Petr T (eds) Proceedings of the second international symposium on the management of large rivers for fisheries. Food and Agriculture Organization & Mekong River Commission, FAO Regional Office for Asia and the Pacific, Bangkok, pp 285–309

Zimmermann G, Bosc P, Valade P, Cornette R, Améziane N, Debat V (2012) Geometric morphometrics of carapace of *Macrobrachium australe* (Crustacea: Palaemonidae) from Reunion Island. Acta Zool (Stockholm) 93:492–500