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Research Article

# First record of giant freshwater prawn *Macrobrachium rosenbergii* (de Man, 1879) from small-scale fisheries in East Africa, confirmed with DNA barcoding

Baraka Kuguru[1], Johan Groeneveld[2,3,*], Sohana Singh[2] and Boniventure Mchomvu[1]

[1]*Tanzania Fisheries Research Institute, PO Box 9750, Dar es Salaam, Tanzania*
[2]*Oceanographic Research Institute, PO Box 10712, Marine Parade, 4056 Durban, South Africa*
[3]*School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, KwaZulu-Natal, South Africa*

Author e-mails: *barakakuguru@gmail.com (BK), jgroeneveld@ori.org.za (JG), ssingh@ori.org.za (SS), b775r83@gmail.com (BM)*

**Corresponding author*

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## Abstract

We report, for the first time in the wild, giant freshwater prawn *Macrobrachium rosenbergii* populations in East Africa. Specimens caught by fishermen in the lower reaches of the Ruvu River and Rufiji Delta in coastal Tanzania were identified based on their morphology, with confirmation through DNA barcode analysis. The East African specimens clustered with the western *M. rosenbergii dacqueti* subspecies in a phylogenetic analysis based on new and published mitochondrial 16S rRNA and cytochrome *C* oxidase subunit I (COI) sequences. Captured specimens spanned a size range of 110–310 mm total length and > 35% of females carried external eggs, implying that populations were established and self-sustaining. No active culture facilities or ponds with *M. rosenbergii* were found within the catchment. Nevertheless, the invasive populations supported a small-scale fishery that used bottom-set seine nets. The demonstrated presence of *M. rosenbergii* in at least two river systems, combined with the existence of favourable brackish water habitats for completing their life cycle, may indicate that river systems in East Africa are at a high risk of invasion by this species. Key information gaps for the region are highlighted.

**Key words:** bioinvasion, exotic species, reproductive viability, river prawn, Tanzania

## Introduction

The giant freshwater (or river) prawn *Macrobrachium rosenbergii* (de Man, 1879) is native to the tropical and subtropical Indo-West Pacific region, extending eastwards from India to Southeast Asia and Papua New Guinea (De Grave et al. 2013a). It is one of the most cultured freshwater prawns in the world, and the FAO Database on Introductions of Aquatic Species (FAO-DIAS 2009) lists at least 40 countries where it has been introduced for aquaculture. Escapees from aquaculture facilities have established exotic populations in Brazil (Silva-Oliveira et al. 2011; Iketani et al. 2016), Venezuela (Pereira et al. 1996), Panama (FAO-DIAS 2009), Martinique Island (Lim et al. 2002), Madagascar (Hanamura et al. 2008), the United States of America (Woodley et al. 2002), Taiwan and Russia (FAO-DIAS 2009).

*Macrobrachium rosenbergii* has not previously been reported from the wild in East Africa, apart from records from Uganda and Kenya in the early 1960s (FAO-DIAS 2009), which were subsequently dismissed as mistaken identification (Bailey and Crichton 1971). At least eight other *Macrobrachium* species are widespread in East African rivers and lakes (Bailey and Crichton 1971). Records from mainland Tanzania (Rufiji, Ruvu, Wami and Pangani rivers) and Kenya (Athi-Sabaki and Tana rivers) include *M. idella* (Hilgendorf, 1898), *M. rude* (Heller, 1862), *M. equidens* (Dana, 1852), *M. lepidactylus* (Hilgendorf, 1879), *M. scabriculum* (Heller, 1862) and *M. patsa* (Coutière, 1899) (cited in De Grave 2013a–f; De Grave et al. 2013b–d). *Macrobrachium moorei* (Calman, 1899) is endemic to Lake Tanganyika, and *M. niloticum* (J. Roux, 1833) is known from the Nile River, including Lake Turkana in Kenya.

There is no evidence as yet for serious ecological consequences following introductions of *M. rosenbergii* to new environments (Anger 2013), as observed for various crayfish species world-wide (Gherardi et al. 2011). Continued spread of *M. rosenbergii* to new environments nevertheless enhances the likelihood of competitive displacement of native species, shifts in species diversity through ecosystems effects (Hobbs et al. 1989; Lodge et al. 2000) and introduction of viral and bacterial disease (New et al. 2009). In contrast, the establishment of exotics has increased fishery yields without apparent detriment to native biodiversity in some situations (Dudgeon and Smith 2006).

The systematics of the *M. rosenbergii* species group has not yet been fully resolved, and some debate remains on whether it comprises a single wide-ranging species (Holthuis 1995), or two genetically and morphologically distinct subspecies (de Bruyn et al. 2004; Wowor and Ng 2007; Iketani et al. 2011): *M. rosenbergii dacqueti* (Sunier, 1925) from the Asian mainland and Malaysia, and *M. rosenbergii rosenbergii* (de Man, 1879) from east of Huxley's Line, in the Philippines and Papua New Guinea.

A fisheries survey of the lower Ruvu River and Rufiji Delta in mainland Tanzania identified occasional small-scale fisheries for freshwater prawns, which generated more income than fish catches. Fishermen reported that the fishery had been active for three to four years, and that prawns were more abundant after periods of flooding. Anecdotal information suggested that *M. rosenbergii* may also be present in the Pangani River, and the Tana River in Kenya. We report, for the first time, wild populations of the giant freshwater prawn *M. rosenbergii* in East Africa. *Macrobrachium rosenbergii* specimens were identified based on their morphology (Wowor and Ng 2007) and DNA barcoding. The size composition, body metrics and egg-bearing status of captured *M. rosenbergii* were used to evaluate whether populations are self-sustaining in the wild.

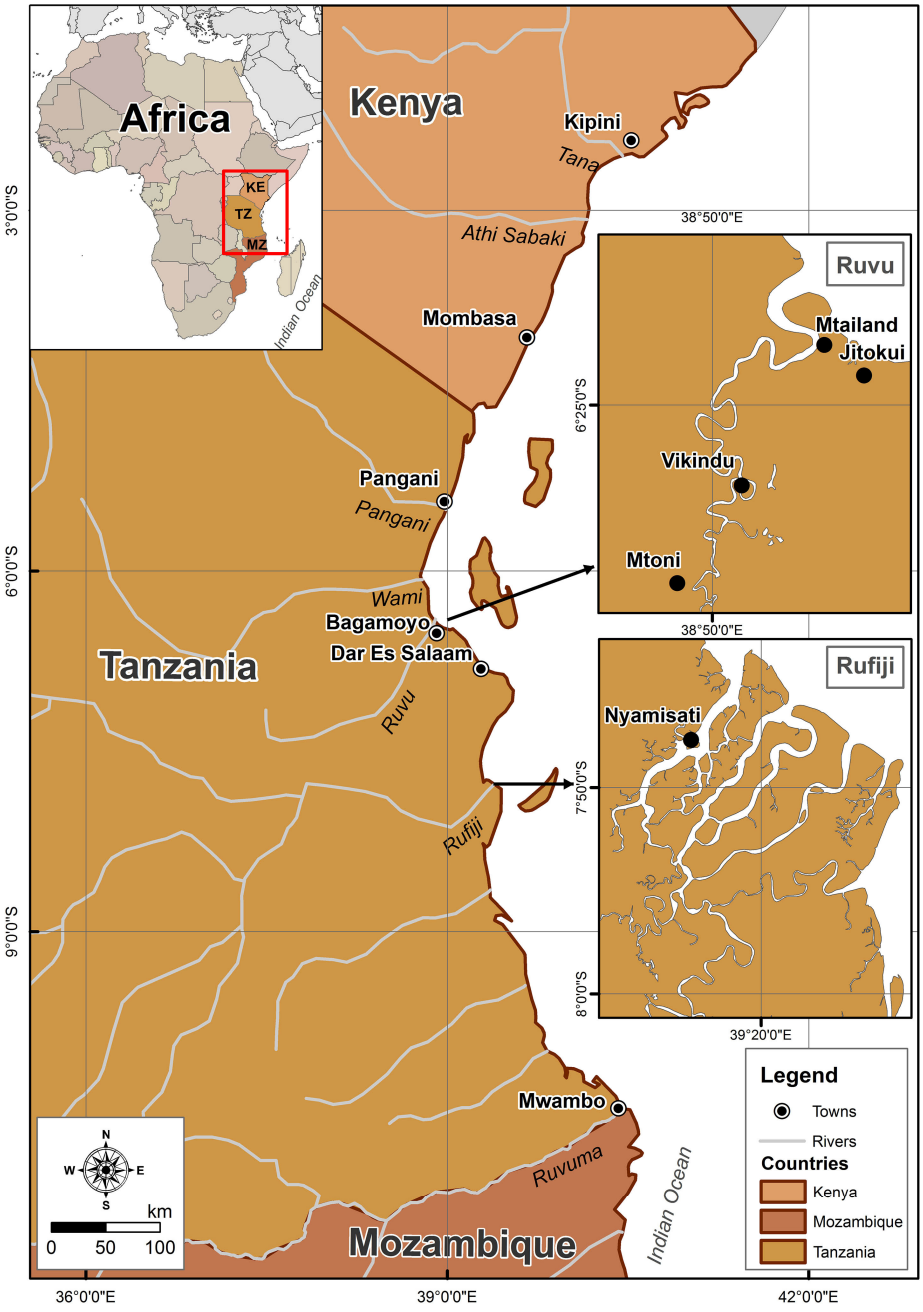


**Figure 1.** Sampling sites in the lower Ruvu River and the Rufiji Delta in Tanzania (black circles), and the location of other major estuaries in Kenya and Tanzania where *Macrobrachium rosenbergii* are likely to be found.

## Materials and methods

Coastal Tanzania (Figure 1) has a humid tropical climate and high seasonal rainfall between October and May. Rivers drain into the Western Indian Ocean (WIO), often forming deltas dominated by dense mangrove forests (Bosire et al. 2016). The Ruvu River (≈ 12,000 km$^2$ catchment basin) terminates in a meandering medium-sized estuary surrounded by rice farms, scattered rural settlements, and dense mangrove forests (Saha et al. 2014). In contrast, the Rufiji Delta drains most of southwestern Tanzania (≈ 179,000 km$^2$ catchment basin, Shagude 2016), terminating in a major mangrove-covered delta system (Wagner and Sallema-Mtui 2016).

**Figure 2.** Male *Macrobrachium rosenbergii dacqueti* (total length 225 mm; 13 teeth on dorsal rostrum margin; 10 on ventral margin) caught in lower Ruvu River, near Bagamoyo. Photograph by Johan Groeneveld.

### *Field sampling and laboratory work*

River prawns were sampled during fisheries surveys of the lower Ruvu River (Nov–Dec 2017) and the Rufiji Delta (Jan–Feb 2018). Fishing gear used by fishers were bottom-set seine nets (50–75 mm mesh), deployed for 1 to 16 h (overnight) before hauling. The nets were operated from dugout canoes, departing for fishing grounds between 05h30 and 10h00, and returning to landing sites between 09h00 and 14h00. The average time spent fishing per day was 4.1 ± 0.4 h (n = 151). The nets caught mainly prawns and several fish species.

Prawns were collected at landing sites (see Figure 1) from fishermen returning from fishing grounds. *Macrobrachium rosenbergii* (Figure 2) was identified based on the numbers of teeth on the ventral and dorsal margins of the rostrum, presence of elongated chelipeds with equal length in large males, and large (giant) size of individual prawns (Bailey and Crichton 1971; Holthuis 1980; Wowor and Ng 2007). Specimens were weighed (W) to the nearest gram (g) and measured with Vernier callipers to the nearest millimetre (mm). The total length (TL) was measured from the tip of the rostrum to the end of the telson, and the carapace length (CL) from the eye socket to the postero-dorsal carapace edge. The endopodite morphology of the second pleopod pair, and larger chelipeds in mature males, were used to determine gender. The presence of eggs in females was recorded.

Physio-chemical information at sampling locations in the lower Ruvu River, measured with a conductivity probe (YSI EC 300A, YSI, USA), was obtained from Saha et al. (2014), and water temperature and salinity readings were taken with a SBE 19plus V2 SeaCAT Profiler in May 2018.

No comparable information could be obtained for the sampling locations in the Rufiji Delta.

Genomic DNA was isolated from leg tissue using the Qiagen DNeasy Blood and Tissue DNA purification kit (Qiagen, CA-USA), following the manufacturers protocol. The cytochrome oxidase subunit I (COI) was amplified using the standard, universal primers LCO1490 and HCO2190 (Folmer et al. 1994) and 16S rDNA was amplified using universal 16S primers 16Sar and 16Sbr (Kessing et al. 2004). The PCR's were carried out in 25 µL reaction volumes, containing 12.5 µL of OneTaq Quick-Load 2X Mastermix (New England BioLabs Inc.), 0.2 µM of each 10 µM primer, 2 µL of 2–10 ng genomic DNA and 9.5 µL of PCR-grade $H_2O$. Thermal cycling comprised denaturation at 95 °C for 10 minutes, 35 cycles of 95 °C for 30 seconds, and annealing temperatures of 50 °C for 30 seconds for COI and 72 °C for 45 seconds for 16S. Final extension was carried out at 72 °C for 10 minutes. The PCR reactions were run with a negative and positive control.

Sequencing was performed at the Central Analytical Facilities at Stellenbosch University. Chromatograms were inspected manually using FinchTV v. 1.4.0 (www.geospiza.com), and species identity verified using the Barcode of Life Data Systems web platform (BOLD; www.boldsystems.org) for COI and GenBank (https://www.ncbi.nlm.nih.gov/genbank/) for COI and 16S. Sequences were aligned using Clustal X implemented in BioEdit v. 7.2.5 (Hall 1999), optimised manually, and deposited at GenBank (accession numbers in Table 1).

### *Data analysis*

For samples from the Ruvu River, linear regression was fitted for TL and CL, and a non-linear regression for TL and W, using a least-squares algorithm in Microsoft Excel. Accurate weight measurements were not available for Rufiji Delta, and no regressions were therefore attempted. A two-sample Student's *t*-test for unequal variance was used to compare mean TL of prawns caught in the Ruvu River with those caught in the Rufiji Delta.

Neighbour-joining phylogenetic trees (Saitou and Nei 1987) were constructed for COI and 16S sequences. Analyses were performed in MEGA X (Kumar et al. 2018) using the Kimura 2-parameter (K2P, Kimura 1980) measure with 1000 bootstrap replicates to determine the mean K2P genetic distances and standard errors. *Macrobrachium idae* (Heller, 1862), *M. lamarrei* (H. Milne Edwards, 1837), and *M. nipponense* (De Haan, 1849) were used as outgroups in the COI alignment, and *M. australiense* Holthuis, 1950, and *M. lar* (Fabricius, 1798) were used in the 16S alignment.

## Results

Of 151 *M. rosenbergii* collected at the Ruvu River, 57 were females, 26 males (a sex ratio of 1:0.46) and 68 specimens were not sexed. The TL of specimens

**Table 1.** GenBank accession numbers and locality of origin of *Macrobrachium* specimens used in the neighbour-joining trees based on COI and 16S rRNA sequences. New records are indicated with an *.

| Species / Subspecies | GenBank Accession | Locality | Reference |
|---|---|---|---|
| | **COI** | | |
| *Macrobrachium rosenbergii dacqueti* | MK113934–38 | Rufiji, Tanzania * | This study |
| | MK113940–43 | Ruvu, Tanzania * | |
| | GQ995505–10 and GQ995517 | Brazil | Iketani et al. 2011 |
| | JF792432–39 | India | |
| *Macrobrachium rosenbergii* | GQ995511–16 and GQ995518 | Brazil | Iketani et al. 2011 |
| *Macrobrachium idae* | FM958070 | – | Wowor et al. 2009 |
| *Macrobrachium nipponense* | KF547935 | – | |
| *Macrobrachium lamarrei* | KX214618 | – | |
| | **16S rRNA** | | |
| *Macrobrachium rosenbergii dacqueti* | MK113944 | Rufiji, Tanzania * | This study |
| | MK113945–48 | Ruvu, Tanzania * | |
| | AY203904 | NE Malaysia | De Bruyn et al. 2004 |
| | AY203905 | Malaysia | |
| | AY203907 | S Vietnam | |
| | AY203908 | SW Thailand | |
| | AY203911 | SE Thailand | |
| | AY203913 | Java, Indonesia | |
| | AY203914 | Vietnam | |
| | AY203915 | SW Malaysia | |
| | GQ985381–88 | Northern Brazil | Iketani et al. 2011 |
| | JF792428–31 | India | |
| *Macrobrachium rosenbergii* | AY203906 | Papua New Guinea | De Bruyn et al. 2004 |
| | AY203909 | Indonesia | |
| | AY203910 | Philippines | |
| | AY203916–22 | Australia | |
| *Macrobrachium australiense* | AY203923 | – | |
| *Macrobrachium lar* | AY203922 | – | |

ranged from 145–310 mm (mean TL = 217 ± 36 (SD) mm; Figure 3). Males (246 ± 25 mm) were larger than females (196 ± 21 mm), and 38% of males were larger than the largest female measured (251 mm). A bimodal size frequency histogram peaked at 175–200 mm and 250–275 mm TL, consistent with a hypothesis of sexual dimorphism. Some 37% of females bore eggs, which ranged in colour from bright orange to grey. The smallest egg-bearing female had a TL of 151 mm and weighed 40 g.

Of 88 specimens collected at the Rufiji Delta, 66 were females and 22 were males (1:0.33). The TL ranged from 110–273 mm (mean TL = 202 ± 43 mm; Figure 3). Males (226 ± 49 mm) were larger than females (194 ± 38 mm), and the size frequency histogram also peaked at 175–200 mm, with a preponderance of individuals larger than 200 mm TL. Nevertheless, the mean TL of *M. rosenbergii* measured at Rufiji Delta was smaller than at the Ruvu River ($p = 0.004$). Of 66 females at Rufiji Delta, 27 (41%) bore eggs. The smallest egg-bearing female measured 161 mm TL.

The number of dorsal rostral teeth on 11 male specimens (145–265 mm TL) collected at the Ruvu River ranged from 11–15 (mode of 14), with the apical tooth included (Figure 2). Counts of ventral rostral teeth ranged from 9–13, with a mode of 12. Chelipeds of males with a TL > 200 mm were

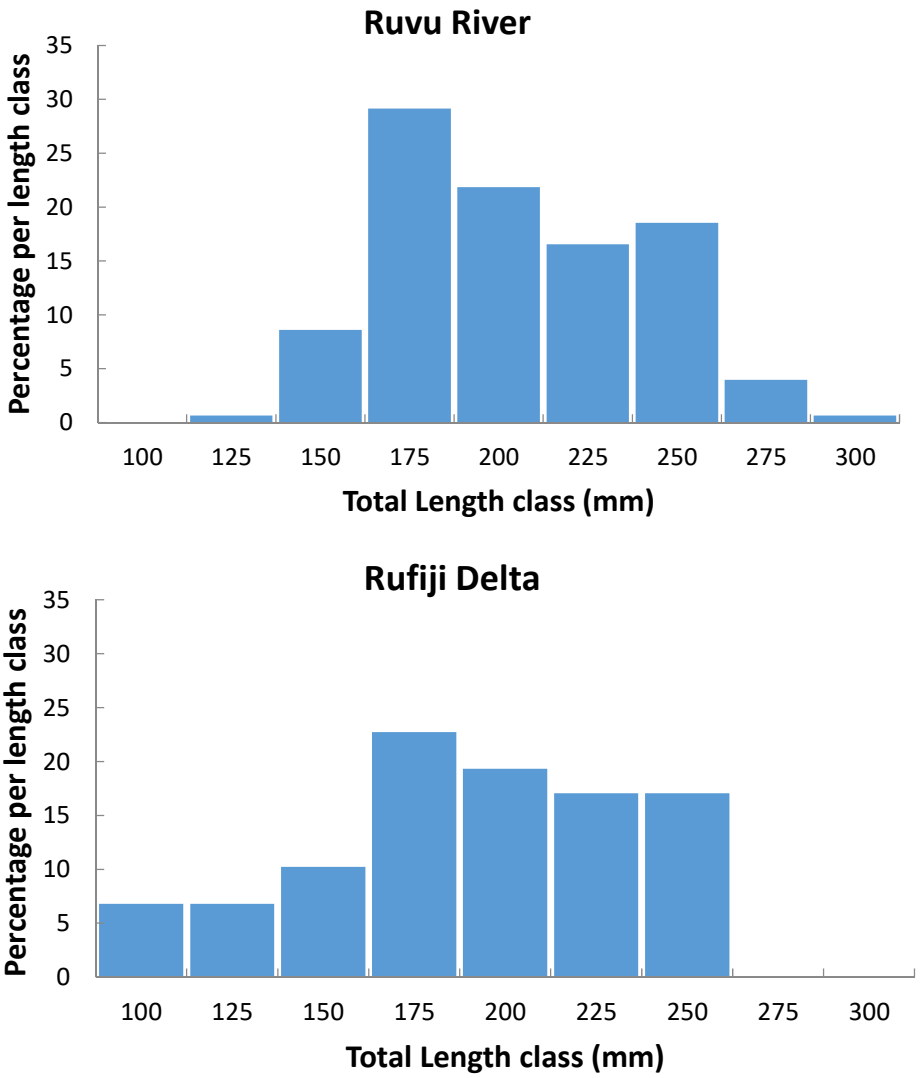


**Figure 3.** Length-frequency distribution (TL, mm) of *Macrobrachium rosenbergii* caught by fishers in the Ruvu River (n = 151) and Rufiji Delta (n = 88), respectively.

elongated, of equal length, and coloured orange and blue. The basal crest in all specimens was relatively high - comparable to the image of *M. r. dacqueti*, rather than that of *M. r. rosenbergii* in Figures 3 and 4 of Wowor and Ng (2007). Based on the morphological characters observed, all specimens were identified as *M. rosenbergii*, and possibly *M. r. dacqueti*.

Individual body weight of specimens collected at the Ruvu River ranged from 25–317 g, with males (mean 153 ± 40 g) weighing twice as much as females (mean 76 ± 26 g). The linear regression of CL and TL (sexes pooled) had a high coefficient of variation ($r^2$ = 0.86, Figure 4). The non-linear W and TL regression also fitted the pooled data well ($r^2$ = 0.95, Figure 4), and the exponent (3.07) was close to 3.0 (all data combined), indicating isometric growth (Froese 2006). Sex-wise W and TL regressions also showed isometric growth in females ($W = 0.00003 \times TL^{2.96}$, $r^2$ = 0.79, n = 57) and males ($W = 0.08 \times TL^{2.6}$, $r^2$ = 0.89, n = 26).

The 16S and COI sequences of five specimens collected from Ruvu River and five from Rufiji Delta were verified against references on GenBank.

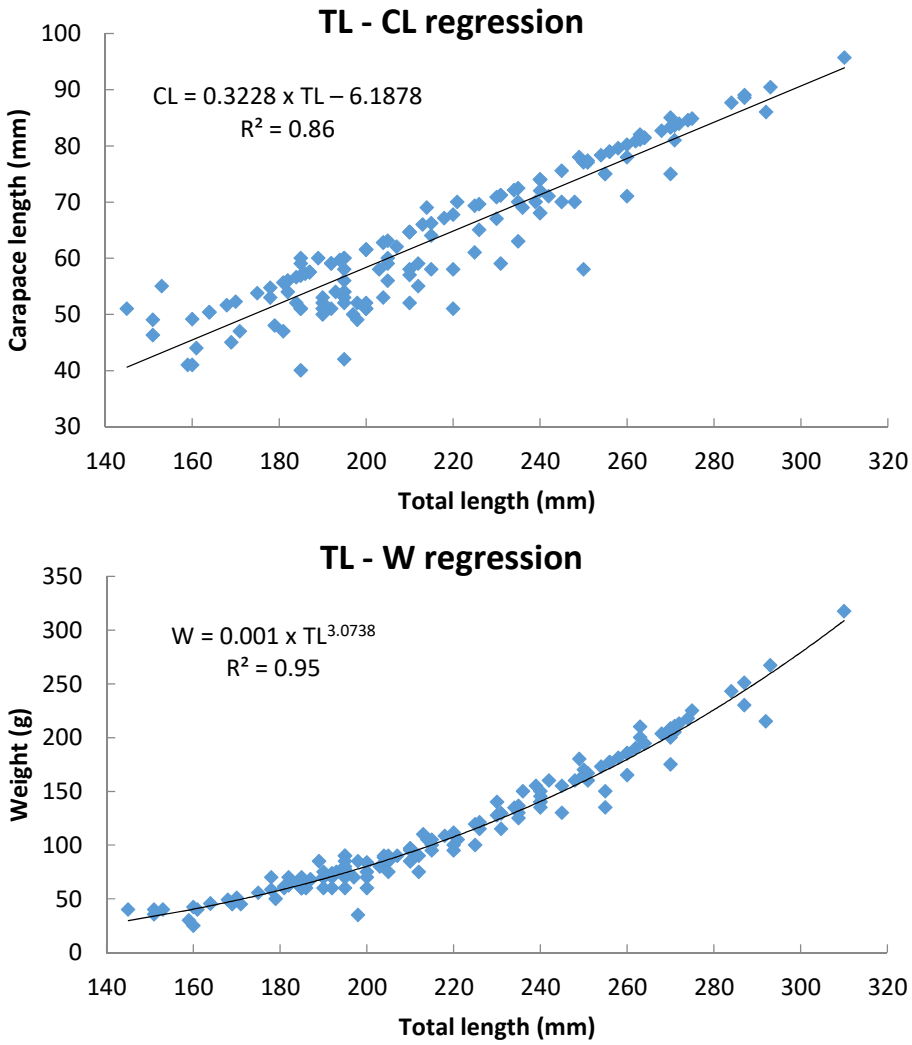


**Figure 4.** Regressions of total length versus carapace length, and total length versus body weight of 151 *Macrobrachium rosenbergii* specimens caught by fishers in the Ruvu River.

The COI alignment consisted of 567 base-pairs with 548 conserved sites, 17 variable sites and 11 parsimony informative sites, and had a 100% identity to *M. rosenbergii* (MF563572) from India. The 16S alignment consisted of 473 base-pairs, with 432 conserved sites, 40 variable sites and 21 parsimony informative sites, and had a 99% identity to *M. rosenbergii* (KM610154), also from India.

The neighbour-joining tree for COI and 16S indicated that there were two distinct clades, supported by high bootstrap values (Figure 5). One clade corresponded to *M. r. rosenbergii*, while the other corresponded to *M. r. dacqueti*. The sequences from East Africa clustered with the *M. r. dacqueti* form. Genetic divergence between *M. r. rosenbergii* and *M. r. dacqueti* was 1.9% using COI, and 5.8% using 16S, comparable to genetic divergence values obtained by Iketani et al. (2011).

## Discussion

Based on phenotypic and genotypic analyses, we provide the first records of *M. rosenbergii* populations in the wild in East Africa. Mitochondrial DNA

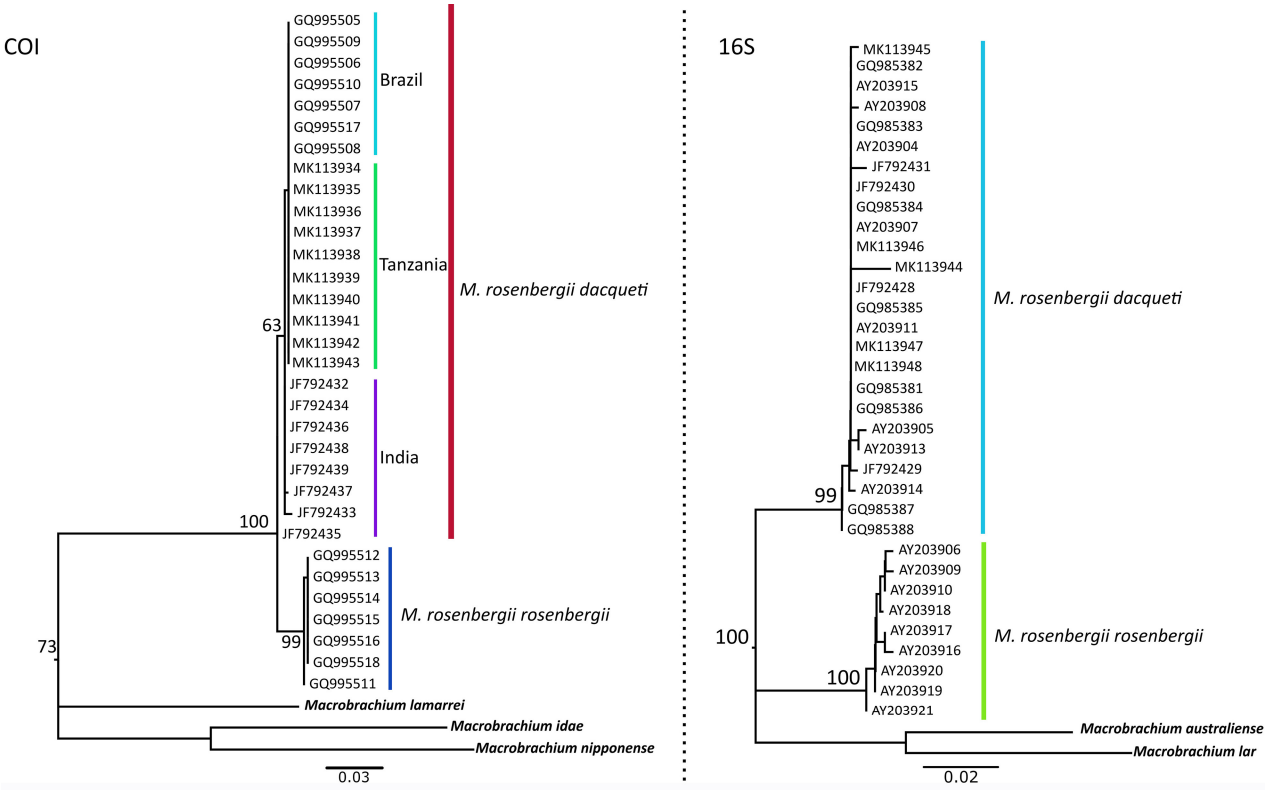


**Figure 5.** Neighbour-joining trees based on COI and 16S rDNA showing the relationships between *Macrobrachium rosenbergii dacqueti* and *M. rosenbergii rosenbergii*. Bootstrap support from 1000 replicates is indicated on the nodes.

sequences (COI and 16S) confirmed that sampled specimens belonged to the western subspecies *M. r. dacqueti*. The vast majority of cultured *Macrobrachium* worldwide, and most invasions where they are not native, comprise of *M. r. dacqueti*, traced to brood-stock imported to Hawaii from Malaysia (Wowor and Ng 2007).

We found no official information on imports or culture of *M. rosenbergii* in Tanzania, and a visit to aquaculture ponds at Kilosa agriculture research centre in the Ruvu catchment basin provided no evidence of past or present *M. rosenbergii* culture. Native *M. idella* was common in rivers and dams near Kilosa, supported by DNA barcoding of specimens collected there, and are used for local consumption (B. Mchomvu, *pers. obs.*). We could therefore not confirm that *M. r. dacqueti* caught by fishermen in the Ruvu River were escapees from upstream dams or aquaculture ponds.

The presence of ovigerous females suggests that *M. rosenbergii* reproduces in the Ruvu and Rufiji systems. Females can carry between 5000 and 100 000 eggs per batch, depending on their size, and may spawn several times per year (Cavallo et al. 2001; New 2002). Samples covered a wide size range of 110–310 mm TL, implying the presence of several age-classes. In combination, these factors suggest the existence of self-sustaining *M. rosenbergii* populations in the Ruvu River and Rufiji Delta, particularly in view of the apparent absence of recent culture facilities in upstream catchments (B. Mchomvu, *pers. obs.*). *Macrobrachium rosenbergii* in East

Africa therefore corresponds to category D2: "Self-sustaining population in the wild, with individuals surviving and reproducing a significant distance from the original point of introduction" in a unified framework for biological invasions (Blackburn et al. 2011). Whether *M. rosenbergii* can disperse between estuaries, as a fully invasive species across multiple sites (category E; Blackburn et al. 2011) remains unclear, and is a key knowledge gap. Based on larval rearing in artificial seawater, Mather and de Bruyn (2003) suggested that *M. rosenbergii* may be capable of at least limited marine dispersal, potentially facilitating invasions to adjacent estuaries.

An ecological niche model constructed by Silva-Oliveira et al. (2011) to assess potential areas at risk of invasion by *M. rosenbergii* predicted a low probability (< 0.36) of suitable habitat in East Africa. The most important contributors to the model were mean annual temperature, downstream distance (proximity to saline waters), and precipitation in July. Our finding of *M. rosenbergii* in the Ruvu and Rufiji systems contradicts the model's prediction, begging the question of which other factors, not considered in the model, are likely to facilitate habitats suitable for *M. rosenbergii* in East Africa.

Most rivers in East Africa are relatively short, often with deltaic estuaries (Duvail et al. 2017) surrounded by large wetlands, thus shortening the downstream distance that egg-bearing females need to migrate to reach estuarine conditions to release their larvae and complete their life cycle. The lower Ruvu River and Rufiji Delta are fringed by dense mangrove forests (Mangora et al. 2016), providing shelter or nurseries for fish and crustaceans, potentially including *M. rosenbergii*, before they migrate upstream to freshwater habitats (Bowles et al. 2000). Seasonal rainfall and a strong tidal influence can facilitate either downstream or upstream migrations of drifting or benthic phases. The lower Ruvu River is ≈ 7 m deep at high tide, well-mixed, with water temperature ranging from 25–29 °C in June 2013 (Saha et al. 2014) and May 2018. At the upstream Vikundu landing site (Figure 1), salinity ranged from 0–3 ppt, and at the downstream Mtailand site, from 3–15 ppt on an outgoing tide in May 2018. These conditions do not coincide with the season during which biological samples were collected (Nov–Jan), but are indicative of habitats available to *M. rosenbergii* in East Africa.

From a fisheries perspective, landings of *M. rosenbergii* can increase fishery yields where fish markets are easily accessible; for example, it is a short trip from Ruvu River landing sites to the Dar-es-Salaam fish market. The bulk of *M. rosenbergii* landed at sampled sites (see Figure 3) were larger than the size at maturation (105–137 mm TL in males and 81 mm in females; Nagamine and Knight 1980; Ra'Anan et al. 1991), suggesting that East African populations are lightly fished. The absence of juveniles < 110 mm TL in landings further suggests that they are not selected by seine nets (50–75 mm mesh), or that juveniles inhabit different habitats than larger conspecifics

(Raman 1967). Nevertheless, whether small-scale fisheries targeting *M. rosenbergii* in East African rivers will control or reduce established populations remains a key knowledge gap, with implications for biodiversity conservation as well as livelihood opportunities for fisher communities.

In conclusion, we demonstrate the presence of self-sustaining *M. rosenbergii* populations in at least two river systems in East Africa, based on morphological characters and DNA barcoding. The populations support small-scale fisheries using bottom-set seine nets. The potential impact of *M. rosenbergii* in East African river systems now needs to be appraised, including their present distribution range throughout the region, impacts on native biota, mode of invasion and spread into new systems, and mitigation measures to reduce further spread of the species. The practicality of existing small-scale fisheries, as a mitigation measure to control established *M. rosenbergii* populations in East Africa, should be investigated.

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## References

Anger K (2013) Neotropical *Macrobrachium* (Caridea: Palaemonidae): on the biology, origin, and radiation of freshwater-invading shrimp. *Journal of Crustacean Biology* 33: 151–83, https://doi.org/10.1163/1937240X-00002124

Bailey RG, Crichton M (1971) Freshwater prawns of the genus *Macrobrachium* (Crustacea: Palaemonidae) in East Africa, with a key for their identification and notes on their exploitation. *Journal of the East Africa Natural History Society and National Museum* 28(120): 1–8

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JR, Richardson DM (2011) A proposed unified framework for biological invasions. *Trends in Ecology and Evolution* 26: 333–339, https://doi.org/10.1016/j.tree.2011.03.023

Bosire J, Mangora MM, Bandeira S, Rajkaran A, Ratsimbazafy R, Appadoo C, Kairo JG (2016) Mangroves of the Western Indian Ocean: Status and Management. WIOMSA, Zanzibar Town, 161 pp

Bowles DE, Aziz K, Knight CL (2000) *Macrobrachium* (Decapoda: Caridea: Palaemonidae) in the contiguous United States: a review of the species and assessment of threats to their survival. *Journal of Crustacean Biology* 29: 158–171, https://doi.org/10.1163/20021975-99990025

Cavallo RO, Lavens P, Sorgeloos P (2001) Reproductive performance of *Macrobrachium rosenbergii* females in captivity. *Journal of the World Aquaculture Society* 32: 60–67, https://doi.org/10.1111/j.1749-7345.2001.tb00922.x

De Bruyn M, Wilson JA, Mather PB (2004) Huxley's line demarcates extensive genetic divergence between eastern and western forms of the giant freshwater prawn, *Macrobrachium rosenbergii*. *Molecular Phylogenetics and Evolution* 30: 251–257, https://doi.org/10.1016/S1055-7903(03)00176-3

De Grave S (2013a) *Macrobrachium lepidactylus*. The IUCN Red List of Threatened Species 2013: e.T198341A2521772. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T198341A2521772.en (accessed 02 November 2018)

De Grave S (2013b) *Macrobrachium lar*. The IUCN Red List of Threatened Species 2013: e.T197866A2503299. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T197866A2503299.en (accessed 02 November 2018)

De Grave S (2013c) *Macrobrachium idella*. The IUCN Red List of Threatened Species 2013: e.T197870A19013807. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T197870A19013807.en (accessed 02 November 2018)

De Grave S (2013d) *Macrobrachium niloticum*. The IUCN Red List of Threatened Species 2013: e.T198039A2509365. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T198039A2509365.en (accessed 02 November 2018)

De Grave S (2013e) *Macrobrachium moorei*. The IUCN Red List of Threatened Species 2013: e.T196882A2477768. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T196882A2477768.en (accessed 02 November 2018)

De Grave S (2013f) *Macrobrachium patsa*. The IUCN Red List of Threatened Species 2013: e.T198320A2520658. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T198320A2520658.en (accessed 02 November 2018)

De Grave S, Shy J, Wowor D, Page T (2013a) *Macrobrachium rosenbergii*. The IUCN Red List of Threatened Species. 2013: e.T197873A2503520. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T197873A2503520.en (accessed 02 November 2018)

De Grave S, Wowor D, Ayhong S (2013b) *Macrobrachium equidens*. The IUCN Red List of Threatened Species 2013: e.T198164A2514114. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T198164A2514114.en (accessed 02 November 2018)

De Grave S, Wowor D, Klotz W (2013c) *Macrobrachium rude*. The IUCN Red List of Threatened Species 2013: e.T197832A2501891. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T197832A2501891.en (accessed 02 November 2018)

De Grave S, Wowor D, Cai X (2013d) *Macrobrachium scabriculum*. The IUCN Red List of Threatened Species 2013: e.T197655A2494633. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T197655A2494633.en (accessed 02 November 2018)

De Man JG (1879) On some species of the genus *Palaemon* Fabr. with descriptions of two new forms. *Notes from the Leyden Museum* 41: 165–184

Dudgeon D, Smith RE (2006) Exotic species, fisheries and conservation of freshwater biodiversity in tropical Asia: the case of the Sepik River, Papua New Guinea. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16: 203–215, https://doi.org/10.1002/aqc.713

Duvail S, Hamerlynck O, Paron P, Hervé D, Nyingi WD, Leone M (2017) The changing hydro-ecological dynamics of rivers and deltas of the Western Indian Ocean: Anthropogenic and environmental drivers, local adaptation and policy response. *Comptes Rendus Geoscience* 349: 269–279, https://doi.org/10.1016/j.crte.2017.09.004

FAO-DIAS (2009) Database on Introductions of Aquatic Species (DIAS). http://www.fao.org/fishery/dias/en (accessed 2 November 2018)

Folmer O, Black M, Hoeh W, Lutz R, Vrijenhoek R (1994) DNA primers for amplification of mitochondrial cytochrome C oxidase subunit I from metazoan invertebrates. *Molecular Marine Biology and Biotechnology* 3: 294–299

Froese R (2006) Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. *Journal of Applied Ichthyology* 22: 241–253, https://doi.org/10.1111/j.1439-0426.2006.00805.x

Gherardi F, Aquiloni L, Diéguez-Uribeondo J, Tricarico E (2011) Managing invasive crayfish: is there a hope? *Aquatic Sciences* 73: 85–200, https://doi.org/10.1007/s00027-011-0181-z

Hall TA (1999) BioEdit: A user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT. *Nucleic Acids Symposium Series* 41: 95–98

Hanamura Y, Koizukmi N, Morioka S, Andriantsoa M, Rafalimanana T (2008) Occurrence of the non-indigenous freshwater prawn, *Macrobrachium rosenbergii* (De Man, 1879) (Decapoda, Caridea, Palaemonidae) in Madagascar. *Crustaceana* 81: 1143–1149, https://doi.org/10.1163/156854008X360860

Hobbs HH, Jass JP, Huner JV (1989) A review of global crayfish introductions with particular emphasis on two North American species (Decapoda, Cambaridae). *Crustaceana* 56: 299–316, https://doi.org/10.1163/156854089X00275

Holthuis LB (1980) FAO species catalogue. Shrimps and prawns of the world. An annotated catalogue of species of interest to fisheries. FAO Fisheries Synopsis 125(1): 271 pp

Holthuis LB (1995) Notes on Indo-West Pacific Crustacea Decapoda III to IX. *Zoologische Mededelingen* 69(13): 139–151

Iketani G, Pimentel L, Silva-Oliveira G, Maciel C, Valenti W, Schneider H, Sampaio I (2011) The history of the introduction of the giant river prawn, *Macrobrachium* cf. *rosenbergii* (Decapoda, Palaemonidae), in Brazil: new insights from molecular data. *Genetics and Molecular Biology* 34: 142–151, https://doi.org/10.1590/S1415-47572010005000115

Iketani G, Aviz MA, Maciel C, Valenti W, Schneider H, Sampaio I (2016) Successful invasion of the Amazon Coast by the giant river prawn, *Macrobrachium rosenbergii*: evidence of a reproductively viable population. *Aquatic Invasions* 11: 277–286, https://doi.org/10.3391/ai.2016.11.3.06

Kessing BH, Croom H, Martin A, McIntosh C, McMillan WO, Palumbi S (2004) The simple fool's guide to PCR. Version 1.0., Department of Zoology, University of Hawaii, Honolulu, 24 pp

Kimura M (1980) A simple method for estimating evolutionary rate of base substitutions through comparative studies of nucleotide sequences. *Journal of Molecular Evolution* 16: 111–120, https://doi.org/10.1007/BF01731581

Kumar S, Stecher G, Li M, Knyaz C, Tamaura K (2018) MEGA X: Molecular evolutionary genetics analysis across computing platforms. *Molecular Biology and Evolution* 35: 1547–1549, https://doi.org/10.1093/molbev/msy096

Lim P, Meunier FJ, Keith P, Noël, PY (2002) Atlas des poissons et des crustacés d'eau douce de la Martinique. Muséum National d'Histoire Naturelle, Paris, France, 124 pp

Lodge DM, Taylor CA, Holdich DM, Skurdal J (2000) Nonindigenous crayfishes threaten North American freshwater biodiversity: lessons from Europe. *Fisheries* 25: 7–20, https://doi.org/10.1577/1548-8446(2000)025<0007:NCTNAF>2.0.CO;2

Mangora MM, Lugendo BR, Mwamahija SS, Semesi, S (2016) Mangroves of Tanzania. In: Bosire J, Mangora MM, Bandeira S, Rajkaran A, Ratsimbazafy R, Appadoo C, Kairo JG (eds), Mangroves of the Western Indian Ocean: Status and Management. WIOMSA, Zanzibar Town, pp 33–49

Mather PB, De Bruyn M (2003) Genetic diversity in wild stocks of the giant freshwater prawn (*Macrobrachium rosenbergii*): implications for aquaculture and conservation. *NAGA, WorldFish Center Quarterly* 26(4): 4–7

Nagamine CM, Knight AW (1980) Development, maturation, and function of some sexually dimorphic structures of the Malaysian prawn, *Macrobrachium rosenbergii* (De Man) (Decapoda, Palaemonidae). *Crustaceana* 39: 141–152, https://doi.org/10.1163/156854080X00049

New MB (2002) Farming freshwater prawns: a manual for the culture of the giant river prawn (*Macrobrachium rosenbergii*). FAO Fisheries Technical Paper 428, Rome, FAO, 212 pp

New MB, Valenti WC, Tidwell JH, D'Abramo LR, Kutty MN (2009) Freshwater prawns: biology and farming. John Wiley & Sons, 560 pp, https://doi.org/10.1002/9781444314649

Pereira G, Egáñez H, Monente JA (1996) First record of a reproductive wild population of *Macrobrachium rosenbergii* (De Mam) (Crustacea, Decapoda, Palaemonidae) in Venezuela. *Acta Biologica Venezuelica* 16: 93–95

Ra'Anan Z, Sagi A, Wax Y, Karplus I, Hulata G, Kuris A (1991) Growth, size rank, and maturation of the freshwater prawn, *Macrobrachium rosenbergii*: analysis of marked prawns in an experimental population. *The Biological Bulletin* 181: 379–386, https://doi.org/10.2307/1542358

Raman K (1967) Observations on the fishery and biology of the giant fresh water prawn *Macrobrachium rosenbergii* de Man. In: Proceedings of the Symposium on Crustacea, Part 2, MBAI, 12–16 January 1965, Ernakulam, 649–669

Saha AK, Gastrich K, Kimaro M, Kiszka J, Anderson EP (2014) A rapid ecohydrological assessment of the Ruvu river estuary, Tanzania. Global Water for Sustainability program (GLOWS). Miami, FL, USA, 72 pp

Saitou N, Nei M (1987) The neighbor-joining method: A new method for reconstructing phylogenetic trees. *Molecular Biology and Evolution* 4: 406–425

Shagude YW (2016) Estuarine environmental and socio-economic impacts associated with upland agricultural irrigation and hydropower developments: the case of Rufiji and Pangani estuaries, Tanzania. In: Diop S, Scheren P, Machiwa J (eds), Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean, Springer, Switzerland, pp 169–182, https://doi.org/10.1007/978-3-319-25370-1_11

Silva-Oliveira GC, Ready JS, Iketani G, Bastos S, Gomes G, Sampaio I, Maciel C (2011) The invasive status of *Macrobrachium rosenbergii* (De Man, 1879) in Northern Brazil, with an estimation of areas at risk globally. *Aquatic Invasions* 6: 319–328, https://doi.org/10.3391/ai.2011.6.3.08

Sunier ALJ (1925) Twee mededeelingen over Palaemoniden. *Tijdschrift der Nederlandsche Dierkundige Vereeniging* (2)19: 115–117

Wagner GM, Sallema-Mtui R (2016) The Rufiji Estuary: climate change, anthropogenic pressures, vulnerability assessment and adaptive management strategies. In: Diop S, Scheren P, Machiwa J (eds), Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean, Springer, Switzerland, pp 183–207, https://doi.org/10.1007/978-3-319-25370-1_12

Woodley CM, Slack WT, Peterson MS, Vervaeke WC (2002) Occurrence of the non-indigenous giant Malaysian prawn, *Macrobrachium rosenbergii* (De Man, 1879) in Simmons Bayou, Mississippi, USA. *Crustaceana* 75: 1025–1031, https://doi.org/10.1163/156855400260569652

Wowor D, Ng PK (2007) The giant freshwater prawns of the *Macrobrachium rosenbergii* species group (Crustacea: Decapoda: Caridea: Palaemonidae). *The Raffles Bulletin of Zoology* 55(2): 321–336

Wowor D, Muthu V, Meier R, Balke M, Cai Y, Ng PK (2009) Evolution of life history traits in Asian freshwater prawns of the genus *Macrobrachium* (Crustacea: Decapoda: Palaemonidae) based on multilocus molecular phylogenetic analysis. *Molecular Phylogenetics and Evolution* 52: 340–350, https://doi.org/10.1016/j.ympev.2009.01.002