A record of Notostraca on Socotra Island and the importance of local conservation of the habitat

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Abstract

The first record of Triops Schrank, 1803 (Crustacea: Branchiopoda: Notostraca: Triopsidae) from Socotra Island is presented herein. Besides Madagascar and the current note, the genus is unknown from Indian Ocean islands. A brief morphological exploration indicates that the Socotran Triops cf. granarius (Lucas, 1864) (trachyaspis form) belongs to an African clade within this widespread Old World species complex and not to T. granarius s.str. from East Asia. Detailed morphological and molecular revision of the poorly studied Middle Eastern and Northern African populations in comparison to East Asian populations are needed to understand this group and the phylogenetic position and status of the Socotran tadpole shrimp. Found in a single locality (the archeological site Eriosh) in the rapidly changing coastal plains on Socotra, together with other large branchiopods (endemic Anostraca and unidentified Spinicaudata), the insular Triops population and the regionally neglected temporary lake habitat deserve a special protection status from a biodiversity conservation perspective. Triops cf. granarius is hereby suggested as a local flagship species for the conservation of temporary pool habitats on the island.

Key words: Triops granarius, Notostraca, Socotra Island, conservation, temporary pool, morphology

Introduction

The extant Notostraca or tadpole shrimp are a fascinating group of freshwater branchiopod crustaceans with an ancient appearance, often named ‘living fossils’ (Longhurst 1955a, Dumont & Negrea 2002, Vanschoenwinkel et al. 2012, Wagner et al. 2017). Triops Schrank, 1803 is found on all continents except Antarctica, occurring mainly in shallow ephemeral freshwater pools where they function as omnivorous grazers, scavengers and predators (Longhurst 1955a–b, Walton et al. 1991, Dumont & Negrea 2002, Boix et al. 2006, Korn et al. 2013). These large branchiopods have economic importance (Brendonck et al. 2008). Tadpole shrimps have been suggested as potential biological control agent of mosquitoes in temporary waters and a control of weeds in paddy fields, and are being explored for their potential in aquaculture (Maffi 1962a–b, Tietze & Mulla 1991, Fry et al. 1994, Takahashi 1994, Su & Mulla 2002, Obregón-Barboza et al. 2001, Brendonck et al. 2008). As an example of their biological control potential, experiments with Triops in intermittently flooded date palm gardens in California have shown reductions of mosquitoes by 73–99% (Su & Mulla 2002). Because of their rapid hatching strategies in nature, instantly emerging from desiccated dormant egg banks after rains, these crustaceans are popular in the pet industry for their easy rearing and handling as short-lived, visually attractive aquarium pets. In rice fields Triops may pose a threat to crops as the animals may uproot young seedlings (Tindall et al. 2009).

Triops is represented by four main morphological lineages concealing a large diversity as illustrated by the complicated nomenclature and by molecular analysis (Longhurst 1955a, Korn et al. 2006, Brendonck et al. 2008, Vanschoenwinkel et al. 2012). Africa and Eurasia harbour members of the widespread Triops granarius (Lucas, 1864) and T. cancridiformis (Bosc, 1801) complexes (Hamer & Rayner 1995, Thiéry 1996, Hassan 2015, Korn & Hundsdorfer 2016) on the mainland as well and the unrevised T. australiensis sakalavus (Nobili, 1905) reported in Madagascar (Longhurst 1955a). These records and the complicated nomenclature are in dire need of revision. Records of Triops from the Arabian Peninsula are relatively few considering the widespread occurrence of shallow short-lived rain pools in the arid region. However, the presence of the genus in the area has long been known
from sediment samples and reported there so far: the endemic Cheung & DeVantier 2006). Socotra is the main island in the Archipelago and two large branchiopods have been Precambrian continental microplate that separated from Oman in Oligocene-Miocene times (brief overview in UNESCO Natural World Heritage Site (Cheung & DeVantier 2006, Van Damme 2009, 2012). The islands sit on a of Africa (Fig. 1A) is well praised for its high biodiversity and endemism which has led to its recognition as a unreported from Indian Ocean islands. Socotra Island, the largest in the Socotra Archipelago and just off the Horn and local conservation of the locality, are briefly presented herein. Besides Madagascar and this record, the genus is increasingly indicate how complicated these species assemblages are. Genetic diversity has been explored to some extent in African populations of the T. granarius complex where several populations from Morocco have been assigned to new species (Korn & Hundsdoerfer 2006, 2016). However, considering the many synonyms for T. granarius in the region (Longhurst 1955a) new assignments should be carefully examined in order not to create new taxa for which a name might be available.

A record of Triops from Socotra Island (Yemen), first observations on its morphology (not a full description) and local conservation of the locality, are briefly presented herein. Besides Madagascar and this record, the genus is unreported from Indian Ocean islands. Socotra Island, the largest in the Socotra Archipelago and just off the Horn of Africa (Fig. 1A) is well praised for its high biodiversity and endemism which has led to its recognition as a UNESCO Natural World Heritage Site (Cheung & DeVantier 2006, Van Damme 2009, 2012). The islands sit on a Precambrian continental microplate that separated from Oman in Oligocene-Miocene times (brief overview in Cheung & DeVantier 2006). Socotra is the main island in the Archipelago and two large branchiopods have been reported there so far: the endemic Branchipodopsis relictus Van Damme, Weekers & Dumont, 2004 resurrected from sediment samples and Streptocephalus sp. of which only the eggs have been found (Van Damme et al. 2004). Based on molecular data, B. relictus was suggested to have closer affinities to Asian rather than to African relatives (Van Damme et al. 2004). Socotra has Afrotropical, Oriental and Palearctic elements in the terrestrial biota, therefore the origins of new findings should be searched for in all directions.

Notostraca were found by the author in the northern coastal plain of Socotra Island (Fig. 1B), at the unique archaeological site Eriosh. Notostraca in Eriosh were first observed alive as part of a survey during a Socotra Karst Project expedition (January 2003) and were briefly mentioned in an unpublished report to EPA Socotra (Van Damme et al. 2004). Sediment was later collected (January 2014) from the same locality for incubation and identification. The rock-art site is the largest of its kind on the island (1 ha) and contains enigmatic petroglyphs of unknown origin carved in limestone, including animal depictions (Doe 1970, 1992). There are few archeological sites of this type on the island and none as impressive as Eriosh (Jansen van Rensburg 2016). Before road construction (Van Damme et al. 2004, Van Damme & De Geest 2006), the limestone outcrops were made up of three slightly concave oval areas of about 90m diameter each (Doe 1970, 1992, Naumkin & Sedov 1993). The area is flooded after rains during the monsoons and transforms into a series of interconnected large shallow freshwater pools, or a fragmented shallow temporary lake. As the archaeologist Doe (1970) observed: “After heavy rain during April the whole surface was covered with a thin layer of mud which had to be scraped. Part of the site was under about 6 inch (sic) of water and camels and goats were being watered here, possibly showing the use of the place by the goatherds in ancient times when the graffiti were made.” Nearly no vegetation grows in this area in contrast to most of the coastal plain which is dominated by Croton socotranus shrubland. As a result of the flooding and the thin sediment cover that remains after drying, the rock art is temporarily protected from erosion. The absence of vegetation in Eriosh prevents destruction by plant roots. For details on the climate in Socotra, see Scholte & De Geest (2010).

The animals for this study were retrieved by collecting and hatching dry sediment containing dormant eggs by using the Sars’ Method (Van Damme & Dumont 2010) as part of ongoing Socotra freshwater biodiversity and conservation studies by the author. The Socotran notostracan is hereby assigned to Triops cf. granarius until further revision (including morphological and molecular analysis).
A RECORD OF NOTOSTRACA ON SOCOTRA ISLAND

Results

Taxonomic Account

Class Branchiopoda Latreille, 1817

Order Notostraca Sars, 1867

Family Triopsidae Keilhack, 1909

Genus *Triops* Schrank, 1803

*Triops cf. granarius* (Lucas, 1864) from Socotra (Figs 2–5)

Material examined. Three specimens were examined for this study, two adult females and one adult male, reared from incubated sediment that was collected 28.I.2014 at Eriosh (alt. 20m, coordinates N12° 35.497' E53°49.048' or N12.5916167° E53.817467°), Socotra Island (Yemen) by KVD (pers. coll.).

Characters of the *T. granarius* species group. The absence of a supra-anal plate, visible with the naked eye (Fig. 2B), places these notostracans in *Triops*. Morphological characters that are considered diagnostic for the *T. granarius* species complex in the classical sense (*sensu* Longhurst 1955a) are present in the Socotran specimens. These features include: *i*) dorsal (nuchal) organ triangular, its anterior margin reaching between the compound eyes, not situated posterior to the eyes (Figs 2B & 5A–B); *ii*) carina with none (or one undeveloped) spine anterior to the terminal spine (Figs 3C–D & 4D–E); *iii*) supernumerary spines present on the ventral face of the apodous
segments (Fig. 3E); iv) telson dorsal margin armature with various median spines in an irregular row, which are not large (Figs 5G–H); telson armature variation in the *T. granarius* species complex is shown in Hamer & Rayner (1995) and Longhurst (1955a); v) number of apodous segments (two females): 11–13, male 13; vi) second maxilla present (Fig. 5D). Females were distinguished from the male, using the mystax and the P11 (modified in females).

Morphological notes on the Socotran population. Length (without furca): 29.1 mm (male), 23 and 27.2 mm (females); Number of body segments (not including telson): 43 of which 13 apodous (male); 41 (11 apodous) and 43 (13 apodous) in the two female specimens. Colour brown to greenish (Figs 2B & 3).

Carapace (lateral view in figs 3A–B & 4A–C; dorsal view in figs 2B & 5A–B) length/width (length from anterior margin to posterior apices of carapace sulcus): 19/15 mm (male), 17.5/13 mm and 19/15.1 mm (females). In dorsal view, the carapace is wider in posterior part in the male than in females, more tapering in the females and giving the male a more round appearance (Figs 5A–B; however only three specimens to compare). In lateral view, the carapace length is about 3–3.5 x height (at highest point) (Figs 3A–B & 4A–C). Female carapace posterior surface covered in minute spines (Figs 3B, 4B–C & 5A), males with only a few scattered spines (Figs 3A, 4A & 5B). Short spines on the carapace carina suggests the *trachyaspis*-form, a known morphological variation in *T. granarius* (Longhurst 1955a) and apparently it is variable here in one population hatched from sediment. The single male studied here lacked this feature, except for a few scattered spines on the posterior surface (Fig. 5B), whereas the two females showed a carapace covered in spines (Figs 2B, 3B, 4B–C, 5A&C). These spines have a chitinized tip (Fig. 5C). Carapace sulcus (Figs 2B & 5A–B) spines ca. 40–50 (females), 40 (male). Sulcus in male about as deep as wide (4 mm), in females about two times as deep as wide (2–3 mm wide, 4–5 mm deep) (Figs 4A–C). Carina on carapace well developed, terminal spines with one small or no anterior teeth, further no carinal spines (Figs 3C–D & 4D–E). Male carina more robust with the posterior end directed ventrally, whereas in females it remains straight (Figs 3D versus 3C & 4B–C versus 4A). In general, the entire dorsum is slightly convex (Figs 3A–B & 4A–C).

Eyes (dorsal view Figs 2B & 5A–B, lateral view Figs 3A–B & 4A–C) well developed, strongly protruding in lateral view; eye field with strong constriction in middle (Figs 5A–B). Dorsal organ triangular with rounded corners, its anterior margin reaching just beyond the posterior margins of the eyes (Fig. 5A–B).

Labrum (Fig. 3F) rectangular.

Second maxilla (Fig. 5D) well developed and round, longest setae on the margin less than the diameter of the structure. Row of spiniform setae on the margin continuous, joined by anterior slender setae in the second half of the structure.

**FIGURE 2.** A, shallow temporary rockpool after rains on the limestone outcrops at the Eriosh archaeological site, Socotra Island (Yemen); no vegetation grows on the site, which is covered in a fine layer of sediment after rains; Photo KVD, January 2003. B, *Triops* cf. *granarius* from Socotra, adult female; scale bar denotes 1 cm.

Thoracopods (only some parts studied) P2 endopodite (Fig. 5E) elongate, about 3.5 times as long as wide and tapering distally and well developed distal claw, straight and about twice the length of the adjacent anterior spine; posterior margin of endopodite implanted with spines just over half of its length, these spines are not equal in size.
(irregular, some are a third to half shorter). P6 endopodite (Fig. 5F) elongate and tapering, about 3x as long as wide and with a pointed apex; distal claw large, curved inwards, and with strongly chitinized tip, twice the length of adjacent spine; spines implanted to about half the posterior margin, four to five distalmost spines, close to distal claw, largest.

Apodous segments with supernumerary spines present on ventral side, clear in the male, about 8–13 per segment (Fig. 3E); in females there are fewer supernumerary spines seen per segment (4–8).

Telson armature (Figs 5G–I) median spines eight and small, forming an irregular row; anterior lateral spines in groups of two to four; posterior marginals relatively small, about 2.5–3 times as long as wide (Figs 5H–I) and implanted with small hairs; additional secondary posterior marginal present (Fig. 5I). Lateral margins of telson implanted with conical spines, and two posterior furcal spines, about as long as wide (Fig. 5H).

**Remarks.** At this point, it is best to assign the Socotran populations to *Triops granarius sensu lato*, in the clear understanding that this is a species group which needs revision and that the animals are not *T. granarius sensu stricto*. The use of the name rather than assigning these animals to one of many available synonyms described from the adjacent land or to a new name is temporary until a more detailed investigation. It is possible that this is a new
species. In particular, molecular analysis and examination of more specimens will help to explore the relationship of the Socotran animals. The type locality of *T. granarius* s. str. is Beijing (China), the East Asian populations likely forming a separate clade (Korn & Hundsdorfer 2006, 2016), therefore there is a high chance that the Socotran populations may be assigned to another name in the future. However the assignment is beyond the scope of this record and would best include other Arabian and African *T. granarius*-like populations in comparison.

**FIGURE 4.** *Triops* cf. *granarius* from Socotra Island (Yemen). A–C, carapace, lateral view in adult male (A) and females (B–C); females have small spines on the surface (*trachyaspis* form). D–E, carina in adult male (D) and female (E). Scale bars denote 5 mm (A–C) and 1 mm (D–E).
From the few limb features examined here, it seems that the Socotran specimens have a closer affinity to the African, not to the Asian clade. The endopodites of the limbs in the Asian populations are suggested to have a more rounded appearance (Longhurst 1955a), and the African more elongate and acute (Korn & Hundsdoerfer 2016). In the specimens from Socotra, this structure is clearly elongate and sharp (Figs 5E & F). However this character has not been illustrated in literature for the Asian populations and has not been part of any larger formal systematic revisions so far.

A brief examination of the endopodite shape in “true” Asian *T. granarius* based on photos of trunk limbs (P3–8) kindly provided by Dr M. Korn (unpubl. data), shows that this is a highly recognisable feature, unmistakably different from the elongate sharp endopodites in the Socotran animals. Furthermore it is clear that the Socotran animals are distinctly different from the Moroccan species that were split by Korn & Hundsdoerfer (2016) from the *T. granarius* group, in the setulation of the second maxilla (much shorter in Socotran populations), the endopodite spines (more irregular in the Moroccan species) and the telson armature (secondary posterior marginal spines present in Socotran animals). Unfortunately other members of the *T. granarius* group have not been described or redescribed adequately and the morphological notes on the populations from the Arabian mainland shown in Thiéry (1996) do not provide enough details for comparison. The only feature Thiéry (1996) mentions are the number of apodous body segments in the Omani female *T. granarius* specimens as being less (8–9) than the Saudi populations (9–12). On Socotra the females have more (11–13) apodous body segments but this feature is variable and only two female specimens were examined so far.

**Local ecology.** *Triops* is found with two other large branchiopods that hatched from the sediment, the endemic anostracan *Branchipodopsis relictus* and a yet unidentified spinicaudatan. Among the small branchiopods, the endemic *Moina diksami* Van Damme & Dumont, 2008 and an unidentified *Daphnia* (*Ctenodaphnia*) sp. were observed (ephippia). No details on the ecological characteristics of the site were collected, except that a series of connected large shallow temporary pools or a very shallow temporary lake forms after rains on the limestone. Dry sediment was stored in the dark at room temperature for two years and *Triops* hatched quickly under constant light conditions, appearing 24–48 hrs after wetting the sediment with bottled spring water at constant room temperature. *Branchipodopsis* hatched simultaneously and raced *Triops* to adulthood; notostracans reached maturity after about two weeks, the anostracans after four to six days.

**Distribution/Biogeography.** **Local.** So far only one locality on Socotra Island is known to harbour *Triops*. Considering that Eriosh has been used traditionally as a watering place for camels and goats during rainy seasons (Doe, 1970) and taking the strong winds on Socotra into account (Cheung & DeVantier 2006, Scholte & De Geest 2010), it is likely that *Triops* may be found elsewhere on the island. Suitable habitats would be available where larger temporary pools are formed.

**Global.** *T. granarius* s. str. was originally described from Beijing, China. The species group has the largest geographical and morphological range among the four major lineages in the genus (Longhurst 1955a, Korn & Hundsdoerfer 2006, 2016). Considering the growing evidence for high diversity in this species group, the Socotran animals may well belong to a different species. The complex is widespread in the Old World and the animals are found in suitable habitats from Japan to South Africa (Longhurst 1955a), Mediterranean (Lanfranco et al. 1991; Marrone et al. 2006, Tzirotzis et al. 2014), Caribbean and the Galápagos (Linder 1960) and Madagascar (Longhurst 1955a). The high dispersal capacity of the dormant eggs allows *Triops* to occupy temporary pools in remote islands such as Hawai‘i and New Caledonia (Longhurst 1955a–b). The Socotran population is the first evidence of *T. granarius* (and only the second of *Triops*) from islands in the Indian Ocean.

**Importance of conservation of the *Triops* locality.** There is no formal protection in place in Socotra for freshwater ecosystems. The locality falls in a rapidly conserved coastal area and in a zone with moderate protection as designed in the original Socotra Conservation Zoning Plan (Resource Use Reserve; EPC/UNDP GEF, 2000). Eriosh is not part of the Socotra National Park, yet just adjacent (<1km; Fig. 1C) to it, and therefore falls on the border of UNESCO terrestrial core and buffer properties. The site is located next to the junction of two major roads (also <1km) on the island and has been damaged by the construction of the Diksam road, which cuts through the centre of the area, destroying a considerable part of it (Van Damme et al. 2004, Van Damme & De Geest 2006). However, the Socotra Resource Use Reserve legally aims to “protect and maintain the unique biological diversity of Socotra islands, as well as other natural, cultural and landscape values of the area in the long term” and in general, the Zoning Plan aims to “protect the genetic material of rare and endemic species in Socotra islands”
(Articles 2.5 and 4a in the Zoning Plan; EPC/UNDP GEF 2000). It is therefore important here to briefly highlight natural values and the existence of rare populations (or species) such as an insular Triops in the western Indian Ocean, for conservation purposes and to mention the importance of a neglected habitat such as temporary pools.

**FIGURE 5.** *Triops cf. granarius* from Socotra Island (Yemen). A–B, carapace in dorsal view of adult female (A) and male (B); female with small spines on the carapace (*trachyaspis* form). C, left posterior corner of carapace in female, dorsal view with spines on the surface. D, second maxilla, female. E, endopodite P2 female, setae on anterior face not shown. F, endopodite P6 female and adjacent endite, setae on anterior face not shown. G–I, telson female (G), details (H) and armature on terminal spines (I). Scale bars denote 10mm (A–B) and 1mm (C–I).
From a biological diversity perspective, as this is the only place on the island know so far where three large branchiopods are found together and the only locality known in an Indian Ocean island besides Madagascar that contains \textit{Triops}, this locality can be considered as important. Furthermore, considering the large cryptic diversity in the \textit{T. granarius} species group, there is a possibility that the Socotran \textit{Triops} may belong to a new species. The anostracan \textit{Branchipodopsis} in this locality is an endemic, so is the cladoceran \textit{Moina} Baird, 1850, while other interesting taxa (Spinicaudata and \textit{Daphnia}) are yet unidentified. The habitat should be locally protected, if only for the branchiopods.

For additional protection beyond the existing Socotra Conservation Zoning Plan, Eriosh could be designated as a Site of Special Scientific Interest (SSSI) or its local equivalent in future conservation management plans on Socotra, to avoid the risk of losing its value for biodiversity. Immediate threats to this locality include the direct destruction through infrastructure development, which is expanding in Socotra along the coastal roads, and pollution (Van Damme & Banfield 2011). Without formal protection there is a high probability that this locality, like much of the northern coastal plain, may be affected in the coming decades, as much of the coastal areas on Socotra are being bought up by foreign investors for development regardless of the biodiversity value of this UNESCO World Heritage site. The typical habitats of \textit{Triops}, ephemeral pools, are rarely incorporated into conservation measures in tropical or subtropical regions in general. However, they play an important role as model systems in conservation biology (Wiggins \textit{et al.} 1980, De Meester \textit{et al.} 2005) and the habitat is increasingly making way to land development globally (Cérégéhino \textit{et al.} 2008, Williams \textit{et al.} 2001). In Europe the conservation of this neglected habitat and in particular of \textit{Triops} populations, is taken seriously as these large branchiopods have become endangered and have gone locally extinct in most countries (Eder & Hödl 2002, Brendonck \textit{et al.} 2008, Goldyn \textit{et al.} 2012). In the UK for example, \textit{Triops cancriformis} is classified as Endangered under the Wildlife and Countryside Act and the only two localities where it is still found, are under legal protection (Hughes 1997, Feber \textit{et al.} 2011, Sellers \textit{et al.} 2017). There is even a \textit{Triops} Conservation Group in the UK which also coordinates ex-situ breeding of the population (Hughes 1997).

The conservation of this particular locality which harbours \textit{Triops} in Socotra may not only be important from the perspective of biodiversity, evolution and biogeography, but perhaps from a cultural perspective as well. These animals may actually contribute to protecting the unique petroglyphs on the island. Because of their active foraging and burrowing habits and the large numbers in which they occur, tadpole shrimps are able to modify the aquatic environment they live in through bioturbation as they stir up sediments (as ecosystem engineers; Croel & Kneitel 2011). Archaeologists suggest that the main reason for which the surface rock art has not been destroyed naturally throughout the centuries is because of the fine sediment that is distributed over the area each monsoon, effectively forming a small protective layer on the soft limestone against erosion (and looters) as well as the absence of shrubs on the site (J. Jansen van Rensburg \textit{pers. comm.}). It is possible that \textit{Triops}, as an active aquatic ecosystem engineer, plays a role in redistributing fine sediment over the inundated rock face after rains and actively uproots seedlings, and may have done so for a very long time. Future development plans for the site should take into account that the dry sediment contains the valuable branchiopod egg bank and should aim to preserve the temporary pools which have an added cultural value as a watering place for herders. Protecting the natural value of the site by conservation of the habitat of the large branchiopods would in this case also protect the cultural values and vice versa. \textit{Triops} as an ancient guardian of an archaeological treasure.

Future conservation efforts on Socotra may take an innovative role in Arabia by incorporating examples of the invertebrate freshwater faunas and their ecosystems into future management plans, in particular by including widely ignored habitats such as temporary pools which harbour a unique biodiversity. The potential of \textit{Triops} in the biological control of mosquito larvae, as well as the potential role in local environmental education, may help in awareness and in establishing a locally positive image for these fascinating large branchiopods. Large branchiopods may be locally promoted on Socotra as flagship species in conservation, to help protect their ephemeral habitats. Why not?

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