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Rapid Communication

Desalination effluents and the establishment of the non-indigenous skeleton shrimp *Paracaprella pusilla* Mayer, 1890 in the south-eastern Mediterranean

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Abstract

A decade long monitoring programme has revealed a flourishing population of the non-indigenous skeleton shrimp *Paracaprella pusilla* in the vicinity of outfalls of desalination plants off the Mediterranean coast of Israel. The first specimens were collected in 2010, thus predating all previously published records of this species in the Mediterranean Sea. A decade-long disturbance regime related to the construction and operation of the plants may have had a critical role in driving the population growth.

Key words: Amphipoda, Caprellidae, brine-effluent plume, chronic disturbance regime, environmental monitoring

Introduction

The caprellid amphipod *Paracaprella pusilla* Mayer, 1890 was described from specimens attached to ascidians collected in Rio de Janeiro, Brazil (Mayer 1890). It is believed to originate in the tropical western Atlantic, but has been widely reported from both tropical and subtropical waters, mainly associated with man-made infrastructure (see Ros and Guerra-García 2012; Fofonoff et al. 2018; and references within). Recently, the species has been reported from the south-western Iberian peninsula, and in several locations in the Mediterranean Sea (Balearic Islands, Tunisia, Israel) (Ros and Guerra-García 2012; Ros et al. 2013, 2016; Fersi et al. 2018). The Israeli specimens, collected in 2014, were associated with drifting colonies of the bryozoan *Bugula neritina* (Linnaeus, 1758) and with bryozoan colonies growing on a shallow (2–4 m depth) sandstone ridge. No *P. pusilla* specimens were found in fouling communities, comprising *B. neritina* among other fouling bryozoans and hydroids, associated with the Ashkelon and Ashdod marinas nearby (Ros et al. 2016).

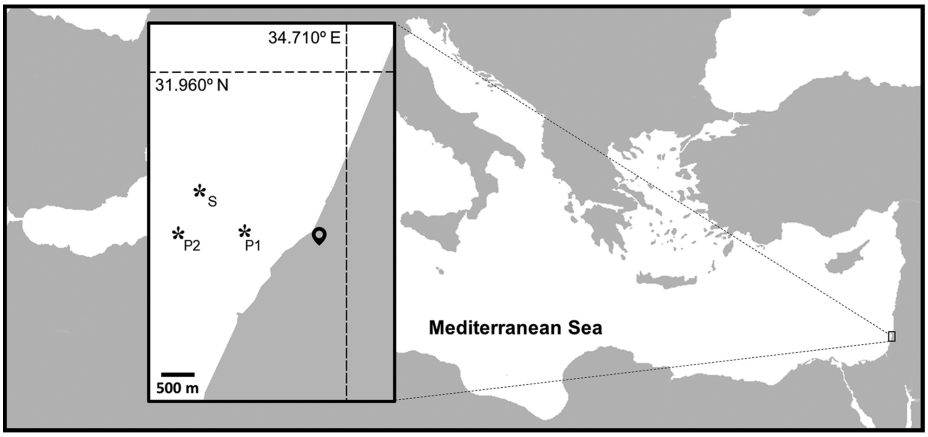

Figure 1. Location of brine and effluent outfalls of the Palmachim and Soreq desalination plants off the Israeli Mediterranean coast. P1, Palmachim outfall 10 m depth; P2, Palmachim oufall 20 m depth, and S, Soreq outfall 20 m depth.

The soft bottom biota, along the shallow Israeli shelf, has been studied as part of the National Marine Environmental Monitoring Program since 2005 (Guarnieri et al. 2017), and through baseline surveys and long term monitoring of polluting sites since 1992 (e.g., Kress et al. 2016a). The value of amphipods as indicators of environmental change is poorly acknowledged (Lo Brutto et al. 2013). Between 1994 and 1999, however, 54,275 amphipod specimens, identified to 53 species were collected, of which 5 were considered to have entered the Mediterranean sea through the Suez Canal – *Cymadusa filosa* Savigny, 1816, *Elasmopus pectinicrus* (Spence-Bate, 1862), *Gammaropsis togoensis* (Schellenberg, 1925), *Hamimaera hamigera* (Haswell, 1879), *Photis lamellifera* Schellenberg, 1928 (Sorbe et al. 2002). In addition, a further non-indigenous species, *Grandidierella bonnieroides* Stephensen, 1948, has been described from subsequent monitoring (Lo Brutto et al. 2016).

The present record, collected on coarse sandy bottoms in the vicinity of outfalls of desalination plants, predates all previously published records of *P. pusilla* from the Mediterranean Sea (Ros et al. 2016, and references within), and confirms the existence of a well-established population along the Israeli coast. Our analysis provides quantitative information on the temporal pattern of expansion of the species along a stretch of coast exposed to salinity, temperature and sedimentological changes for over a decade.

Materials and methods

Study area

Five desalination plants along the Israeli coastline, at the south-eastern corner of the Mediterranean Sea, produce 587 Mm^3 y^{-1} drinking water. The Israel Water Authority plans to increase production to 1,100 Mm^3 y^{-1} by 2030 (http://www.water.gov.il/Hebrew/Planning-and-Development/Desalination/Pages/tama34.aspx). The Palmachim and Soreq seawater reverse osmosis (SWRO) desalination plants are located at the central Mediterranean coast of Israel (Figure 1). The capacity of the Palmachim SWRO plant (initial capacity 30 Mm^3 y^{-1}, outfall at 10 m depth, operational in 2007), was tripled in 2014 (capacity 90 Mm^3 y^{-1}, marine outfall moved at 20 m depth, operational in April 2014). The Soreq plant began operation in 2013 (capacity 150 Mm^3 y^{-1}, outfall at 20 m depth) (Supplementary material Table S1). The distance between the two outfalls is about 850 m. Environmental parameters (salinity, temperature and granulometry) are presented (Appendix 1).

Sampling

A baseline survey for the Palmachim desalination plant was conducted in 2004, centering on the intake and outfall sites (Kress et al. 2005). Monitoring surveys began in September 2008, one year after the plant began operation (Kress et al. 2009), and were conducted twice annually, in May–June and September–October (Kress et al. 2010, 2011, 2012, 2013). A baseline survey for the Soreq plant was conducted in 2008–2009 (Shoham-Fridar et al. 2009) and completed in 2012 (Kress et al. 2013). The integrated Palmachim-Soreq deeper outfalls monitoring plan was conducted twice annually since November 2014 (Kress et al. 2014, 2015, 2016b, 2017, 2018). The plants did not operate at full installed capacity during the years that were monitored. The number and location of monitoring sites has also been modified over the years due changes in brine volumes, outfall locations, construction, and data from monitoring surveys (Table S2).

Samples were collected in spring (May–June) and fall (September–October) using the research vessels "Etziona" (2004, 2008–2016) and "Mediterranean Explorer" (2017). At each site three replicate sediment samples were collected with a 32 × 35 cm Van-Veen grab (KAHLSICO, model WA265/SS214, 20 L). Samples were preserved in 70% ethanol and within days sieved on a 250 µm mesh. Near bottom salinity and temperature were measured using a CTD (*SBE* 16plus *V2* SeaCAT, Sea-Bird Electronics). Samples for grain size analysis were frozen and grain size distribution was determined using sieved lyophilized sediment.

Results

Occurrence

A total of 2390 specimens of *Paracaprella pusilla* were collected from 38 of the 119 sites sampled under the Palmachim-Soreq outfalls monitoring plan 2010–2017 (Table S2). All the specimens were collected in spring (May–June), none collected during fall (September–October). In May 2010, two specimens of *P. pusilla* were collected in VM2 and VM3 sites, an ovigerous female and an immature female, respectively. The species was next recorded in 2014, when 248 specimens were collected. Successively, 282, 1669, 189 specimens were collected in 2015, 2016, and 2017, respectively (Figure 2).

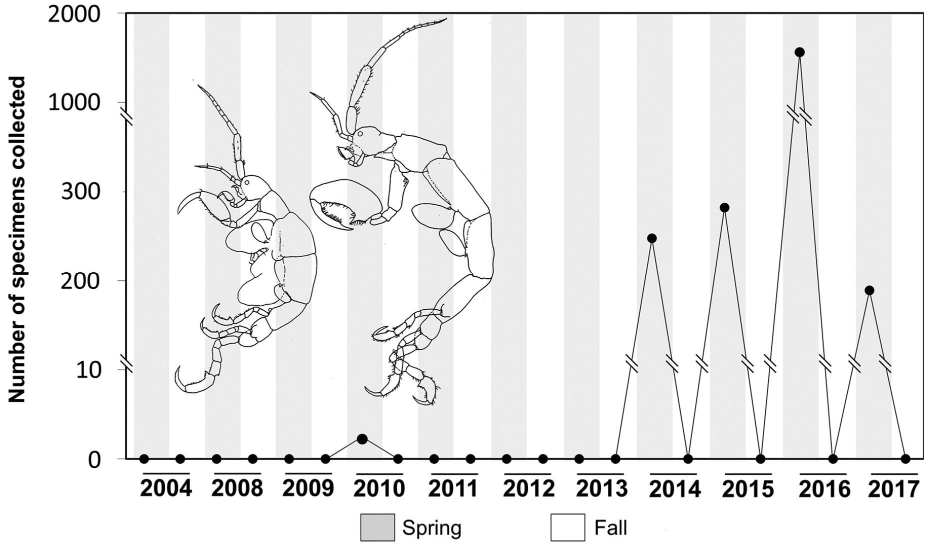

Figure 2. Total abundance of *Paracaprella pusilla* Mayer, 1890, Palmachim and Soreq brine disposal sites, Israel.

Figure 3. *Paracaprella pusilla* Mayer, 1890; male collected in 2016. Scale bar = 1 mm. Photograph by Davide Iaciofano.

The specimens display the species' distinguishing characters: (i) large anterolateral projection of pereonite 2, (ii) small dorsal tubercle on pereonite 2, (iii) proximal knob on the basis of gnathopod 2, (iv) lateral pleura in pereonites 3 and 4, especially developed in pereonite 3 (see Mayer 1903; Ros et al. 2013) (Figure 3). *Paracaprella pusilla* aggregated next to the

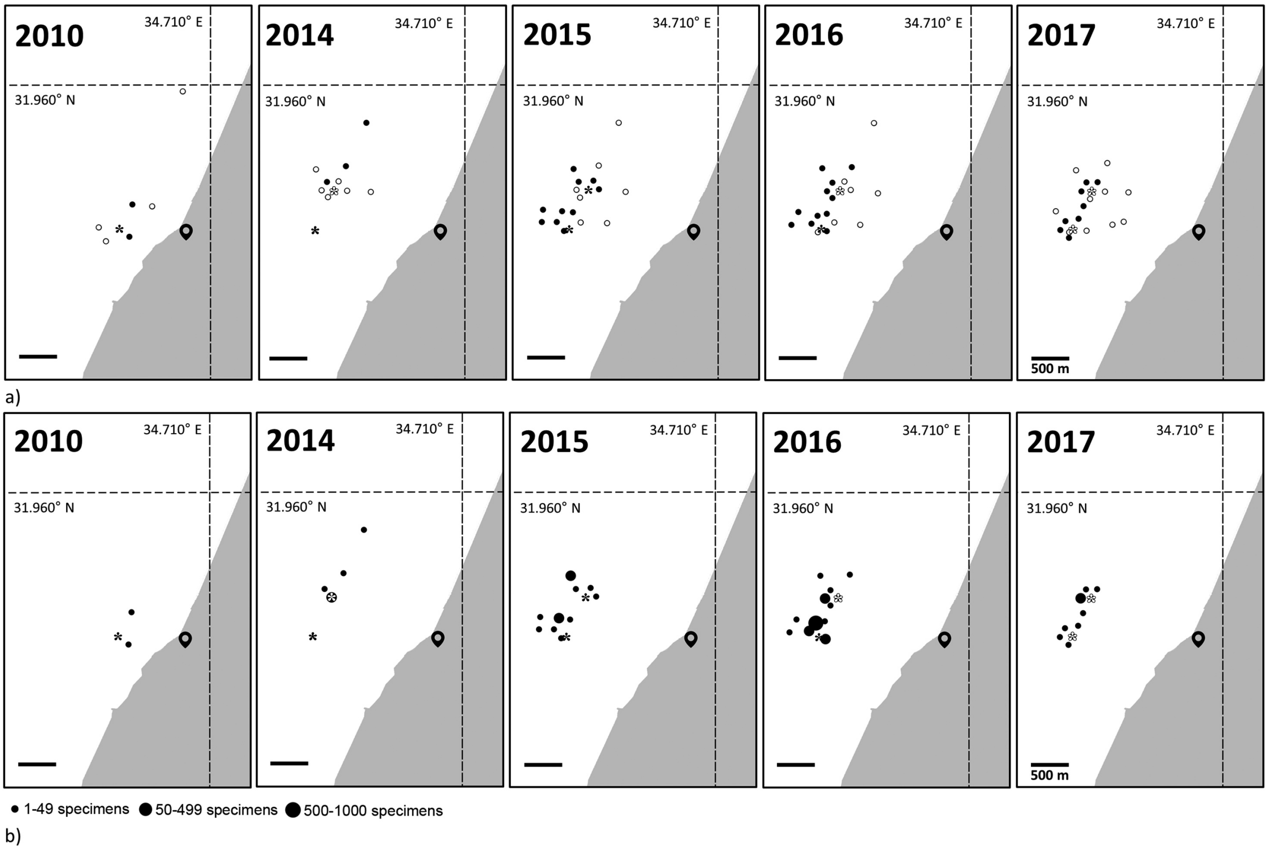

Figure 4. (a) Presence/absence of *Paracaprella pusilla* in 2010, 2014–2017 at the brine disposal sites of the desalination plants of Palmachim and Soreq. (b) *Paracaprella pusilla* abundance in 2010, 2014–2017, and per site (see Table 1 for coordinates). ○ absence and ● presence of *Paracaprella pusilla*; outfalls marked with *. For details see Supplementary material Table S2.

Palmachim-Soreq outfalls (Figure 4). In May 2014, 240 specimens were collected next to the Soreq plant outfall that began operation in 2013. In May 2015 and 2016 specimens were collected in 10 and 12 sites respectively, located to the west and north-west of the outfalls, the direction of the prevailing current, and their numbers increased significantly. In June 2017, specimens were collected in 10 sites, though an apparent decline in their abundance was noted.

Discussion

The number of recorded non-indigenous metazoan species in the Mediterranean Sea is far higher than in any other European Seas and is substantially greater in the Levant than elsewhere (Galil et al. 2014; Lo Brutto et al. 2016). Israel has by far the highest number and percentage of earliest records of species introduced through the Suez Canal into the Mediterranean Sea, of which over 70% were subsequently recorded in other Mediterranean countries (Galil et al. 2018a, b). *Paracaprella pusilla* was collected in the Suez Canal in 1924 (Schellenberg 1928), therefore, finding that the Israeli record of *P. pusilla* predates all previously published records of the species in the Mediterranean Sea (Ros and Guerra-García 2012; Ros et al. 2013, 2016; Fersi et al. 2018) conforms to a well-established pattern.

The most obvious and direct effect of desalination is the hypersaline brine plume, which extent varies depending on site characteristics, effluent volume, mode of discharge and prevailing hydrographic conditions (Kress and Galil 2015). In the studied area, the brine and effluent volume rose from 36.5 Mm^3 y^{-1} from Palmachim outfall at 10 m depth in 2008 (Kress et al. 2009), to 334.8 Mm^3 y^{-1}, from both Soreq and Palmachim outfalls at 20 m depth in 2017 (Kress et al. 2018) (Table S1). *Paracaprella pusilla* specimens were not identified from samples of soft bottom biota collected by similar means at the same timeframe along the Israeli shallow shelf. Samples were collected twice annually, in spring (May–June) and fall (September–October), yet *P. pusilla* specimens were recorded only in spring, when near bottom temperatures ranged from 22.06–22.09 °C in 2010, to 19.81–23.80 °C in 2015, whereas in fall temperatures were perceptibly higher, 29.78–29.43 °C in 2010, and 25.86–30.49 °C in 2015 (Kress et al. 2011, 2016 b). Similarly, it was earlier collected at Zikim, where the seawater temperature was about 20 °C, at Palma de Mallorca and Ibiza at about 21.5 and 20.5 °C respectively, and in the Cádiz marina from September to November and again in July when temperature reached 24.8 °C (Ros and Guerra-García 2012; Ros et al. 2013, 2016). The largest numbers of *P. pusilla* specimens were collected within the area affected by the plume and the very highest abundance (2014: 240 specimens at site SO24, outfall; 2016: 746, 300, 297, 208 specimens at sites VM47, SO26, VM45, VM40 respectively) were found in close proximity to the outfalls and in the direction of the prevailing current to the north-west. However, the effluents did not constitute the sole environmental stressor: trenches were dug for the intake and outfall pipes, the dredged material (289,000 m^3 for the extension of the Palmachim pipes alone) was dumped at a distance of 100–200 m, subsequently partly dispersed during winter storms and partly backfilled after the pipes were placed inside the trench (Kress et al. 2014, 2015, 2016b). Anthropogenic disturbance has been considered a risk factor, reducing native diversity and increasing the dominance of non-indigenous species (Von Holle and Simberloff 2005; Piola and Johnston 2008; Lenz et al. 2011). Our findings concur with earlier ones that posited that introduced species are more likely to establish self-maintaining populations in severely disturbed environments (Piola and Johnston 2008; Dafforn et al. 2009, 2013; Crooks et al. 2011; Lenz et al. 2011).

Paracaprella pusilla has often been found on fouled, man-made structures (Ros and Guerra-García 2012, tab 1; Ros et al. 2013). Indeed, the previously published Israeli record of *P. pusilla* was found attached to the fouling bryozoan *Bugula neritina*, next the Ashkelon SWRO plant (Drami et al. 2011; Ros et al. 2016). Yet, in other instances the species was reported to inhabit fine to coarse sediments (Cooksey et al. 2004; Díaz et al. 2005; Fersi et al. 2018). The sediments at the vicinity of the Soreq and Palmachim outfalls are chiefly composed of coarse to fine sand, with the exception of the areas immediately surrounding the outfalls, which were composed largely of *G. nummaria* (Linnaeus, 1758) shells and shell fragments and are likely to have been deposited during construction work (Kress et al. 2015, 2016b, 2017, 2018). However, the diffusers of both Soreq and Palmachim outfalls are heavily biofouled, though the photographs obtained during a maintenance survey do not allow the identification of the fouling organisms (Kress et al. 2016b, 2017, 2018).

In September 2008, a year after the Palmachim SWRO plant began operation, a monitoring survey recorded that samples collected next to the outfall were inordinately rich in Erythraean molluscs (i.e. *Rhinoclavis kochi* (Philippi, 1848), *Retusa desgenettii* (Audouin, 1826), *Transkeia bogii* (Van Aartsen, 2004), and *Conomurex persicus* (Swainson, 1821)) (Kress et al. 2009). The authors cautioned that the proximity of the Suez Canal and the resulting Erythraean propagule pressure to areas impacted by the brine-effluent plume may enhance establishment of opportunistic biota (Kress et al. 2009; Kress and Galil 2015). Studies conducted in Israeli coastal waters have shown that chronic pressure regimes (e.g., high levels of pollution, physical disturbance due to maintenance dredging, terrestrial runoff etc.), as well as episodic short-term events, have been responsible for the highest increase in the number and abundance of invasive non-indigenous species (Guarnieri et al. 2017; Innocenti et al. 2017). Our results confirm that the Israeli shelf is prone to the introduction and establishment of non-indigenous species, that anthropogenically altered sites are high-risk "invasible" locations, and that the process of invasion may be extremely fast.

Five desalination plants currently operate along Israel's 180 km long coastline, producing 587 Mm^3 y^{-1} drinking water. The Israel Water Authority plans to increase production to 750 Mm^3 y^{-1} by 2020, and to 1750 Mm^3 y^{-1} by 2050 (http://www.water.gov.il/Hebrew/Planning-and-Development/Desalination/Pages/tama34.aspx). The plants combined effects and possible synergy with other anthropogenic stressors (e.g., propagule pressure, pollution, eutrophication, climate change) are likely to facilitate bioinvasions. We recommend monitoring for non-indigenous biota within an ecosystem-based marine management context to effectively address the complex interactions of natural and human pressures (including desalination effluents) that drive invasions in marine ecosystems.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. Environmental parameters: salinity, temperature and granulometry

Table S1. Volume of brine and effluents disposed annually (2010, 2014–2017) by the Palmachim and Soreq desalination plants through the marine outfalls (depth and location).

Table S2. Location of monitoring sites and *Paracaprella pusilla* Mayer, 1890 abundance.

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