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Population dynamics of the invasive freshwater shrimp *Neocaridina davidi* in the thermally polluted Gillbach stream (North Rhine-Westphalia, Germany)

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ABSTRACT

Ornamental species of the aquarium pet trade contribute more and more to the introduction of previously exotic species in Europe. Among these, freshwater crustaceans play an increasingly larger role. Especially in thermally altered streams they may become invasive; however, field data on population ecology of invasive crustaceans are very rare. The aim of this study was to analyze the population dynamics of the invasive freshwater shrimp *Neocaridina davidi* (indigenous to China and other Asian countries) in a year-round warm-water habitat in the Gillbach stream (North Rhine-Westphalia, Germany), where this species forms a stable population. The species reached abundances between 0.23–1.39 individuals per m^2. *N. davidi* is highly productive and detectable in the whole Gillbach stream and in the lower Erft River, too. Egg ratio and cohort development were documented for a period of 27 months. Among adults, between 45 and 59% were females (average 50.5%). Life span was about 12 months in the field and up to 21 months under laboratory conditions. Development times under field and laboratory conditions were similar, ovigerous females appeared about 7 months after hatching. The population in the Gillbach stream was multivoltine with about two generations per year. Only 2–3% of eggs reached adulthood in the field most probably due to intensive predation by indigenous and invasive fish species. One specimen could already be detected in the Lower River Rhine. *N. davidi* is omnivorous and well adapted to different freshwater habitats. The risk of further spreading to other European river systems is obvious.

1. Introduction

Humans increasingly contribute to the global exchange of species (Gozlan et al., 2010; Havel et al., 2015). Unintentional introductions, including transport via canals and the ballast water of ships (Nentwig, 2007), play important roles. In fact, new species are being spread more rapidly than at any time before (Ricciardi et al., 2013). Whereas the release of animals for nutrition or hunting has a long tradition (Nentwig, 2007), more recently the aquarium pet trade has contributed to the introduction of previously exotic species in Europe (Chucholl, 2013; Chucholl and Wendler, 2017; Lipták and Vitázková, 2015; Patoka et al., 2016) and elsewhere (Heerbrandt and Lin, 2006). Some of these species may negatively impact their new ecosystems, by competing for resources, decreasing biodiversity, altering habitats, and acting as vectors of pathogens and hosts of ectosymbiotic species, which may transfer their hosts to native species (Gherardi, 2007; Emde et al., 2016; Patoka et al., 2016; Ohtaka et al., 2017). Among the invasive species, freshwater crustaceans account for an increasingly larger share (Patoka et al., 2016). In the case of recently introduced North American crayfish, these species are carriers of crayfish plague, which then infects the European crayfish species and adversely influences indigenous European ecosystems (Aquiloni et al., 2011; Pârvulescu et al., 2012). In the USA and Canada, the invasion of opossum shrimp has altered different freshwater ecosystems in both countries (Spencer et al., 1991).

Hot springs or thermally altered streams may allow released exotic species to form self-sustaining populations of in a temperate surrounding (Piazzini et al., 2010; Klotz et al., 2013; Emde et al., 2016). Moreover, global warming is leading to changing ecosystems that support these biological invasions and altering populations of indigenous species (Walther et al., 2009).

In recent years, the ornamental atyid shrimp *Neocaridina davidi* (Bouvier, 1904), native to China, Korea, Taiwan, and Vietnam (Cai, 1996; Karge and Klotz, 2013), has become an invasive species in the USA, Japan and Europe. Freshwater shrimps of the Infraorder Caridea, comprise roughly 800 species belonging to eight families. The largest family is the Atyidae (approx. 480 species) with about 50 epigean and subterranean taxa in Europe and the Mediterranean region (Christodoulou et al., 2016). Members of a minor part of this family are amphidromous (Vogt, 2013; Heerbrandt and Lin, 2006, Dudgeon, 1985), but most are confined to freshwater and are characterized by

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abbreviated or suppressed larval development. This is especially evident in the genera *Caridina* and *Neocaridina* (Karge and Klotz, 2013; Vogt, 2013; Pantaleão et al., 2015; Lai and Shy, 2009; Shih and Cai, 2007).

The population dynamics of freshwater shrimps are well known from studies on *Atyaephyra desmarestii* (Millet, 1831), a species with a prolonged planktonic development exclusively in freshwater (Karge and Klotz, 2013; Vogt, 2013; Schoolmann et al., 2015). Extensive studies were carried out by Fidalgo (1989a,b), Galhano (1979), Dhaouadi Hassen et al. (2006) and Dhaouadi Hassen and Boumaïza (Dhaouadi Hassen and Boumaïza, 2008, 2009) in Portugal and Tunisia. Oh et al. (2003) examined the population structure of *Neocaridina denticulata denticulata* (De Haan, 1844) in a Korean stream, and de Silva (1988) of *Caridina simoni* Bouvier, 1904 in Sri Lanka. *N. davidi* is also known as *N. heteropoda* and under other synonyms (Bouvier, 1925; Cai, 1996; Cai and Ng, 1999; De Grave and Fransen, 2011; Mitsugi et al., 2017), as is often the case for ornamental species. Today, *N. davidi* is the accepted name, and the characteristics of this species have been verified by genetic and morphological analyses (Klotz et al. 2013; Klotz and von Rintelen, 2014; Mitsugi et al., 2017). *N. davidi* tolerates a wide range of temperatures (Englund and Cai, 1999; Klotz et al., 2013) and is omnivorous (Tropea et al., 2015; Lai and Shy, 2009; Pantaleão et al., 2017; Weber and Traunspurger, 2016; Schoolmann and Arndt, 2017).

Despite the potentially fundamental impact of *N. davidi* on indigenous faunal components, nearly nothing is known about the population dynamics of this species in habitats where it is invasive. However, to estimate the invasive potential of *N. davidi*, requires a determination of its growth and reproduction rates in the field. The aim of this study was to analyze the population dynamics of invasive *N. davidi* in the Gillbach stream, a tributary of the River Erft and River Rhine that is heavily thermally polluted by an influx of cooling water. This resulting year-round warm-water habitat harbors a variety of tropical and subtropical species. We hypothesized that this potentially highly productive shrimp would be able to establish a stable population in the stream because, its larval development has been completely suppressed (e.g. Karge and Klotz, 2013; Vogt, 2013; Pantaleão et al., 2017), an adaptation of this land-locked species. It should allow a larval withstanding the water current in the stream. A potentially high production of offspring might bear the risk of the occasional occurrence of cold-adapted juveniles surviving conditions in temperate river systems. This assumption is supported by the fact that this species presumably originates from temperate Eastern China (Karge and Klotz, 2013).

2. Material and methods

The Gillbach stream (North Rhine-Westphalia, Germany) is about 25 km long and is a small tributary of the River Erft (Fig. 1). As a result of the input of cooling water from a power plant, the stream suffers severe thermal pollution that also extends to the River Erft (Friedrich, 1973; Friedrich, 2005). The stream's former spring was sacrificed to brown coal surface mining at Bergheim and Fortuna-Garsdorf between the 1950s and 1980s. Today cooling water from one of the biggest brown coal power plants of Germany Niederaußem, a district of Bergheim (near Cologne), supplies the stream with a substantial discharge of about 300 l/sec (Klotz et al., 2013; Emde et al., 2016; Düsseldorf, 2015) and a temperature of up to 28.5 °C (personal observation, 23.07.2014). Near the coolant water influx, the Gillbach is recharged by a small volume of cleaned municipal sewage water (30–40 l/s). Over the Gillbach's course through a predominantly agrarian landscape there are only three draining canals (Totenbach, Todtenbach, Flothgraben), all of which supply the Gillbach with surface-water during periods of intense rainfall (Fig. 1).

Since the 1970s different invasive species of ornamental pets and tropical freshwater plants released into the Gillbach seem to have established partially self-sustaining populations (Klotz et al., 2013; Emde et al., 2016; Hussner and Lösch, 2005). For example, the submerged macrophyte *Vallisneria spiralis* L., which commonly grows in the tropics and subtropics, is found in the streambed (Fig. 2B and D) of the Gillbach. It is wide-spread in areas, that are not shaded by riverine shrubs and trees. *V. spiralis* is also wide-spread in the lower Erft River (Hussner and Lösch, 2005). In addition, since 2009, two species of Asian freshwater shrimp have been regularly found in the upper part of the Gillbach: *Neocaridina davidi* (Bouvier, 1904) and *Macrobrachium dayanum* (Henderson, 1893). Between 2011 and 2013, both species seemed to have generated stable populations (Klotz et al., 2013), *M. dayanum* only in the warmest part of the Gillbach. Klotz et al. (2013) also found *N. davidi* near the mouth of the Gillbach at the Erft River.

In the present study population dynamics of *N. davidi* were investigated in a section of the Gillbach in the area of the municipality of Rommerskirchen (51°2,619′N, 6°42,008′E, Figs. 1 and 2C and D). Here, the stream has a mean width of about 3.5 m (0.5–0.8 m depth) and steep banks, that are mostly free of riparian shrubs and trees, except three young alders (*Alnus glutinosa* (L.). The only submerged macrophyte in this section was *V. spiralis* L. (Hussner and Lösch, 2005).

Samples were obtained at roughly 2-month intervals between October 2013 and December 2015. Routine sampling was carried out using a steel sieve (mesh size 1 mm) mounted on a telescope pole (Schoolmann et al., 2015) which allowed the collection of shrimp over a distance of 100 m at a rate of 30 min/catch (catches per unit effort, CPUE). The survey area was 350 m^2. *N. davidi* specimens were separated from the by-catch and fixed in 70% ethanol for further investigation. Occasionally, samples were taken in the lower Erft River to control the development of a stable population in this part of the river.

In the laboratory, sampled individuals of *N. davidi* were sexed and their morphological parameters (total length, carapace length and rostrum length) analyzed. Males can be recognized by their specialized pleopods. Length was determined using a sliding caliper (adults) or a stereomicroscope equipped with an ocular micrometer (juveniles). All individuals were assigned to the appropriate size class: late juveniles (7–9 mm), premature (9–11 mm), and adults (9 classes at 2-mm intervals from 11 to 29 mm). Small juveniles (< 7 mm) were counted and measured but not considered quantitatively, because they partly passed through the steel sieve of 1 mm mesh size. In addition, freshly hatched individuals and early juvenile stages prefer the bottom of the water body (Pantaleão et al., 2015; own observation). Only individuals with a total length > 7 mm can be sexed (Pantaleão et al., 2017; De Silva, 1988). A mesh size of 1 mm was used to efficiently sample large individuals which were the focus of the study. Eggs of ovigerous females were counted after they had been brushed from the female pleopods. Three cohorts were defined for the analysis of the growth and survival of *N. davidi*. They were identified based on peak abundances, which could be followed over the course of ontogenetic development.

In laboratory studies, the survival rate of 100 individuals of one cohort from the Gillbach stream, originating from five females of one catch that were transferred into an aquarium, was investigated. Juveniles were caught after hatching, on June 13, 2015, and reared in a 15-l aquarium (22–24 °C; 13:11 h light: dark photoperiod) supplied with stones covered with algae, with living *Tubifex* twice a week, and leaves with biofilms (Schoolmann and Arndt, 2017). The shrimps were kept until the last individual had died. Reproduction took place, but all juveniles were caught and transferred within 3 days after hatching.

3. Results

3.1. Seasonal pattern

Relatively high abundances (0.23–1.39 individuals per m^2 CPUE) of *N. davidi* of grey-brown individuals were present in the investigated area of the Gillbach stream. Every second sampling, a monitoring for further dispersal of the species in the Gillbach stream was carried out, which revealed the occurrence of all length classes of *N. davidi* (including ovigerous females) along the entire length of the stream from