NOTE

Introduction of the Ponto-Caspian Bloody-red Mysid *Hemimysis anomala* into the Lake Michigan Basin

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ABSTRACT. *Hemimysis anomala G.O. Sars, 1907, a mysid species native to the Ponto-Caspian region, was discovered during fall 2006 in the Lake Michigan basin. Large numbers of individuals formed aggregations (averaging 1,540 ± 333 individuals/m2) in a shallow docking basin connected to the channel linking Lake Michigan and Muskegon Lake. The population included females (63%), males (35%), and juveniles (2%). The global invasion pattern in* H. anomala *is similar to that in another Ponto-Caspian peracarid crustacean,* Echinogammarus ischnus. *As with* E. ischnus, *the expansion of* H. anomala *in North America is anticipated.*

INDEX WORDS: *Exotic species, biological invasion, mysid, Great Lakes.*

INTRODUCTION

The Laurentian Great Lakes have experienced a dramatic sequence of invasions by nonindigenous species (NIS), especially after the completion of the St. Lawrence Seaway in 1959 (Grigorovich *et al*. 2003). The Ponto-Caspian region, which encompasses the Black, Azov, Caspian and Aral seas, has been an important source of these NIS (Grigorovich *et al*. 2003). Many species endemic to this region are currently involved in range extensions and have colonized new habitats in the North and Baltic seas in Europe (Grigorovich *et al*. 2002). Once established in key European waterways, these NIS including mussels (*Dreissena polymorpha, D. bugensis*), crustaceans (*Nitocra incerta,*

Schizopera borutzkyi, *Cercopagis pengoi*, *Echinogammarus ischnus*), and fishes (*Neogobius malanostomus*, *Proterorhinus marmoratus*) subsequently appeared in the Great Lakes (Grigorovich *et al*. 2003). Joint consideration of the invasion histories of NIS in Europe, physicochemical requirements that enhance their survival in ballast water, and inbound shipping traffic to the Great Lakes allowed a risk assessment of future introductions into the Great Lakes (Grigorovich *et al*. 2003). In this study, we describe the first North American record of a predicted invader, the Ponto-Caspian bloody-red mysid *Hemimysis anomala* G.O. Sars, 1907. We also describe its demographic structure in a novel habitat in the Lake Michigan basin and review its ecological attributes, geographic distribution, and dispersal patterns in Eurasia.

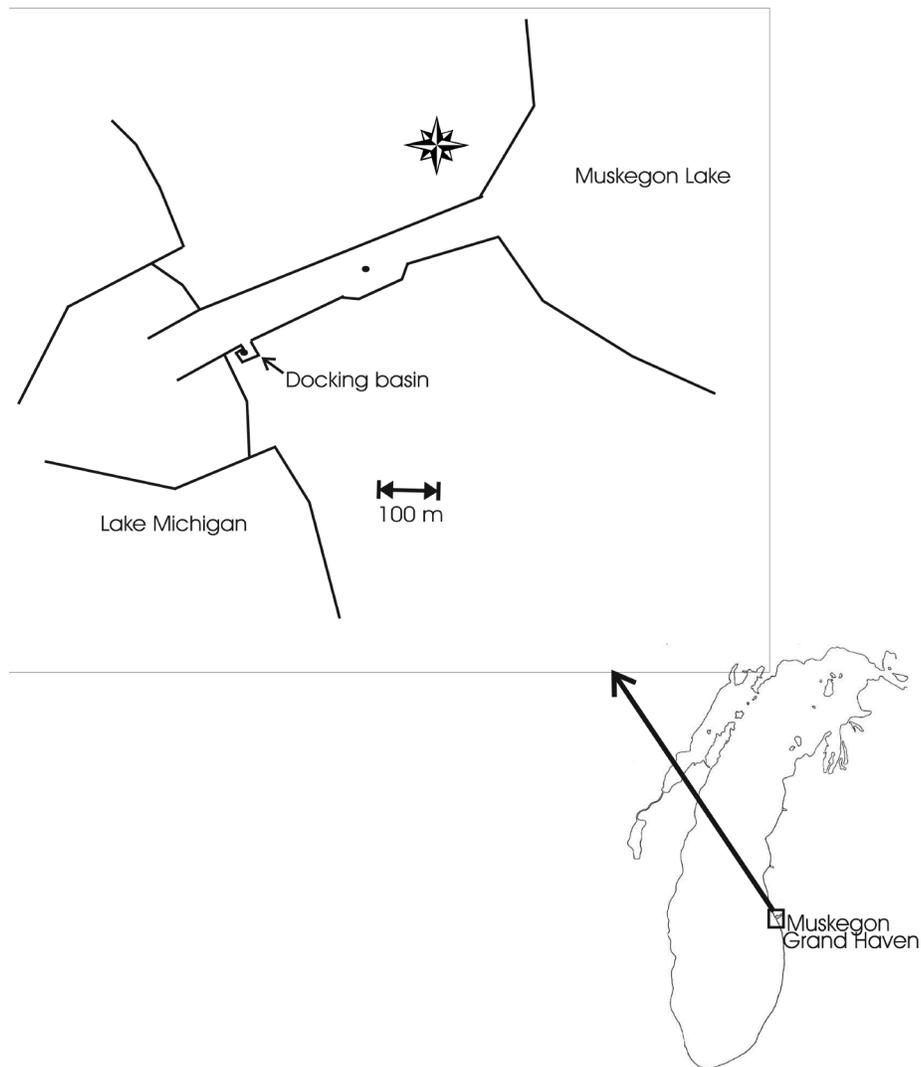*Corresponding author. E-mail: steve.pothoven@noaa.gov

FIG. 1.   Map showing location of sampling area in Lake Michigan basin with detail of Muskegon channel area with locations (●), where H. anomala *was captured.*

METHODS AND MATERIALS

Collections for this study were taken during November 2006 at stations in Muskegon Lake (4–22 m deep), the channel area connecting this drowned river mouth to Lake Michigan, the nearshore of Lake Michigan (10 m deep) off Muskegon, Michigan and along the channel wall at Grand Haven, Michigan (Fig. 1). The mysids were first collected with a dip net on 7 Nov 2006 and preserved in 80% ethanol. Further sampling was done using a 0.5-m diameter 153-μm mesh or a 1-m diameter 1,000-μm mesh plankton net pulled from near bottom to surface. Lake whitefish *Coregonus clupeaformis*

were collected from the Muskegon channel by angling on 27 Nov 2006 to examine stomach contents.

Morphological and reproductive characteristics of *H. anomala* were examined using a Leica dissecting microscope (6 to 50×). Total body length (from the anterior tip of the carapace to the posterior margin of the telson) was measured using an ocular micrometer to the nearest 0.05 mm. Gender was determined by the presence (in males) or absence (in females) of elongated pleopods IV that are modified for copulating (Fig. 2A, C). Females are characterized by rudimentary pleopods. Mature females contain well-developed oostegytes. Body length ($\log_{10}$ (n + 1) transformed) of males and fe-
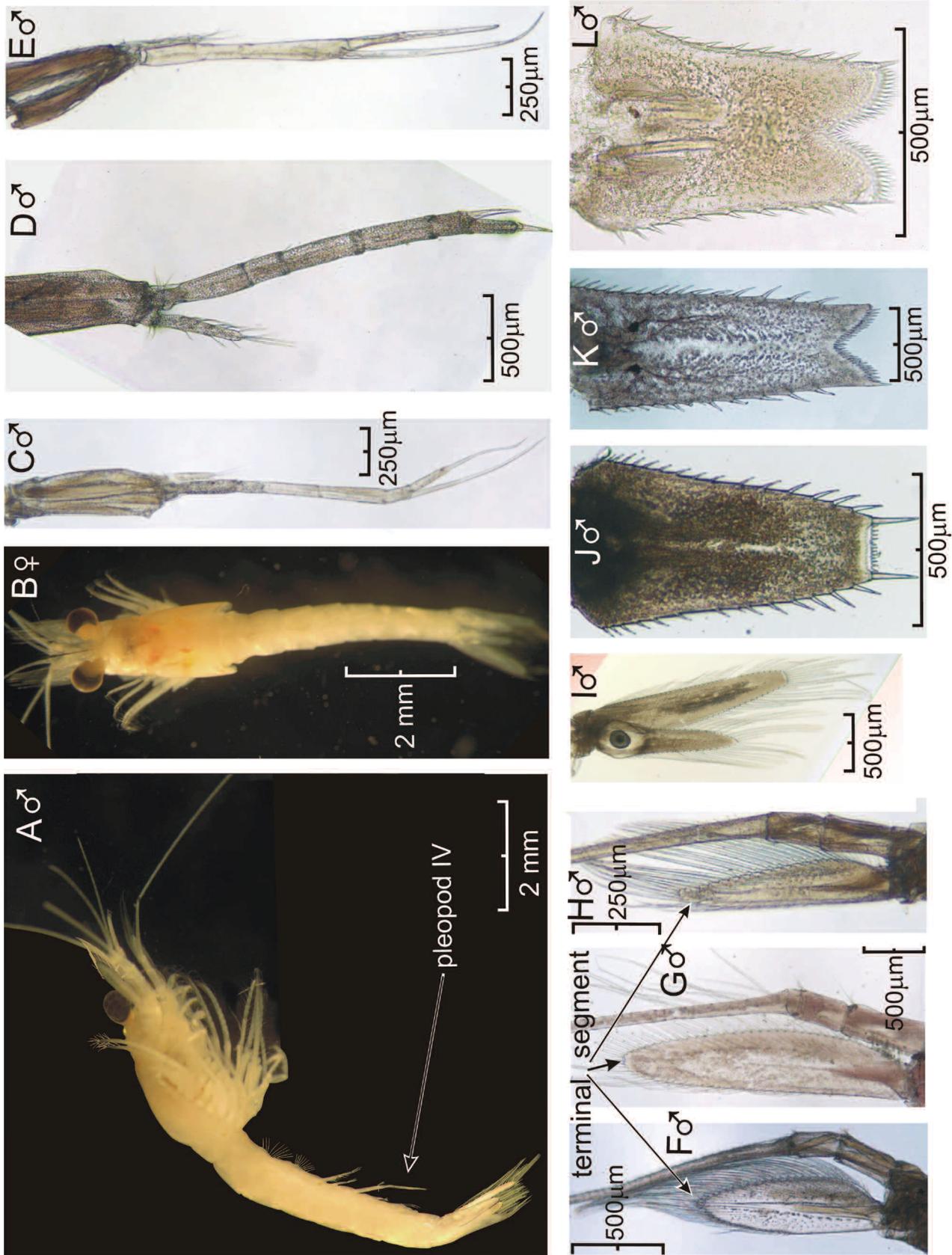
FIG. 2. Morphological features of North American freshwater mysids. **Hemimysis anomala** *from Lake Michigan basin: (A) lateral view, (B) dorsal view, (C) pleopod IV, (D) pleopod IV, and (E) pleopod IV. Male* **Mysis relicta** *from Lake Superior: (D) pleopod IV, (F) outer ramus of antenna II, (G) outer ramus of antenna II, (I) endopod of uropod, and (J) telson. Male* **Mysis relicta** *from Lake Superior: (D) pleopod IV, (F) outer ramus of antenna II, (G) outer ramus of antenna II, and (K) telson. Male* **Taphromysis** *from Mississippi River: (E) pleopod IV, (H) outer ramus of antenna II, and (L) telson.*

males was compared using a *t*-test (Statistica 6.0). In total, we examined and measured 236 individuals. Representative voucher specimens of *H. anomala* were deposited into the Canadian Museum of Nature, Ottawa, Ontario (as entire specimens preserved in ethanol; catalogue numbers CMNC 2007-0001).

Identification of Mysids

The taxonomic classification of mysids relies on adult male morphology (Birshtein 1968, Băcescu 1969, Komarova 1991). *Hemimysis anomala* is a very distinctive species that can be easily recognized by its characteristically truncated telson that is spined along its entire margin and has a wide, straight posterior margin (Fig. 2J–L). The genera *Mysis* and *Taphromysis* are characterized by a bifurcated tip of the telson (Fig. 2K, L), whereas in the genera *Neomysis* and *Deltamysis* the distal margin of the telson is narrowly truncated and/or convex at the tip (Smith 2001). The form of the telson is not subject to gender dimorphism in *H. anomala* (Reznichenko 1971) although Reznichenko (1959) reported that immature and adult *H. anomala* may have a telson with an apical cleft. Male *H. anomala* can be further discriminated from male *Neomysis* and *Deltamysis* by an exopod on pleopod IV with over three segments (Fig. 2C), while that in the latter two genera consists of two or less segments (Smith 2001). An elongated exopod on pleopod IV consisting of six or seven segments serve to distinguish male *Hemimysis*, *Taphromysis* and *Mysis* from all other mysid genera in North America (Fig. 2C-E). Male *H. anomala* and male *Mysis* differ in two respects: (1) pleopods V consist of two rami each with over three segments in *Hemimysis*, whereas those of *Mysis* consist of one unsegmented ramus (Birshtein 1968); (2) outer ramus on antenna II (antennal scale) is elongate with a distinct terminal segment, which at the point of insertion on the outer ramus is more than a third of the largest outer ramus width in *Hemimysis* (Fig. 2F), while *Mysis* has a narrowly lanceolate antennal scale with an indistinct terminal segment, which at the point of insertion on the outer ramus is less than a quarter of the largest outer ramus width (Fig. 2G).

RESULTS AND DISCUSSION

Hemimysis anomala is a nektonic species hiding on the bottom during the day and ascending into the pelagic zone at night (Komarova 1991, Ketelaars *et al*. 1999). As with *Echinogammarus ischnus*, *H. anomala* is among few Ponto-Caspian metazoans capable of surviving and reproducing in salinities of 0.1 to 18.0‰ (Mordukhai-Boltovskoi 1970). This mysid inhabits marine and estuarine littoral habitats overgrown by the brown (*Cystoseira*) and red algae and freshwater habitats covered with only a thin layer of silt (Ioffe *et al*. 1968, Komarova 1991). It occurs most frequently on hard bottom substrates including rocks, zebra mussel clusters or smashed shells, less frequently on sand, silty sand or mud, and least frequently in the soft-bottom profundal (Ioffe *et al*.1968, Komarova 1991). *H. anomala* is found in varying depths: 6–20 m in the Black Sea, up to 30 m in the Caspian Sea (Băcescu 1954), 20–50 m in the Zaporozhie (= Dneprovskoye) Reservoir and in shallow ponds (1.5 m) of the Ingulets irrigation system (Zhuravel 1960). Overgrowth of aquatic plants and silt accumulation limit the distribution of *H. anomala* (Ioffe 1973).

We first discovered *Hemimysis anomala* on 7 Nov 2006 adjacent to the channel wall in a docking basin connected to the channel linking Lake Michigan and Muskegon Lake. Large aggregations of *H. anomala* were observed in the Muskegon docking basin almost daily over the course of a month. The density of individuals in the swarms was estimated at $1{,}540 \pm 333$ (SE) individuals/m^2 (or 513 ± 128 individuals/m^3). No individuals were collected at any other site during the day. A few individuals were collected at night in the Muskegon shipping channel (0.25 ± 0.25 individuals/m^2) and the center portion of the docking basin (0.75 ± 0.75 individuals/m^2). Using a spotlight at night, we observed that the aggregations of mysids in the docking basin had dispersed, but most individuals were still located within 1 m of the channel wall. These observations were generally consistent with behavior observed elsewhere where mysids aggregated in areas out of direct sunlight, in rocky crevices and cavities or around jetties during the day, and then dispersed at night (Komarova 1991, Salemaa and Hietalahti 1993, Holdich *et al*. 2006). Water temperatures ranged from 6.4 to 8°C over the course of the study. Experiments revealed that the species prefers water temperature between 9 and 20°C and avoids areas warmer than 20°C (Ioffe 1973).

Most *H. anomala* appeared healthy at time of collection and were reddish in color. Living mysids *H. anomala* are predominantly bloody-red in color (Komarova 1991). This coloration is believed to be associated with its life in concealment under crepuscular light condition (Komarova 1991). Due to
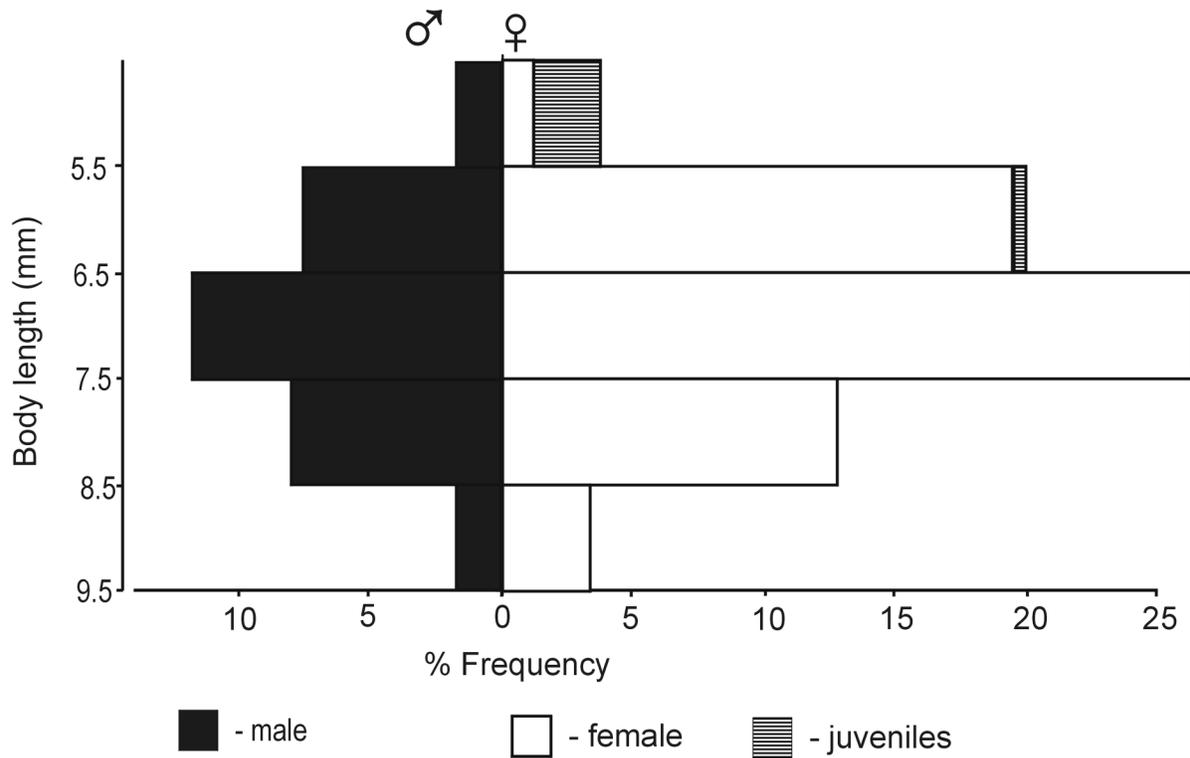
FIG. 3. *Length-frequency distribution of* **Hemimysis anomala** *in Lake Michigan basin in November 2006. n = 236*

the contraction of its ivory-yellow chromatophores, the bloody-red mysid is capable of changing its body color from bloody-red to ivory-yellow to almost transparent with a touch of ivory-yellow color (Komarova 1991). Several individuals had rust-red spots on their integuments that may be lesions.

The natural range of this species encompasses isolated habitats scattered across the Ponto-Caspian regions: eastern coast of the Caspian Sea, lower Don River, Azov Sea, Dnieper-Bug Liman, Tiligul Liman, lower Dniester River and Liman, the lower Danube River and freshened parts of the Black Sea proper (Komarova 1991, Black Sea Environmental Internet Node 1999). *Hemimysis anomala* is considered endangered in several isolated Ukrainian localities including Dnieper-Bug Liman, the River Zelenaya draining into the Sea of Azov and Tiligul Liman in the northwestern Black Sea coast (Komarova 1991, Black Sea Environmental Internet Node 1999). Since reservoirs of the southern European part of the former USSR resemble the estuaries of Ponto-Caspian rivers in several respects, *H. anomala* and other Ponto-Caspian invertebrates were used intensively for stocking and biomanipu-

lation programs to provide food for fishes (Zhuravel 1963; reviewed in Grigorovich *et al*. 2002). The distribution of *H. anomala* has expanded due to stocking and other human-mediated vectors including the interconnection of river basins through canals, reservoir construction, and transfer by commercial ships (Grigorovich *et al*. 2002). *Hemimysis anomala* was intentionally stocked into the following man-made reservoirs in the southern former USSR: Tsimlyanskoye, Sengileevskoye, Yegorlykskoye, Novo-Troitsk, Kuibyshev (Russia), Zaporozhie, Karachunovskoye, Oktiabrskoye, Simferopol, Chernorechensk (Ukraine), and Dubossary (Moldova) (Ioffe *et al*. 1968, Grigorovich *et al*. 2002). The first established population of *H. anomala* outside of the Ponto-Caspian basin was reported in 1962 in the Kaunass reservoirs in the Baltic Sea basin (Lithuania), where the species was deliberately stocked (Gasiunas 1964). It subsequently spread into the Baltic Sea proper in 1992, the River Rhine basin in 1997, and United Kingdom English Midlands in 2004 (Salemaa and Hietalahti 1993, Ketelaars *et al*. 1999, Holdich *et al*. 2006).

Prior research predicted the invasion of the Great Lakes by *H. anomala* either by direct transmission from the Ponto-Caspian region or through a secondary invasion site such as the Baltic Sea or River Rhine (Ricciardi and Rasmussen 1998, Ketelaars *et al*. 1999, Grigorovich *et al*. 2003). The invasion pattern for *H. anomala* is similar to *Echinogammarus ischnus*, which has a recent invasion history in the Ponto-Caspian region, Baltic and North seas, and the Great Lakes (Cristescu *et al*. 2004). Early observations of both species in the Lake Michigan basin were near Muskegon Lake. It is entirely possible that both species were transported to Lake Michigan at the same time but were noticed in the field at different times: *E. ischnus* in 1998, *H. anomala* in 2006. Records of deliberate introductions indicate that successfully introduced invertebrates may remain undetected for 1 to 20 years following initial stocking (reviewed in Grigorovich *et al*. 2003). Because *H. anomala* seeks concealment, it is difficult to collect with traditional net tows and may go unnoticed in many areas (Salemaa and Hietalahti 1993, Ketelaars *et al*. 1999, Borcherding *et al*. 2006).

Obligate sexual reproduction may inhibit the establishment of peracarid crustaceans in a novel habitat because either gravid females or both males and females must to be transmitted from the source population. However, *H. anomala* possesses several life history features that may facilitate its establishment in new habitats including rapid growth and maturation (Ioffe *et al*. 1968, Ioffe 1973). In the Zaporozhie Reservoir, this mysid breeds from April to October producing four generations a year (Ioffe 1973). Ovigerous females appear when water temperatures reach 8–9°C and at 11–12°C females carry neonates in their marsupium. Females of the first generation born in late May (10–16°C) start to breed 45 days later; second and third generations reach sexual maturity in less than a month (Ioffe 1973). Clutch size varies with female size and season, ranging from 14 to 66 eggs. In the Zaporozhie Reservoir, reproduction generally ceases in October (Ioffe *et al*. 1968). According to Mordukhai-Boltovskoi (1960), most female *H. anomala* produce at least two broods. In the Lake Michigan basin we observed two females that carried embryos in November at 8°C. Clutch sizes in our study were 2 and 17, and all embryos were at the gastrula stage (mean size: 570 ± 9 μm).

The population in the Lake Michigan basin was dominated by females 6.5 to 8.5 mm long (Fig. 3). Of the 149 females examined, only 22 (15%) possessed marsupial oostegites in their brood chambers and were in a reproductive condition. Body length of females (7.03 ± 0.07 mm) did not differ significantly from that of males (6.88 ± 0.12 mm) (*t* test, P = 0.59). The *H. anomala* in the Lake Michigan basin are smaller than those in marine environments, where males can reach 11 mm and females 16 mm (Komarova 1991)

Fish predation can control the abundance of large zooplankton species in the nearshore of Lake Michigan (Evans 1990). *H. anomala* is a large-bodied, lipid-rich prey item that has been rapidly assimilated into fish diets in some areas where it invaded (Borcherding *et al*. 2006). The lake whitefish (n = 9) we collected were eating fish eggs and *Bythotrephes longimanus*, and no *H. anomala* were found in stomachs. Nonetheless, we know that large-bodied zooplankton, including the native mysid, *Mysis relicta*, are eaten by several species of fish in the region including alewife *Alosa pseudoharengus*, which selectively prey on *M. relicta* (Pothoven and Vanderploeg 2004). Therefore, high densities of planktivorous fish may ultimately limit *H. anomala* abundance, particularly in the nearshore, where fish density is generally higher than in offshore areas (Evans 1990).

The introduction of mysids into aquatic systems can have profound and unexpected results. *H. anomala* are omnivorous, have a high feeding rate (Ketelaars *et al*. 1999), and are likely able to switch feeding modes with ontogeny or as food availability changes (Borcherding *et al*. 2006). The introduction of another mysid, *M. relicta,* was associated with reduced zooplankton abundance, especially for cladocerans (Nero and Sprules 1986, Langenland 1988, Spencer *et al*. 1999) and lower fish growth or abundance in North American and European lakes (Morgan *et al*. 1978, Langenland *et al*. 1991). Similarly, cladoceran abundance declined after the establishment of *H. anomala* in the Biesbosch reservoirs in the Netherlands (Ketelaars *et al*. 1999). Mysids can also alter zooplankton behavior and spatial distribution (Nero and Sprules 1986). Therefore, the invasion by a mysid, such as *H. anomala,* clearly has the potential to alter the food web structure of the Great Lakes, but the extent of its impact will depend on its abundance and spatial distribution in the Great Lakes and connecting waters. Our study does reveal congruence in invasion patterns between *H. anomala* and *E. ischnus*, suggesting that the further expansion of the former in North America is anticipated.

ACKNOWLEDGMENTS

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