Biological Synopsis of the Bloody Red Shrimp (*Hemimysis anomala*)

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ABSTRACT

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The blood red shrimp (*Hemimysis anomala*) has the potential to cause great ecological threats in Canadian waters. The department of Fisheries and Oceans Canada is conducting a risk analysis to determine the ecological risk that this species poses in Canada. As the first step toward the risk analysis, a synopsis summarizing information on the biology of *H. anomala* was required. *H. anomala* is a mysid native from the Ponto Caspian region. In the middle of the 20th century, *H. anomala* with a number of other Ponto-Caspian mysids were deliberately introduced to lakes and reservoirs of Eastern Europe with the intention of increasing fish production. A few decades later, *H. anomala* has extended its distribution to Western Europe. In 2006, it was first reported in the Great Lake basin (Lake Michigan and Ontario). At this point, no ecological effect of *H. anomala* has been found in the Great Lakes but several alterations are predicted if the expansion continues to increase.

RÉSUMÉ

Marty, J. 2008. Exposé Synoptique sur la Biologie de la Crevette *Hemimysis anomala*. Can. Manuscr. Rpt. Fish. Aquat. Sci. 2842: viii + 36p.

La crevette *Hemimysis anomala* pourrait être responsable d'importantes altérations écologiques dans les eaux Canadiennes. Pêches et Océans Canada souhaite conduire une étude de risques afin de déterminer les effets potentiels de l'invasion de cette espèce au Canada. Dans ce but, cet exposé synoptique vise à rassembler les informations sur la biologie de *H. anomala*. *H. anomala* est une espèce native de la région Ponto-Caspienne. Dans les années 1950, elle fut introduite volontairement dans plusieurs lacs et réservoirs Eurasiens afin d'accroître la production piscicole. En quelques décennies, *H. anomala* a envahi l'Europe de Ouest. In 2006, cette espèce a été observée pour la première fois dans le bassin des Grands Lacs (Lacs Michigan et Ontario). Aujourd'hui, aucun impact écologique de *H. anomala* n'a été reporté pour les Grands Lacs malgré que de nombreuses altérations soient prédites si l'expansion de l'espèce se poursuit.

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1-INTRODUCTION

In the middle of the 20th century, Ponto-Caspian mysids were deliberately introduced to lakes and reservoirs of Eastern Europe with the intention of increasing fish production. A few decades later, several species had extended their distribution in Western Europe and to the Great Lakes Basin. These introductions yielded mild to severe modifications of the food web in these ecosystems which had further effects on humans (Ricciardi 2007). Among the Ponto-Caspian species who succeeded in their invasion is *Hemimysis anomala*, the bloody red shrimp. In 2006, it was found in two locations in the Great Lakes. *H. anomala* is predicted to extend its distribution in the near future, if not already, to large areas of the Great Lakes basin (Pothoven *et al.* 2007). As the first step toward a risk assessment in Canada, this synopsis aims to present the characteristics, the ecology and the known impacts of *H. anomala*.

2-NAME AND CLASSIFICATION

From ITIS database (2007).

Kingdom:	Animalia
Phylum:	Arthropoda
Subphylum:	Crustacea, Brünnich, 1772
Class:	Malacostraca, Latreille, 1802
Subclass:	Eumalacostraca, Grobben, 1892
Superorder:	Peracarida, Calman, 1904
Order:	Mysida, Haworth, 1825
Family:	Mysidae, Haworth, 1825

Genus: *Hemimysis*, Sars, 1869

Species: *Hemimysis anomala*, G. O. Sars, 1907

Common scientific name: *Hemimysis anomala,* G. O. Sars, 1907

Common English name: bloody red mysid (shrimp)

Common names in other languages: Dutch: *Kaspische Aasgarnaal*, German: *Schwebegarnele*, Finnish: *Kaspianhalkoisjalkainen*, Russian: *Myzida anomal'naya*, Swedish: *Röd pungräka*, *Röd immigrantpungräka*, Ukrainian: *Myzida anomal'na*.

Voucher Specimens: Canadian Museum of Nature, Ottawa [CMNC 2007-0001]

4-DESCRIPTION

4.1-Visual Aspect

Hemimysis anomala is ivory-yellow in colour or translucent and exhibits pigmented red chromatophores in the carapax and telson (Salemaa & Hietalahti 1993, Janas & Wysocki 2005) (Fig. 1). The intensity of colouration varies with the contraction or expansion of the chromatophores in response to light and temperature conditions (Salemaa & Hietalahti 1993, Ketelaars *et al.* 1999, Pothoven *et al.* 2007). Short term changes in colour have been observed, including darker organisms in shaded environments (Salemaa & Hietalahti 1993). Juveniles are more translucent than adults (Ketelaars *et al.* 1999). Preserved individuals may lose their colour. Total length of the males is 8–10 mm, females are slightly longer, typically up to 11 mm in the summer (Bacescu 1954, Komarova 1991), and even up to 16.5 mm in winter (Bacesco 1940).

4.2-Morphological Details

A detailed review of *H. anomala* morphology is given by Pothoven *et al*. (2007) and summarized below. The taxonomic classification of mysids is based on the morphology of the adult male (Pothoven *et al.* 2007). *H. anomala* can be distinguished from other mysid species, including the Great Lakes native opossum shrimp, *Mysis relicta*, 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*, although immature and adult *H. anomala* may have a telson with an apical cleft (Reznichenko 1959 in Pothoven *et al.* 2007). Male *H. anomala* can be further discriminated from male *Neomysis* and *Deltamysis* by an exopod on pleopod IV with over three segments (Fig. 2C). In *Neomysis* and *Deltamysis* , the exopod on pleopod IV 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 in Pothoven *et al.* 2007) and (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).

5-DISTRIBUTION

5.1-Native Distribution

H. anomala is an endemic Ponto-Caspian species and has been observed in the coastal regions of the Caspian, Black and Azov seas, in their lagoons and up to 50 km upstream in the rivers Don, Dnestr, Dniepr, Pruth and Danube (Bacescu 1954, 1966, Dediu 1966, Komarova 1991, in Wittmann 2007). It was originally found across a wide range of salinities, ranging from 18 ‰ to freshwater (Bacescu 1954, Mordukhoi–Boltovskoi 1979, Komarova, 1991). Before human manipulations, *H. anomala* was known as an estuarine or marine species, penetrating less than 60 km into river reaches (Wittmann 2007).

5.2-Non-Native Distribution and Invasion History in Europe

Historically, few mysids expanded their distribution in the continental waters of Europe before the 1950s (Wittmann 2007). In the late 1940s, a massive intentional introduction of mysids began in several Eastern European reservoirs, lakes and rivers, with the objective of increasing fish production. Although poorly reported, one hundred million mysids (*Paramysis*, *Limnomysis* and *Hemimysis*), together with a great variety of other invertebrates (*Gammarus lacustris*, *Dikerogammarus haemobaphes* and *Corophium curvispinum*) (Gasiunas 1968, Borodich & Havlena 1973, Mordukhai-Boltovskoi 1979) were introduced to more than 200 water-bodies of the former Soviet Union between 1948 and 1965 (Wittmann 2007). In the 1980s, most of the intentional introductions of mysids stopped when the adverse effects of these introductions on the food web of recipients ecosystems were recognized (Ketelaars *et al.* 1999, Wittmann 2007). However, ceasing intentional introductions had no direct effect on the ongoing invasion of the organisms (Wittmann 2007). During the following decades, as a result of increasing navigation traffic and the opening of new navigation routes, several Eurasian nonindigenous species (mussels (*Dreissena polymorpha, D. bugensis*), crustaceans (*Nitocra incerta*, *Schizopera borutzkyi*, *Cercopagis pengoi*, *Echinogammarus ischnus*), and fishes (*Neogobius malanostomus*, *Proterorhinus marmoratus*)) were able to extend their distribution outside of their watershed, invade central and western European waters and subsequently the Great Lakes (Grigorovich *et al.* 2003, Pothoven *et al.* 2007). Among mysids, four species were particularly successful in their expansion into central and western Europe: *Hemimysis anomala*, *Paramysis lacustris*, *Katamysis warpachowskyi* and *Limnomysis benedeni* (Wittmann 2007).

In the 1950s and 1960s, *H. anomala* was intentionally introduced into several impoundments on the River Dniepr (Ukraine), water reservoirs near Chernorechensk and Simferopol on the Crimean peninsula, and the Dubossary reservoir (Moldavia) (Zhuravel 1960, Komarova 1991). In 1962, *H. anomala* was first found outside of the Ponto-

Caspian basin when it was transferred from the Dniepr hydropower reservoir to reservoirs in Lithuania (Kaunass reservoir on the River Nemunas) (Gasiunas 1968, Mordukhai-Boltovskoi 1979). Further expansion in Europe was reported for the Baltic Sea (1992, Salemaa & Hietalahti (1993)), the River Rhine and Danube basin (1997-1998, (Wittmann 2007)), and the United Kingdom English Midlands (2004, (Holdich *et al.* 2006)) (see Table 1 for a summary of occurrence). Based on information from the mitochondrial DNA of *H. anomala*, Audzijonytes *et al.* (2007) were able to identify two routes of invasion into northern and western Europe (Fig. 3). The first route started in the lower Dnieper River (northwest Black Sea) and expanded toward the Baltic Sea and further to the Rhine delta. Another distinct pathway occurred from the Danube Delta and spread across the continent via the Danube River and down to the River Rhine via the Danube canal. The Danube lineage was responsible for the invasion of England and North America (Audzijonytes *et al.* 2007). According to the most recent samples analyzed, both lineages are now mixed in Europe (Audzijonytes *et al.* 2007).

5.3-Non-Native Distribution and Invasion History in North America

The invasion of *H. anomala* along with 16 other Ponto-Caspian species was predicted in the Great Lakes basin, via direct transmission from the Ponto Caspian basin or by secondary invasion sites (Ricciardi & Rasmussen 1998, Grigorovich *et al.* 2003), despite the ballast water-regulations implemented in 1993. In 2006, the first occurrence of *H. anomala* was reported in the Lake Michigan basin, near Muskegon Lake (Pothoven *et al.* 2007) and in southern Lake Ontario at Nine Mile Point near Oswego, NY (Kipp & Ricciardi 2007). These occurrences very likely resulted from ballast water release from transoceanic ships (Kipp & Ricciardi 2007). Because of concealment behaviour and difficulty collecting *H. anomala* using traditional net tows, it is possible that its invasion remained undetected for many years in the Great Lakes (Reid *et al.* 2007). Previous study has shown the similarity in the invasion pattern between *H. anomala* and *Echinogammarus ischnus* (Cristescu *et al.* 2004) and it is likely that both organisms were introduced into the Great Lakes during the same time period (1998), when *E. ischnus* was first reported (Pothoven *et al.* 2007). Over the last two years, three of the Great Lakes (Michigan, Erie and Ontario) have been confirmed as invaded (Fig. 4, Table 2).

Today, there is considerable effort in place to report *H. anomala* sightings in the Great Lakes basin via the *Hemimysis anomala* Survey & Network (National Center for research on Aquatic Invasive Species 2007). New confirmed and potential sightings can be reported at mysis.glerl@noaa.gov and this information is used to update the list of sites of occurrence for the Great Lakes.

6-BIOLOGY AND NATURAL HISTORY

6.1-Reproduction and Growth

H. anomala, as with all peracarid crustaceans, requires sexual reproduction. *H. anomala* breeds from April to September/October. Water temperature has an important effect on the development of *H. anomala* by limiting the number of broods per year (2-4, Ioffe 1973) and could therefore limit its expansion into colder areas. According to Mordukhai-Boltovskoi (1960), most female *H. anomala* from the Caspian region produce at least two broods, although more studies should be conducted on this topic as the number of generations per year remains uncertain (Borcherding *et al.* 2006). Ovigerous females generally appear when the water temperature reaches 8-9°C and neonates can be observed in the marsupium when the temperature reaches 11-12°C. Given these temperatures, *H. anomala* breeds from April to September in the Biesbosch reservoirs (The Netherlands) (Ketelaars *et al.* 1999), although ovigerous females were found as late as November in Lake Michigan (Pothoven *et al.* 2007). In the Baltic Sea, breeding females were found in October and fully developed ovocytes were observed in late April, indicating the long breeding period for *H. anomala* compared to other mysids found in the northern Baltic (Salemaa & Hietalahti 1993). Variation in brood size has been reported according to seasons with higher brood size in the spring (29±10.9) compared to the end of summer (20±3.6) (Borcherding *et al.* 2006). The number of eggs per brood generally varies from 2 to 70 and is correlated to female length (Ketelaars *et al.* 1999; Salemaa & Hietalahti 1993, Borcherding *et al.* 2006, Pothoven 2007). Specifically, based on data retrieve from Ketelaars *et al.* (1999), brood size (number of marsupial oostegites) can be predicted using the following linear regression model based on female length (mm) (Fig. 5):

$$\text{Brood size} = -14.2 + 3.7 \times \text{Length} \qquad (r^2=0.45, n=120, p<0.0001)$$

There is no evidence that this equation could be applied to the Great Lakes where the mean size of *H. anomala* is smaller than measured in Europe (Pothoven *et al.* 2007). Further sampling would be required to collect a larger number of individuals (only two samples were collected in November 2006, Grigorovich (Wilson Environmental Laboratories) pers. comm.).

The development of young individuals does not require a naupliar stage but instead directly follows several life instars that are differentiated according to body length. The number of stages varies from 4 to 6, depending on authors and/or *Mysis* species (Borodich & Havlena 1973). After 45 days, at the end of stage IV, the individuals reach sexual maturity. Similarly to all arthropods, *H. anomala* has a chitinous exuvia that sheds during growth.

6.2-Population Dynamics

The number of organisms found at a given site varies greatly, which limits our ability to produce reliable density estimates. In the Great Lakes, the finding of a single organism is often reported although higher densities, comparable to that of eastern Europe, have been reported in Lake Michigan (Table 2) (Pothoven *et al.* 2007). Extremely high densities of *H. anomala*, up to >6 ind·L^{-1}, were recorded in eastern Europe reservoirs (Ketelaars *et al.* 1999). Within a population of *H. anomala*, the density of adults is generally greatest from November to the end of summer (Ketelaars *et al.* 1999). During this time period, the number of females is generally greater than males (Ketelaars *et al.* 1999). Similar variations in sex ratio were also reported in the Great Lakes (Pothoven *et al.* 2007) (Fig. 6) and may be related to male mortality after breeding and longer lifespan of females compared to males (Ketelaars *et al.* 1999).

Borcherding (2006) reported changes in the length-weight relationship of virgin females based on sampling periods (see Fig. 3 in Borcherding et al. (2006)). Although relationships of each sampling period were statistically significant, it is important to note that they differed greatly in their portion of explained variance (from 9 to 56%). Based on the overall data set, a better length-weight relationship could be constructed as follows (Fig. 7):

$$\text{Log}_{10}\ \text{Wet weight} = -2.78 + 2.26 \times \text{Log}_{10}\ \text{Length} \qquad (r^2=0.6,\ n=158,\ p<0.0001)$$

In this equation, units are in mg and µm for weight and length respectively. The length was measured from the tip of the rostrum to the tip of the telson.

6.3-Physiological Tolerances and Behaviour

The main hydrological and physiological characteristics of a series of eastern European ecosystems with *Hemimysis* are presented in Wittmann (2007) (Table 3). Although most mysids are found in marine environments, *H. anomala* is a brackish-water species, able to adapt to freshwater, shown by its invasion of various types of aquatic systems (seas, coastal shores, rivers, reservoirs and lakes). It is generally recognized that *H. anomala* is not sensitive to environmental variations which increases its probability of further expanding its distribution. For instance, in contrast with most other mysids, *H. anomala* has the ability (along with *E. ischnus*) to survive and reproduce under a wide range of salinities (from 0.1 to 18, Table 3) (Wittmann 2007), which may have facilitated its survival during intercontinental transportation in ballast waters (Pothoven *et al.* 2007, Reid *et al.* 2007).

Water temperature is reported to influence *H. anomala* development and growth. Based on field observations, this organism has been reported to occur in water temperature ranging from 0-28°C, however, its preferred temperature range is 9-20°C (Ioffe 1973, Kipp & Ricciardi 2007). As previously mentioned, low temperatures have been related to decreases in the number of eggs per broods (Ioffe 1973). Low temperatures may also reduce the growth rate of adults by direct physiological effects or indirectly by reducing the food resources available (Borcherding *et al.* 2006). Populations are able to survive over the winter when water temperatures approach zero, but not without substantial mortality (Borcherding *et al.* 2006). However, Dumont (2006) observed large and active swarms under cold water conditions (3°C) and even under frozen lake surfaces.

6.4-Habitat

H. anomala is ubiquitous to all types of water-bodies from salt to freshwater. It is a sublittoral species (Salemaa & Hietalahti 1993), living in a wide range of depths (from the surface to 50m). In Lake Reeserward (Germany), *Hemimysis anomala* was mostly found in surface waters (0-3 m) and mid-depth waters (4.5-9 m) (Borcherding *et al.* 2006). A deeper depth distribution has, however, been occasionally reported (20 m in the Black Sea, 30 m in the Caspian Sea (Bacescu 1954) and up to 50m in the Dnieper reservoir (Zhuravel 1960)).

H. anomala is nektonic and actively swims back and forth within a swarm (Salemaa & Hietalahti 1993) that can be abundant enough to occupy several squares meters of area (Dumont 2006). *H. anomala* can move very quickly in the water column, up to a speed of several centimeters per second (Borcherding *et al.* 2006). Because of its fast reaction to disturbance, sampling methods used for mysids may be inadequate and should be adapted to fast swimming organisms (Borcherding *et al.* 2006). The swarm avoids direct light and high flow velocity by aggregating above deep sediments or under rocks, in cavities or cracks and crevices during the day and disperses at night to feed in the sublittoral zone (Salemaa & Hietalahti 1993, Dumont 2006). When at the bottom, *H anomala* was found on hard/rocky sediment rather than on soft/silty substrate (Pothoven *et al.* 2007). In addition, *H anomala* is scarcely found in sites with dense vegetation (Pothoven *et al.* 2007). In many cases, *H. anomala* was found in anthropogenic habitats consisting of massive concrete shores (Pothoven *et al.* 2007, Wittmann 2007). In particular, most observations of *H. anomala* in Europe have been reported from harbours, reinforcing the hypothesis of ballast water release as a vector of introduction. The concealment behaviour makes *H. anomala* difficult to locate during the day, possibly explaining why it was not found earlier in the Great Lakes (Reid *et al.* 2007). Further, the concealment behaviour of *H. anomala* indicates a preference for slow moving waters, suggesting that flow velocity may limit the expansion of this organism. Again, no data are available to support this hypothesis but flow may be a variable to consider when localizing potential sites of invasions.

Adult *H. anomala* migrates diurnally in the water column. During daylight, swarms remain in dark areas but migrate to the upper water column at dusk where they feed during the night until morning (Janas & Wysocki 2005, Borcherding *et al.* 2006) (Fig. 8). Juveniles do not migrate as much as adults because of their transparency, which make them less vulnerable to predation in the upper water column (Borcherding *et al.* 2006).

6.5-Feeding and Diet

To feed, *H. anomala* uses its thoracic limbs to capture preys with its endopods or to remove food particles from its body that are filtered by its exopods (Ketelaars *et al.* 1999, Borcherding *et al.* 2006). *H. anomala* may play a critical role in food web dynamics because it serves as a link between primary and secondary producers. It is able to adapt its feeding behaviour depending on food availability and exhibits ontogenetic changes in diet (Borcherding *et al.* 2006, Pothoven *et al.* 2007). *H. anomala* is generally reported as an omnivorous organism, with a high feeding rate (Ketelaars *et al.* 1999), feeding primarily on cladocerans zooplankton (*Daphnia* and *Bosmina*) and copepods and rotifers (Borcherding *et al.* 2006). According to Dumont (2006), *H. anomala* could also be detritivorous and cannibalistic. Based on gut content analysis from the Reesevard (Rhine region, Germany), detritus, phytoplankton (mainly diatoms and green algae), insect larvae may also be part of the diet of *H. anomala* (Borcherding *et al.* 2006). Feeding behaviour differs according to age with younger organisms (<4 mm length) relying to a larger degree (11 %) on algal material than adults (4 %). In contrast, the proportion of zooplankton in the diet reaches 26% for adults compared to 9 % for juveniles (Borcherding *et al.* 2006). Most of the variation in the feeding behaviour of large *H. anomala* is related to light conditions. During the day, the content of algal material in adults gut was significantly higher; the proportion of detritus increased with depth. The proportion of zooplankton in the stomach of large organisms was higher at night (Borcherding *et al.* 2006).

7-CONSERVATION STATUS

H. 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 (Alexandrov 1999, Pothoven *et al.* 2007). *Hemimysis anomala* has been classified with a global conservation status of G5 (globally secure) (NatureServe 2007). The conservation status for the North America has not been assessed yet as the result of incomplete/unavailable information.

8-IMPACTS ASSOCIATED WITH INTODUCTION

The early intentional introduction of *H. anomala* in lakes and reservoirs of Eurasia were intended to increase fish production. *H. anomala*, a lipid-rich organism, is comparable to fish or *M. relicta* as a high-quality energy food source (Borcherding *et al.* 2006). In the River Rhine, the contribution of *H. anomala* as prey for young-of-year (YOY) perch (*Perca fluviatilis*) varies from 20 to 100% (Borcherding *et al.* 2006). Further, based on a feeding experiment, YOY perch grew extremely fast when feeding on *H. anomala* (Borcherding *et al.* 2007). Stomach contents of Lake whitefish (*Coregonus clupeaformis*), contained no *H. anomala* in sites were the invader was found in Lake Michigan (Pothoven *et al.* 2007). Nonetheless, although not yet reported in the literature, fish predation may limit the abundance of *H. anomala* and possibly explain why this invader is currently endangered in its native locations (J. Wittmann (Department of Ecotoxicology, Medical University of Vienna), pers. comm.). Parasitism may also threaten H. anomala from its native locations, with rust spotted illness that is a widespread illness in the Volga River basin and found in some individuals (Ioffe et *al.*, 1968).

H. anomala is omnivorous, with a high feeding rate and a reproductive rate of more than two broods per year (Ketelaars *et al.* 1999). In the Biesbosch reservoir (The Netherlands), the invasion of *H. anomala* caused a decline in both zooplankton and phytoplankton biomass (Ketelaars *et al.* 1999). Zooplankton community changes consisted in the disappearance of several cladocerans (*Daphnia sp., Bosmina sp.*) as well as rotifers and ostracods. Furthermore, carnivorous zooplankton (*Bythotrephes longimanus* and *Leptodora kindti*) also disappeared from this system, likely the result of resource competition and direct predation (Ketelaars *et al.* 1999). Based on laboratory feeding experiments, Ketelaars et *al.* (1999) found all zooplankton groups in the gut content of *H. anomala*, including predatory species. Uncertainties regarding the top-down effects of *H. anomala* on zooplankton exist when algal production is low and therefore limits zooplankton production (Ketelaars *et al.* 1999). In addition, possible effect of the decrease in zooplankton density on fish production because of *H. anomala* remains unknown and requires further study. Finally, further studies on the diet of *H. anomala* are required as current dataset are based on the analysis of a small number of organisms, over a rather short time period and for a limited number of ecosystems.

The predation of *H. anomala* on zooplankton also affects primary producers (Borcherding *et al.* 2006). This top-down interaction has been observed after the introduction of *Mysis relicta* in several ecosystems (Lasenby *et al.* 1986) and was responsible for the doubling of algal biomass in a Norwegian lake (Koksvik *et al.* 1999), suggesting the potential effect of invaders controlling primary producers via the reduction of grazing pressure. Grazing experiments and gut content analysis revealed the ability of *H. anomala* to feed on algal material (Ketelaars *et al.* 1999, Borcherding *et al.* 2006). Ketelaars et *al.* (1999) suggested that adult *H. anomala* may switch their diet toward algae when zooplankton production is low. As previously discussed, algae represents the preferred food for juveniles compared to adults (Borcherding *et al.* 2006). Therefore, the effect of *H. anomala* on algae depends on the abundance of young individuals and on the abundance of zooplankton as a food source for adults.

Although not specific to *H. anomala*, Ponto-Caspian invaders have also induced modifications to the physico-chemical properties of ecosystems (Leppäkoski & Olenin 2000, Ojaveer *et al.* 2002, Ricciardi 2007). As a result of its high predation rate relative to other mysids, the production of fecal pellets by *H. anomala* may increase the concentration of surface water nutrients (Ricciardi 2007). Additional release of dissolved organic compounds may also occur in systems where juvenile *Hemimysis* are present via their consumption of algal material (Ricciardi 2007).

In the Great Lakes, no effect on the food web has been detected following the occurrence of *H. anomala*, despite the many predicted consequences of its invasion (Ricciardi 2007). When a lack of information exists on the effects of a given invader in a given region, it is possible to predict its potential effects by 1- considering the reported effect of the organism in other regions where an invasion has already occurred and 2- by considering the effects of other similar invaders already present in the system. Based on these 2 empirical approaches, Ricciardi (2007) identified several possible threats of *H. anomala* invasion to the Great Lakes, summarized in Fig. 9.

The success of a new invader is usually dictated by its ability to occupy an ecological niche that is not already used by resident species (Ricciardi & Atkinson 2004). Ponto-Caspian species are phylogenetically (Audzijonyte *et al.* 2007) and ecologically (Ricciardi 2007) distinct from native species of the Great Lakes and therefore may find little barriers to their expansion. For example, *Mysis* are usually considered deep-water species, living in the hypolimnion and therefore have a restricted effect on the overall water column. In contrast, *H. anomala* is found in a wide range of depths, from pelagic to sublittoral habitats. Its concealment behaviour and/or deep-water migration during the day allow this organism to avoid fish predation and access resources in the surface water layers during the night. In addition to the predicted cascading effects of *H. anomala* on the food web of the Great Lakes, the invasion of *H. anomala* may increase the biomanification of contaminants in high trophic levels (Ricciardi 2007). For instance, previous studies have shown the importance of *Mysis* to increased mercury contamination in fishes by feeding in the littoral zone of lakes (Cabana *et al.* 1994).

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Table 1: Locality, year of collection and of the first literature record. Number refers to sites presented in Figure 3. River kilometers are numbered by convention in downstream (*) or upstream (†) order. S (‰), salinity in parts per thousand. Modified from Audzijonyte *et al.* (2007).

No.	Locality	S‰	Latitude	Longitude	Year	n	First record	Reference
Ponto-Caspian native range								
1	Russia: Caspiam Sea basin, Volga delta	<1	45.83	47.84	2003	5	2003	(Audzijonyte *et al.* 2007)
2	Russia: Sea of Azov basin, Don delta	<1	47.17	39.33	2003	3	1930s	(Mordukhai-Boltovskoi 1939)
3	Ukraine: Black Sea basin, Dnieper delta	<1	46.6	32.58	2004	3	1957	(Zhuravel 1959)
4	Ukraine: Black Sea basin, Dnieper delta	<1	46.38	30.27	2005	5	1936	(Bacescu 1940)
5	Romania: Black Sea basin, Danube delta	<1	45.16	29.66	2006	3	≤1953	(Bacescu 1954)
Invaded localities								
6	Lithuania: Kaunas water reservoir	<1	54.89	24.04	2004	5	1967	(Gasiunas 1968)
7	Finland: Tvärminne, Gulf of Finland, Baltic Sea	6–7	59.92	23.45	2005	9	1992	(Salemaa & Hietalahti 1993)
8	Poland: Gulf of Gdansk, Baltic Sea	6–8	54.55	18.56	2006	10	2002	(Janas & Wysocki 2005)
9	Germany: Lake Schwerin, Mecklenburg-Vorpommern	<1	53.63	11.45	2005	8	2001	(Zettler 2002)
10	UK: Holme Pierrepont, Nottingham, England	<1	52.94	-1.1	2006	8	2004	(Holdich *et al.* 2006)
11	USA: Muskegon Channel, Lake Michigan, Michigan	<1	43.23	-86.34	2006–07	9	2006	(Pothoven *et al.* 2007)
12	The Netherlands: Rhine Delta, Maas, Biesbosch reservoir	~1	51.76	4.76	1998	2	1997	(Faasse 1998)
13	The Netherlands: near Dintel River, Rhine delta	1–2	51.66	4.37	2005	5	1998	(Kelleher *et al.* 1999)
14	Germany: Bad Honnef, Lower Rhine (rkm 640)*	0	50.63	7.21	2005	7	1997	(Schleuter *et al.* 1998)
15	Germany: Mittellandkanal between Weser and Ems rivers	1	52.31	7.63	2005	5	2001	(Rehage & Terlutter 2002)
16	Austria: Linz, Upper Danube (rkm 2133)†	0	48.32	14.31	2005	6	1998	(Wittmann *et al.* 1999)
17	Austria: Vienna, Upper Danube (rkm 1935)†	0	48.28	16.36	2005–06	13	1998	(Wittmann *et al.* 1999)
18	Hungary: Dunaújváros, Middle Danube (rkm 1578)†	0	46.96	18.96	2005	6	2005	(Wittmann 2007)
19	Serbia: Veliko Gradiste, Middle Danube (rkm 1059)†	0	44.77	21.52	2005–06	13	2005	(Wittmann 2007)
20	Bulgaria: Lower Danube (rkm 625)†	0	43.75	24.57	2006	3	2006	(Audzijonyte *et al.* 2007)
21	Romania: Lower Danube (rkm 299)†	0	44.35	28.02	2006	1	2006	(Audzijonyte *et al.* 2007)

Table 2: Summary of monitored sites in the Great Lake Basin (Source: National Center for research on Aquatic Invasive Species 2007). USGS: United States Geological Survey, DFO: Department of Fisheries and Oceans Canada, OMNR: Ontario Ministry of Natural Resources, INSH: Illinois Natural History Survey, NOAA GLERL: National Oceanic and Atmospheric Administration- Great Lakes Environmental Research Laboratory.

Region	Country	State or province	City	Source	Depth	Method of collection	Date	Presence/Absence	Number of specimens
Lake Erie	USA	NY	Dunkirk	USGS			Apr-07	**P**	1
	Canada	ON	Kingsville	DFO	25-50 cm above bottom	Bottle traps (12-24 hours) and zooplankton net (night)	20-Aug-07	**P**	
	Canada	ON	Port Dover	OMNR	5.5 m	White perch gut content	01-Aug-06	**P**	
	Canada	ON	Port Stanley	DFO	25-50 cm above bottom	Bottle traps (12-14 hours) and zooplankton net (night)	22-Aug-07	**P**	
	USA	PA	Presque Ile			Bottle traps	summer-fall 2007	**A**	
	USA	OH	Toledo			Dipnet sweeps	12-Nov-06	**A**	
Lake Huron	USA	MI	Thunder Bay, Alpena			Plankton tows and bottle traps	May-07	**A**	
Lake Huron-Georgian Bay	Canada	ON	Bying Inlet / Britt dock	DFO			10-Jul-07	**A**	
	Canada	ON	Midland Docks	DFO			11-Jul-07	**A**	
	Canada	ON	Parry Sound CG dock	DFO			09-Jul-07	**A**	
	Canada	ON	Penetanguishene	DFO			12-Jul-07	**A**	
	Canada	ON	Point Au Baril	DFO			10-Jul-07	**A**	
	Canada	ON	Snug Harbour	DFO			10-Jul-07	**A**	
Lake Michigan	USA	MI	Charlevoix			Multiple triplicate 500 micron vertical net hauls	Jun-07	**A**	
	USA	IL	Chicago	INHS	7m	Neuston net towat the surface	31-Jul-07	**P**	1
	USA	MI	Elk Rapids	DFO			21-Jun-07	**A**	
	USA	MI	Escanaba	DFO	bottom of lake	Night sampling with a zooplanton net	24-Jun-07	**P**	
	USA	MI	Grand Haven					**P**	
	USA	MI	Ludington	DFO			20-Jun-07	**A**	
	USA	MI	Milwaukee	DFO		Pictures taken from divers	01-Aug-07	**P**	3
	USA	MI	Milwaukee	DFO	bottom of lake	Night sampling with zooplankton net	26-Jun-07	**P**	
	USA	MI	Donges Bay	Janssen		Trap and scuba observation	04-Sep-07	**P**	2 in trap 3 seen
	USA	MI	Bradford Beach	Janssen		Trap	27-Sep-07	**P**	15
	USA	MI	Muskegon	NOAA GLERL			07-Nov-06	**P**	1540 ± 333 individuals/m2

Table 2 (continuation)

Region	Country	State or province	City	Source	Depth	Method of collection	Date	Presence/Absence	number of specimens
Lake Michigan	USA	MI	Naubinway	DFO	25-50 cm above bottom	Bottle traps (12-14 hours) and zooplankton net (night)	22-Jun-07	**P**	
	USA	WI	Rowleys Bay	DFO	bottom of lake	Night sampling with zooplankton net	25-Jun-07	**P**	
	USA	WI	Sheboygan			Brown Trout gut content - may have been *Mysis relicta*	10-Mar-07	**P?**	
	USA	IL	Waukegan		10 ft	Yellow Perch gut contents	25-Sep-07	**P?**	
	USA	IL	Waukegan		9m	Yellow Perch gut contents	15-Aug-07	**P?**	
	USA	MI	West Traverse Bay			Multiple triplicate 500 micron vertical net hauls and bottle traps	Jun-07	**P**	
Lake Ontario	Canada	ON	Bowmanville	OMNR		Night nearshore surface tows	Sep-07	**A**	
	Canada	ON	Cobourg	OMNR		Night nearshore surface tows	Sep-07	**P**	
	Canada	ON	Collins Bay	OMNR		Night nearshore surface tows	Sep-07	**A**	
	Canada	ON	Hamilton Harbour, Burlington	DFO	2-3 m	Bottle traps	June 14	**P**	1
	Canada	ON	Hamilton Harbour, Burlington	DFO	2-3 m	Bottle traps	June 20	**P**	1
	Canada	ON	Hamilton Harbour, Burlington	DFO	25-50 cm above bottom	Bottle traps (12-14 hours) and zooplankton net (night)	June 15 & July 4	**P**	
	Canada	ON	Long Point	OMNR		Night nearshore surface tows	Sep-07	**A**	
	USA	NY	Olcott		1 m	Bottle traps	27-Jun-07	**P**	1
	USA	NY	Oswego	Normandeau Ass.	6m	Gillnets set overnight over rocky substrate	May-06	**P**	150
	Canada	ON	Pickering	OMNR		Found in the intake water samples at Pickering Nuclear Generating Station	Nov 22 & Dec 6, 2006	**P**	14

Table 2 (continuation)

Region	Country	State or province	City	Source	Depth	Method of collection	Date	Presence/Absence	number of specimens
Lake Ontario	Canada	ON	Presque Ile	OMNR		Night nearshore surface tows	Sep-07	**P**	
	Canada	ON	Whitby	OMNR		Night nearshore surface tows	Sep-07	**P**	
Lake St. Clair	Canada	ON	Lighthouse Cove and Belle River Marina	DFO			25-Jul-07	**A**	
Detroit River	Canada	ON	Windsor	DFO			July 16-17, 2007	**A**	
	Canada	ON	LaSalle	DFO			17-Jul-07	**A**	
	Canada	ON	Amherstburg	DFO			18-Jul-07	**A**	
St. Clair River	Canada	ON	Sarnia	DFO			July 23-24, 2007	**A**	
	Canada	ON	Port Lambton	DFO			25-Jul-07	**A**	
Welland Canal	Canada	ON	Port Colbourne	DFO	25-50 cm above bottom	Bottle traps (12-14 hours) and zooplankton net (night)	22-Aug-07	**P**	

Table 3: Hydrological and physicochemical characteristics of sampling stations from Eastern Europe where *Hemimysis anomala* (modified from Wittmann (2007)).

Variables	**Mean**	**St. Dev.**	**min.**	**max.**	**n**
All samples:					
Depth (m)	4.0	5.4	0	60	103
Water current ($m \cdot s^{-1}$)	0.2	0.2	0	0.8	98
Temperature (°C)	17.2	4.5	2	28	78
Salinity	2.1	4.2	0.1	18	87
Conductivity ($\mu S \cdot cm^{-1}$)	3792.0	6947.0	279	29200	87
pH	7.9	0.5	6.4	8.7	63
Carbonate hardness (°d)	8.6	975.0	6	12	60
Oxygen ($mg \cdot l^{-1}$)	7.2	1.4	4.0	10.8	63
Turbidity (NTU)	28.6	26.3	5	137	63
All regions, drift samples excluded:					
Water current ($m \cdot s^{-1}$)	0.0	0.1	0	0.4	69
All sample types, samples in the Caspian Lake excluded:					
Salinity	1.5	3.3	0.1	18	82
Conductivity ($\mu S \cdot cm^{-1}$)	2697.0	5486.0	279	29200	82

Figure 1: Close-ups of *Hemimysis anomala* (body size: 6 to 8 mm). Photo Credits: NOAA, Great Lakes Environmental Research Laboratory (http://www.glerl.noaa.gov/hemimysis/hemi_photo_gallery.html).

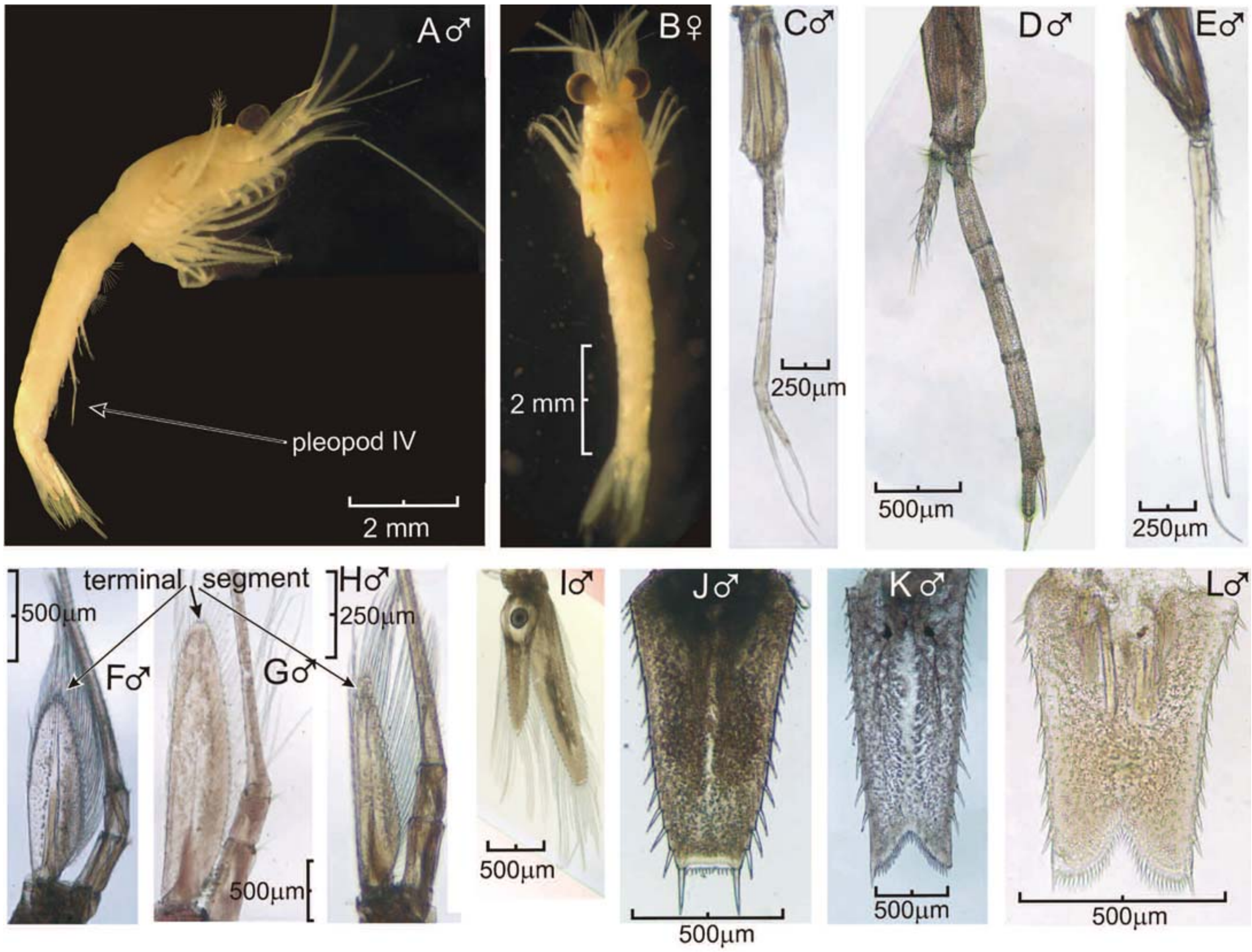

Figure 2: Morphological features of North American freshwater mysids. *Hemimysis anomala* from Lake Michigan basin: (A) lateral view, (B) dorsal view, (C) pleopod IV, (F) outer ramus of antenna II, (I) endopod of uropod, and (J) telson. Male *Mysis relicta* from Lake Superior: (D) pleopod IV, (G) outer ramus of antenna II, and (K) telson. Male *Taphromysis* from Mississippi River: (E) pleopod IV, (H) outer ramus of antenna II, and (L) telson. (reproduced from Pothoven *et al.* (2007)).

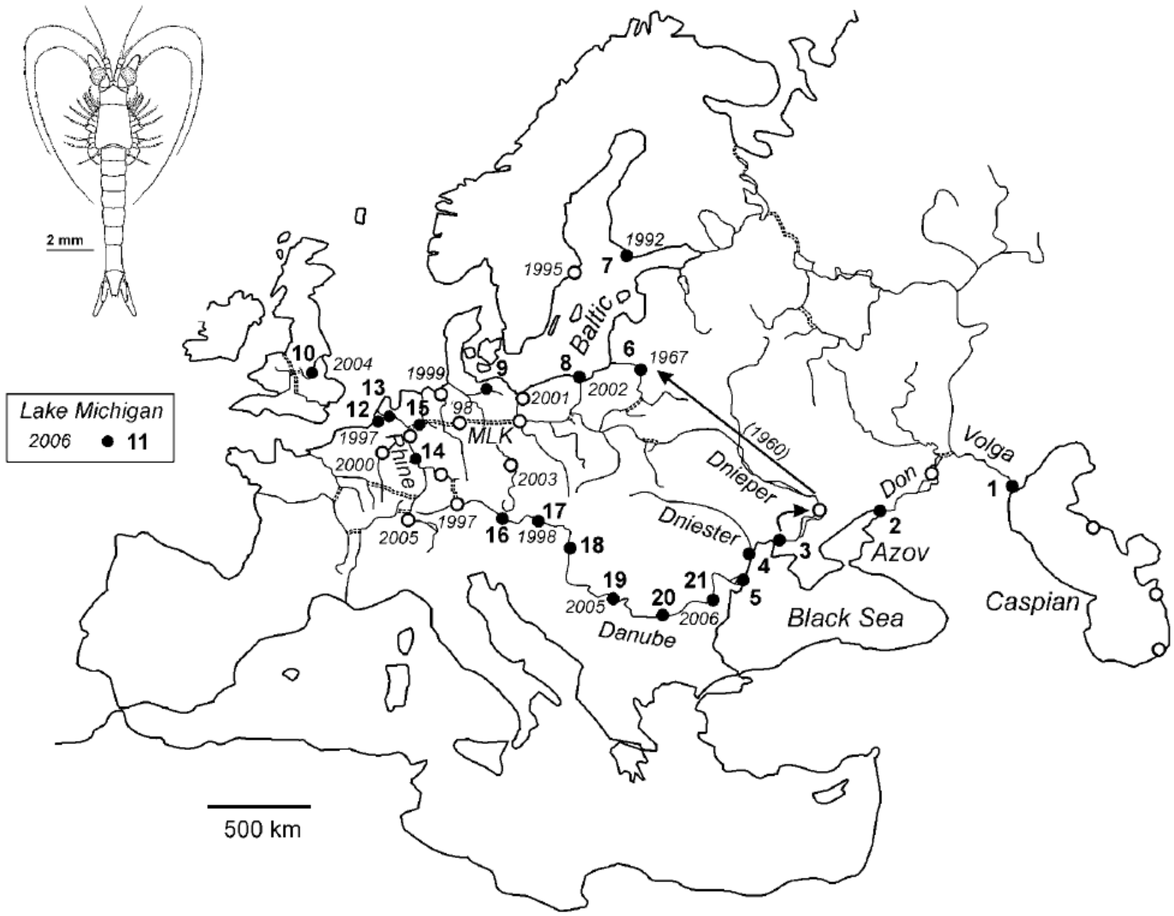

Figure 3: European distribution, range extension for *Hemimysis anomala*. Black symbols and bold numbers indicate samples used for genetic analysis in Audzijonyte *et al.* (2007). White symbols, italic numbers denote the year of the first finding (modified and updated after Wittmann, 2007), man-made canals are shown in dashed double lines. MLK, Mittellandkanal.

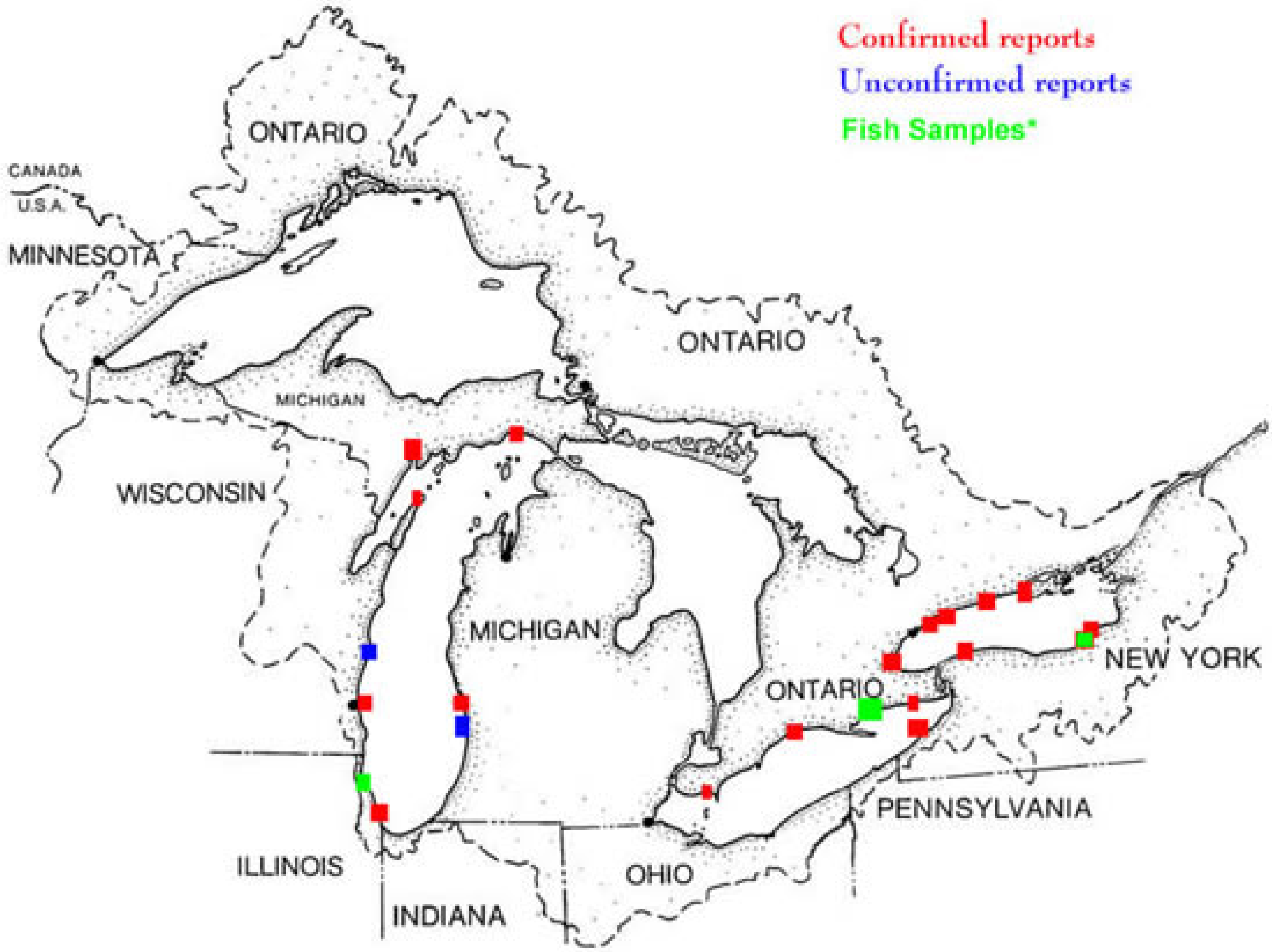

Figure 4: Map of site occurrence in the Great Lakes region. *Fish Samples are samples taken from the gut contents of fish which have been confirmed as *Hemimysis anomala*. Gut contents leave some uncertainty as to the exact location at which the fish may have consumed the shrimp. Source: NOAA, Great Lakes Environmental Research Laboratory web site (2007). (http://www.glerl.noaa.gov/hemimysis/hemi_reports.html)

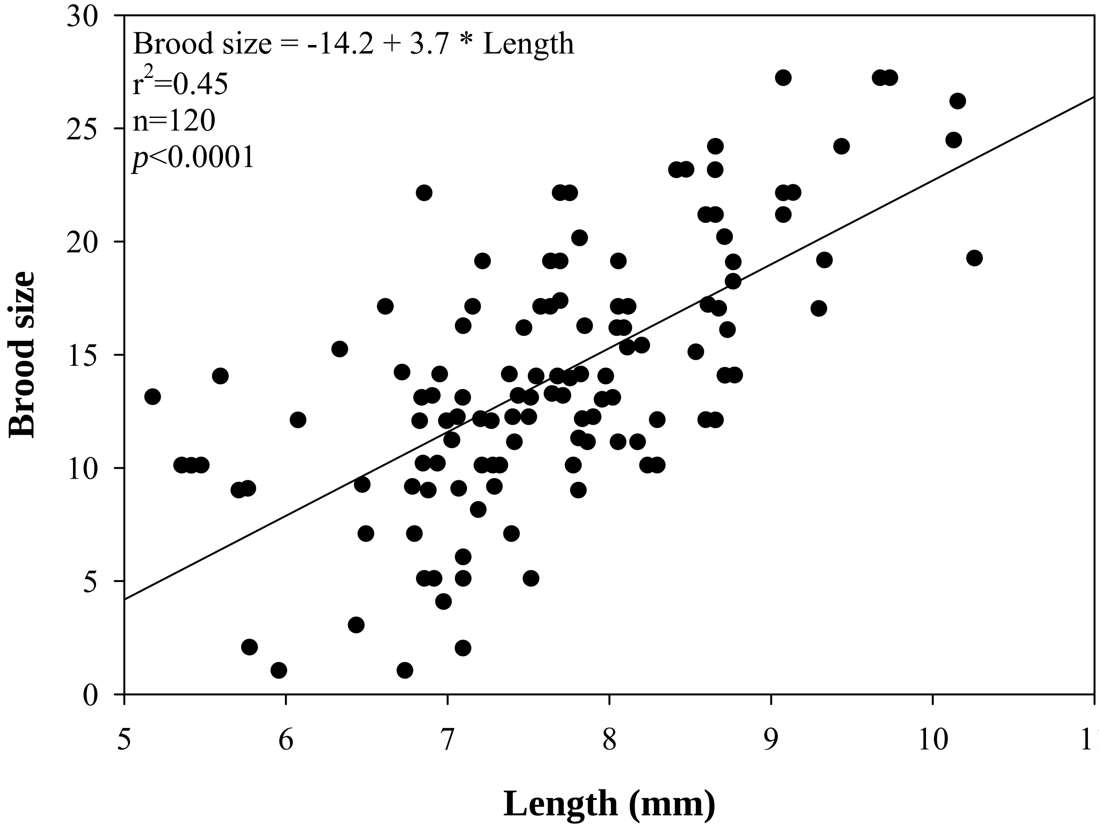

Figure 5: Simple linear relationship between *Hemimysis anomala* brood size (number of eggs) and female length. Modified from Ketelaars *et al.* (1999).

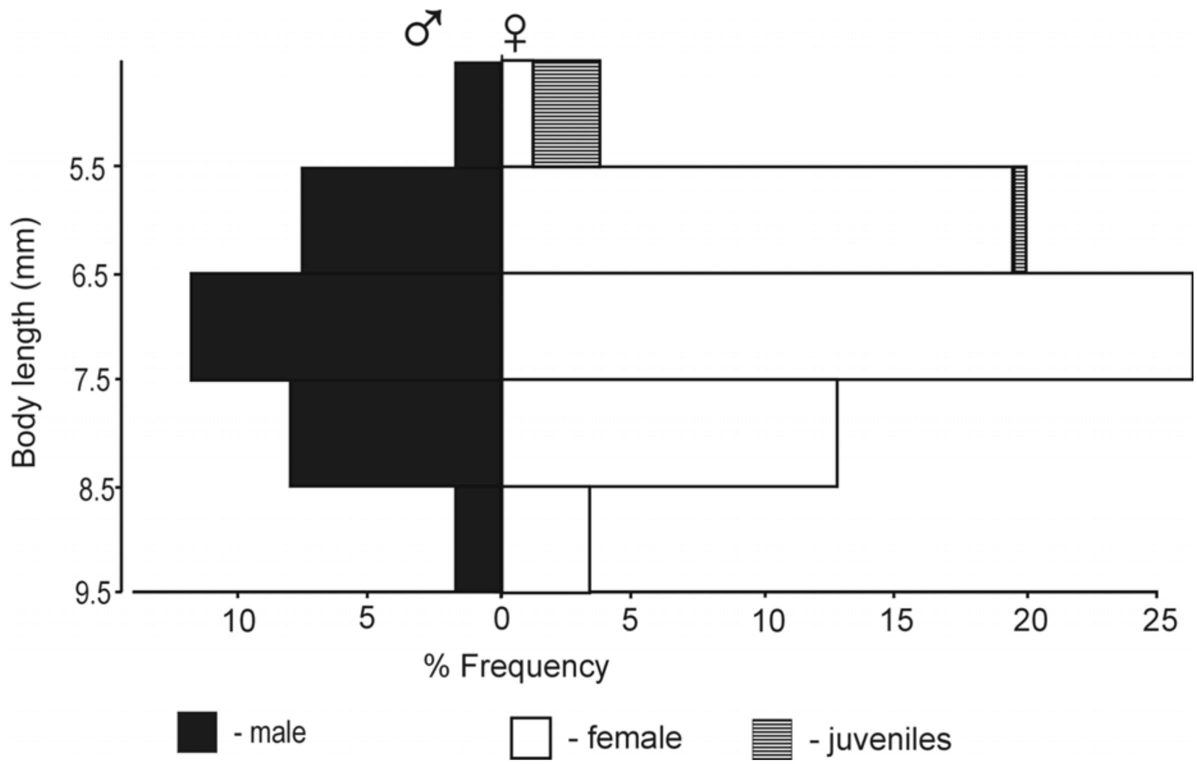

Figure 6: Length-frequency distribution of *Hemimysis anomala* in Lake Michigan basin in November 2006. n = 236. From Pothoven *et al.* (2007).

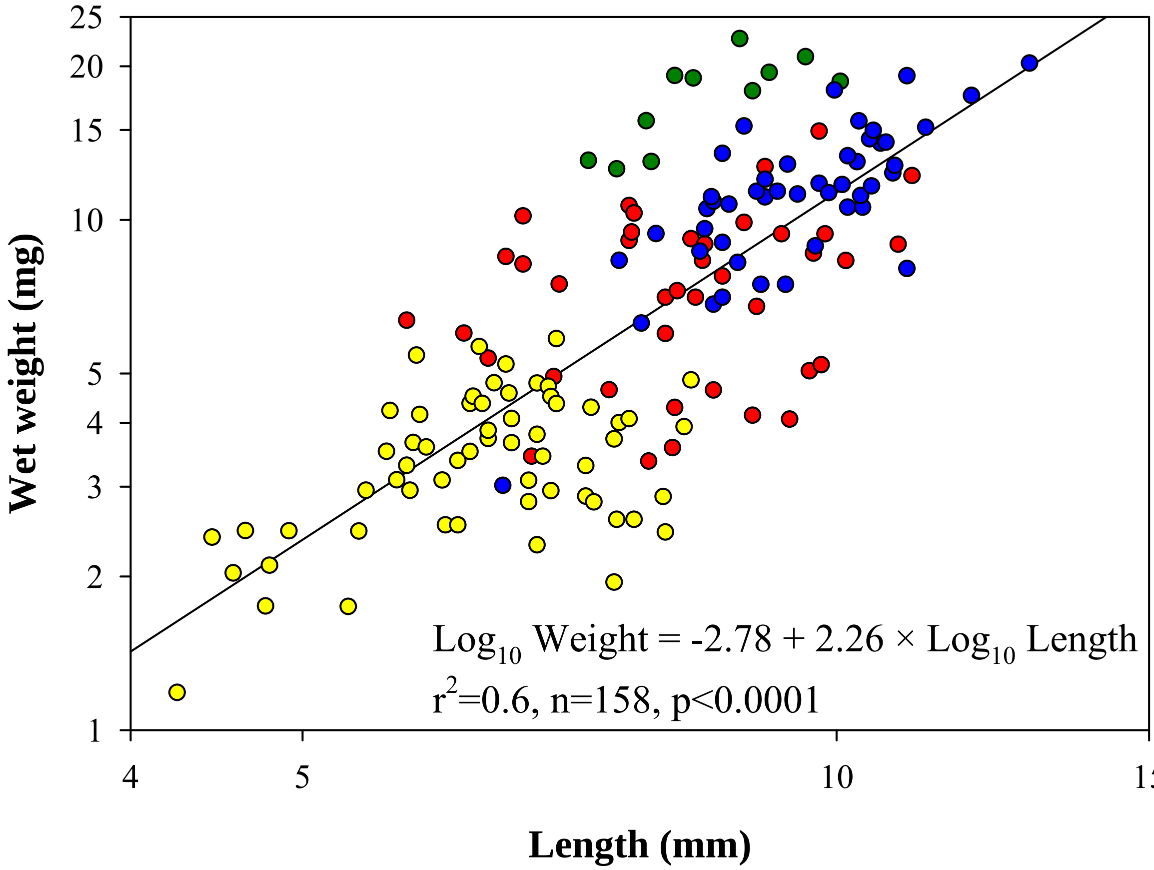

Figure 7: Length–weight relationships of *Hemimysis anomala* from Lake Reeserward (Lower Rhine, Germany), based on data from 4 sampling periods. Yellow: September 2002, Red: December 2002, Blue: February 2002 and Green: April 2003. Data retrieved from Borcherding *et al.* (2006).

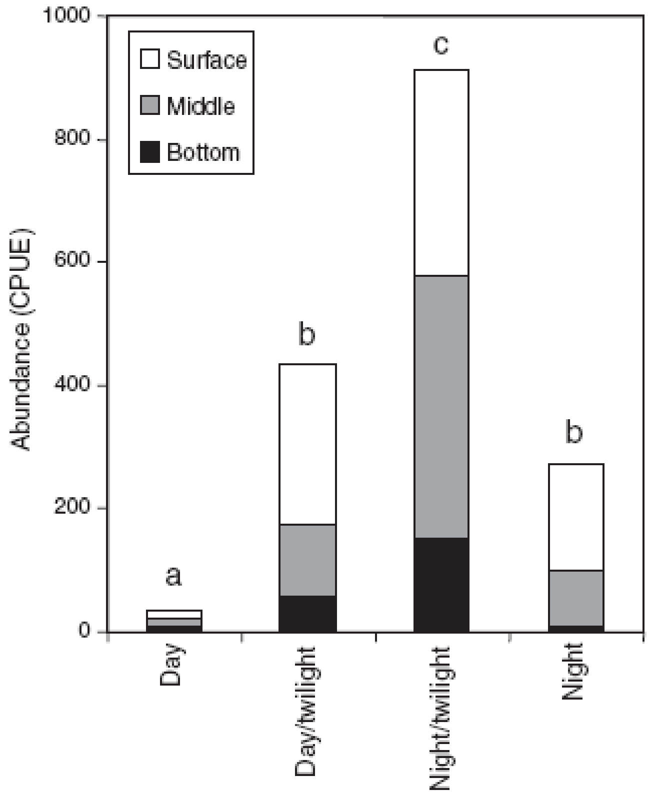

Figure 8: Mean abundance (CPUE) of *Hemimysis anomala* at three depth levels in Lake Reeserward for the different daylight conditions; significant differences are marked with small letters (Bonferroni post hoc test, P < 0.05). The time of day was characterised by four groups: day = the whole sampling period during the day; day/ twilight = the main part of the sampling period was during the day including a twilight period; night/ twilight = the main part of the sampling period was during the night including a twilight period; night =the whole sampling period occurred during the night. From Borcherding *et al.* (2006).

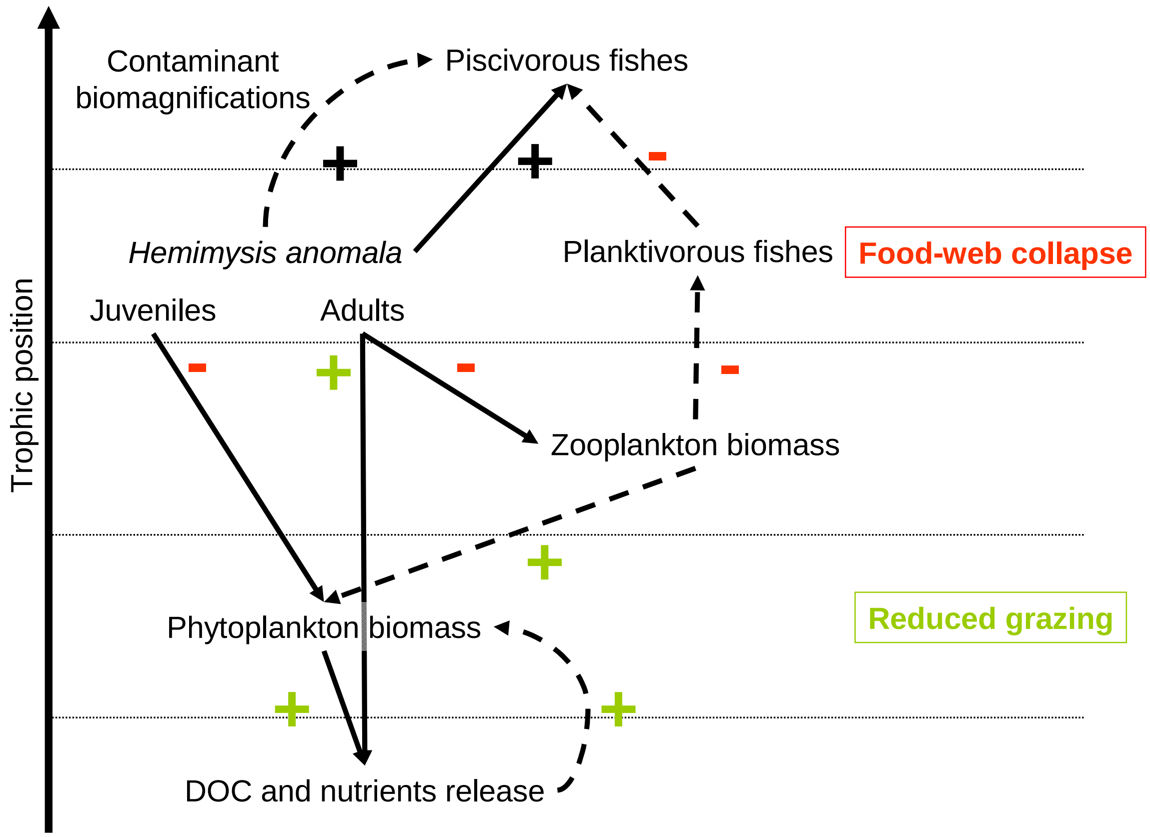

Figure 9: Trophic position of *Hemimysis anomala* in the food web and potential impacts (food web collapse, eutrophication and contaminant bioaccumulation) expected for the Great Lakes.