

An Overview of the Impacts of Eutrophication and Chemical Pollutants on Copepods of the Coastal Zone

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Nancy Marcus (2004) An overview of the impacts of eutrophication and chemical pollutants on copepods of the coastal zone. *Zoological Studies* 43(2): 211-217. During the last three decades, coastal zones around the globe have shown increasing evidence of degradation, primarily due to human activities. Eutrophication resulting from increased nutrient input and chemical pollution (e.g., heavy metals, organochlorine compounds, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons) from point and non-point sources are among the most serious threats to the health of coastal marine communities. This article summarizes our understanding of the impacts of eutrophication and chemical pollution on copepods with specific attention to those species that reside in the water column as nauplii, copepodites, and adults. Consideration is also given to the impact of these stressors on copepod resting eggs and the resulting population dynamics of the species. Based on the information available to date, future studies must address the sublethal effects that occur in response to chronic, low-dosage stressors and the impacts of multiple stressors working in concert. While every effort should be made to reduce degradation of marine environments, some evidence exists which suggests that copepods are capable of acclimating/adapting to some stressors, and that population levels may eventually return to pre-stress levels. <http://www.sinica.edu.tw/zool/zoolstud/43.2/211.pdf>

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During the last 3 decades, estuaries and other coastal zone systems around the globe have shown increasing evidence of degradation, primarily due to human activities. This is of great concern because these regions have enormous ecological and economic importance, e.g., they are widely recognized as essential nursery grounds for a variety of commercially important fish and invertebrates. Planktonic copepods are important components of marine pelagic food webs, especially in the rich productive estuaries of coastal regions. The nauplius stage is a key component of the diet of the many fish larvae that develop in inshore nursery habitats. While most of the life cycle of these copepods is spent in the water column, the eggs of some species sink to the seabed and remain dormant in the sediments for periods of days to years.

The international Group of Experts on the Scientific Aspects of Marine Environmental

Protection (GESAMP) has defined pollution as the "introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of seawater and reduction of amenities". This definition emphasizes the by-products of human activities. Two phenomena that fit this definition are eutrophication of coastal waters and the introduction of chemical toxicants into the marine environment. Eutrophication is the buildup of organic matter in a system (Nixon 1995, National Research Council 2000). Increased nutrient input stemming from human activity is a major cause of this enrichment. For example, the nutrient content of runoff that enters streams and ultimately coastal oceanic waters often originates from fertilizer used on agricultural lands. Hazardous chemical com-

pounds (e.g., heavy metals, organochlorine compounds, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons) originating from industrial activity also enter the marine environment. Eutrophication and chemical pollution are considered to be among the most serious threats to the health of coastal marine systems today (Kennish 1997, National Research Council 2000). Eutrophication is often accompanied by hypoxia and an increase in the abundance of nuisance algal species, in particular toxic phytoplankton taxa.

Scientific assessments of the biotic impacts of eutrophication and chemical pollution have usually focused on mortality of commercially important species. Moreover since widespread kills of fish and invertebrates (e.g., crabs and shrimps) are obvious to the eyes and nose, they have received considerable attention from the news media. Narrow attention to major mortality events of these taxa alone, however, likely misses subtle community- and ecosystem-level changes, which only become manifest after a long period of time. For instance it may take years for the sublethal impacts of stressors (e.g., hypoxia and toxicants) on individual development, growth, and reproductive rates to become evident at the community level. Moreover, eutrophication accompanied by changes in the species composition of the primary producers could lead to shifts in the zooplankton community. These bottom-up processes may eventually affect higher trophic levels. Shifts in the planktonic copepod community structure could have major impacts on fish populations since copepods are a major prey item in the diets of larval and juvenile fish.

This paper focuses on our current understanding of the impact of eutrophication and chemical pollution on marine copepod species that reside in the water column as nauplii, copepodites, and adults. Since some of these species have benthic resting eggs, it is necessary to consider processes taking place not only in the water column, but also on the seabed. The studies that I describe were selected to exemplify the effects of eutrophication and chemical pollution on copepods. This is not a comprehensive review of the available literature.

IMPACTS OF EUTROPHICATION

Eutrophication may affect copepods via several different mechanisms. Increased organic mat-

ter in the form of phytoplankton may initially be beneficial as it provides more food for grazing copepods. This was observed for the Japanese brackish-water system of Lake Shinji, Ohashi River, Lake Nakaumi, and Sakai Strait. A comparison of the mesozooplankton community of these waters in 1995-1997 to the community assemblage present 40 yr earlier revealed that an increase in biomass had occurred (Uye et al. 2000). If on the other hand, zooplankton grazing cannot keep pace with increased phytoplankton growth or there is a shift in species composition, an excessive buildup of organic matter followed by sedimentation to the seafloor may occur. A comparison of the plankton community structure of Osaka Bay, Japan to neighboring waters revealed that the primary production rate was highest in the inshore highly eutrophic area; yet net-zooplankton (which was dominated by copepods) was not abundant (Uye et al. 1999). The authors concluded that the net-zooplankton could not keep up with the production of phytoplankton, perhaps because the species composition had shifted to a size too small to be consumed by the copepods that dominated the net-zooplankton community. Hypoxic bottom waters were evident in Osaka Bay during the period of study in the 1990s as would be expected when too much organic matter sinks to the seabed. The impact of hypoxia on copepods is addressed below.

Since eutrophication is a process that typically takes place over many years, long-term data sets are necessary to demonstrate community-level changes in composition. Freshwater systems have received a great deal of study in this regard, and there is evidence of a shift in prominence from calanoid to cyclopoid copepods as lakes undergo eutrophication (e.g., Gannon and Stemberger 1978, Maier 1996); however I could only find a few "before and after" field studies that addressed these issues in coastal marine systems. Uye (1994) studied the structure of the summer copepod community in 2 eutrophic bays of Japan. A comparison of the results to data sets from 40 yr earlier revealed that the median body weight of the copepod community (derived from individual sizes) increased in the direction of offshore, and that the value for this parameter was also lower in Tokyo Bay compared to Osaka Bay. Tokyo Bay was considered more eutrophic because the nitrogen-loading rate was approximately 50% higher than in Osaka Bay. It was suggested that over time and thus with increasing eutrophication, there had been a general shift to smaller-sized copepods

with egg sacs, in particular the cyclopoid *Oithona davisae*. The prominence of this species was attributed to a change in the food spectrum (small flagellates became more abundant) and/or the fact that it does not spawn eggs into the water column. The recent behavioral work of Paffenhofer and Mazzocchi (2002) on *Oithona plumifera* supports the suggestion that small motile flagellates are the preferred prey of cyclopoids. The possession of egg sacs was cited as an advantage in regions that develop hypoxic/anoxic bottom waters as a result of eutrophication. Spawned eggs that fall to the sediments may be prevented from hatching due to reduced oxygen levels. Uye also suggested that the shift to smaller-sized copepods contributed to the decline in the bay's planktivorous fish populations due to "bottom-up" processes. However it is also possible that a "top-down" mechanism was responsible since predatory jellyfish had also become abundant. A study of another system however found no evidence of change in community structure accompanying eutrophication. A comparison of the mesozooplankton community of the Japanese brackish-water system of Lake Shinji, Ohashi River, Lake Nakaumi, and Sakai Strait to the community assemblage present 40 yr earlier showed no substantial change in the community structure (Uye et al. 2000). According to the authors, these water bodies had been subjected to greater nutrient loading from domestic sewage and agriculture during the last few decades. Copepods were dominant members of the zooplankton community in all of the systems, but there was no evidence for a shift to smaller-sized species with egg sacs even though benthic anoxia occurred in the system.

Studies of benthic communities have revealed that reduced diversity accompanies eutrophication, and there is some evidence that it also occurs in copepod communities. Siokou-Frangou et al. (1998) found a less-diverse zooplankton community in Elefsis Bay, a semi-enclosed region in the Aegean Sea, compared to the neighboring waters of Saronikos Gulf. The dominant copepod species in the bay was *Acartia clausi*. The bay region was considered eutrophic based on nutrient levels and chlorophyll concentrations, but it had also experienced hydrocarbon and heavy metal pollution. In an earlier paper (Siokou-Frangou et al. 1995), it was reported that this bay experienced some hypoxia during summer months. However, there was no indication that copepod species with egg sacs were dominant in Elefsis Bay, as Uye (1994) had reported for the eutrophic bays of Japan. The

authors concluded that eutrophication of Elefsis Bay contributed to the reduction in zooplankton faunal diversity, however since the bay also experienced chemical pollution, eutrophication may not have been the only factor.

According to Ingrid et al. (1996) one must consider the structure of the grazing community in order to predict how a system will respond to nutrient enrichment. They suggested that every system has a critical level in terms of nutrient supply, and that organic matter will build up when that level is exceeded. Grazers affect that critical level through a variety of mechanisms. Grazers determine how much material passes through the grazing food chain versus that which sediments out to the bottom. In the process, they sequester nutrients and release nutrients through excretion and fecal pellet production. More food particles will avoid ingestion, accumulate, and settle to the bottom if the material is not appropriate for grazers. Prey selectivity is determined by many factors, but size is regarded as very important. Subsequent autotrophic and heterotrophic bacterial production will be determined by the rate at which the grazers return nutrients to the system and deliver organic matter to the seafloor in the form of fecal pellets. The example is given of a stable coastal system in which oligotrich ciliates compete with the smaller life stages of copepods for small food particles, and in turn are the prey of larger stages. Under limited and transient food conditions, the authors suggest that ciliates with their higher growth rates will out-compete the copepods. However, under high nutrient concentrations, copepods should fare better because the growth of larger diatoms, which are the preferred food of copepods, should be favored. The authors suggest that *Acartia* spp. may be key elements in food webs because they act as both predators consuming ciliates and competitors consuming phytoplankton.

In addition to trophodynamic effects, eutrophication often leads to the occurrence of hypoxia/anoxia. In coastal waters, the reduction in dissolved oxygen usually begins at the sediment-water interface and extends upwards into the water column. A classic example of eutrophication leading to the increased occurrence of hypoxia/anoxia is Chesapeake Bay on the northeast coast of the US. Roman et al. (1993) reported that the vertical distribution of *Acartia tonsa* in Chesapeake Bay was altered by the presence of benthic hypoxia. Subsequent studies by Stalder and Marcus (1997) showed that *A. tonsa* did not avoid hypoxia suggesting that increased mortality

would occur. On the other hand, Decker et al. (2003) subsequently showed that *A. tonsa* from Chesapeake Bay avoided hypoxia whereas *A. tonsa* from Florida did not. Stalder and Marcus (1997) had used animals from Florida in their study. These results suggest that over time, *A. tonsa* responds to chronic hypoxia in the environment by altering its migratory behavior. The appropriate experiments have not been done to clarify whether this response is due to physiological or genetic adjustments or both. Although this means that mortality might not increase, the distribution of the species may be compressed into upper oxygenated layers. This change in the vertical distribution might affect the susceptibility of the species to predation as shown by Breitberg et al. (1997). In addition, species that become sluggish due to hypoxia will be more susceptible to predation than those which can maintain avoidance behavior (Breitberg et al. 1997). Changes in predation rates will alter the flow of energy in stressed systems.

In addition to the potential lethal effect of hypoxia on copepods, it is also important to recognize that sublethal responses can affect population dynamics and hence community structure over longer time periods. Work in progress in our laboratory is directed at clarifying the sublethal impacts of hypoxia on copepods. Our research shows that hypoxic dissolved oxygen concentrations that do not lead to mortality of *A. tonsa* nevertheless result in reduced development, growth, and reproductive rates.

Hypoxia/anoxia caused by eutrophication may also impact copepod population dynamics by preventing hatching and reducing the viability of benthic resting eggs. In addition, benthic stages have to cope with exposure to hydrogen sulfide that often accompanies anoxic conditions. Marcus et al. (1997) showed that the mortality rates of non-diapause copepod eggs of *Acartia tonsa*, *Centropages hamatus*, and *Labidocera aestiva* that were subjected to anoxia and/or hydrogen sulfide were similar regardless of which stressor was tested. On the other hand, the species differed in their sensitivity to stressors. *A. tonsa* was most sensitive, surviving only about 2-3 wk. Diapause eggs are much more tolerant of exposure, however, as evidenced by no reduction in hatching success for the diapause eggs of *C. hamatus* that were exposed to sulfide and/or anoxia for 20 wk (Marcus and Lutz 1998), whereas substantial mortality was observed for non-diapause eggs of *C. hamatus* exposed for only 4 wk (Marcus et al.

1997).

IMPACTS OF CHEMICAL POLLUTION

Chemical pollutants may affect marine organisms through various pathways. Dissolved materials may be absorbed directly from seawater. Contaminated particles may be ingested. In both cases, the contaminants may be assimilated and passed up to higher food levels via trophic transfer or they may be eliminated in fecal pellets (McManus et al. 1983). Benthic organisms in bays and estuaries are at particular risk of exposure because chemical pollutants are often associated with fine sediments that accumulate in low-energy environments. The biological impact of stressors occurs at various levels including the individual, population, and community levels. Most studies of chemical stressors have focused on short-term impacts on individuals as evidenced by cellular, biochemical, physiological, and behavioral responses as well as determining lethal dosages. Although many studies have speculated on the population- and community-level effects, few studies have actually documented zooplankton population- and community-level effects due to chemical pollution because long-term study is required.

Generally the highest levels of chemical contaminants are found in estuaries and coastal waters adjacent to large urbanized and industrial areas compared to other portions of the oceans. Whereas many studies of the impact of chemical pollutants are done with organisms isolated from the field, the 1974 CEPEX (Controlled Environmental Pollution Experiment) project was a multidisciplinary study of the impact of chemical pollutants on marine systems. The approach used large enclosed mesocosms. Reeve et al. (1977) summarized the results of the CEPEX experiments that pertained to the effects of copper on copepods. The study revealed the lethal and sublethal effects of copper exposure. The ingestion and filtration rates of animals taken from control bags were compared to animals taken from bags with 5 or 10 $\mu\text{g L}^{-1}$ of copper. When offered a standard food, the ingestion and filtration rates were higher for the control animals. In addition, egg production was much higher for the controls. Changes in the bags also revealed the potential impact of changes on the copepod community. With fewer copepods, due to higher mortality upon exposure to copper and possibly also reduced feeding, phytoplankton were able to bloom because they were no longer

being cropped by the herbivore grazers.

Two and a half decades later, there is renewed interest in the effects of metals on copepods. While previous research focused primarily on the lethal effects of metals in the dissolved state, current research is considering sublethal effects, food web transfer, and biogeochemical cycling. Hook and Fisher (2001) determined the impact of Hg, Cd, and Ag on *A. tonsa* and *A. clausi*. The concentrations tested were at environmentally realistic levels such as those that occur in urbanized estuaries. They exposed adults to food that had been exposed to metals and also dissolved metals in the water. They found that exposure to contaminated food resulted in assimilation of the metals primarily into internal tissues. With direct exposure, the metals showed up in the exoskeleton, particularly in the case of Hg. The metals led to sublethal effects (e.g., decreased egg production and hatching, ovarian development, and protein concentration in eggs) at concentrations 2~3 orders of magnitude less than lethal concentrations. That study emphasized the importance of considering uptake pathways (as pointed out by Corner et al. 1976), cumulative body burdens, and different toxins. The study also emphasized the need for investigations of the effects of long-term chronic exposure to metals. In a subsequent study, Hook and Fisher (2002) showed similar responses to Zn and Mn, although the concentrations that led to an effect differed among the various metals that were tested. The results of that study also showed that toxicity was associated with the degree of binding to sulfur. The authors suggested that the metals interfere with sulfur binding to the enzymes associated with vitellogenesis, leading to decreased egg production.

Large numbers of copepod eggs have been found in the seabed sediments of bays and estuaries, and it has been suggested that these resting eggs are critical to the perpetuation of planktonic populations. The resting egg assemblage most likely includes a mixture of quiescent non-diapause eggs and diapause eggs. Since the seabeds of many urbanized estuaries and bays are contaminated with various chemical toxicants, there is concern that the viability and hatching of resting eggs will be adversely affected in such areas. The impact of hydrogen sulfide on copepod egg viability was already mentioned above. However, those results suggest that diapause eggs should be more tolerant of introduced chemical toxicants than non-diapause eggs as is the case for the dia-

pause and non-diapause stages of many other organisms. Lindley and co-workers examined the viability of copepod resting eggs from British estuaries in which the degree of chemical contamination varied. In their initial paper (Lindley et al. 1998), the highest hatching success (92%) was observed for resting eggs from the estuary having the lowest concentration of PAHs and the lowest hatching success (14%) from the estuary with the highest concentration of PAHs. Although the concentration of PAHs was used as an indicator of contamination, it is certainly possible that other stressors contributed to the differences in hatching success. Given the design of the study, it is not possible to know if the eggs were diapause or non-diapause, though it seems likely that they were the latter. Subsequently, Lindley et al. (1999) examined the impact of 2 organochlorine compounds on copepod eggs of *Eurytemora affinis* and *A. bifilosa*. The eggs that they tested were most likely not diapause eggs since the control eggs hatched within a few days. Although the concentrations tested were generally higher than natural values, the results indicated that exposing eggs to these compounds led to reductions in viability and hatching. On the other hand, no effect on hatching success was detected in resting eggs exposed to Orimulsion and fuel oil #6 (Suderman and Marcus 2002). In that 3-mo microcosm study, intact sediments from Tampa Bay, FL, USA were dosed with one of 5 hydrocarbon treatments via hydrocarbon-coated sand and compared to untreated controls. *Acartia tonsa* eggs were nonviable in all treatments after only a few weeks of incubation, as evidenced by a marked decline in the abundance of nauplii that hatched from a sub-sample of the sediments. However, there was no evidence that exposure to concentrations of 700 or even 7000 ppm (levels expected in the event of a spill) of either fuel led to significant increases in resting egg mortality as compared to the controls. The results indicate that regardless of environmental conditions, eggs of *A. tonsa* from Tampa Bay sediments are likely quiescent non-diapause eggs, and that these eggs do not remain viable in the seabed for extended periods of time.

There is evidence that copepod species may adapt to the presence of chemical stressors analogous to what Decker et al. (2003) observed for hypoxia. In a study of the effects of copper on *A. tonsa* from Biscayne Bay, FL, USA, Reeve et al. (1976) observed considerable variation in the 24-h LC₅₀ values, which he attributed to physiological and/or genetic differentiation among seasonally

separated populations. He concluded that there was wide genetic variability within species in tolerance to toxic substances, such that populations that may be reduced dramatically in an area may return to their original population size over time. To substantiate this idea, Reeve et al. referred to an unpublished observation by John Steele of the copepods from Loch Ewe in Scotland. Copepods from Loch Ewe were not affected by copper concentrations (no citation provided) comparable to those tested as part of the CEPEX experiments. Steele suggested that the ambient copper concentrations were higher in the Loch than in Saanich Inlet where the CEPEX experiments were conducted, and as a result, the Scottish animals were more accustomed to higher copper levels and were thus more tolerant. However Reeve et al. also pointed out that the chelating abilities of the waters may have differed such that the levels of biologically available copper were not the same.

CONCLUSIONS

Copepods are critical components of marine food webs. They play fundamental roles in the transfer of organic matter. In estuaries and other coastal systems, they are an essential part of the diet of many commercially important fish and invertebrate species. Therefore it is essential to consider how copepods are affected by stressors in the coastal environment. Despite the call for studies of the long-term chronic effects of exposure of zooplankton to hydrocarbons (Corner et al. 1976), we still have a very poor understanding of the sublethal impacts of chemical contaminants on marine copepods, the dominant mesozooplankton in coastal waters. The problem is much more complex however. Since a species likely encounters multiple stressors in the environment and also interacts with other species as predator or prey, simply elucidating the impact of a single stressor on a single species has limited value in predicting ecosystem-level changes. While every effort should be made to reduce contamination of our coastal waters, evidence suggests that despite chronic exposure to certain stressors, some copepod species are able to maintain population densities through acclimation and adaptation.

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