Eutrophication and the macroscope

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Abstract It is important to view eutrophication as an increase in the supply of organic matter to an ecosystem rather than as a simple problem of nutrient pollution. This emphasizes that eutrophication is a fundamental change in the energetic base that may propagate through the system in various ways and produce a variety of changes. Some of these changes may be desirable (e.g., increased secondary production) and some may not (e.g., hypoxia). Defining eutrophication in terms of changing nutrient concentrations or chlorophyll levels or species composition confuses symptoms with the underlying phenomenon. While nutrient enrichment is the most common cause of eutrophication, it is not the only one. As recent and ongoing nutrient reductions make an impact in the coastal waters of the wealthier nations, we will see an increasing number of systems in which primary production is decreasing. This reduction in the supply of organic matter is here defined as oligotrophication, a phenomenon now well documented in lakes. So far, there has been little appreciation of this limnological study by coastal marine ecologists or managers, but there is much we can learn from it. The great ecologist H.T. Odum long argued that we need 'macroscopes' to help ecologists see the problems they study as they are embedded in the larger scales of nature and society. Marine eutrophication (and oligotrophication) is a perfect example of a problem that must be studied with a view toward the larger scales as well as toward the microscopic details. While much of the hardware (e.g., satellite imagery) for the mythical macroscope has been developed in the last 30 years, many ecologists and managers still look at eutrophication as a local problem linked to local sources of nutrient enrichment. Such a parochial view isolates eutrophication from its long intellectual history—a history that is linked to the development of our understanding of production in coastal waters. It also neglects the intellectual richness and complexity of eutrophication. One example of the importance of the macroscopic view is the emerging importance of climate-induced changes in phenology and the consequences of changing phenology on productivity. These changes may lead to eutrophication or oligotrophication. Climate changes may also exacerbate or alleviate conditions such as hypoxia that are associated with eutrophication. Seeing eutrophication in the macroscopic view is important for understanding and managing the phenomenon.

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Eutrophication in Coastal Ecosystems: Selected papers from the Second International Symposium on Research and Management of Eutrophication in Coastal Ecosystems, 20–23 June 2006, Nyborg, Denmark

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Eutrophication

At the International Symposium on Nutrient Dynamics in Coastal and Estuarine Environments held in Denmark in 1993, I offered a definition for the term 'eutrophication' as a noun meaning "an increase in the rate of supply of organic matter to an ecosystem" (Nixon, 1995). In addition to simplicity and brevity, the main arguments in favor of the definition are that it focuses on eutrophication as a change in the rate of supply of carbon and energy to an ecosystem, and it thus differentiates the phenomenon of eutrophication from its various causes (e.g., nutrient enrichment, reductions in grazing pressure, increases in water residence time) and from its various consequences (e.g., hypoxia, fish kills, turbidity). Since the increase in the supply of organic matter can be due to allochthonus or autochthonus sources, this definition also links the large body of study dealing with the responses of coastal waters and sediments to organic loading from sewage and manufacturing wastes with more recent studies that focus on the impacts of increased primary production within the system. For example, the well-known Pearson–Rosenberg (1978) model of macrobenthic succession in response to organic loading has proven useful in understanding benthic responses to inorganic nutrient enrichment (Heip, 1995).

While the definition I proposed seems to have proven useful (it is recently cited 50–70 times each year according to Science Citation Index), it is not without its critics. Three points raised at the symposium that produced the collection of articles in this issue of *Hydrobiologia* are important and deserve comment. First, K. Sand-Jensen, who acted as respondent to the talk on which this article is based, noted that total system production may not increase with nutrient loading, but the types and relative abundance of the primary producers may change as rooted macrophytes are replaced by macroalgae or phytoplankton (e.g., Sand-Jensen & Borum, 1991). The results of our experimental studies with shallow (1 m deep) coastal lagoon mesocosms containing eelgrass, macroalgae, epiphytes, and phytoplankton agree with his findings (Nixon et al., 2001), but nutrient addition experiments with the deeper (5 m deep) phytoplankton-based MERL mesocosms show total system production increasing over a very wide range in nutrient loading (e.g., Nixon et al., 1986, 2001). At least for shallow systems, however, Sand-Jensen's point is well taken. Nonetheless, one definition cannot do everything—species substitution may be one of the consequences of nutrient enrichment but it may not be a cause or a direct consequence of eutrophication. In shallow macrophyte-dominated systems, species substitution can be a conspicuous change, while in phytoplankton-dominated systems the shifts in species with nutrient enrichment may be equally important but less easily observed and documented.

Second, in discussion following the talk, R. Elmgren made the good point that the impact of adding 100 g of carbon as cellulose to a bay is quite different from adding an amount of nitrogen (N) or phosphorus (P) that will stimulate the fixation of 100 g of carbon by the phytoplankton. He was right, of course, since the N and P may be recycled many times and stimulate the fixation of much more carbon. However, this seems to me to be a distinction that lies outside the definition. The addition of organic matter may produce some responses that are similar to those resulting from stimulating in situ primary production (e.g., hypoxia in bottom water), but not others (e.g., species shifts in primary producers). My definition does not assume a stoichiometric equivalence between nutrient addition and carbon addition.

Third, in preparation for the talk, it was brought to my attention that some managers object to the definition because it requires expensive monitoring of primary production to document that eutrophication is occurring or being remediated. This is an important perspective that I had not appreciated, but I do not think it is a good reason to reject the fundamentals of the definition. As a practical matter, the research community can also offer some solutions that may be useful. For example, we have known for about 50 years that primary production can, in some cases, be computed from measurements of phytoplankton biomass and light in the water column (Ryther & Yentsch, 1957), and a recent review by Brush et al. (2002) of many more studies in the United States and Europe suggests that this approach

applies across a wide variety of coastal systems. Since it is relatively inexpensive to monitor chlorophyll, vertical light attenuation coefficients, and incident radiation, perhaps in association with periodic calibrations using local ^{14}C uptake measurements, it seems that the issue of costly monitoring can be averted in phytoplankton-based systems. Macrophyte-dominated systems are another matter, but in such shallow waters data on area coverage by macroalgae and/or sea grasses may be a useful proxy for production (e.g., Sfriso et al., 1989). The increasing availability of reliable in situ oxygen monitoring equipment that can be deployed for days or weeks is also making it possible to conduct relatively inexpensive free water measurements of total system metabolism (e.g., Bergondo et al., 2005), a technique pioneered by H.T. Odum half-a-century ago to give a more macroscopic view of production than bottle incubations (e.g., Odum & Hoskin, 1958).

Andersen et al. (2006) have just reviewed some of the more common definitions used for coastal eutrophication and noted that the management community within Europe has chosen to define the phenomenon in terms of nutrient pollution and 'undesirable' changes in the biology or ecological status of an area. I suppose this is understandable from a regulator's perspective, but as they point out, it embodies an anthropocentric view of what is 'desirable' in nature and raises issues of 'reference conditions' against which change can be measured. For me such a definition is too limited and makes eutrophication a pollution problem arising from one type of pollutant (nutrients, or just nitrate in the case of the EC Nitrates Directive) rather than embedding eutrophication in the more basic ecological issue of changing the energetic base of ecosystems. One definition missed by Andersen et al. (2006) is that offered by Ulanowicz (1986, p. 80) in which eutrophication was defined as "any increase in system ascendancy due to a rise in total system throughput that more than compensates for a concomitant fall in the mutual information of the flow network." While this is certainly too much jargon to appeal to regulators, it does seem consistent with my emphasis on eutrophication increasing the supply of organic matter. Andersen et al. (2006) also argue strongly for including the measurement of primary production in European eutrophication monitoring programs. If their advice is heeded, it will increase the common ground between the research and management communities with regard to understanding and dealing with eutrophication.

The eutrophication generation

It is customary for the president of the Coastal and Estuarine Research Federation to give a farewell address at end of his or her term of office. Linda Schaffner ended her presidency in 2005 with a talk at the biennial meeting in Norfolk, Virginia in which she exclaimed: "This is the eutrophication generation!" If we accept a generation time of 20 years (an arbitrary demographic standard), then there were probably three generations in her audience, but for those of us who began our scientific careers in the late 1960s and early 1970s, she was certainly right. A quick search of my office produced a pile of books and special journal issues on (largely) marine eutrophication about 0.75 m high. The earliest appeared in 1969 (Eutrophication: Causes, Consequences, Correctives published by the U.S. National Academy of Sciences) and the most recent are the excellent special issues of Limnology and Oceanography that appeared in January 2006, and Ecological Applications that appeared in July 2007. The first was almost completely devoted to fresh waters, while marine and freshwater systems are about equally represented in the most recent Limnology and Oceanography. The Ecological Applications special issue is completely devoted to coastal marine systems. An exhaustive history of coastal marine eutrophication and the evolving interplay between science and management related to the issue in Europe has recently been published by de Jong (2006).

A search of the Aquatic Sciences and Fisheries Abstracts (ASFA) database confirms that about half of the articles published in recent years on the topic of eutrophication appear to focus on marine systems (Fig. 1). It is tempting to interpret the rapid increase in eutrophication citations between the early 1970s and the early 1990s as the research community responding to increasing impacts of nutrient enrichment from increasing fertilizer use, fossil fuel combustion, and protein consumption (e.g., Nixon, 1995; Rabalais & Nixon, 2002; de Jong, 2006; Howarth & Marino, 2006), but I suspect that this is only part of the story. The increasing study of eutrophication is part of a larger trend that has been driven by at least three

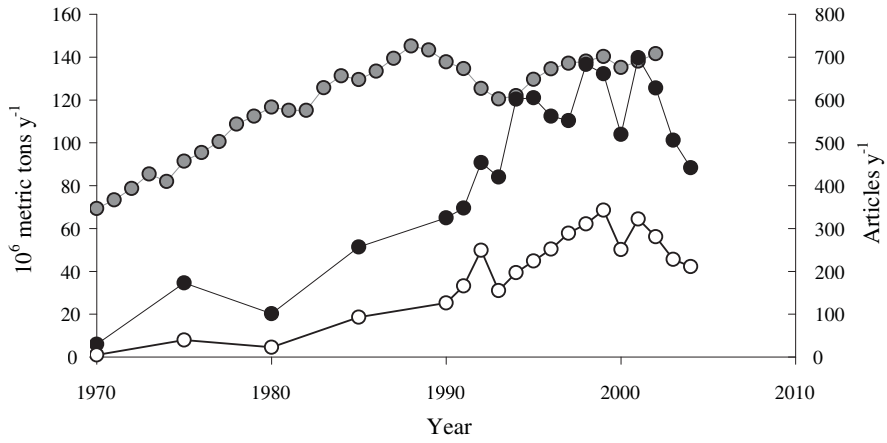

Fig. 1 World consumption of synthetic fertilizer since 1970 (total N, P_2O_5, K_2O International Fertilizer Industry Association, http://www.fertilizer.org/ifa/statistics/indicators/ind_cn_world.asp) and the number of publications dealing with the subject of eutrophication (solid circles) and marine eutrophication (*open circles*) as reported on line by Aquatic Sciences and Fisheries Abstracts (ASFA)

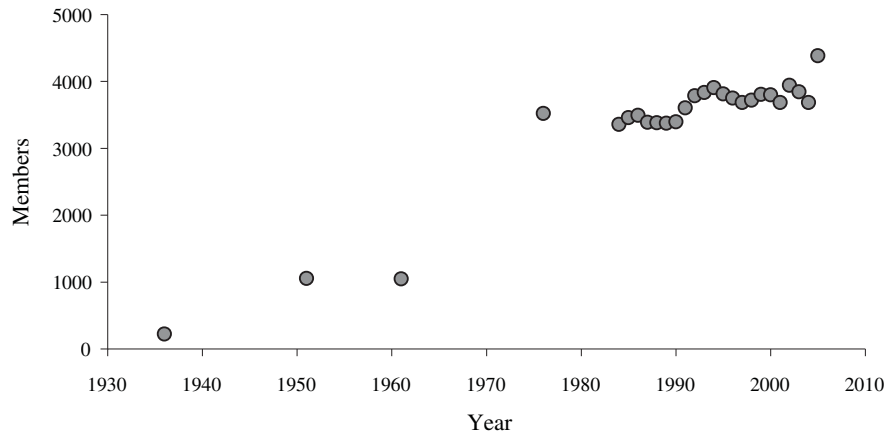

Fig. 2 Membership in the American Society of Limnology and Oceanography (ASLO) over time (data from Susan Jones, ASLO Business Office, e-mail from Sybil Seitzinger 5/30/06)

factors: the production of large numbers of 'baby boomer' Ph.D. research scientists after about 1975, the rise of the environmental movement in the 1970s, and the availability of increasing amounts of government funding for scientific research after the Second World War. The impact of these factors can be seen in the time series of membership in The American Society of Limnology and Oceanography (ASLO) (Fig. 2). It may also be argued that a sharply expanding economy in Europe, North America, and parts of Asia also provided the means by which societies were willing and able to invest in environmental research and the specialized education it requires. A good integrated measure of the expanding economy that does not require numerous inflation corrections is the world inventory of annual carbon dioxide (CO_2) emissions that documents the 'Great Acceleration' after about 1950 (Steffen et al., 2007) (Fig. 3). In macroscopic view, the wealth created by industrial expansion also made it possible to train and support the scientists who identified and documented many of the environmental problems caused by that 'Acceleration'. The link between the carbon dioxide problem and marine eutrophication goes well beyond the fixation and release of nitrogen during fossil fuel combustion and the use of fossil fuels in fertilizer production. The growing number of scientific articles dealing with coastal eutrophication is mirrored on a much larger scale by the growing number of articles being added each year to the ASFA database (Fig. 4), by the growing scale of human impacts on the environment, and by resource consumption on an unprecedented scale (Steffen et al., 2007).

There are, of course, fads in scientific research (Rigler & Peters, 1995), but the scientific community can also be surprisingly steadfast in its attention to some issues regardless of how their importance may change. For example, the ASFA database shows that the number of publications dealing with oil pollution has remained relatively constant at about 150–200 per year since the mid-1970s, with the exception of a brief peak of over 400 around 1980 (almost certainly

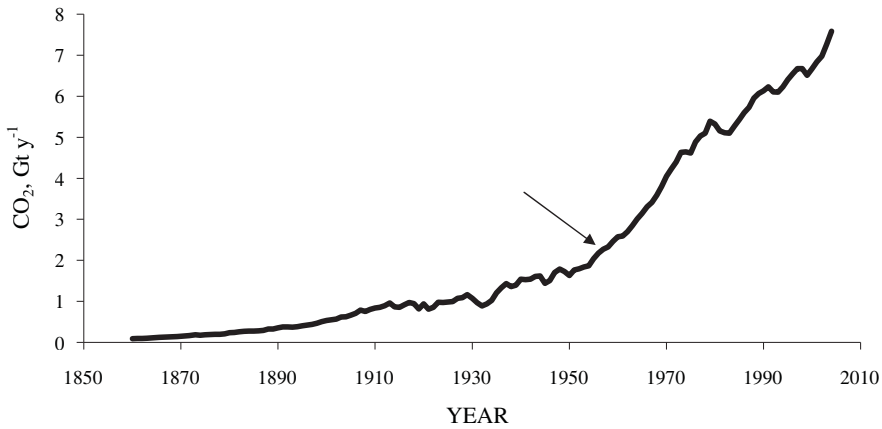

Fig. 3 Global emissions of carbon as carbon dioxide (data provided by M.E.Q. Pilson, Graduate School of Oceanography, Univ. of Rhode Island, from http://cdiac.esd.ornl.gov/ftp/ndp030/global.1751_2003.ems up to 2003. Emissions for 2004 and 2005 calculated from data published by British Petroleum in June 2006). Arrow marks the publication of Revelle and Suess's (1957) famous paper on the coming CO_2 problem

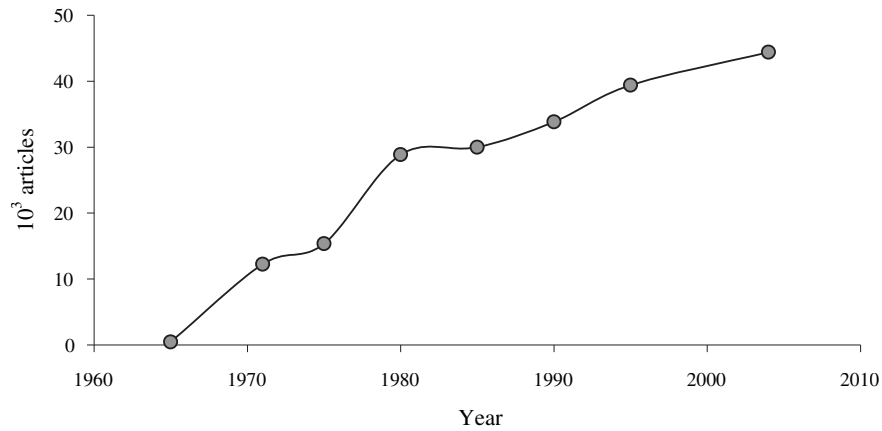

Fig. 4 The number of publications added to the Aquatic Sciences and Fisheries (ASFA) database during various years (data from Vicki Soto, Supervisor of Aquatic and Meteorological Sciences, ASFA; e-mail 5/22/06)

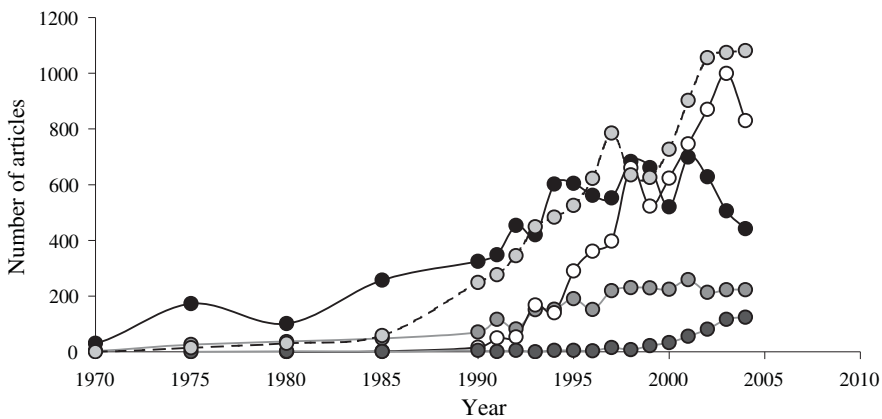

Fig. 5 The number of publications on various topics relating to aquatic ecology indexed by ASFA by year of publication. Arranged from highest to lowest the topics are: climate change, biodiversity, eutrophication, overfishing, invasive species

due to the *Amoco Cadiz* disaster on the coast of Brittany in March, 1978). The attention paid to oil pollution is steadily increasing despite the declines in the volume of oil spilled in U.S. coastal waters (and presumably also in Europe) as a result of better management, education, and engineering (Valiela, 2006). Data compiled by the U.S. Coast Guard show oil spills averaging about 15 million gallons per year in the 1970s have declined to 1 or 2 million gallons per year around 2000. While eutrophication has received considerably more attention than overfishing for many years, eutrophication has recently been overtaken by biodiversity as a favored topic for study (Fig. 5). Publications in which climate change is a

key phrase have increased from fewer than 50 in 1980 to almost 5,000 in 2006. For the future, however, the expanding coastal populations of the developing world, an increasing world demand for meat protein, and the increasing production of biofuels assure that marine eutrophication will continue to demand the attention of marine ecologists and managers (Nixon, 1995; Valiela, 2006).

Coastal marine oligotrophication?

Despite the probable spread of marine eutrophication, especially in developing (often tropical) countries, there are beginning to be cases in which improved fertilizer and livestock management and advanced wastewater treatment are significantly reducing the flow of nutrients to coastal systems (e.g., Yamamoto, 2003; Carstensen et al., 2006; Greening & Janicki, 2006; Soetaert et al., 2006; Philippart et al., 2007). The decline in nutrient inputs to increasing numbers of temperate coastal systems in wealthier countries means that we will almost certainly begin to see an increasing number of articles dealing with marine oligotrophication or 'trend reversal' as it is called in Europe (e.g., Carstensen et al., 2006; Philippart et al., 2007). This is an almost unexplored phenomenon in marine systems. Only some 5–20 articles on this topic have appeared in the ASFA database each year since 1990, and almost all of these deal with the oligotrophication of lakes and reservoirs (e.g., Ney, 1996; Stockner et al., 2000; Anderson et al., 2005). The observations of lake oligotrophication suggest that we should anticipate important changes in both ecosystem structure and function. For example, an analysis of 35 case studies by Jeppesen et al. (2005) found declines in phytoplankton biomass and changes in taxonomic composition, increases in the ratio of zooplankton biomass to phytoplankton biomass, declines in total fish biomass, and increases in the relative abundance of piscivores. The small sample of marine systems suggests that their responses will also involve complex changes in structure in virtually all trophic levels and declining yields at least for some important species (e.g., Yamamoto et al., 2003 for the Seto Inland Sea and Philippart et al., 2007 for the Wadden Sea). In anticipation of a growing interest in the topic, I would like to offer a definition for oligotrophication that parallels that of eutrophication:

Oligotrophication (noun) – a decrease in the rate ofsupply of organic matter to an ecosystem.

This definition shares all of the strengths (and limitations) of the earlier eutrophication definition, and the same would preclude the use of the awkward term 're-oligotrophication' that has started to appear in the limnological literature (e.g., Jeppesen et al., 2002). By this definition, it is also clear that the coming oligotrophication due to nutrient reductions is the second oligotrophication of coastal marine systems. The first was a reduction in organic inputs from sewage that accompanied the move to full secondary treatment of urban and industrial wastes in wealthier countries during the 1970s and 1980s (National Research Council, 1993). The impact of very large expenditures on sewage infrastructure on the amount of organic matter actually reaching coastal systems is very difficult to determine. Significant improvements in sewage treatment technology were accompanied by large increases in the populations connected to sewage systems. In the United States, the overall balance may have been a net decrease in organic matter discharged by treatment plants of about 25% (Stoddard et al., 2002). Unfortunately, the research community and the resource base were much smaller during that first major change, and the ecological impacts (aside from increases in dissolved oxygen) were seldom documented.

The intersection of two great inquiries in marine ecology

Eutrophication (and oligotrophication) will continue to be a major focus of our research not just because nutrient fluxes between land and the coastal ocean will be changing (both increasing and decreasing), but also because eutrophication lies at the intersection of two of the great inquiries of marine ecology. The first of these inquiries, the basis of marine production, developed largely in Europe, within a few hundred kilometers of the meeting that stimulated this collection of articles. The second, the impact of human activities on the sea, began for eutrophication and nutrient pollution in a coastal lagoon on Long Island, New York.

It seems appropriate and useful for an introductory article to spend a little time on the development of

these two lines of inquiry, and my task is made much easier with regard to the first because of an excellent history of our understanding of primary production in marine systems written by Mills (1989).

The agricultural model

Very briefly, the development of marine ecology as a quantitative science can be traced to the establishment of the Kiel Commission for the Study of the German Seas in 1870. The major task of the Commission was to learn why some regions of the sea produced so many more fish than others. Beginning in the early 1880s, Victor Hensen at Kiel emphasized quantitative sampling of the plankton and benthos and focused on the metabolism of the sea as well as measurements of standing crops. By 1887, Karl Brandt had come to Kiel and begun the development of chemical analyses of plankton and sea water. He first identified nitrogen as the probable limiting factor for production in 1899. As Mills (1989, p. 53) noted, "The history of plankton dynamics after 1899 is largely the history of the knowledge of the nitrogen cycle." By 1901, the Norwegian botanist H. H. Gran showed that denitrification was widespread in the Baltic and the coastal North Sea. The Kiel Commission was a forerunner of the modern International Council for the Exploration of the Sea (ICES), which first met in Copenhagen in 1902. The ICES began the first regular monitoring of the coastal environment in the Baltic and North Sea and supported the efforts of Emil Rabin at Kiel to improve nutrient analyses between 1902 and 1917.

In 1893, the 'Copenhagen Program' began with the goal of relating climate to fisheries yields, which stimulated much of the early study in Scandinavia and Germany on physical oceanography and the links between physical and biological processes. Improved understanding of physical mixing led Alexander Nathansohn at Kiel in 1906 to identify its importance in supplying nutrients to surface waters and stimulating productivity. The first actual measurements of plankton production in a marine system were made in the Oslo Fjord by Gaarder and Gran in 1916 using the 'light and dark bottle' oxygen technique. Similarly, the importance of eelgrass and benthic communities in shallow-water ecosystems was quantified for the first time by Peterson and others working at the Danish Biological Station between 1915 and 1920. Analytical advances during the 1920s by Atkinson and Harvey at the Plymouth Laboratory in England made it possible to quantify the importance of seasonal cycles in the abundance of the major nutrients and provided some of the foundation on which Gran during 1931–1935 formalized the concept of the compensation depth, the basis of our modern understanding of the spring bloom. Finally, during 1954–1960, Steemann-Nielsen obtained the first measurements of primary production by the phytoplankton over an annual cycle using the ^{14}C technique (Richardson & Heilmann, 1995). His stations were in the Kattegat, just offshore from the site of the meeting that stimulated this collection of articles. There is certainly no more appropriate venue for discussion of the important links between nutrients and the supply of organic matter to marine ecosystems. However, it is important to remember that these links were virtually always viewed in a positive light—more nutrients, more primary production, more fish—what Cushing (1975) called the 'agricultural model' of production in the sea (Nixon et al., 1986; Nixon, 1995; Nixon & Buckley, 2002).

Of ducks and dead zones—why didn't we see it coming?

While the positive link between nutrients and production was developed in Scandinavia and northern Europe, the view of nutrients as a marine pollutant first emerged in the United States. As far as I am aware, the first reference to nutrient overenrichment came from John Ryther's (1954) identification of duck waste being responsible for the development of nuisance phytoplankton blooms ($>10^{10}$ cells l^{-1}) in Moriches Bay and Great South Bay on Long Island, NY. At that time, it was believed that ducks needed to be raised on water, and data on the duck food supplied to produce some four million ducks each year (Ryther, 1989) suggest that the N and P loading to the bays may have been about 8.8 and 1.2 mmol m^{-2} d^{-1}, respectively, a very intensive fertilization. The dense phytoplankton blooms were believed to have a negative impact on tourism and were also blamed for the loss of a productive oyster fishery, "…though a definitive cause-and-effect relationship was never established" (Ryther, 1989).

The impact of Ryther's 1954 article was neither immediate nor great, and when the American Association for the Advancement of Science published the

first monograph devoted to *Estuaries* (Lauff, 1967), only one chapter out of 71 dealt with nutrients as a pollutant, and that was written by B. H. Ketchum, Ryther's colleague at the Woods Hole Oceanographic Institution. Even 5 years later, when Ketchum (1972) edited the landmark volume, *The Water's Edge*: *Critical Problems of the Coastal Zone*, only three pages out of 393 were devoted to nutrients as a pollutant. Things were no different in Europe, where Wulff (1990) noted that "The concept of 'marine eutrophication' was unheard of until about 20 years ago." A more detailed discussion of the history of the pollution side of marine eutrophication, especially as it developed in Europe, is given by de Jong (2006).

The question naturally arises as to why it took so long for the potential negative impacts of nutrient enrichment to be widely recognized by the coastal research and management communities. As early as 1957, Revelle and Suess (Fig. 3) eloquently pointed to the coming CO_2 problem when they wrote, "…human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and the oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years." With some modification, a similar statement could have been made about the human perturbation of the N and P cycles. While it is true that the anthropogenic fixation of atmospheric N for fertilizer began to increase dramatically only after 1950, the growing need for fertilizer to support the human population had been clear for decades (Smil, 2001). Moreover, large amounts of N and P from human waste began to be released from urban sewer systems during the last quarter of the 1800s (Fig. 6), and the impacts on coastal receiving waters must have been dramatic. There were also ambitious monitoring programs in many rivers that included ammonium and nitrate as well as organic N (actually only the more easily oxidized components of organic N). These measurements were made in the belief that the various forms of N were good chemical indicators of bacterial contamination from sewage and could thus be used to separate contaminated water from sources suitable for drinking (Hamlin, 1990). While N concentration proved to be an imperfect way to judge drinking water, the early measurements often showed very large increases in N being carried into estuaries as cities grew along the rivers and the public demanded running water, flush toilets, and sewer systems to collect and dispose of the waste (Nixon et al., 2008). In spite of what must have been intense fertilization of many urban coastal areas during the first quarter of the twentieth century, virtually all of the early concerns of sewage impact focused on human disease, odors, and discoloration.

I think there are at least five reasons for our late awakening to the potential problems of nutrient enrichment. First, eutrophication is the most subtle of a suite of problems associated with the discharge of raw or partially treated sewage—it is completely understandable that the first concerns were contamination of seafood and the hydrogen sulfide odors associated with low oxygen. Second, while the role of nutrients in marine production was well established by the turn of the twentieth century, the entire focus was on the positive effects of nutrient stimulation. Third, the number of marine ecologists was very small and specialized, and many were focused on taxonomy and systematics. Pollution issues in urban estuaries were usually the province of city engineers,

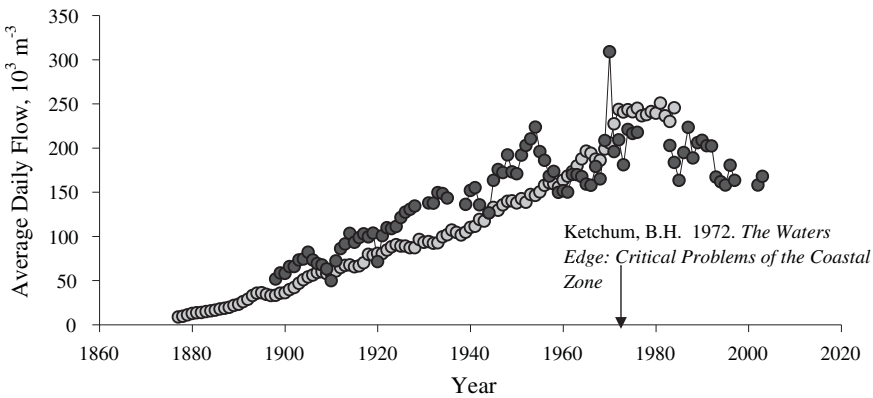

Fig. 6 The average daily flows of water and sewage in the city of Providence, Rhode Island as reported in the Annual Reports of the City Engineer (Nixon et al., 2008)

public heath scientists, or sanitarians. It is difficult for us to appreciate how small the marine research community was and how limited its resources were. The research groups at Kiel and, later, at Plymouth were very unusual in their interdisciplinary focus on marine production. But even these made progress slowly. Consider that over the 40 years between 1887 and 1927, when it was one of the most active marine research groups in the world, the 'Kiel school' averaged just 2.6 publications each year (Mills, 1989). Fourth, there was a general impression that the water residence times of most estuaries were too short for nutrient impacts to be as severe as they were in lakes (e.g., Schindler, 1981). Fifth, unlike the relatively well-mixed atmosphere, estuaries are isolated from each other and their pollution problems are often discovered and studied with a very local perspective. It was difficult to untangle the impact of nutrients in urban estuaries from the impacts of organic loading (also eutrophication by my definition), overfishing, dredging, filling, and various other human impacts. Nutrient-driven coastal eutrophication only emerged as an internationally recognized pollution problem when non-point sources from fertilizers and N-enriched atmospheric deposition became widespread and caused unambiguous impacts in many more coastal areas that were not urban: And that is when there were growing numbers of environmental scientists and environmental advocates watching the coast.

From a belated start, there has been much progress made during the last 35 years in understanding the causes and consequences of marine eutrophication, and there is now a widespread recognition that the phenomenon can have severe, undesirable consequences (Colombo et al., 1992; Vollenweider et al., 1992; Nixon, 1995; Cloern, 2001; Rabalais, 2002; Howarth & Marino, 2006; Schindler, 2006; Smith et al., 2006; Valiela, 2006; and many others). The major sources of N and P reaching coastal waters have been identified and, in many cases, quantified. The pathways by which N and P enter coastal waters are also well known, though some have proven difficult to quantify (e.g., groundwater). The ecological responses are still being documented—some are relatively well understood (e.g., hypoxia) while others remain speculative (e.g., links to disease). It is also safe to say that almost all of the research attention has been directed to nutrient-driven eutrophication. As a result, we know relatively little about system responses to eutrophication that may be the result of physical changes (e.g., increases in water residence time or turbidity), climate change (e.g., changes in freshwater inflow), or 'top-down' effects (e.g., removal of filter feeders). An excellent example of how such changes can cause eutrophication in spite of decreasing nutrient enrichment from wastewater is described by Cloern et al. (2007) for San Francisco Bay, CA. We also know almost nothing about the ecological consequences of oligotrophication in coastal marine systems, and there appears to have been little discussion of what we might learn of this phenomenon from limnology. Coastal marine ecosystems differ from lakes and reservoirs in some fundamental and important ways (Nixon, 1988), but just as we learned much from the earlier manifestation of eutrophication in lakes, we can and should learn much from their first experiences with oligotrophication.

The macroscope

The great ecologist H.T. Odum used to joke (but in all seriousness) in the 1970s that ecologists needed to invent a 'macroscope' that would help them see how their studies fit into the larger scales of nature (Nixon, 1996). As Odum wrote in *The System in the Sea* (Platt, 1993), "Always select the scale one size larger than your problem, because it is half driven from the larger side. That's the first principle of the systems approach." Much of the hardware (and software) for the mythical macroscope has now been invented, including satellites, the internet, search engines, high-speed computers, underway sensors, and many other additions to the ecologist's tool box. Environmental scientists are also learning to work together on cross-disciplinary problems, on larger systems, and in bigger teams. For example, the frequency of single-authored articles in the journal *Ecology* has declined from over 90% in 1920 to about 25% today (Paine, 2005). Only 15% and 12% of the articles in *Estuaries* and *Continental Shelf Research*, respectively, were by single authors up to the early 1990s (Nixon, 1996).

Coastal marine eutrophication is the quintessential problem requiring macroscopes as well as microscopes. Moreover, its study has done a lot to engage coastal ecologists with the macroscopic approach. As defined here, eutrophication is an intellectually rich

problem that weaves together plant, animal, and microbial physiology, physics, climatology, hydrology, biogeochemistry, soil science, agriculture, forestry, urban infrastructure, demography, and nutrition. It involves every level of the ecosystem from abiotic factors to top carnivores. It draws on our skills of observation across wide scales of time and space. The eutrophication literature is full of the results of studies using microscopes, satellite images, sediment cores, stable and radioactive isotopes, analyses of shells and scales and bones, field surveys, buoy sensor data records, mesocosm experiments, long time-series analyses, historical documents, field manipulations, physiological rate measurements, plant and animal tissue analyses, growth studies, and complex numerical models of atmospheric chemistry, oceanic circulation, and ecosystems.

Part of the intellectual richness of the eutrophication (and oligotrophication) phenomenon as defined here springs from its great complexity. Because increases in the supply of organic matter are so often associated with nutrient fertilization, we are faced with the many sources of nutrients: both natural and anthropogenic, fixed and mobile, point and non-point. And with many forms—with N alone we must contend with ammonium, nitrite, nitrate, dissolved organic N (a complex mix itself), dinitrogen gas, nitrogen oxides, ions, solids, gases, vapors, aerosols, particles—all moving through many pathways including groundwater, pipes, streams, sheet flows, tidal and sub-tidal flows, dust, migrating animals, detritus, and the atmosphere. However, the macroscopic view demands that we also look beyond nutrients and keep our eyes and minds open to the possibilities of other factors (such as climate change) that may alter the supply of organic matter and energy in marine ecosystems (e.g., Schell, 2000; Schulman, 2005; Grebmeier et al., 2006; Cloern et al., 2007; Fulweiler et al., 2007). These factors may themselves change the supply of nutrients or interact in important ways with changing nutrient inputs to modify the outcome of nutrient enrichment or removal. Eutrophication is a lot more interesting than 'nutrients in, dead fish out'.

Phenology and eutrophication

In proposing a definition of eutrophication, I gave some examples of changes other than increasing nutrient inputs that might lead to eutrophication, including the effect of dams in reducing river sediment loads and increasing downstream estuarine water clarity, and the closing of passes through barrier spits that might increase water residence time in coastal lagoons, and the over-harvesting of filter-feeding animals. A provocative recent review even concluded that, "the accumulation of plant biomass in shallow benthic habitats is more likely controlled by consumer effects than by nutrients" (Heck & Vallentine, 2007, p. 378). Of course, these factors might also change conditions in ways that lead to oligotrophication, for example, the 'artificial lake effect' by which dams can reduce the concentrations of inorganic nutrients and change nutrient ratios. However, I would like to close with the speculation that there may be another important and even larger scale macroscopic factor that can stimulate eutrophication or oligotrophication in coastal marine systems—climate-induced changes in ecosystem phenology. Phenology has been a common term long used by botanists, but climate change is making it popular with a much wider audience (e.g., Schwartz, 2003) and there is now a well-established European Phenology Network (http://www.dow.wau.nl/msa/epn/about_EPN.asp). Defined simply, phenology is the science of the relations between climate and periodic biological phenomena.

It is becoming clearer that climate-induced changes in phenology can have profound effects on coastal ecology (e.g., Townsend & Cammen, 1988; Sullivan et al., 2001; Grall & Chauvaud, 2002; Edwards & Richardson, 2004; Oviatt, 2004; Ozaki et al., 2004; Fulweiler & Nixon, this volume, and many of the articles cited in support of the macroscopic view). In the case of the system that I know best, Narragansett Bay, RI (USA), changing phenology may be reducing productivity at the same time that other aspects of climate change may be exacerbating hypoxia, a condition normally associated with eutrophication. Very briefly, warmer and cloudier winters seem to be delaying or eliminating the initiation of the traditional late winter–early spring diatom bloom (Li & Smayda, 1998; Keller et al., 1999; Borkman, 2002; Oviatt et al., 2002) (Fig. 7). The summer and autumn blooms that are replacing the winter–spring bloom are often less intense and of much shorter duration, with the result that the mean annual and summer chlorophyll concentrations in the middle of the bay are only about one-third of those found in the 1970s (Li & Smayda, 1998; Fulweiler

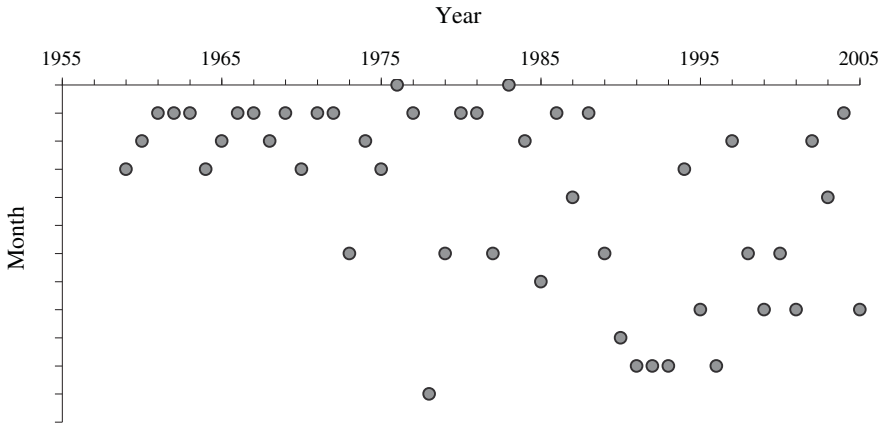

Fig. 7 The month of maximum phytoplankton bloom (chlorophyll concentration) in the West Passage of Narragansett Bay (compiled by Betty Buckley, University of Rhode Island, from various sources, including T. Smayda, MERL, and the Graduate School of Oceanography plankton monitoring program)

et al., 2007; Nixon et al., 2008; Fulweiler and Nixon, this volume). Declines in chlorophyll have also been documented in the lower bay (Hawk, 1998; Oviatt, 2004). Because of the high correlation between chlorophyll and ^{14}C uptake in this bay (Keller, 1988a, b), the decline in chlorophyll almost certainly means that at least the mid- and lower bay have been undergoing oligotrophication. We attribute the decline in production to climate change because reductions in anthropogenic N inputs to the bay are only just beginning and measurements show essentially unchanging N inputs during at least the last quarter century (Nixon et al., 2005, 2008). The input of anthropogenic P has declined significantly in recent decades, but ecosystem-level experiments have shown that the bay is strongly N limited during summer when productivity is the greatest (Oviatt et al., 1995) and DIN/DIP (dissolved inorganic nitrogen/dissolved inorganic phosphorus) ratios in the surface water are very low during summer (Pilson, 1985).

While chlorophyll (and presumably primary production) has been declining in mid-bay, a growing number of observations have documented that portions of the upper bay experience recurring episodic hypoxia in the bottom waters during summer, particularly during the weakest neap tides (e.g., Granger et al., 2000; Bergondo et al., 2005; Deacutis & Kiernan, 2006; Melrose et al., 2007). These measurements are too recent to establish whether the extent, duration, or intensity of hypoxia is increasing, but the general impression has long been that the major passages of the bay have been too well mixed vertically to develop hypoxia.

If it is correct that hypoxia has increased even as the standing crop of phytoplankton has declined (and macrophyte production is very small relative to phytoplankton in this system), two climate-related changes may be involved. First, water temperatures have been increasing during the last 30 years at about 0.04°C y^{-1} (Nixon et al., 2004). Based on theoretical considerations, heterotrophic respiration increases with temperature at twice the rate of net primary production (Harris et al., 2006), so that the temperature increase may have made some contribution to an increasing oxygen demand in the bay. There also appear to have been significant declines in the mean wind speed over the upper bay. During the windiest months (F, M, A) mean speed has been declining since about 1970 (from about 20 to about 16 km h^{-1}) while the wind speed declined markedly only after 1996 for the least windy months (J, A, S) (Pilson, 2008) (Fig. 8). Between 1964 and 1995, the mean (±SD) summer wind speed was about 15.3 ± 0.6 km h^{-1}, while it averaged only about 13.5 ± 0.5 km h^{-1} during the next 10 years, the period during which regular oxygen monitoring really began. Since the power of the wind to mix the water column vertically varies approximately as the cube of the speed, this would represent a drop of some 30% in summer wind mixing potential during the last decade (Niiler & Kraus, 1977; Husby & Nelson, 1982). The decline in speed appears to have been associated with the easterly, cross-bay component of the wind rather than the north-directed component that aligns with the greatest fetch of the bay (Pilson, 2008). While intriguing, these changes have so far only been described for a single monitoring station and the 'step function' decline in the summer mean wind speed is particularly suspicious. If the wind reduction is confirmed, the situation in Narragansett Bay will

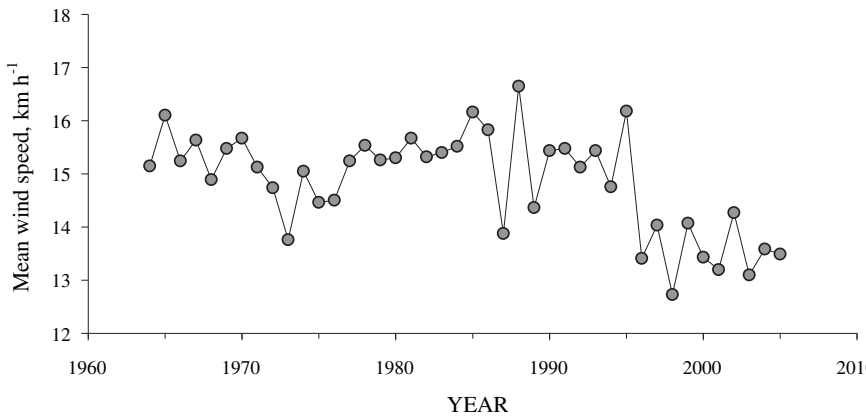

Fig. 8 Mean wind speed measured by the National Weather Service (NOAA) at the T. F. Green airport in Warwick, RI during the least windy months of the year; July, August, and September 1964 through 2005 (modified from Pilson, 2008)

not be unique. Conley et al. (2007) have shown that changes in wind were probably responsible for declining concentrations of dissolved oxygen in some Danish coastal waters despite significant nitrogen discharge reductions and a similar situation is emerging in western Long Island Sound in the United States. (L. Swanson, State University of New York, Stony Brook, pers. comm.).

With such a possible decline in wind mixing, the question arises about other factors that might potentially increase vertical stratification in the upper bay. The warming surface water is obvious, but the most dramatic warming is in winter and the summer increase is small. Stratification in the Upper Bay is much more related to vertical salinity differences that are largely a function of river flow. While there has been a long-term increase in rainfall in this area (about 30% over the last century), the average annual river flow does not appear to have increased, at least since 1970 (Pilson, 2008).

In response to concerns about the hypoxia in the Upper Bay and fears that it may be spreading down the bay, as well as a dramatic fish kill in a side embayment of Narragansett Bay proper, state regulators and politicians have mandated major reductions in N discharge from the larger sewage treatment plants. When fully implemented, these reductions may lower the amount of N entering Narragansett Bay from land between May and October by about 35–40% (Nixon et al., 2008). This will almost certainly have a major impact on primary production in the bay during the time when benthic and pelagic animals are growing. However, this impact will fall on a bay that has already had a large reduction in primary production, or at least in the mean standing crop of phytoplankton in mid bay. We believe that this has already had an impact on the benthos and on benthic-pelagic coupling, at least in the mid-bay (Fulweiler et al., 2007; Fulweiler & Nixon, this volume).

Neither the reduced concentrations of chlorophyll nor the potential role of changes in the wind have been part of a management/policy discussion that has focused only on the traditional picture of nutrients (which activists imply have been increasing in spite of the evidence to the contrary), hypoxia (which may or may not have been getting worse), and dead fish (one significant kill in the last 100 years). The macroscopic view would include the dramatic impacts of climate change (warming and cloud cover) on the timing and magnitude of primary production, the consequences of these changes on higher trophic levels (e.g., warmer winters allow the earlier appearance and greater abundance of ctenophores that prey on the herbivorous copepods during spring and summer; Sullivan et al., 2001), and the potential role of changes in the wind on hypoxia. What are the ecological and economic trade-offs in possibly improving hypoxia in the upper bay at the cost of increasing food limitation over the mid and lower bay (about 70% of the total area of the system)?

We must also be mindful that Narragansett Bay and virtually all the coastal systems have been exposed to many pressures in addition to climate change since they began receiving large amounts of nutrients in the second half of the 1800s (urban, point-source dominated) or the second half of the 1900s (non-point-source dominated). In a talk at the most recent (autumn 2007) meeting of the Coastal and Estuarine Research Federation, Carlos Duarte

pointed out that those who believe that reducing nutrient inputs will return coastal ecosystems to some pristine state have forgotten that the 'baseline' has been changing. Like Peter Pan, he said, they want to return to 'Neverland' where time stands still and nothing ever changes. The scientific community, of course, does not make decisions about policy. However, I do suggest that all of us, scientists, regulators, politicians, and even the activists need to consider coastal marine eutrophication and oligotrophication as the fundamental ecological processes they are. They are not simple 'pollution problems' but major ecological changes that must be viewed through the macroscope.

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