BRIEFING BOOK

"Red Tide," a synopsis of its causes and effects, and discussion of pertinent research by the Middle Atlantic Coastal Fisheries Center.

by John B. Mahoney, James P. Thomas and Walter J. Blogoslawski
U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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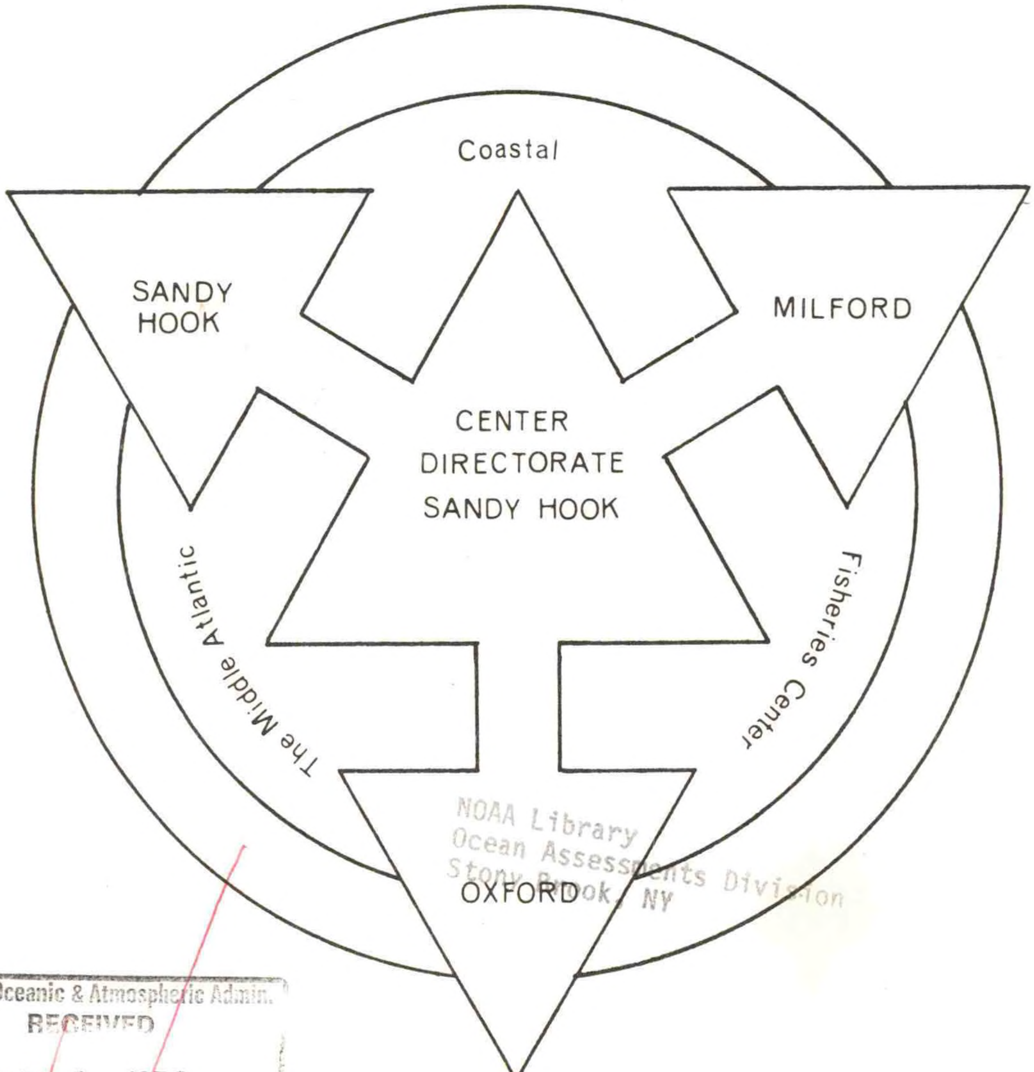
MIDDLE ATLANTIC COASTAL FISHERIES CENTER



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SUMMARY

1. GENERAL INFORMATION ON RED TIDES

Red tide is a common term for a discoloration of natural waters caused by microscopic, usually photosynthetic, organisms. The condition is, basically, a localized superabundance of microorganisms. The tiny plants are known, collectively, as the phytoplankton and may be considered the functional counterparts in the sea of terrestrial graze plants. Their superabundance in the water is brought about by a combination of factors which favor their growth and accumulation in a locale including adequate nutrient supply and a favorable hydrological and meteorological situation. The red tide phenomenon is especially notable because some of the events result in a catastrophic mortality of aquatic animals whereas other red tides toxify shellfish, without killing them, to a level which makes them unsafe for human consumption. Most of the toxic events are caused by a variety of phytoplankter known as dinoflagellates. Many dinoflagellate red tides are relatively harmless, however. Red tides caused by diatoms, the most abundant kind of phytoplankter in the sea, are non-poisonous.

The study of red tides gained impetus approximately 30 years ago. We now know much about the nutritional and physiological preferences of the organisms and the physical conditions which foster their growth. Their toxins have been isolated and assayed. Control of the problem via killing the microorganisms had just limited success when it was tried on a large scale in Florida waters but has had complete success, on a smaller scale, in fish ponds in Israel. Detoxification of toxin vectors, discussed in Section 4 of this report, is a promising recent approach to solving the paralytic shellfish poison problem. Some workers have found the combination of factors causing red tides in their locales to be very complex and ephemeral. In other locales, such as in the Oslofiord in Norway, where the problem was traceable to man's misuse of the environment, alleviation was accomplished.

2. ANNUAL CYCLE OF PHYTOPLANKTON PRODUCTIVITY IN RARITAN, LOWER, AND SANDY HOOK BAYS

Between November 1973 and March 1975, the spatial and temporal distribution of phytoplankton primary productivity, biomass (abundance), phytoplankton species identification, inorganic nutrients, temperature, salinity and photosynthetically active radiation were measured monthly at twelve stations and at three to six depths within Raritan, Lower, and Sandy Hook Bays. Phytoplankton primary production within this system appears to be the highest recorded for any estuary in the world. This system produces 750 to slightly over 1000 grams of organic carbon per square meter per year. Values from other areas range from 150 to 500 gm $C/m^2/yr$. The annual cycle of phytoplankton productivity in these waters is characterized by a winter low, spring and summer maximum, and a decline in the fall. The spring bloom is dominated by netplankton, principally by the diatoms, *Skeletonema costatum*, *Rhizosolenia delicatula*, and *Asterionella japonica*; the summer maxima is dominated by nannoplankton.

In winter, primary productivity was relatively low and uniform throughout the area. With the advent of the spring bloom, productivity generally increased along the south or New Jersey half of the bay system. By March, extreme differences in productivity existed in the area with the highest rates occurring in Sandy Hook Bay and the upper part of Raritan Bay. At this time, the lowest rates occurred between the Narrows and Rockaway Point. This condition persisted in April and May with the New Jersey half of the bay system continuing and increasing in importance as the area of highest productivity. In June and through the summer, photosynthetic capacity on the Sandy Hook side of the Rockaway-Sandy Hook transect remained characteristically higher due to the influence of increased photosynthetic capacity in Sandy Hook and Lower Bays. The highest rates of photosynthetic capacity occurred in and throughout Raritan Bay and Sandy Hook Bay in July. At this time, the lowest rates occurred between the Narrows and Rockaway Point. In August, rates of primary productivity began decreasing at the upper end of Raritan Bay, but were still very high on the south shore from Perth Amboy to Sandy Hook. The decline continued into September. The highest values were then found in Lower Bay. The area between the Narrows and Rockaway Point remained low. In October the highest values were found near the Narrows. By November the system was again relatively homogeneous. The low point in primary productivity came in December and values were generally low and uniform throughout Raritan, Lower, and Sandy Hook Bays. The annual cycle then began again with values increasing in January toward the spring bloom in March.

A strong linear relationship was found between phytoplankton growth rate and daily photosynthetically active radiation. This indicates that light is the most important environmental variable regulating production per capita.

Nutrients including phosphate, ammonia, nitrite, nitrate, and silicate were also measured each month at these same 12 stations. Nutrient concentrations in Raritan, Lower, and Sandy Hook Bays are the result of riverine and sewage input, utilization by phytoplankton, and in situ regeneration by microbial organisms, zooplankton, and fish. Nutrients, such as nitrite, nitrate, ammonia and phosphate, enter the estuary by river transport of sewage. Consequently, their concentrations are determined by river flow. Others, such as silicate are derived by terrestrial erosion and their concentrations are affected by total quantity brought to the system by river flow. River flow is maximum in April and minimum in November. Sewage input of nitrite, phosphate, and ammonia is nearly constant year round.

With the exception of silicate, the nutrients measured are generally abundant throughout the year. Silicate, which is required by diatoms, was generally present in high concentrations in the winter months and in decreased concentrations with the development of the spring bloom. Low or zero values of silicate found principally in the New Jersey half of the bay system, during several months following the spring bloom, suggest that silicate may limit diatom abundance during the warmer months. Phosphate in the area originates principally from a constant source, the raw and treated sewage inputs from the metropolitan area. It was abundant most of the time. A zero concentration was found only once, at the head of Raritan Bay during the spring bloom. Evidence of heavy utilization of phosphorous during spring bloom was found where phytoplankton productivity was highest, both in Sandy Hook Bay and the upper end of Raritan Bay. Ammonia, which is a prime source of nitrogen for phytoplankters, was also abundant throughout the year. Like phosphate, it is principally derived from sewage input to the system. Evidence of utilization of ammonia was seen in the areas of highest phytoplankton productivity both during the spring bloom and the summer maximum.

Raritan, Lower, and Sandy Hook Bays appear to be highly enriched with regard to concentrations of phosphate, ammonia and combined nitrite-nitrate (breakdown products derived in part from sewage oxidation). The presence of abnormally high levels of these nutrients compared with the concentrations of silicate could lead to nutrient depletion and limitation of net phytoplankton productivity (diatoms) by silicate. In general, however, phosphate, nitrate, nitrite, and ammonia do not appear to be limiting phytoplankton production throughout the year. If these nutrients are limiting, it is only for short periods of time (less than our monthly sampling interval) and only at isolated stations and depths. Silicate may be limiting or nearly so to silica-requiring phytoplankton, particularly along the south shore of Raritan-Lower Bay during the late spring and summer when phytoplankton primary productivity is high.

3. RED TIDES IN NEW YORK HARBOR AND ADJACENT WATERS

Personnel of the Sandy Hook Laboratory have observed annual occurrence of red tide (phytoplankton blooms) in New York Harbor and adjacent waters for the past 13 years (1962 to 1975). Three species, *Massartia rotundata*, *Olisthodiscus luteus* and *Prorocentrum micans* dominated most of the occurrences. Although many of the episodes were apparently benign in nature, some had definite or indicated adverse effects on biological and recreational resources of the area, including a possible role in fish mortality, respiratory discomfort among bathers, and diminishment of aesthetic value of beaches. However, the general severity of these occurrences has not been comparable to that of blooms of highly toxic species in other locales. The phytoflagellate blooms occurred during the warmer months, from the middle of June to the end of September; most frequent occurrence was between the end of June and the end of August. The usual pattern included an outbreak in late June or early July followed by one or two more later in July or August. Most episodes lasted 1-2 weeks, but on two occasions, blooms persisted 4-6 weeks, although with decreased intensity during approximately the latter two-thirds of their history. The order of bloom dominance frequency was *O. luteus* followed by *M. rotundata* and *P. micans*. In New York Harbor waters, the greatest phytoflagellate bloom incidence was in Sandy Hook Bay and in the tidal Navesink and Shrewsbury Rivers draining into the bay. Red water was also frequently found in Lower New York Bay proper, and occasionally in Raritan Bay. In the ocean, the area of most frequent occurrence was between the tip of Sandy Hook and Belmar, New Jersey, 40 km to the south. On several occasions during the past 12 years, blooms extended about twice this distance to the south.

The most frequent pattern of bloom development was initiation in the bay area with spread to the coastal area 1-2 days later. On several occasions, coincident with outgoing tides, bloom water was observed flowing out of the bay around Sandy Hook and moving south along the New Jersey coast. On other occasions, especially with spring tides, blooms arising in the tidal rivers flowed out to both bay and ocean. In Sandy Hook Bay, the dispersion of the bloom was usually fairly uniform throughout. In the ocean, dispersion varied from isolated patches to a continuous although irregularly dense band along shore. Persistence of the blooms was at times roughly the same in bay and ocean, with eventual concurrent decline in both areas. More frequently, it appeared that the bay had a nurturing effect in that cell numbers in bloom patches flushed out to the ocean declined more rapidly than in the bay bloom water.

Determination of the causes of the New York Harbor blooms have been the subject of a small, but ongoing study at this Laboratory for several years. Available information suggested there was an association between the blooms and eutrophication of the waters. The initial component of the study of the blooms was an attempt to ascertain such a relationship. Since the same species bloom annually in the polluted New York Harbor waters, it was suspected that these species possessed nutritional capabilities which provided them an advantage in this kind of environment. There is evidence that sewage discharges introducing substantial amounts of organic matter can favor development of blooms. Therefore, work was concentrated on the nutrient aspect.

The effects on growth of the organisms of a variety of organic carbon, nitrogen and phosphorous compounds were studied because these elements are important in algae nutrition and sometimes growth-limiting in the environment. C compounds were tested at 50, 25 and 5 mg C/l; N compounds at 1.4, 0.7 and 0.14 mg N/l; and P compounds at 0.5, 0.25 and 0.1 mg P/l. In the low concentrations: M. rotundata used 11, O. luteus used 14, and P. micans used 16, of 21 organic compounds; M. rotundata used 14, O. luteus 7, and P. micans 14, of 16 organic N compounds; M. rotundata used 6, O. luteus 8, and P. micans 7, of 8 organic P compounds. The results do not indicate that organic nutrients were more beneficial to the three species than the inorganic. There is clear evidence, however, that a variety of organics can either substitute for the inorganic forms or at least enhance growth when present with the organics.

The phytoflagellate blooms in the New York Harbor area are not the highly poisonous variety of "red tides". However, their frequency of occurrence and detrimental effects pointed to a situation which required investigation. We suspected that the blooms were a component of a syndrome, including also radical depletion of benthic fauna and chronic fish disease having common root in environmental degradation of the area. We consider our results showing that growth of all three dominant species is stimulated by a wide variety of organic nutrients, in concentrations resembling or approaching natural levels, to be evidence associating the blooms with the eutrophication of the waters.

4. TOXIC DINOFLAGELLATE BLOOMS IN NEW ENGLAND

In New England waters a dinoflagellate commonly identified as *Gonyaulax tamarensis* is responsible for toxic blooms. When edible molluscs, such as the blue mussel (*Mytilus edulis*), soft clam (*Mya arenaria*), or surf clam (*Spisula solidissima*), filter-feed on large numbers of *Gonyaulax tamarensis*, they accumulate a paralyzing poison (paralytic shellfish poison, PSP) in their tissues. While this poison may not affect the molluscs directly, animals higher in the food chain which eat molluscs may suffer severe symptoms and even death. In humans, PSP poisoning is evident initially as a numbness of the tongue, lips and fingertips, which then spreads to the limbs. Muscle spasms and respiratory paralysis can follow which may cause death in two to twenty-four hours, depending on the amount of toxin ingested. There are few fatalities; survivors of PSP poisoning seem to have no lasting after-effects.

Regarding the history of New England red tides, in Maine, incidence of significant red tide poisoning was first recorded in the summer of 1958. At that time, the shellfish beds in eastern Washington County, adjacent to New Brunswick, Canada, were closed. In the intervening years to 1972 there were only minor instances of toxicity in shellfish. However, in September 1972, the entire coast of Maine was closed to shellfishing because of high PSP levels, with some areas not reopened until September 1973. This closure was devastating to this fishery. In 1974 two red tides were noted, one occurring in late May and the other, in late August. The entire coastline was closed because exceptionally high PSP levels were found in many areas. In 1975 the red tide again appeared in late May.

In New Hampshire, prior to 1972, there were no reports of toxic shellfish. During mid-September 1972, large patches of red water, caused by Gonyaulax tamarensis, were seen on and near the shore. This, combined with the non-fatal poisoning of two people after ingestion of toxic clams, and sightings of hundreds of dead and dying shore birds, caused closure of the entire coast for several months. Two red tides occurred in 1974 and the clam beds were again closed. In early June of 1975 the toxic tide returned and caused another closure.

Massachusetts waters also had red tide in September 1972 and high PSP levels caused closure of clam and mussel beds for over a month. Over 2,000 Massachusetts waterfowl, representing 13 different species, were killed during the height of the event. In late May and early September of 1974, intense red tides appeared, and the beds were closed for the entire season. In 1975 a red tide effectively closed shellfishing for 6-8 weeks in the northern Cape Ann region. The causative organism of the New England red tides has not yet been found in Connecticut, New York or New Jersey waters.

Thirty-three people became ill from ingestion of PSP-tainted shellfish during the 1972 red tide and public health officials banned the harvest and sale of soft clams, hard clams, and mussels from Maine to Massachusetts. Connecticut and New York halted the importation and sale of shellfish from these New England states, and destroyed large quantities of already harvested raw and packaged shellfish. The embargo and adverse publicity severely damaged the seafood industry in the affected states. In 1974, two red tides in New Hampshire closed shellfish beds and sent 4 people to the hospital. Although these were non-fatal cases, the resulting publicity again reduced sales of seafood products. In 1975 two people became ill from eating toxic snails taken from a Massachusetts shellfish bed. These cases were widely publicized and the shellfishery was temporarily suppressed. The fishery regained normal operation about 6-8 weeks after the shellfish beds were re-opened by the Massachusetts Public Health Department.

A means for inactivation of the toxin in aquaria and in live molluscs is suggested. Investigators at the Milford Laboratory found that ozone gas could inactivate Gymnodinium breve toxins in both laboratory grown cultures and field samples and could detoxify paralytic shellfish poisons. These toxins were rendered completely inactive after 5-minute doses of 2% ozone in air, flowing at a rate between 55 and 110 ml/min. Control solutions treated just with air retained their original toxicity.

To study toxin inactivation in the field a continuous-flow ozone contacting system was assembled at Hodgkins Cove, Massachusetts, in August 1974.

Ozonized red water was flowed over non-toxified Milford-obtained clams (Mya arenaria) and mussels (Mytilus edulis, and Modiolus demissus) and similar toxified species from the Gloucester area. Equal numbers of control animals were set in similar trays which received untreated water. No motile cells were found after ozonization, and approximately 60% of the ozonized dinoflagellates showed disrupted cell walls. Bioassays to test extracts of the clams and mussels in ozonized red tide seawater indicated that ozone treatment does prevent shellfish from accumulating paralytic shellfish poison during red tide outbreaks. In non-ozonized seawater, shellfish used for controls held at the same time and flow rate accumulated from 10-35 times the amount of toxin necessary for closure of the shellfish beds (i.e. 80 ug/100 gms of meats).

A trial was then made of ozone depuration and detoxification of clams and mussels which contained high levels of toxin. The following reductions in toxicity were obtained: blue mussel, 30% reduction; surf clam, 31% reduction; and soft clam, 0% reduction. Soft clams were held in the ozonized water for only 14 working hours of the experiment, which apparently was too short a time for depuration and detoxification. A series of ozone detoxification experiments with red-tide contaminated surf clams was then completed which demonstrated a 17% reduction in toxicity over controls for a 96-hour depuration time. Since these tests demonstrate ozone's effectiveness in detoxification of G. tamarensis toxins, removal of toxin from shellfish contaminated by red tides may be feasible.

1. INTRODUCTION: BACKGROUND INFORMATION ON THE RED TIDE PHENOMENON

1.1 Nomenclature

"Red tide" is a general term for a discoloration of natural waters, visible to the unaided human eye, caused by concentrations of microscopic organisms. This term is not an accurate one, first because the discolorations can be red, yellow, brown, green, and other colors depending on the organisms involved and the stage of the episode. Secondly, the condition is not a direct function of tide (i.e. the periodic rise and fall of sea waters due to the attraction of the moon and sun), although tide may influence its distribution. "Bloom" is another term widely used to indicate the condition in the developing sense. This is also a weak term because it implies to many people the flower of a plant or the opening of the buds. However, both terms are useful because of wide acceptance. There is some precedence in the literature (e.g. Rounsefell and Nelson, 1966) for restricting the term "red tide" to episodes which cause obvious adverse effects (e.g. fish kills). However, the desirability of maintaining this distinction is doubtful since the term red tide is also applied to blooms of non-toxic species (e.g. Sweeney, 1975). The term originated in Japan where only some of the occurrences are noxious (Hart, 1966). It might be best to refer to catastrophic episodes of the poisonous variety as "toxic dinoflagellate blooms." Equal explicitness is preferable when reference is made to non-poisonous blooms which produce catastrophic effects (e.g. a fish-kill through a bloom decay produced oxygen sag) or to apparently harmless occurrences.

Most microorganism-caused water discolorations are brought about by photosynthetic species although bacteria and microscopic animals can also produce discolorations. The photosynthetic microorganisms in a body of water are collectively known as the phytoplankton and individually as phytoplankters or phytoplanktonts. The prefix "phyto" indicates that the organisms have the ability to directly use solar energy in their nutrition. The term plankton denotes collectively all organisms, both plants and animals, that essentially move passively in a body of water.

The term primary productivity refers to the rate of carbon fixed per unit area per unit of time by phytoplankton. It characterizes phytoplankton productivity or sustained crop yield in an area. According to Raymont (1963) it is the rate of production of organic (plant) material rather than the numerical crop of plant cells present in any area at a given time which ultimately determines the real productivity of the area.

1.2 Fundamental Role of the Organisms

Red tides, which are overgrowths or dense concentrations of phytoplankton, can be very striking and interesting when they occur, especially because of their sometimes catastrophic side effects. This dramatic aspect may detract from the idea that red tides are an irregular expression of the ongoing and vital processes of an endemic photosynthetic community rather than infestation by an invasive agent. Consideration of the fundamental role of the phytoplankton helps place these occurrences in proper perspective.

According to Lebour (1928) the phytoplankton utilizes salts and gases in the sea water, and harnesses light energy through chlorophyll or other pigments to build up the complex protoplasm of which it is composed. "It therefore occupies the base of the food chain, all animals being dependent on plants, eating them directly or indirectly. Thus a small sea animal eats the plant and is itself eaten by a larger animal, and so the great food cycle goes on. The phytoplankton is sometimes aptly termed the "meadows of the sea." Dawson (1966) stated that the minute size of the phytoplankton belies its importance in the organic economy of the sea; compared with less than a mere 1 percent of the sea area suitable for benthic plants are the vast "meadows of the oceans." The phytoplankton has often been called the "grasses of the ocean." What these terms imply, of course, is an anology of the phytoplankton as the counterparts of graze plants in agriculture. Photosynthetic forms developed differently in the terrestrial and aquatic environments but many of them have similar functions in the respective environments.

1.3 Organisms Associated with Red Tides

According to Wood (1965) the organisms associated with red tides belong to three main groups, diatoms, dinoflagellates and blue-green algae (Figs. 1-8). The diatoms are the most important constituent of the phytoplankton (Lebour, 1928). They are often described as single cells with siliceous walls having the structure of a pillbox with an overlapping lid. There are thousands of variations on this basic structure. Diatoms are non-motile or, at best, feebly motile. According to Lebour (1928) they may be found anywhere in the sea or fresh water; the marine forms are usually more abundant near land. They are usually more numerous and larger in cold and temperate climates and are never evenly distributed. Regular periods of maximum and minimum occur, in northern temperate regions there being two maxima, one in early spring and the other in autumn.

The dinoflagellates are next in importance to the diatoms; they are universally distributed and are most abundant in the warmer season (Lebour, 1928). Dawson (1966) describes the dinoflagellates as motile unicells, the great majority having a characteristic organization related to the insertion of two ventral flagella. The longer flagellum emerges from a longitudinal groove and produces forward motion by a sculling movement. The other flagellum lies in a transverse groove and its movement provides a rotational motion.

The blue-green algae form an important part of the plankton in the tropics where they may exceed all other phytoplankters in numbers (Wood, 1965). According to Dawson (1966) all the blue-greens are individually microscopic. The simpler members are unicellular, but are usually aggregated in muscilaginous, palmelloid colonies. Most of the species occur as simple, uniseriate flaments, commonly within a stratified and colored mucilagenous or gelatinous sheath.

1.4 Primary Productivity and Phytoplankton Abundance

Phytoplankton abundance is determined by the difference or balance between import and production of new plant material and attrition by way of death, predation, sinking to sediment or export (dilution). Environmental factors responsible for new phytoplankton synthesis include regulators such as light intensity, plant macro- and micro-nutrients, vitamins, salinity, temperature, etc. The genetic constitution of the organism will determine tolerance to these factors as well as set the upper limits on the organism's ability to grow and profit from favorable combinations of environmental factors or variables.

Additionally, the water column itself, its vertical structure and density stability can determine abundance of phytoplankton. On the one hand, mixing via wind or tidal force acts to evenly redistribute phytoplankton cells throughout the water column, while on the other hand, quiescence or stability of water column may often lead to uneven vertical distributions of phytoplankton. These relatively higher concentrations of cells at specific layers in the column result from a behavioral phenomenon known as phototaxis or "swarming". Phytoplankton which have flagella (dinoflagellates, chrysomonads, and others) may have an advantage over non-flagellated species since the former can respond to quantity or quality or color of light and through swimming, determine their own vertical distribution. Hasle (1954) has reported that some dinoflagellates (P. micans) swim as much as 5 meters/day vertically in response to light. On several occasions, high concentrations of flagellates have been observed in upper-lighted-layers of New Jersey coastal water, while significantly lower concentrations were found below (Fig. 9).

1.5 Where Red Tides are Found

Prakash (1975) stated that red tides are generally confined to coastal waters or those regions of the sea where active upwelling (which brings nutrient-rich bottom water to the surface) takes place. Wood (1965) said that red tides have been recorded from a number of regions in the tropics and temperate waters, but apparently only the red tides caused by a blue-green alga, Trichodesmium sp. are oceanic.

1.6 Origin of Red Tides

There have been different view points as to how a red tide arises. According to Wood (1965) red tides represent outbursts of phytoplankton production. On the other hand, (Ryther, 1955) believed that prodigious growth of organisms is not necessary to produce red water; it is necessary, he stated, only to have conditions favoring the growth of a moderately large population of a given species, and the proper hydrographic and meterological conditions to permit the accumulation of organisms at the surface in localized areas. Yentsch (1975), summarizing the above two view points, stated that some ecologists believe that large concentrations of dinoflagellates are "accumulations" brought about by interaction between behavior and hydrography whereas other ecologists feel that blooms occur because of complex biochemical relationships with water chemistry. However, Yentsch said most ecologists feel that blooms are explained by both theories: concentrating mechanisms coupled directly or indirectly with enrichment is a necessity. Prakash (1975) believes that the development of a bloom should be looked upon as a process comprising two main components, 1) initiation of a bloom, and 2) subsequent development and continuation of this bloom to the extent that it becomes visible.

Therefore, an occurrence of red tide is the result of a complex interaction of factors. We at least know what the major factors are. The first requirement is a seed population. The particular body of water must not be inimical to the species (e.g. unfavorable salinity, presence of toxic substances). There must be a regime of factors promoting abundant growth of the species including adequate nutrient supply and favorable water temperature and light intensities. Then, recalling that the plankters have only feeble swimming ability, the hydrological and meterological conditions prevailing in the particular area at that time will largely determine the subsequent fate of the bloom. Warm, sunny, calm weather and dead calm seas usually promote bloom development. In addition to these factors, more subtle influences may be operating which we are not aware of or do not know enough about at present. For example, plant hormones from terrestrial plants or produced by the endemic phytoplankters could be present in sufficient quantity to stimulate or retard growth of all or certain phytoplankton in a body of water.

The presence of contributing factors does not guarantee that a red tide will occur. Also, the contributing factors combine to produce a bloom but there is no necessity for them to have the same proportional influence in each instance. For example, if the locus of a bloom were in a nutrient-rich body of water, the rate of growth of the bloom plankters could be sufficiently high to replace that part of the population dispersed by wind or tide. Conversely, hydrological and meterological conditions could promote an accumulation of plankters in a locale not sufficiently nutrient-rich to support their rapid growth. Therefore, a single explanation of how red tides arise can be offered in the general, but not in the specific sense. Explanation of specific red tides should be sought through examination of probable contributing factors, but such study must be tailored to fit the particular species and locale.

1.7 Possible Effects of Red Tides

Keeping in mind, especially, that the term "red tide" has been extended to include phytoplankton blooms of species belonging to different groups (Fogg, 1965), we may interpret particular episodes as having benign or detrimental effects depending on their environmental impact. Some dinoflagellate blooms are toxic and may cause detrimental effects including the mass mortality of fish. But many others are non-toxic. Diatom blooms are not known to produce the toxic condition. Adding to the classification difficulty is the finding that toxicity of particular plankters apparently may vary with the locale. Wood (1965) cites the blue-green algae, Trichodesmium, as being associated with fish mortality on the coast of India, but not the Trichodesmium blooms in Australian waters. To lend familiarity to the situation wherein one plankter is toxic where another is benign, it is useful to again draw a comparison between the phytoplankton and terrestrial plants. We can recall that some land plants such as poison ivy may cause deleterious effects, whereas others, e.g. the grains, have very beneficial uses.

The detrimental effects of red tides, both toxic and non-toxic varieties, can be summarized as follows. According to Prakash (1975), in several regions of the world, red tide outbreaks have been responsible for harmful effects on public health, large-scale fish mortalities and destruction of other marine life, and have spelled disaster for coastal fishing, tourist and recreational industries. Non-toxic blooms may also be detrimental since dissolved oxygen sag as a secondary effect of decomposition and decay of such blooms may jeopardize the survival of many coastal marine organisms. Wood (1965) stated that the red tides which produce mass mortalities of fish are usually of short duration with a short set-back to fish production. In some regions, e.g. on the Gulf coast of Florida, fish mortality is a serious problem. This variety also causes such symptoms as respiratory discomfort, sore throat and eye irritation among bathers and sometimes in people who are just near the water. Dinoflagellate species on the northwest and New England coasts of the United States cause a paralytic shellfish poisoning which is distinct from the fish mortality. Paralytic shellfish poisoning occurs when shellfish feed on poisonous plankters. The shellfish are not themselves poisoned, but accumulate sufficient toxin to sicken people or shorebirds, etc. which eat them.

1.8 Impact of Red Tides in New York Harbor and Adjacent Waters.

Most of the red tides in the New York-New Jersey area have thus far been nontoxic with the remainder only mildly toxic. The episodes usually arouse much regional public interest. Communications media, i.e. newspapers, television and radio, frequently report on the occurrences and contribute to public awareness. There is also sufficient communications spill-over from one area to another to, for example, cause many people in the New York-New Jersey area to be aware of the catastrophic red tides in Florida and in the New England states. An important peripheral function of the red tide study at the Sandy Hook Laboratory has been to cooperate with New Jersey Department of Environmental Protection biologists in diagnosing the probable effects of particular episodes. Recommendations in this regard made by DEP have contributed to avoidance of massive reductions in seafood consumption and tourism in years subsequent to 1968, when a major, widely publicized, red tide occurred along the New Jersey shore, resulting in an estimated $1.1 million loss to Monmouth County alone.

2. ANNUAL CYCLE OF PHYTOPLANKTON PRODUCTIVITY IN RARITAN, LOWER, AND SANDY HOOK BAYS

2.1 Description of Annual Cycle

Between November 1973 and March 1975, the spatial and temporal distribution of phytoplankton primary productivity, biomass (abundance), phytoplankton species identification, inorganic nutrients, temperature, salinity and photosynthetically active radiation were measured monthly at twelve stations and at three to six depths within Raritan, Lower, and Sandy Hook Bays (Fig. 10a and b). Phytoplankton primary production within this system appears to be the highest recorded for any estuary in the world. This system produces 750 to slightly over 1000 grams of organic carbon per square meter per year. Values from other areas range from 150 to 500 gm $C/m^2/yr$ (Thomas, 1966). The annual cycle of phytoplankton productivity in Raritan, Lower, and Sandy Hook Bays (Figs. 11-14) is characterized by low-winter photosynthesis, a spring bloom and a summer maximum followed by a rapid decline in primary productivity during fall. The spring bloom (March) is dominated by netplankton (organisms larger than 20 microns) and principally by the diatoms, *Skeletonema costatum*, *Rhizosolenia delicatula*, and *Asterionella japonica*, which form long chains or colonies of cells. The summer peak in photosynthesis (Figs. 11-14) is due to the rich abundance of nannoplankton (organisms smaller than 20 microns) and principally one of several species. During our study, it was *Nannochloris atomus*, a green alga.

2.2 Spatial and Temporal Distribution of Phytoplankton Primary Productivity in Raritan, Lower, and Sandy Hook Bays

In winter, primary productivity at constant and optimal light intensities (photosynthetic capacity) was relatively low and uniform throughout Raritan, Lower, and Sandy Hook Bays with some slight increase in Sandy Hook Bay (Fig. 15). With the advent of the spring bloom, productivity generally increased along the south or New Jersey half of the bay system. By March, extreme spatial heterogeneity existed with the highest rates of photosynthetic capacity occurring in Sandy Hook Bay and toward the upper end of Raritan Bay. At this time, the lowest rates in photosynthetic capacity occurred between the Verrazano Narrows and Rockaway Point. This condition persisted on into April and May with the New Jersey half of the bay system continuing and increasing in importance as the area of highest productivity (Fig. 15). In June and through the summer, photosynthetic capacity on the Sandy Hook side of the Rockaway-Sandy Hook transect remained characteristically higher due to the influence of increased photosynthetic capacity in Sandy Hook and Lower Bays. The highest rates of photosynthetic capacity occurred in and throughout Raritan Bay and Sandy Hook

Bay in July. At this time, the lowest rates occurred between the Narrows and Rockaway Point. In August, rates of primary productivity began decreasing at the upper end of Raritan Bay, but were still very high on the south shore from Perth Amboy to Sandy Hook. The decline continued into September. The highest values were then found in Lower Bay. The area between the Narrows and Rockaway Point remained low. In October the highest values were found near the Narrows. By November the system was again relatively homogeneous. The low point in primary productivity came in December and values were generally low and uniform throughout Raritan, Lower, and Sandy Hook Bays. The annual cycle then began again with values increasing in January toward the spring bloom in March.

Throughout the year and during the summer, we have evidence that the Raritan-Lower Hudson estuary is "nutrient saturated". Relatively strong linear relationships were found between growth rate (production) per unit biomass (chlorophyll a) of phytoplankton and daily photosynthetically active radiation (Einstein's/m^2/day). Figure 16 depicts this relationship and we infer from it that light is the most important environmental variable regulating production per capita or per unit biomass. Additionally, the high productivity biomass ratios in summer indicate the presence of vigorous physiologically "robust" cells. Though this linear relationship does "explain" productivity as a function of light, it does not totally explain or account for changes in abundance of phytoplankton. We suspect that light intensity primarily determines productivity and the additions via production are balanced by losses through grazing and estuarine dilution with adjacent coastal water. In the areas of the estuary contiguous to coastal sea water, flushing rate is high relative to slower flushed portions near the head of the estuary. Consequently, significantly higher standing stocks or biomass concentrations are observed near the head of the estuary.

2.3 Nutrient Sources and Utilization in Raritan, Lower, and Sandy Hook Bays

Nutrients, phosphate (Fig. 17), ammonia (Fig. 18), nitrite and nitrate (Fig. 19), and silicate (Fig. 20) were also measured each month at these same 12 stations and depths between November 1973 and March 1975. In general, these inorganic nutrients are abundant throughout the year. Silicate appears to be an exception to this generalization. Zero concentrations were observed at one or two of our 12 stations during our April, May, June and July cruises. These low concentrations of silicate were observed on the Jersey side of the bay.

Nutrient concentrations in Raritan, Lower, and Sandy Hook Bays are the result of riverine and sewage input, utilization by phytoplankton, and in situ regeneration by microbial organisms, zooplankton, and fish. Nutrients, such as nitrite, nitrate, ammonia and phosphate, enter the estuary by river transport of sewage. Consequently, their input concentrations are determined by river flow. Others, such as silicate are derived by terrestrial erosion and their input concentrations are affected by total quantity brought to the system by river flow. River flow is maximum in April and minimum in November. Sewage input of nitrite, phosphate, and ammonia is nearly constant year round (Kirschner, personal comm. to O'Connors and Duedall, 1975). Utilization of nutrients by phytoplankton is greatest during the summer maximum and spring bloom when phytoplankton density and production is high. Regeneration rates of nutrients are highest when metabolic activity is highest due to temperature. Nutrients are released as the breakdown products of metabolism.

2.3.1 Silicate

Silicate is principally supplied by river flow and probably to a lesser extent by regeneration and is abundant in the spring at the start of the spring bloom of S. costatum, a diatom. Diatoms characteristically require silica in building their frustules, the outer box-like covering of the organism. Diatom growth can be limited by silica, but in most estuarine systems nitrogen or phosphorous is usually the limiting nutrient before silica.

In Raritan, Lower, and Sandy Hook Bays silicate was generally high in winter. As a result of the spring diatom bloom, silicate concentrations began decreasing in March. Zero concentrations of silicate were found at scattered surface locations in March, May, June, and July (Fig. 20). These zero concentrations were limited principally to the south or New Jersey half of the Raritan-Lower Bay system from Perth Amboy to Sandy Hook Bay. The highest rates of primary productivity were also found here (Fig. 15). During this period, the phytoplankton species shifted in dominance from the silica - requiring diatom, S. costatum (a net phytoplankter), to the green alga, N. atomus (a nannoplankter), which is not known to have a requirement for silica. Zero concentrations of silicate also occurred more sporadically near the Verrazano Narrows (June) and near the entrance of the Ambrose Channel off Sandy Hook (May, July, October, and November).

Whether or not silica is limiting phytoplankton production is debatable because the entire system is never depleted of silicate over large areas or for extended periods of time (more than one month). However, the number of measurements which are low or zero do suggest that silicate may limit diatom production and abundance during the warmer months. If this is true, then species not having a high requirement for silica (N. atomus, dinoflagellates) may have a distinct advantage over diatoms.

Schelske and Stoermer (1972) in investigating Lake Michigan found silica not only to be limiting for diatoms, but also to cause the phytoplankton population to shift from diatoms to blue-green algae. They suggested that a disproportionate amount of phosphate from sewage input was added to the system causing silica to become limiting before phosphate. The rationale for this argument is that, in nature, phytoplankton cells generally take up silica, carbon, nitrogen, and phosphorus (Si, C, N, P) in well defined ratios. These ratios were presented in Redfield (1934) who stated that phytoplankton take up one atom of phosphorous for every 16 atoms of nitrogen and every 105 atoms of carbon during photosynthesis. If the C:N:P ratio in the water (usually oceanic waters) is much different from 105:16:1 then the nutrient, which is present in less than its ideal proportion is the most likely to become limiting - given sufficient light, etc. Schelske and Stoermer (1972) found that the fresh water diatom, Asterionella formosa, took in 2000 atoms of silica for every one of phosphorous. Marine diatoms take 2.5 to 1 atom of C for each Si (Strickland, 1960). Ratios of Si: N: P for water entering Lower Bay are 10:26.6:2.5 (O'Connors and Duedall, 1975) and indicate the effect sewage discharges have on these ratios. Such a situation increases the likelihood that silica may become limiting before phosphorous or nitrogen and increases the probability that a phytoplankter having a low silica "need" will dominate and grow until its abundance is either limited by N, P, etc. light or losses via gravity, diluting, etc.

2.3.2 Phosphorous

Inorganic phosphate originates principally from a constant source, the raw and treated sewage inputs from the metropolitan area. Because its input to the rivers is large and relatively constant over the year (Kirschner, personal comm. to O'Connors and Duedall, 1975), we see its concentration diluted when river flow is high and concentrated when river flow is low.

During our studies in 1973 and 1974 phosphate was generally abundant (Fig. 17). A zero concentration was found only once at the surface at the head of Raritan Bay during the spring bloom. Evidence of heavy utilization of phosphate, during the spring bloom, was found where phytoplankton productivity was highest, both in Sandy Hook Bay and toward the upper end of Raritan Bay. The highest phosphate concentrations during the year occurred in September in Sandy Hook Bay. During September, water temperatures were near maximum causing high rates of microbial metabolism. These high metabolic rates probably resulted in the mineralization of organic nutrients to dissolved inorganic forms. River flow was also less allowing phosphate to accumulate following the precipitous decline of the summer bloom of nannoplankton. The combination of high regeneration rates, decreased utilization rates, and lower river flow and flushing rates probably contributed to these maximum concentrations of phosphate.

2.3.3 Nitrogen

Ammonia may be considered both a nutrient and a toxicant depending on its concentration. Generally, toxic levels of ammonia do not exist in the Raritan-Lower Bay system (Fig. 18). As a nutrient, ammonia is preferentially utilized by many phytoplankton in lieu of more oxidized forms of nitrogen (nitrite, nitrate) (Bates, 1976). In fact, nitrate is frequently not used until ammonia is exhausted (Pomeroy, 1970). Such may not be true in the case of dinoflagellates (Eppley and Harrison, 1975).

In the Raritan-Lower Bay system, ammonia is generally abundant. Ammonia, like phosphate, is principally derived from sewage input to the system. As with phosphate, its input is relatively constant throughout the year. When river flow is high its input is diluted. When river flow is low and temperatures are high, maximum concentrations are found (unpubl. data). Evidence of utilization of ammonia is seen in the areas of highest phytoplankton productivity both during the spring bloom and during the summer maxiumum (Fig. 15). Zero concentrations were found only during November near the entrance to Ambrose Channell, off Sandy Hook. At this station zero concentrations were found throughout the entire euphotic layer. A combination of dilution by seawater and utilization by phytoplankton could explain the condition. In waters without significant organic wastes usually only very low concentrations of ammonia are found.

2.4 Conclusions

Raritan, Lower, and Sandy Hook Bays appear to be highly enriched with regard to concentrations of phosphate, ammonia and combined nitrite-nitrate (breakdown products derived in part from sewage oxidation). In addition, Remsen (1971) found high concentrations of urea (11.2 μM/litre) in the Hudson estuary. The presence of abnormally high levels of these nutrients compared with the concentrations of silicate could lead to nutrient depletion and limitation of net phytoplankton productivity (diatoms) by silicate. In general, however, phosphate, nitrate, nitrite, and ammonia do not appear to be limiting phytoplankton production throughout the year. If these nutrients are limiting, it is only for short periods of time (less than our monthly sampling interval) and only at isolated stations and depths. Silicate may be limiting or nearly so to silica-requiring phytoplankton, particularly along the south shore of Raritan-Lower Bay during the late spring and summer when phytoplankton primary productivity is high.

3. RED TIDES IN NEW YORK HARBOR AND ADJACENT WATERS

3.1 Causative Species

Personnel of the Sandy Hook Laboratory have observed annual occurrence of phytoplankton blooms in New York Harbor and adjacent waters for the past 13 years (1962 to 1975). Three species, Massartia rotundata, Olisthodiscus luteus and Prorocentrum micans dominated most of the occurrences. M. rotundata and P. micans are dinoflagellates; O. luteus is also a flagellate, but its exact taxonomic classification is in question. Collectively, the three species can be called phytoflagellates.

3.2 Bloom Effects

Although many of the episodes were apparently benign in nature, some had definite or indicated adverse effects on biological and recreational resources of the area, including a possible role in fish mortality (Ogren and Chess, 1969), respiratory discomfort among bathers, and diminishment of aesthetic value of beaches. However, the general severity of these occurrences has not been comparable to that of blooms of highly toxic species in other locales (e.g. in New England, Florida).

3.3 Description of Blooms

The phytoflagellate blooms occurred during the warmer months, from the middle of June to the end of September; most frequent occurrence was between the end of June and the end of August. The usual pattern included an outbreak in late June or early July followed by one or two more later in July or August. Most episodes lasted 1-2 weeks, but on two occasions, blooms persisted 4-6 weeks, although with decreased intensity during approximately the latter two-thirds of their history. The order of bloom dominance frequency was O. luteus followed by M. rotundata and P. micans.

In New York Harbor waters, the greatest phytoflagellate bloom incidence was in Sandy Hook Bay and in the tidal Navesink and Shrewsbury Rivers draining into the bay. During these blooms, red water was also frequently found in Lower New York Bay proper, but was not observed in Raritan Bay. In the ocean, the area of most frequent occurrence was between the tip of Sandy Hook and Belmar, New Jersey, 40 km to the south. On several occasions during the past 12 years, blooms extended about twice this distance to the south. Bloom water was rarely observed beyond 10 km from shore. Most surveillance, however, was within 10 km of shore and was not sufficient to preclude the existence of blooms further offshore.

The most frequent pattern of bloom development was initiation in the bay area with spread to the coastal area 1-2 days later. On several occasions, coincident with outgoing tides, bloom water was observed flowing out of the bay around Sandy Hook and moving south along the New Jersey coast. On other occasions, especially with spring tides, blooms nutured in the tidal rivers flowed out to both bay and ocean. In Sandy Hook Bay, the dispersion of the bloom was usually fairly uniform throughout. In the ocean, dispersion varied from isolated patches to a continuous although irregularly dense band along shore. Round or elongated patches most often ranged between approximately 100 m to 1000 m in diameter or length. Sometimes only a single patch was seen, at other times there were several patches separated by water containing a relatively sparse phytoplankton. At times, the red water would impinge on the beaches and at the other times it lay some distance (within 10 km) offshore. Impingement of the bloom water on the beaches appeared to be largely a function of tide. Wind influenced distribution to a lesser degree except during storms; storms and accompanying heavy seas completely dispersed some blooms. Depending on the tide, the red water might oscillate north and south several km along the coast but the overall drift was southerly. A southward current flow along the New Jersey shore is a typical component of the hydrology of the area in summertime.

Persistence of the blooms was at times roughly the same in bay and ocean, with eventual concurrent decline in both areas. More frequently, it appeared that the bay had a nurturing effect in that cell numbers in bloom patches flushed out to the ocean declined more rapidly than in the bay bloom water. Generally, the cell numbers in red water along the ocean beaches decreased with distance south from Sandy Hook.

The above three species, along with Exuviella sp. and Peridinium trochoidium, also cause red tides each summer in Long Island, New York in such locales as Manhasset Bay and Hempstead Harbor.

3.4 Nutritional Studies

Determination of the causes of the New York Harbor blooms has been the subject of a small, but ongoing study at this laboratory for several years. Our field observations and results of pollution studies (Federal Water Pollution Control Administration, 1967) suggested there was an association between the blooms and eutrophication of the waters. As the initial component of a study of the blooms at this laboratory, we attempted to ascertain such a relationship.

Considering that the same species bloom annually in the polluted New York Harbor waters, a question was asked ourselves was, "Do these species possess nutritional capabilities which can provide them an advantage in this kind of environment?" According to Prakash (1975) there is evidence suggesting that dinoflagellate blooms in inshore coastal waters are associated with the introduction of organic compounds of terrigenous origin. A beneficial effect on planktonic algae linked with the introduction of significant amounts of terrigenous humic substances is one aspect. Humic substances can bind metals in the water and may, thereby, depending on the particular circumstances, lessen a toxic condition to the plankters or make required metals available to them. Another aspect is related to the entry of nutrients in coastal waters: sewage discharges introducing substantial amounts of organic matter can favor development of blooms. Since available information indicated there was an association between the blooms and eutrophication, we concentrated our work on the nutrient aspect. We considered that a propitious utilization of organic nutrients by the species which dominate the New York Harbor blooms would indicate that they are particularly advantaged by the waste-derived fertilization of these waters. The promotion of phytoplankter blooms via utilization of organic nutrients might come about in a number of ways. If inorganic forms of essential nutrients became scarce, in a situation which otherwise favors rapid phytoplankton growth, utilization of organic forms could permit phytoplankters to flourish. In phytoplankton blooms in Long Island, New York bays, nitrogen limited phytoplankton growth and the supply was used before decomposition of organic nitrogen to nitrite and nitrate was completed, the organisms able to utilize the nitrogen in the earliest stages of decomposition had a distinct advantage (Ryther, 1954). Specific phytoplankters could be advantaged in a different way if the organic nutrient were used as a supplement rather than as an alternate to the inorganic nutrient. Provasoli (1960) believes that, although the creation of blooms cannot be considered as depending principally on the heterotrophic effect, there is undoubtedly an advantage for the algae which can utilize organic compounds as building blocks or carbon sources; the bypassing of minor syntheses when the synthetic products are present in the environment could collectively permit a noticeable, even substantial, increase in growth.

We decided to study the effects on growth of the organism of a variety of organic carbon, nitrogen and phosphorous compounds because these elements are important in algae nutrition and sometimes growth-limiting in the environment. North, Stephens and North (1972) advised that the heterotrophic and photoassimilitory abilities of algae have been studied extensively in this laboratory, but, unfortunately, few of these studies can be applied to natural algae populations because the usual culture technique incorporated abnormally high concentrations of organic nutrients. Accordingly, our work was directed towards the demonstration of utilization of organic nutrients in "natural" concentrations. This is represented in our tests by the results from the lowest concentrations of nutrients employed. However, it was our experience that response to a nutrient concentration gradient would often present a clearer picture of the phytoplankter's use or non-use of a nutrient than response to a single concentration. Therefore, nutrients were tested in high, medium and low concentrations. The high concentration approximated the highest concentration commonly, or at least on several occasions reported for that kind of nutrient (i.e. total carbon, phosphorous, nitrogen); the medium and low concentrations were one-half to one-tenth or one-quarter, respectively.

3.4.1 Utilization of Inorganic and Organic Carbon Sources

Most of the carbon compounds incorporated in these tests were from tabulations of C sources utilized by one or more phytoplankters (Danforth, 1962). Some of the principal polysaccharides of brown, red and green algae (Percival and McDowell, 1967) such as laminaran, alginic acid, galactose, rhamnose, and xylose were also tested. These were included because on several occasions during the last ten years, phytoplankton blooms followed the occurrence of late spring kills of benthic algae in the rivers which then decomposed rapidly in surface waters. Three concentrations were employed: 50, 25 and 5 mg C/l.

M. rotundata used 11 of the 21 C sources tested. Results indicate that M. rotundata used at least the following 9 C sources in the lowest concentration: glucose, trehalose, melibiose, lactose, sucrose, glycerine, galactose, alginic acid, and bicarbonate. Amylopectin may have also been stimulatory in this concentration. Glycerin was inhibitory in the higher concentrations. Although with an inhibitory trend, the other C sources used in the lowest concentration, along with mannose and amylopectin, were stimulatory at 25 mg C/l. In the highest concentration (50.0 mg C/l), 5 of the C sources used at 5.0 mg C/l were decidedly inhibitory and the remaining 4, including trehalose, melibiose, sucrose and galactose were stimulatory; amylopectin and mannose were also used. Trehalose, melibiose, and mannose were most stimulatory in the high concentration and, in fact, utilization of mannose decreased with decreasing concentration. O. luteus used at least 18 of the 21 C sources. Growth was stimulated by bicarbonate and at least 14 of the organic C sources tested at 5.0 mg C/l. As was the case with M. rotundata, alginic acid may have been utilized. Of the group of 15 C sources, in the highest concentration at least 7 were used and, at 25 mg C/l, at least 10 were used, although in most cases these concentrations were apparently approaching toxic levels. P. micans utilized 16 of the 21 C sources: bicarbonate and 14 organics were utilized at 5.0 mg C/l. In the intermediate concentration, rhamnose, laminaran, trehalose, mannose, glycolic acid, glycerin, amylopectin and bicarbonate were stimulatory; these, except rhamnose and glycolic acid, were also stimulatory in the highest concentration. Again, the higher concentrations approached toxic levels; conversely, sucrose was stimulatory only in the highest concentration.

3.4.2 Utilization of Inorganic and Organic Nitrogen Sources

Because urea can be relatively abundant and represents an important potential supply of nitrogen for phytoplankton production in New York Harbor (Remsen, 1971), it was included in these tests. Data on presence or abundance of amino acids in New York Harbor waters were not available, but ornithine, serine and glycine were the three predominate free amino acids in Buzzards Bay, Massachusetts (155, 393, and 12 ug/l, respectively, which translates to roughly 5, 8, 0.29 ug-at N/l, respectively). Determinations of amino acids in dry marsh grass, Spartina alterniflora, and in decomposing organic detrital material (primarily that of benthic algae and shore plants) from a salt marsh indicated that some amino acids such as serine, proline, leucine, phenylalanine and others may be preferentially metabolized (Hall, Weimer and Lee, 1970). Urea and the previously mentioned amino acids were tested at 1.4, 0.7 and 0.14 mg N/l (100, 50 and 10 ug-at N/l, respectively); the lower concentration fits concentrations (9-11 ug-at N/l) found on at least one occasion for urea in New York Harbor waters (Remsen, 1971).

Results show that all three phytoplankters used ammonium, nitrite and nitrate N. M. rotundata was the more delicate of the three, being completely inhibited by the higher concentrations of $NaNO_2$ and NH_4Cl; O. luteus was hardiest. All used uric acid, but only P. micans showed dramatic growth response to the lowest concentration. Urea was a good nitrogen source for M. rotundata, but the higher concentrations were progressively toxic. O. luteus grew well on urea and was only partially inhibited by the highest concentration. Only a small increase in growth of P. micans resulted from addition of urea in the lowest concentration. However, its use by this species was consistent in separate tests.

Growth of M. rotundata was stimulated by at least 12 of the 14 amino acids in the lowest concentration tested. At 0.7 mg N/l all amino acids were stimulatory; in fact, 10 of the 14 were more stimulatory in this concentration than in the lowest. At 1.4 mg N/l, 9 amino acids were utilized best and the remainder either elicited little additional response or were toxic to various degrees. O. luteus was stimulated by at least 5 amino acids added at 0.14 mg N/l. At 0.7 mg N/l the same 5 amino acids stimulated an increased level of growth; proline, leucine and thymine were also used in this concentration although not in the lowest. Except for threonine, which was partially inhibitory, these same amino acids stimulated best growth in the highest concentration. P. micans utilized at least 11 of the 14 amino acids in the lowest concentration. All 14 amino acids were stimulatory at 0.7 mg N/l with increased growth in most cases. Ornithine, serine, glycine, arginine, threonine, methionine, and xanthine were even better N sources at 1.4 mg N/l but proline, thymine, glutamine and asparagine were partially inhibitory, phenylalanine was non-stimulatory and valine was completely inhibitory in this concentration.

3.4.3 Utilization of Inorganic and Organic Phosphorous Sources

Besides orthophosphate, a group of 8 organic P compounds and 2 polyphosphates were tested. The organics were chosen from a compilation of dissolved organic phosphorous compounds utilized by marine, euryhaline or fresh water algae (Johannes, 1964), although data on their specific occurrence in the environment is sparse or absent. Eppley (1962) suggested that, because of the widespread occurrence of polyphosphates in algal cells and the release of polyphosphate on cell death and mineralization, these substances are of ecological significance. Accordingly, two types of polyphosphates, pyrophosphate and metaphosphate, were included. Each type of phosphorous was tested in three concentrations: 0.5, 0.25 and 0.1 mg P/l.

Results show that M. rotundata utilized all the phosphorous compounds tested. At 0.1 mg P/l, the two polyphosphates and 6 of the 8 organic P sources were stimulatory. For most of the compounds, growth increased with increased concentrations. Sodium glycerophosphate and 5'-adenylic acid were stimulatory in the higher concentrations, but not in the lowest. Riboflavin-5'-phosphate was partially inhibitory in the highest concentration. O. luteus used all the P sources in all the concentrations tested; growth increased with increased concentrations. P. micans utilized all the compounds in all concentrations except riboflavin-5'-phosphate, which was not used. Again, the higher concentrations were more stimulatory than the lower.

3.5 Conclusions

The results of this study do not indicate that organic nutrients were more beneficial to the three species than the inorganic. There is clear evidence, however, that a variety of organics can either substitute for the inorganic forms or at least enhance growth when present with the organics.

In summary, the phytoflagellate blooms in the New York Bight are not the poisonous variety of "red tides" such as documeted by Hutner and McLaughlin (1958). However, their frequent occurrence along New Jersey north shore beaches, a recreational area of prime importance; their lowering of the quality of these beaches to aesthetically unpleasant levels; and evidence that the blooms are occasionally catastrophic to marine life and at least mildly poisonous to bathers, all pointed to a situation which required investigation. We suspected the blooms were a component of a syndrome, including also radical depletion of benthic fauna (Pearce, 1972) and chronic fish disease (Mahoney, Midlige and Deuel, 1973) having common root in environmental degradation of the area. Observation that the blooms had greater incidence in eutrophic waters of or near New York Harbor compared to relatively pristine New Jersey coastal waters just to the south, suggested that nutrient supply was a critical factor in the occurrence of these blooms. The major role of mineral nutrients in phytoplankton nutrition and the normally greater abundance of inorganic than organic nutrients in the environment, including polluted waters, is not ignored. Nevertheless, demonstration that growth of all three of our isolates is stimulated by a wide variety of organic nutrients, in concentrations resembling or approaching natural levels (a capacity not shared by all phytoplankters), is considered evidence associating the blooms with the eutrophication of the waters.

4. TOXIC DINOFLAGELLATE BLOOMS IN NEW ENGLAND

4.1 Poison Producing and Vector Organisms

In New England waters a dinoflagellate identified as *Gonyaulax tamarensis* or, in the opinion of some current taxonomists, as *Gonyaulax excavata*, is responsible for toxic blooms. When edible molluscs, such as the blue mussel (*Mytilus edulis*), soft clam (*Mya arenaria*), or surf clam (*Spisula solidissima*), filter-feed on large numbers of *Gonyaulax tamarensis*, they accumulate a paralyzing poison (paralytic shellfish poison, PSP) in their tissues. While this poison may not affect the molluscs directly, animals higher in the food chain which eat molluscs may suffer severe symptoms and even death.

In the northeast United States shellfish may bioaccumulate toxin during the late spring and early fall, the rate of concentration depending on the species of shellfish, their efficiency in filter-feeding, and the duration of the red tide event. Blue mussels have been reported to feed selectively on dinoflagellates even when other algal foods are predominant. Oysters do not appear to feed on *G. tamarensis* and, thus, only rarely become poisonous after occurrence of a red tide. Surf clams filter and hold toxin for at least nine months even when few *G. tamarensis* cells are present in the water. Soft clams become toxic at a lower rate than blue mussels, and do not hold toxin in their tissues as do surf clams.

4.2 Effects of PSP in Humans

The ingestion of PSP-tainted shellfish has been identified with human and other vertebrate animal mortalities for at least three hundred years (Prakash, Medcof and Tennant, 1971). Symptoms begin with numbness of the tongue, lips, and finger tips, then it appears in the appendages. Muscle spasms and respiratory paralysis can follow which may cause death in two to twenty-four hours, depending on the amount of toxin ingested. Survivors of PSP poisoning seem to have no lasting after-effects. Fortunately, human fatalities are few.

4.3 PSP Test Procedure

The standard procedure to determine toxicity in suspect shellfish is presented by the Association of Official Agriculture Chemists (1965). Female mice from a stock colony weighing 19-21 gms are used for the bioassay. After the reference toxin has been used for assay standardization, using 1 ml intraperitoneal injections, death times and dilutions of poison provide data to determine the conversion value (CF) giving ug of poison equivalent to 1 mouse unit. The average CF value is then used as a reference point for additional assays. In the extraction procedure shellfish are obtained fresh, opened and rinsed with fresh water and 100 gms of meats carefully removed, avoiding damage to the body of the mollusc. The meats are ground in a blender until homogeneous, acidified with hydrochloric acid to pH 3, and boiled for 5 minutes. After cooling to room temperature, the mixture is settled and the clear supernatant is injected intraperitoneally into a series of 6 mice. After appropriate dilutions, any shellfish showing more than 80 ug of toxin per 100 gms of meats is considered hazardous and unsafe for human consumption.

The purpose of this report is to outline the past history of PSP red tides in New England waters and to suggest means for ozone inactivation of the toxin in controlled water situations and in live molluscs.

4.4 History of New England Red Tides

4.4.1 Prevalence in Maine

The first recorded incidence of significant red tide poisoning in Maine was during the summer of 1958 (Hurst, 1975). At that time eastern Washington County, adjacent to New Brunswick, Canada, showed PSP in shellfish well above the 80 ug "acceptable" level and the shellfish beds were subsequently closed. Maine then developed a monitoring procedure whereby shellfish from six sampling stations are assayed twice a month from May 1 to June 15, then weekly to October 1 or until 80 ug/100 gms of meats are obtained. At this level, the area is closed. From October 1 to May 1 four stations are sampled monthly providing year-round data on toxin levels.

During 1961 low PSP levels were found along the entire Maine coast. However, PSP levels were high only in Washington County where soft clams had PSP values of over 600 ug/100 gms of meats. In the years 1962 to 1971 most of the Maine coast was free of red tides and the resulting toxicity situation, although there were minor isolated instances of toxicity in shellfish.

On August 9, 1972 shellfish from Quoddy Bar-Lubec showed values over 280 ug for soft clams. In the days following, other stations gave similar high scores so that on September 17, 1972 the entire coast of Maine was closed to shellfishing with some areas not reopened until September 1973. This closure was devastating to the fishery.

During 1973 no red tide events were noted and shellfish remained below 80 ug of toxin, enabling the fishery to recover somewhat from the devastating closure in the summer of 1972.

However, in 1974 two red tides were noted, one occurring in late May and the other, in late August. The entire coastline was closed because exceptionally high counts were found in many areas. In 1975 the red tide appeared in late May but did not reappear in August.

4.4.2 Prevalence in New Hampshire

Going down the coast, events recorded in Maine had an effect in New Hampshire. However, New Hampshire does not have a commercial shellfishery and had not monitored its waters until the major red tide of 1972. Prior to 1972 no reports exist which suggest the presence of any toxic shellfish. During mid-September 1972, large patches of red water were seen on and near the shore. The causative organism was identified by University of New Hampshire scientists as Gonyaulax tamarensis. This report, combined with the non-fatal poisoning of two clam diggers after ingestion of toxic clams and sightings of hundreds of dead and dying birds, caused closure of the entire coast for several months. In June and September of 1974 the clam beds were again closed. In early June of 1975 the toxic tide returned and caused another closure. During the closed shellfish season the loss to licensed clam diggers was estimated at $200,000 (Sasner, Ikawa, and Barrett, 1975).

4.4.3 Prevalence in Massachusetts

Massachusetts waters also showed traces of red tide about September 19, 1972. Clams gathered north of the Cape Ann region gave counts of over 9,000 ug per 100 gms of meats, thus all clam and mussel beds were closed for over a month. Sasner, Ikawa, and Barrett (1975) reported that over 2,220 Massachusetts waterfowl, representing 13 different species, were killed during the height of the 1972 red tide event. Typical stomach content analysis of dead birds revealed the partially digested remains of toxic clams. In 1973 the red tide was not intense enough to force closure of the shellfish beds, but during late May and early September of 1974, an intense red tide appeared, and the beds had to be closed for the entire season. Only one red tide event occurred in 1975 on June 12-13, which effectively closed shellfishing for 6-8 weeks in the northern Cape Ann region.

The causative organism of the New England red tides has not yet been found in Connecticut, New York, or New Jersey waters. This possibly may be due to temperature or hydrographic differences between the tri-state waters and northern New England waters. However, some scientists at the New York Ocean Science Laboratory, Montauk, New York did detect some limited toxicity in clam livers in the late summer of 1972. They were extracting large quantities of clam for anti-cancer research and found the material toxic to mice upon injection.

4.5 Adverse Public Health and Economic Effects of the 1972, 1973 and 1975 Outbreaks

The 1972 red tide prompted public health officials to ban the harvest and sale of soft clams, hard clams, and mussels from Maine to Massachusetts. Connecticut and New York halted the importation and sale of shellfish from these New England states, and destroyed large quantities of already harvested raw and packaged shellfish. Unfortunately, the public associated shellfish with other seafood products, such as crab, lobster and shrimp, and with the adverse publicity from the 1972 ban, New Englanders stopped purchasing seafood for over a month. The embargo damaged the seafood business in the affected states, putting some companies out of business, many clam diggers on unemployment relief, and restaurant and fish markets closed, having lost thousands of dollars in seafood sales. In addition, 33 people were reported ill from ingestion of PSP-tainted shellfish during the 1972 red tide. No one died, but the bad publicity only heightened the decrease in seafood sales.

As the red tide skipped 1973 in Massachusetts, the public returned to purchasing large quantities of seafood, including shellfish; however, two red tides in May and August of 1974 closed shellfish beds and sent 4 people to the hospital in New Hampshire. Although these were also non-fatal cases, more adverse publicity again reduced sales of seafood products.

By 1975 only one red tide occurred in early June. Two people were made sick from eating toxic snails taken from a Massachusetts shellfish bed. These cases were widely publicized and the shellfishery was temporarily suppressed. After adverse publicity subsided, the shellfishery resumed normal activity about 6-8 weeks after the shellfish beds were re-opened by the Massachusetts Public Health Department.

4.6 Ozone Experimentation

4.6.1 Detoxification of Paralytic Shellfish Poison

Ozone has been used for a number of years in the disinfection of water and wastewater. It kills bacteria and viruses more rapidly than does chlorine (O'Donovan, 1965; Eisenhauer, 1968; Majumdar and Sproul, 1974). Spotte (1970) reported that dissolved organics could be removed from circulating aquarium water using ozone gas. As early as 1929, Voille reported the effectiveness of ozone in the sterilization of seawater; and ozone is used routinely in France to disinfect seawater in shellfish depuration stations (Anon., 1972). Ozone has also been used to eliminate marine microorganisms which could be pathogenic to fish and shellfish (Blogoslawski et al., 1975b).

In late 1972 and early 1973 investigators at the Milford Laboratory of the National Marine Fisheries Service, Middle Atlantic Coastal Fisheries Center, Milford, Connecticut found that ozone gas could inactivate *Gymnodinium breve* toxins in both laboratory grown cultures and field samples (Blogoslawski et al., 1973; Blogoslawski et al., 1975a) and could detoxify paralytic shellfish poisons (Thurberg, 1975). In the latter studies, *G. catenella* toxin was obtained as a purified reference standard and *G. tamarensis* toxin was extracted from toxic clams during a red tide that closed shellfish beds in Maine and New Hampshire. These toxins were rendered completely inactive after 5-minute doses of 2% ozone in air, flowing at a rate between 55 and 110 ml/min. Control solutions were treated with compressed air to be certain that it was ozone and not the action of air bubbling through the solutions that inactivated the toxins. All samples treated with air retained their original toxicity. The data obtained from these PSP studies are presented in full in a paper by Dawson et al. (in press) and summarized in Table 1.

Upon receipt of an invitation to study toxin inactivation from Dr. Christopher Martin, Station Director, University of Massachusetts Marine Station, Gloucester, the Pathobiology field team journeyed to Hodgkins Cove and assembled a continuous-flow ozone contacting system on August 27, 1974. The ozone generation equipment was set on automatic operation to ozonize 864 liters of toxic seawater per day. This water was directed to flow over non-toxified Milford-obtained clams (*Mya arenaria*) and mussels (*Mytilus edulis*, and *Modiolus demissus*) and similar toxified species from the Gloucester area. Equal numbers of control animals were set in similar trays which received 864 liters of untreated water per day (Fig. 21). This lab experiment was conducted before, during, and after the peak of a PSP red tide bloom using seawater from the bloom area.

On August 30, 31, and September 1, during the *G. tamarensis* bloom, which turned the seawater bloody red, counts in the raw water reached 1.5 x 10^7 motile cells/liter. No motile cells were found after ozonization, and approximately 60% of the ozonized dinoflagellates showed disrupted cell walls. Ozonized cells were characteristically larger than untreated controls, indicating possible damage to cell permeability.

After the G. tamarensis counts subsided to about 3000 cells/ liter, samples of the clams and mussels were prepared for toxicity testing using the standard mouse bioassay. Bioassays to test extracts of clams (Mya arenaria) and mussels (Mytilus edulis and Modiolus demissus) in ozonized red tide seawater indicated that ozone treatment does prevent shellfish from accumulating paralytic shellfish poison during red tide outbreaks. In non-ozonized seawater shellfish used for controls, held at the same time and flow rate, accumulated from 10-35 times the amount of toxin necessary for closure of the shellfish beds (80 ug/100 gms of meats). Such information has obvious significance for depuration stations, (Newburyport, Mass.). The field study ended on September 5, 1974, but additional tests at Milford were continued to confirm initial findings.

In May 1975, the Massachusetts Science and Technology Foundation funded a project for the Milford Pathobiology Task Group to test ozone detoxification of shellfish contaminated by red tide metabolites. After a red tide event of about 2 days' duration (June 10-12), 3 members of the National Marine Fisheries Service staff journeyed to Gloucester, Massachusetts to attempt ozone depuration and detoxification of clams and mussels which contained high levels of toxin. The team arrived on June 13 and set up ozone equipment to pass ozonized seawater across 10 trays which contained 60 surf clams, S. solidissima, 65 soft clams, M. arenaria, and 560 blue mussels, M. edulis. The control consisted of five additional trays which received untreated seawater containing 40 surf clams, 65 soft clams, and 210 blue mussels. The experiment was conducted for 3 days (June 17-19).

Using the standard mouse bioassay procedure, we obtained the following reductions in toxicity during the experimental period with ozonized seawater against control animals: blue mussel, 30% reduction; surf clam, 31% reduction; and soft clam, 0% reduction. Soft clams were held in the ozonized water for only 14 working hours of the experiment, which apparently was too short a time for depuration and detoxification.

In September 1975, a series of ozone detoxification experiments with red-tide contaminated surf clams (S. solidissima) was completed with a 17% reduction in toxicity over controls for a 96-hour depuration time. Currently, we are working with the Physioecology Task in determining the physiological responses of ozonized and control surf clams during depuration. In addition, we have provided both raw and ozonized clam and mussel extracts to Drs. M. Tin-Wa, University of Chicago Medical Center, Chicago, Illinois and Edward Schantz, University of Wisconsin, Madison, Wisconsin for chemical structure determination of the raw and ozonized portions of Gonyaulax tamarensis. Once surf clams become toxic, they can remain toxic for up to 9 months in the wild without an additional red tide event. Thus, the small inshore surf clam fishery has been effectively destroyed from Maine to northern Massachusetts since 1972 because successive blooms have occurred about 10 months apart.

4.7 Conclusions

Ozone depuration of coliform bacteria from shellfish has been practiced for more than 40 years in Spain and France (Anon., 1972). Such ozone-depurated shellfish have high consumer acceptance. Based on the European experience with ozone depuration and our work, which demonstrates ozone's effectiveness in detoxification of G. tamarensis toxins, we believe that it is feasible to remove toxin from shellfish contaminated by red tides. Obviously, additional experimentation into the physiological responses of the animals to ozone detoxification is needed to understand the mechanisms that retain toxins and determine the ozone dose necessary to release toxins without tainting the flesh of ozone depurated or, more precisely, detoxified shellfish.

ACKNOWLEDGEMENTS

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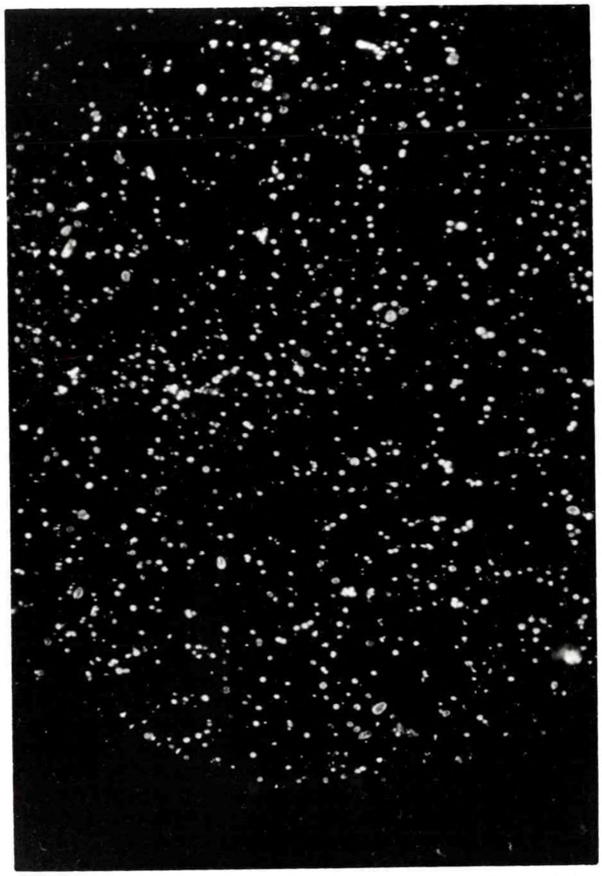


FIGURE 1: Darkfield view showing numerous tiny phytoplankters (Nannoplankters). Diameter of cells approximately 3 microns. These are often numerically dominant in New York Harbor blooms. Photo by J. O'Reilly.

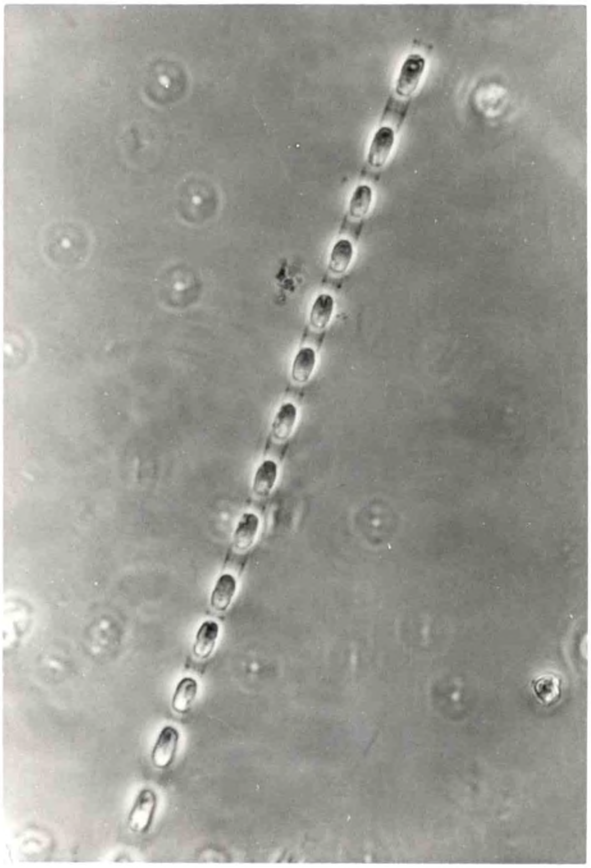


FIGURE 2: The diatom, Skeletonema costatum, typical chain of cells. Diameter of each cell 6 microns. Most abundant diatom in New York Harbor. Common in polluted areas. Note spines which connect cells as well as resemblence to human spinal column. Photo by Myra Cohn.

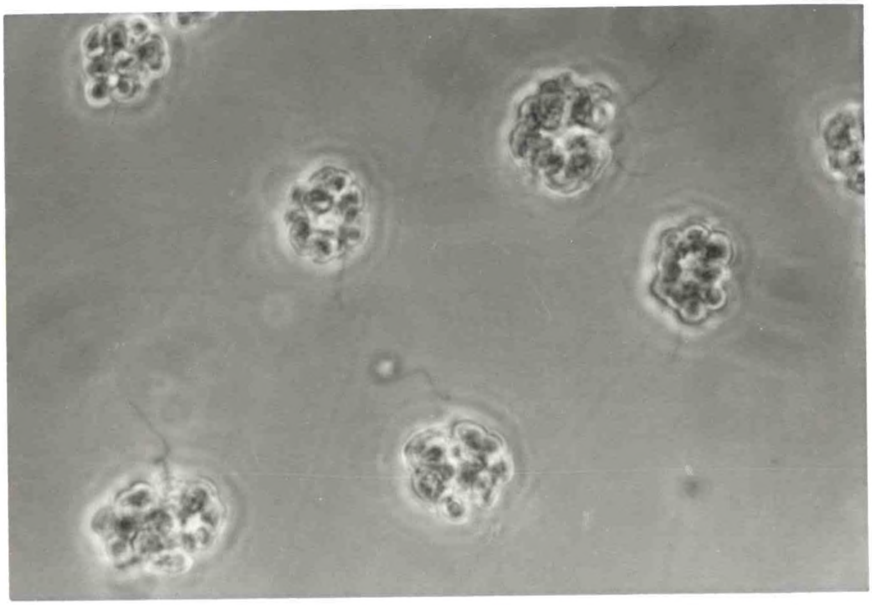


FIGURE 3: Group of cells of phytoflagellate, Olisthodiscus luteus. Diameter of each cell about 20 microns. This species has dominated most red tides in New York Harbor and along New Jersey beaches. Note whip-like flagella. Photo by Myra Cohn.

FIGURE 4a(left): The dinoflagellate, Massartia rotundata. Approximate diameter 10 microns. Second dominant species in red tide blooms in New York Harbor - New Jersey shore area. Photo by Myra Cohn.

FIGURE 4b(right): The dinoflagellate, Heterocapsa triquetra, about 25 microns wide. Frequently abundant, although not dominant in New York Harbor red tides. Suspected toxic species. Photo by Myra Cohn.

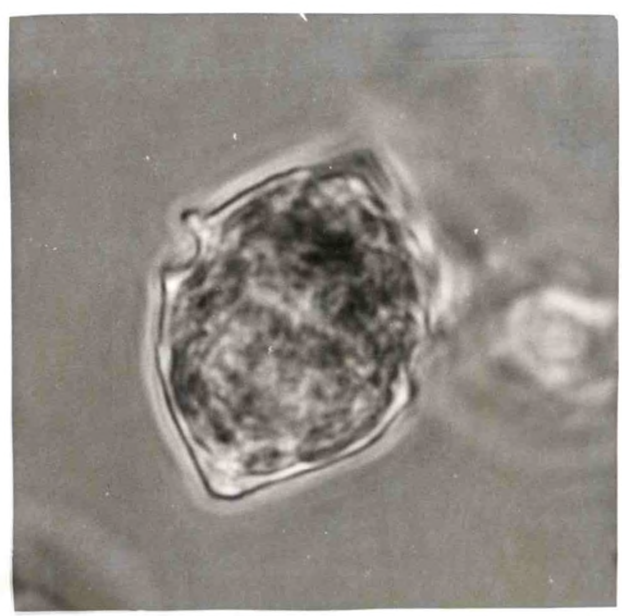


FIGURE 5: The dinoflagellates Prorocentrum micans, left, diameter approximately 28 microns, and Prorocentrum minimum, upper right, approximate diameter 17 microns. P. micans is third dominant species and P. minimum is frequently numerous in New York Harbor red tide blooms. P. micans has been associated with several instances of catastrophic red tides in different parts of the world. Photo by Myra Cohn.

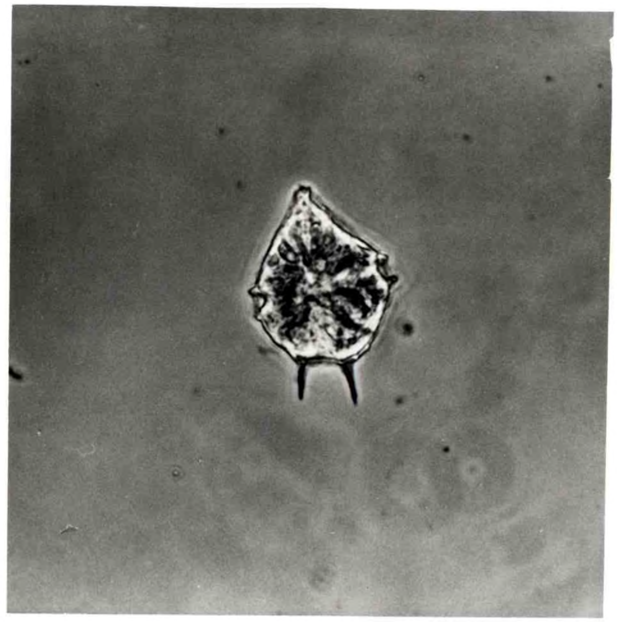


FIGURE 6a and 6b: Two views of the dinoflagellate, <u>Gonyaulax diacantha</u>, approximate width 27 microns. This armored species has morphological features in common with <u>Gonyaulax tamarensis</u> which is responsible for poisonous red tide outbreaks in New England. Note armored plate arrangement (below). Photos by Myra Cohn.

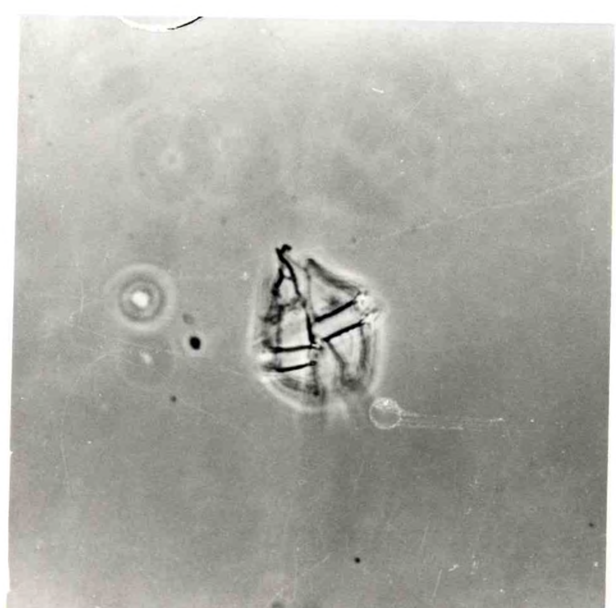


FIGURE 7a(right): Euglena proxima, phytoflagellate about 50 microns long and about 22 microns wide at the top. Occasionally abundant in New York Harbor red tide blooms. Photo by Myra Cohn.

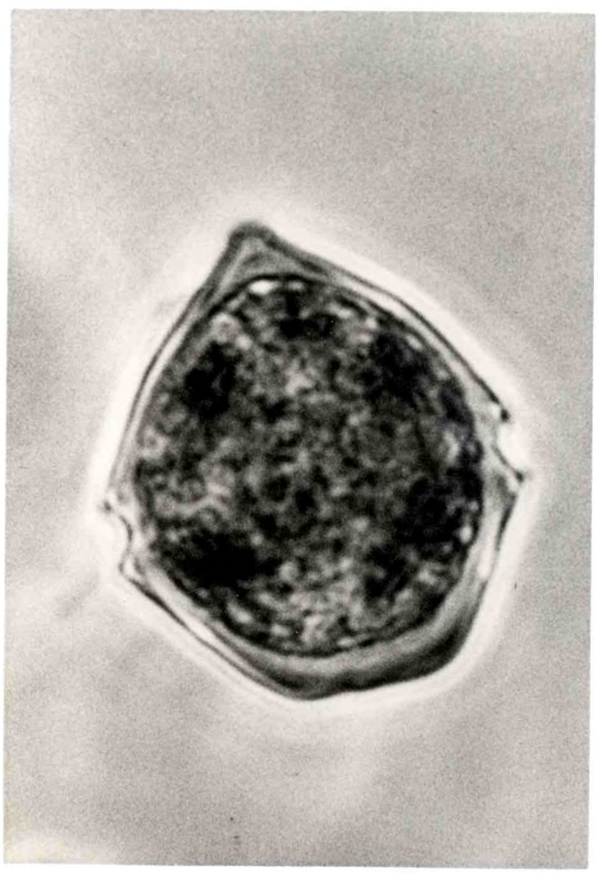


FIGURE 7b(left): The dinoflagellate, Peridinium trochoideum, enlarged to show detail. Approximate diameter 24 microns. Frequently abundant although not dominant in New York Harbor red tide blooms. This species is suspected of being toxic. Photo by Myra Cohn.

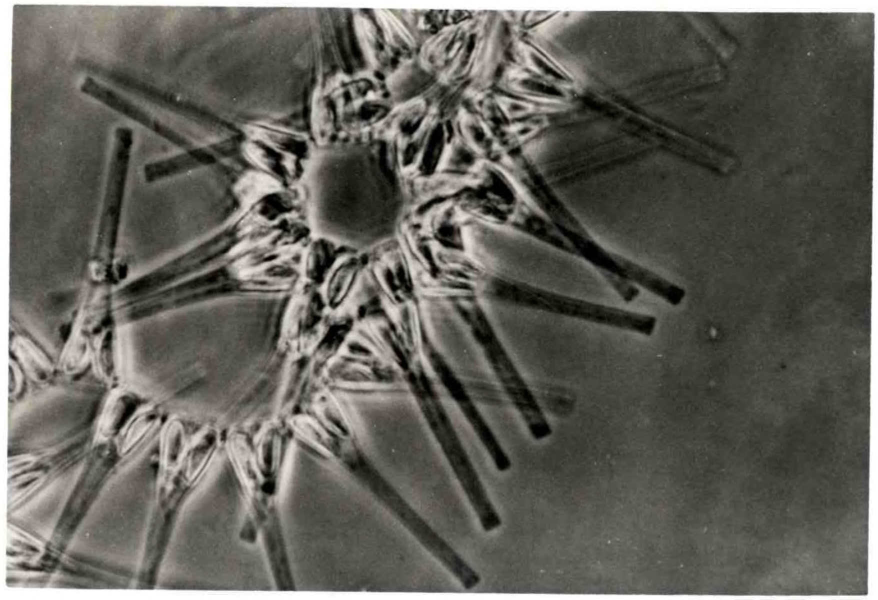


FIGURE 8a(above): The diatom colony, Asterionella japonica, individual cells in typical starlike configuration. Colonies are united into a chain. Width of enlarged part of cell about 6 microns.

FIGURE 8b(below): The diatom, Thalassiosira nordenskioldii, individual cells in characteristic long chain. Diameter of octagonal valve 12 microns. Both are major components of the diatom flora of New York Harbor. Photos by Myra Cohn.

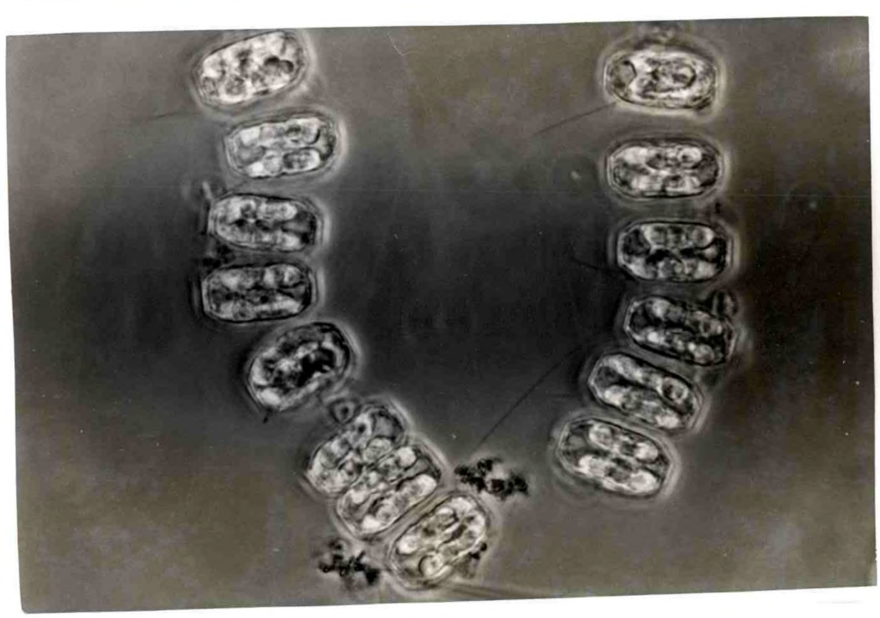


Figure 9. Depicts vertical profile of Olisthodiscus luteus (flagellate) abundance during a red-tide in July 1972. Abundance of the motile O. luteus decreased 90-fold from surface to 2 meters below surface while abundance of non-motile forms (diatoms) increased slightly from surface to 2 meters. Additionally, samples of water collected further offshore (3/4, 2 miles) also had much higher concentrations of O. luteus in surface strata than below. Surface water abundance of O. luteus, however, decreased progressively as we proceeded offshore. Concentrations of O. luteus in surface samples at 1/4, 3/4 and 2 miles east of Sandy Hook bathing beach were 27, 639, 11, 125 and 3,772 cells/liter respectively.

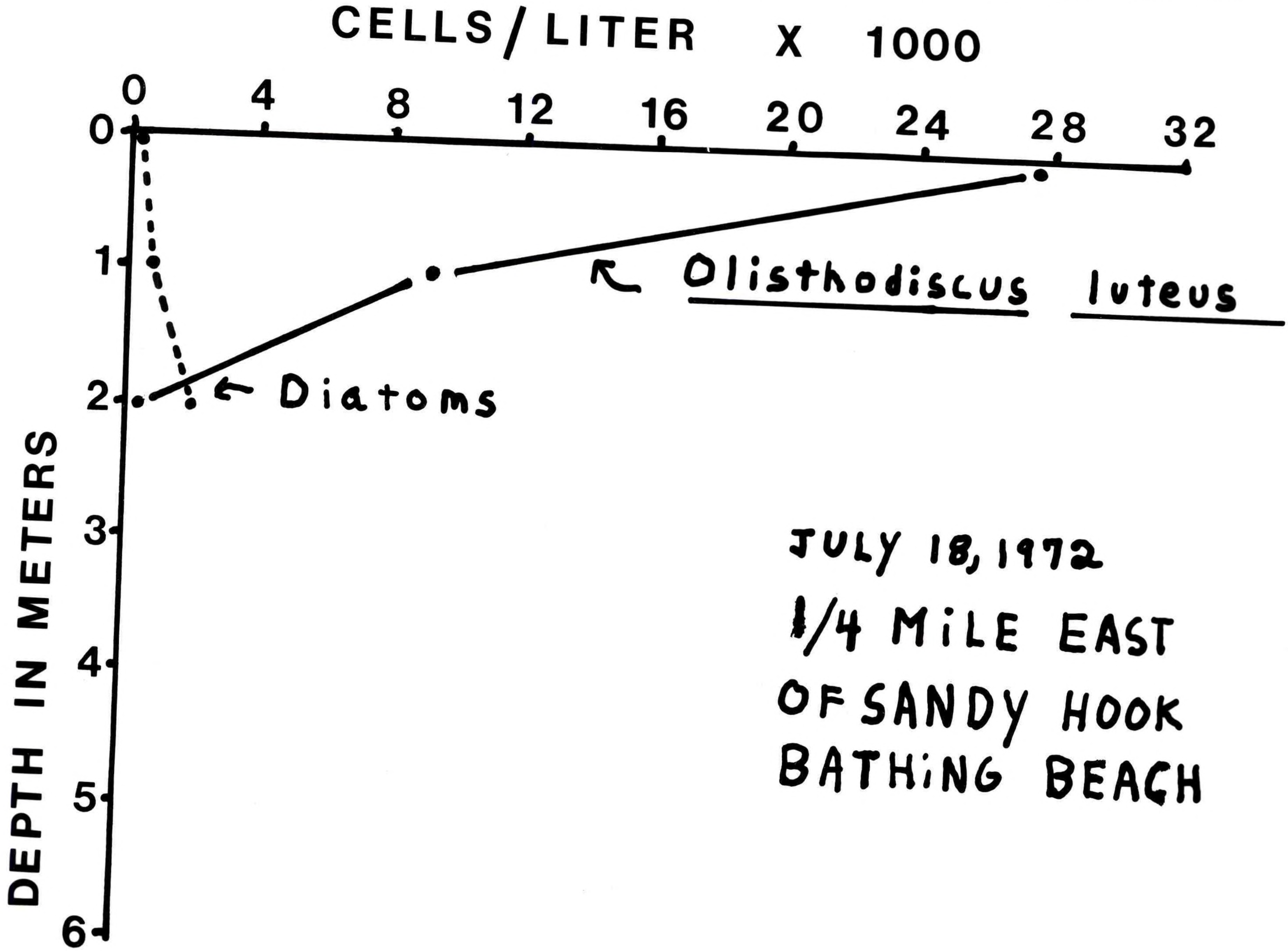
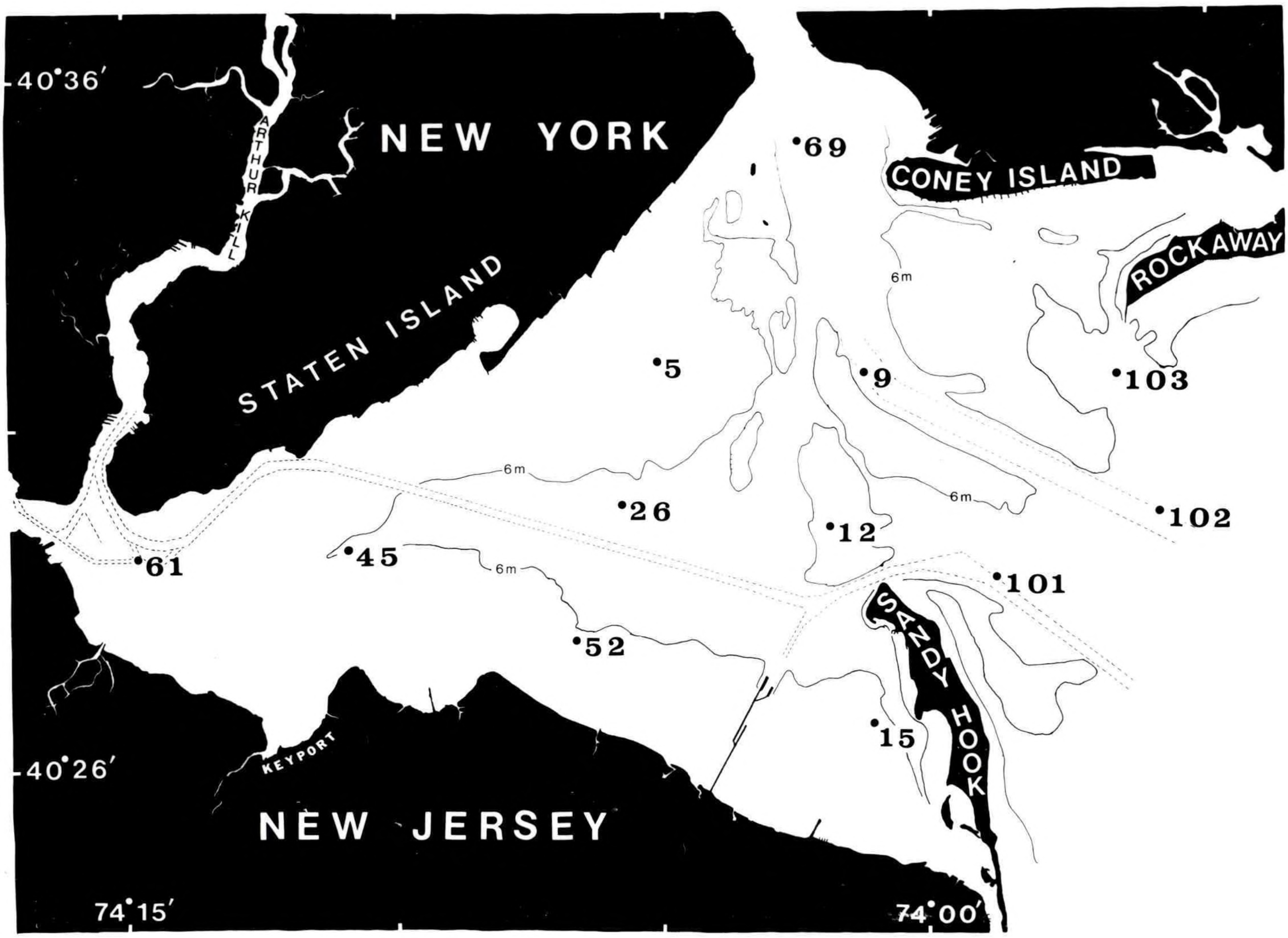

CELLS/LITER X 1000
0
4
8
12
16
20
24
28
32
0
1
2
3
4
5
6
DEPTH IN METERS
Olisthodiscus luteus
Diatoms
JULY 18, 1972
1/4 MILE EAST
OF SANDY HOOK
BATHING BEACH

Figure 10a. Map depicting station location for primary productivity studies in Raritan, Lower, and Sandy Hook Bays.



40°36′
NEW YORK
ARTHUR KILL
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
6m
•69
•5
•9
•103
•26
•12
•102
•61
•45
•101
•52
•15
SANDY HOOK
KEYPORT
40°26′
NEW JERSEY
74°15′
74°00′

Figure 10b. Map depicting geographical divisions of Lower New York Bay into Raritan Bay and Sandy Hook Bay based on *Coastal Pilot* designations.

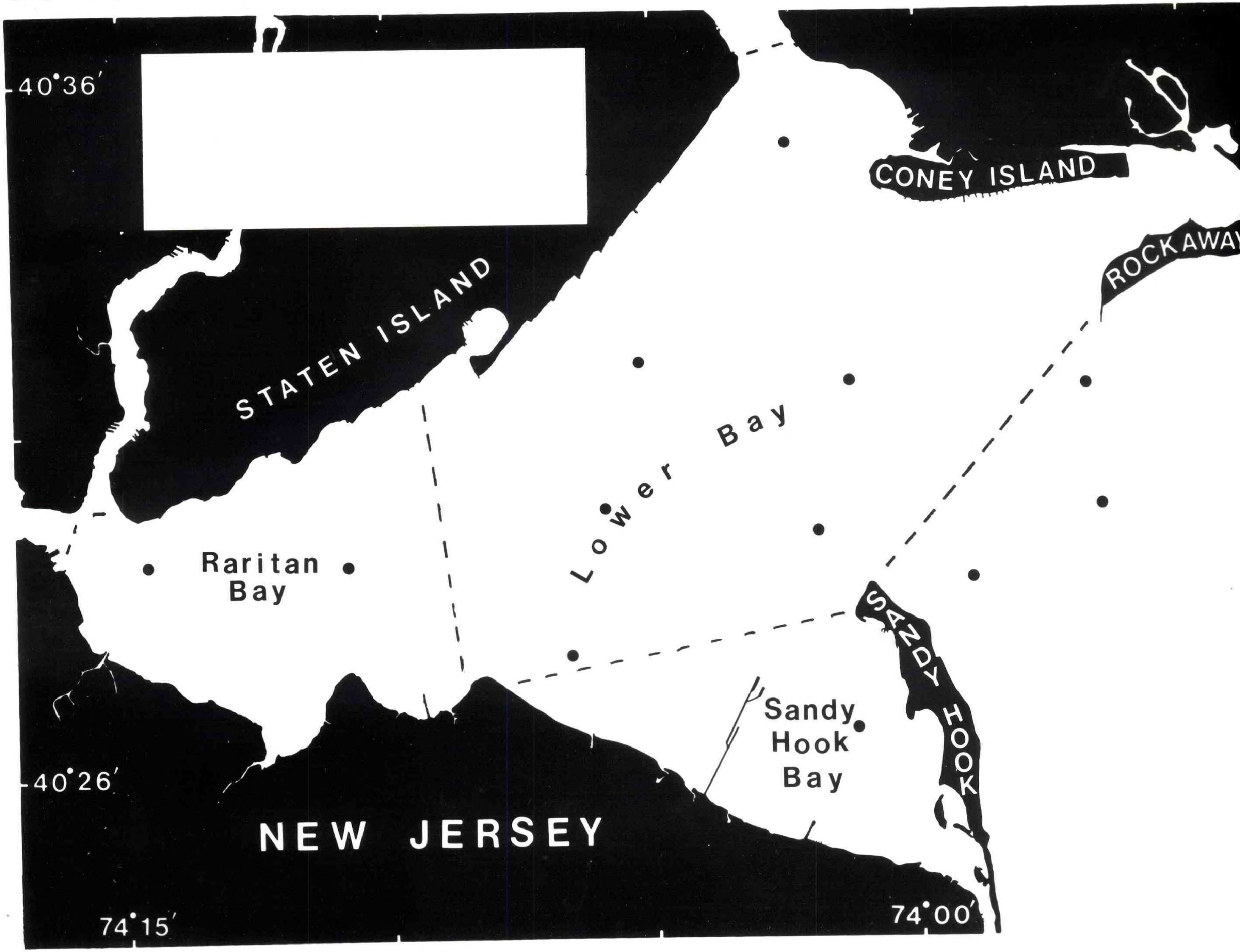

40°36′
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
Lower Bay
Raritan Bay
SANDY HOOK
Sandy Hook Bay
40°26′
NEW JERSEY
74°15′
74°00′

Figure 11. Annual curve for phytoplankton primary productivity at station 69 near the Verrazano Narrows. Depicted are the contributions of individual fractions to the total phytoplankton primary productivity as follows:

1. photoassimilated carbon released as dissolved organic matter (DOM) from the natural populations of phytoplankton residing at this station;

2. nannoplankton primary productivity (NAN), that fraction less than 20 microns and greater than 0.45 microns; and

3. netplankton primary productivity (NET), that fraction greater than 20 microns in size.

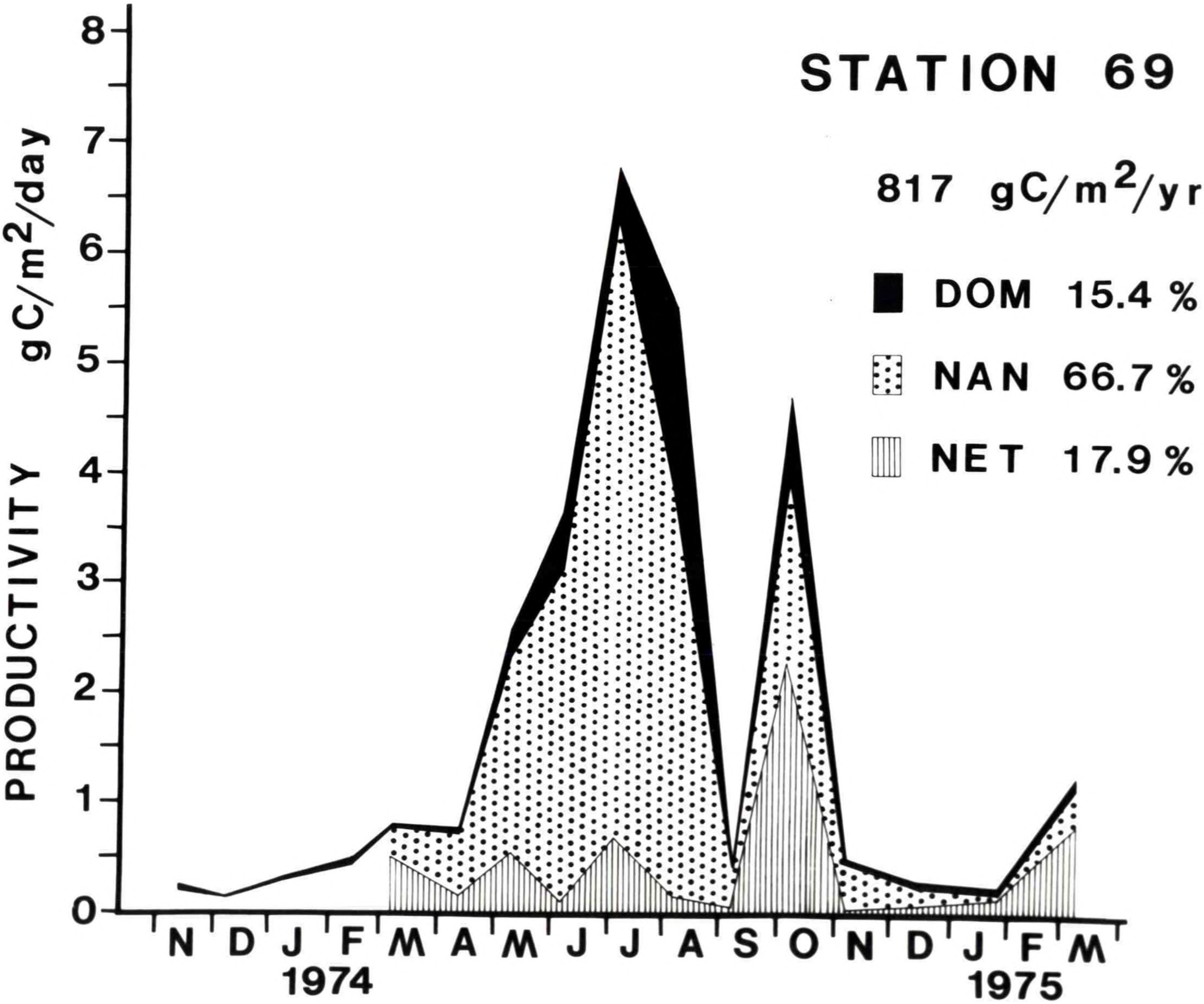

STATION 69
817 gC/m2/yr
DOM 15.4 %
NAN 66.7 %
NET 17.9 %
PRODUCTIVITY gC/m2/day
0
1
2
3
4
5
6
7
8
N D J F M A M J J A S O N D J F M
1974
1975

Figure 12. Annual curve for phytoplankton primary productivity at station 102 near the entrance to Ambrose Channel. Fractions are as described in Figure 11.

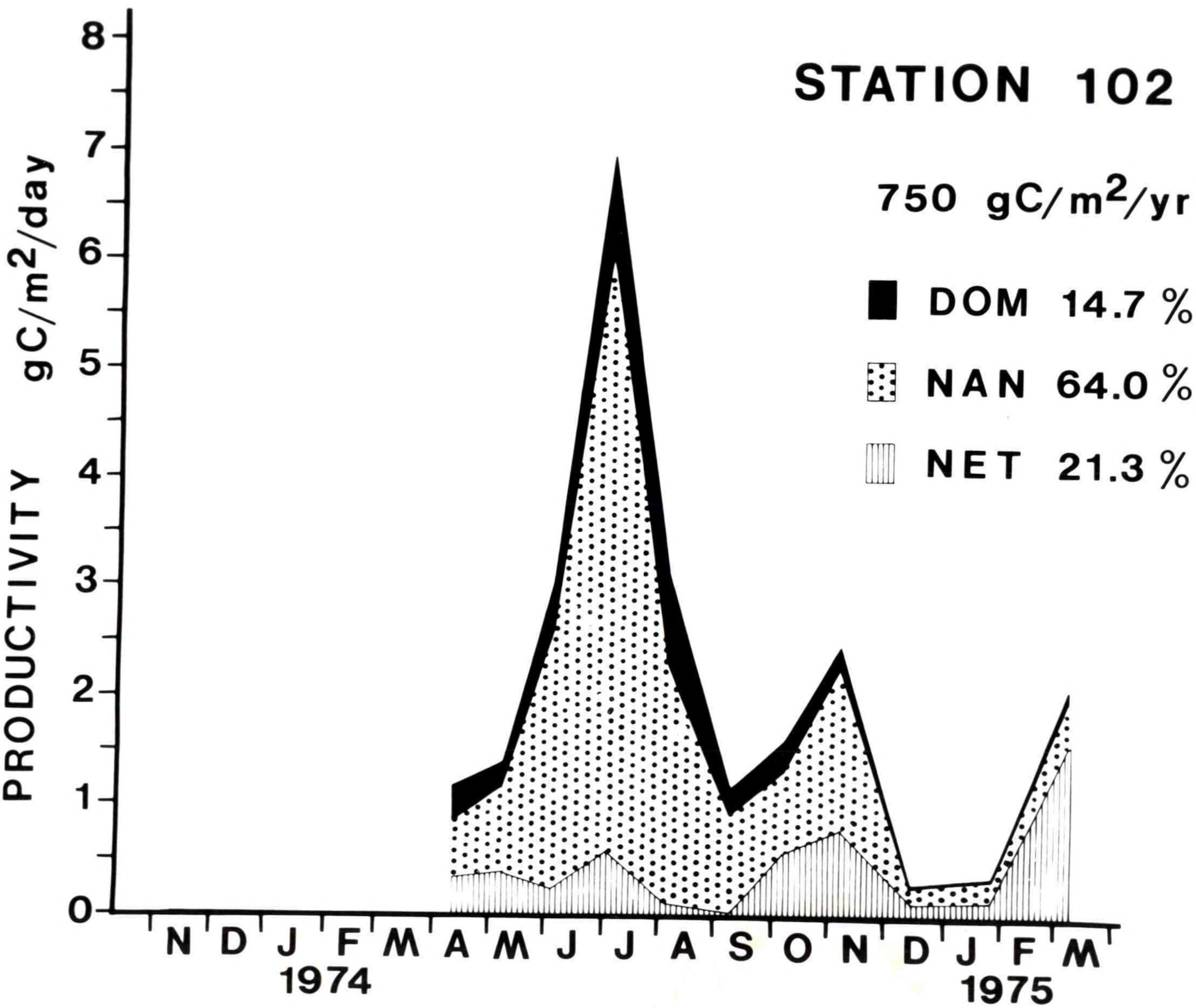
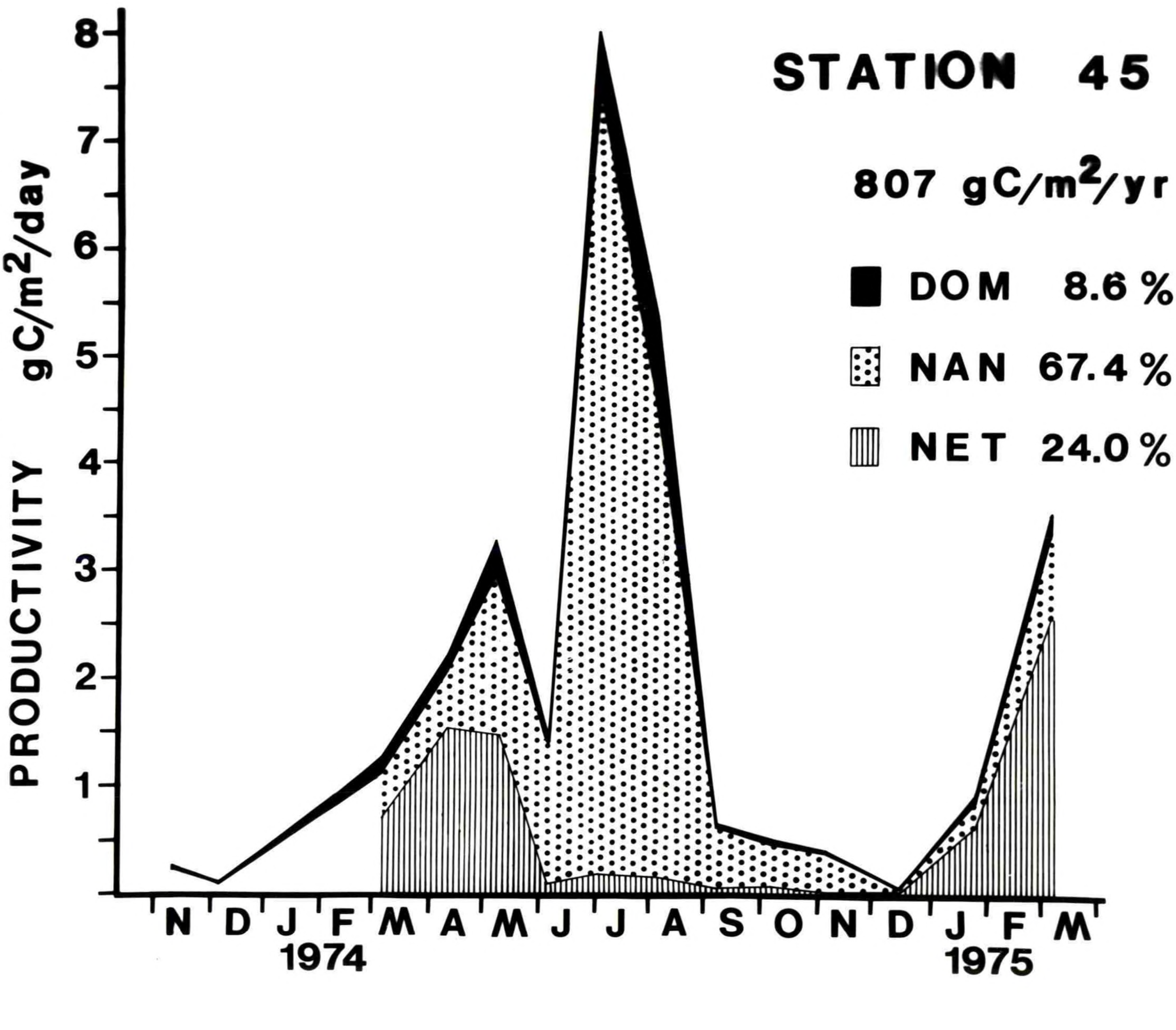

STATION 102
750 gC/m2/yr
DOM 14.7 %
NAN 64.0 %
NET 21.3 %
PRODUCTIVITY gC/m2/day
0
1
2
3
4
5
6
7
8
N D J F M A M J J A S O N D J F M
1974
1975

Figure 13. Annual curve for phytoplankton primary productivity at station 45 near the head of Raritan Bay. Fractions are as described in Figure 11.



STATION 45
807 gC/m²/yr
DOM 8.6 %
NAN 67.4 %
NET 24.0 %
PRODUCTIVITY gC/m²/day
8
7
6
5
4
3
2
1
N D J F M A M J J A S O N D J F M
1974
1975

Figure 14. Annual curve for phytoplankton primary productivity at station 15 in Sandy Hook Bay. Fractions are as described in Figure 11.

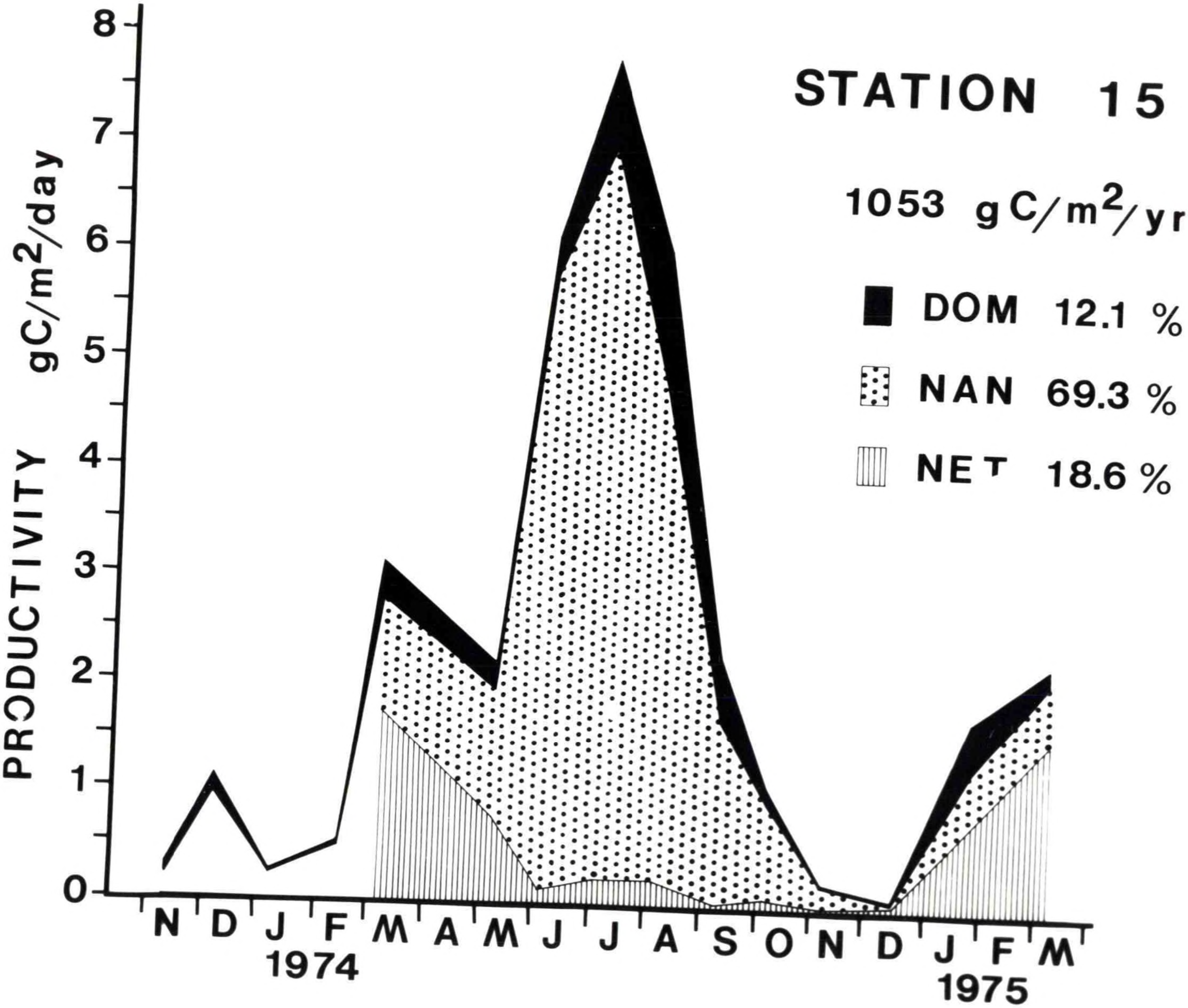

STATION 15
1053 gC/m²/yr
DOM 12.1 %
NAN 69.3 %
NET 18.6 %
PRODUCTIVITY gC/m²/day
8
7
6
5
4
3
2
1
0
N D J F M A M J J A S O N D J F M
1974
1975

Figure 15. Surface distributions of total phytoplankton primary productivity in Raritan, Lower, and Sandy Hook Bays between November 1973 and March 1975. Values are in milligrams carbon taken up during photosynthesis per cubic meter per hour (mg C m^{-3} hr^{-1}).

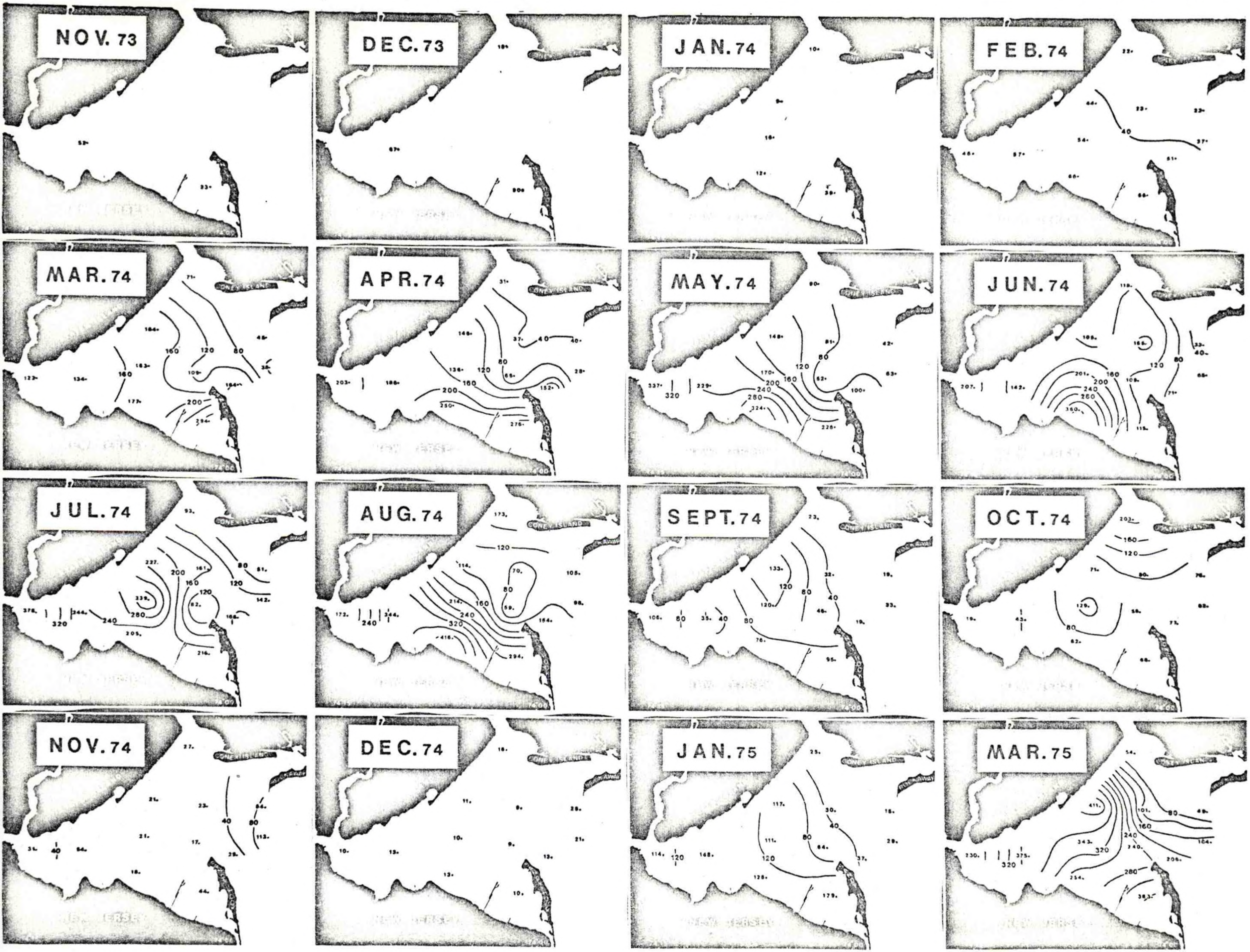
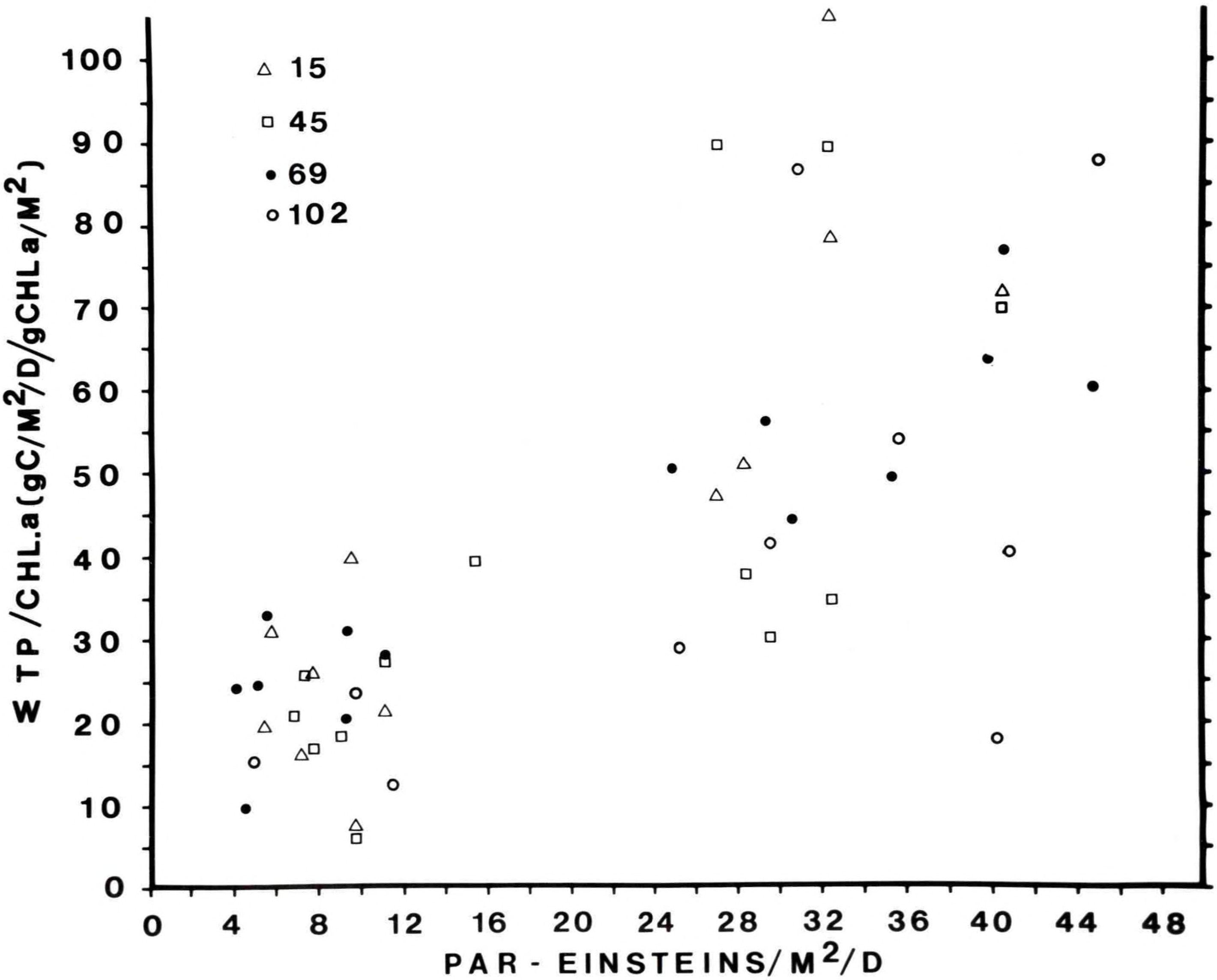

NOV. 73
DEC. 73
JAN. 74
FEB. 74
MAR. 74
APR. 74
MAY. 74
JUN. 74
JUL. 74
AUG. 74
SEPT. 74
OCT. 74
NOV. 74
DEC. 74
JAN. 75
MAR. 75

Figure 16. Depicts assimilation number (i.e. carbon taken up during photosynthesis per quantity of chlorophyll a shown as ΣTP/ Chl a in units of grams carbon per square meter per day per gram chlorophyll a per square meter) plotted against photosynthetically available radiation (PAR) in Einstein's per square meter per day. Approximately 57,000 gram calories equal one Einstein.



W TP /CHL.a (gC/M^2/D/gCHL a/M^2)
PAR - EINSTEINS/M^2/D
15
45
69
102
0
10
20
30
40
50
60
70
80
90
100
0
4
8
12
16
20
24
28
32
36
40
44
48

Figure 17. Surface distributions of inorganic phosphate concentrations in micromoles P per litre ($\mu M/\ell$).

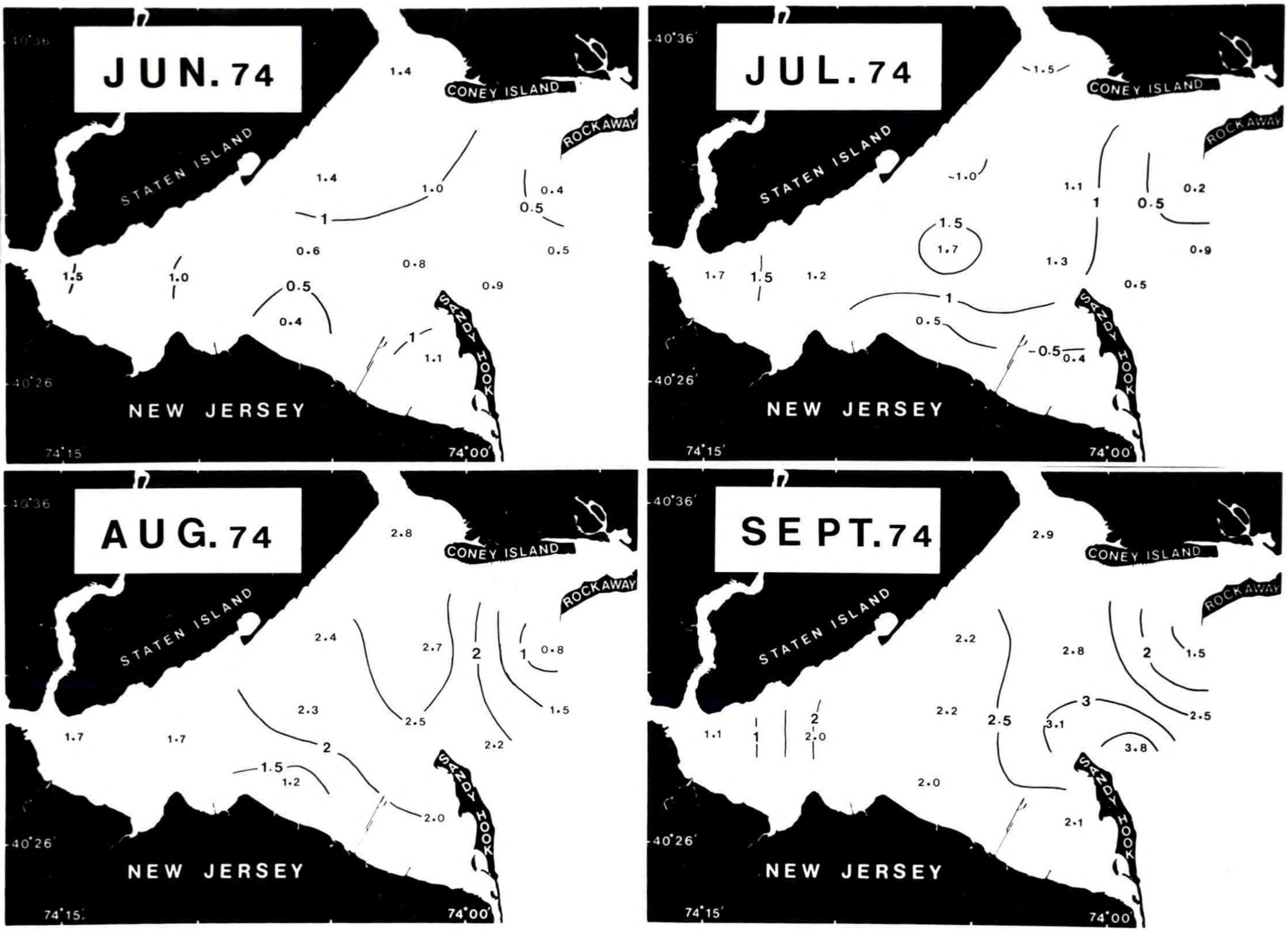

JUN. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
NEW JERSEY
SANDY HOOK
40°36'
40°26'
74°15'
74°00'
1.4
1.4
1.0
1
0.4
0.5
0.5
0.6
0.8
1.5
1.0
0.5
0.4
0.9
1
1.1
JUL. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
NEW JERSEY
SANDY HOOK
40°36'
40°26'
74°15'
74°00'
1.5
1.0
1.1
1
0.5
0.2
1.5
1.7
0.9
1.7
1.5
1.2
1.3
1
0.5
0.5
0.5
0.4
AUG. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
NEW JERSEY
SANDY HOOK
40°36'
40°26'
74°15'
74°00'
2.8
2.4
2.7
2
1
0.8
2.3
2.5
1.5
1.7
1.7
2
2.2
1.5
1.2
2.0
SEPT. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
NEW JERSEY
SANDY HOOK
40°36'
40°26'
74°15'
74°00'
2.9
2.2
2.8
2
1.5
2.2
3
2.5
2.5
3.1
1.1
1
2
2.0
3.8
2.0
2.1

Figure 18. Surface distributions of ammonia concentrations in $\mu M/\ell$.

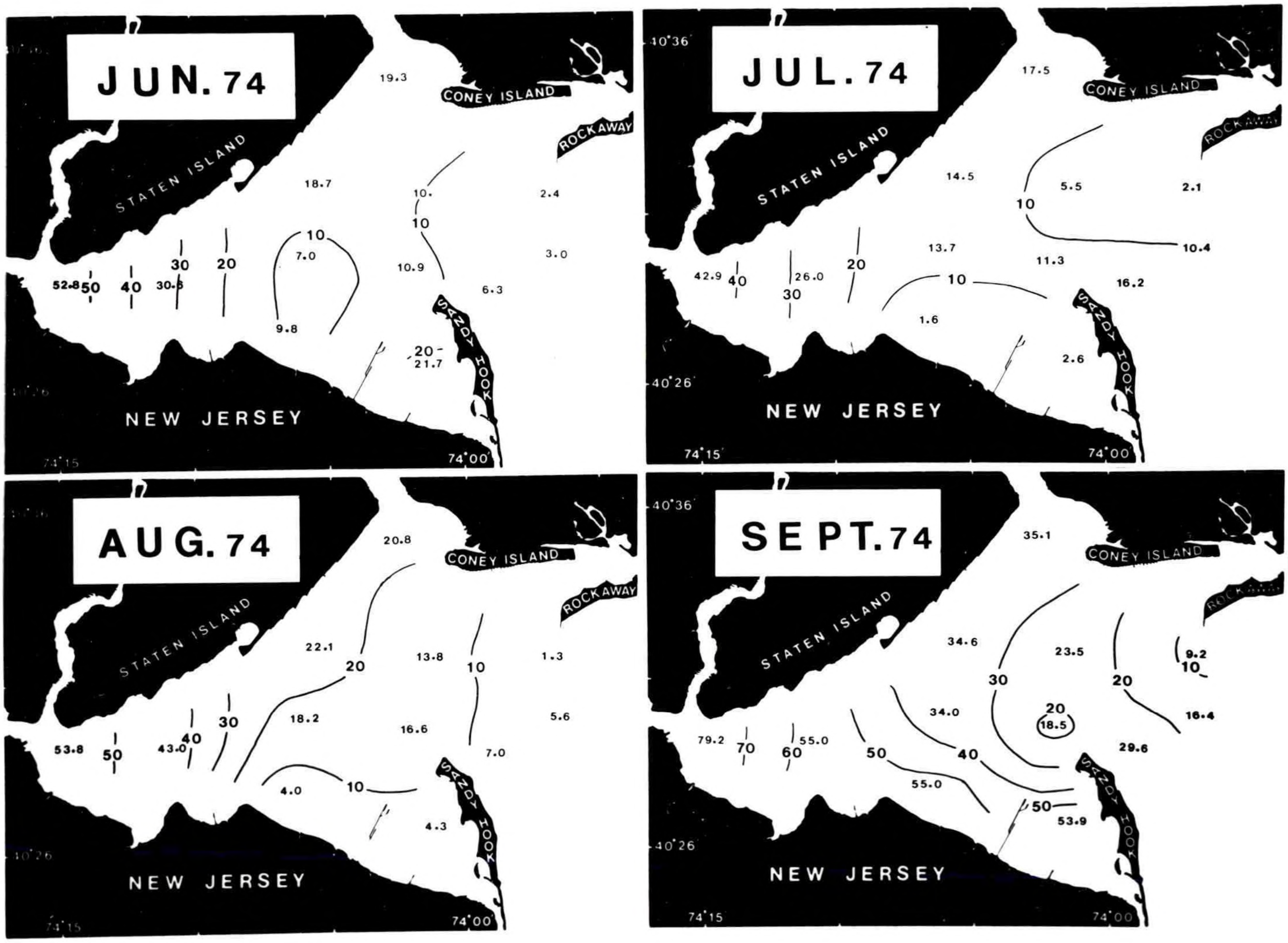

JUN. 74
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
19.3
18.7
10
2.4
3.0
7.0
10.9
6.3
52.8
50
40
30.8
30
20
9.8
20
21.7
74°00'
JUL. 74
40°36'
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
17.5
14.5
5.5
2.1
10
10.4
13.7
11.3
16.2
42.9
40
26.0
30
20
1.6
2.6
40°26'
74°15'
74°00'
AUG. 74
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
20.8
22.1
20
13.8
10
1.3
5.6
18.2
16.6
53.8
50
43.0
40
30
7.0
4.0
10
4.3
74°00'
SEPT. 74
40°36'
STATEN ISLAND
CONEY ISLAND
SANDY HOOK
NEW JERSEY
35.1
34.6
23.5
9.2
10
30
20
20
34.0
18.5
16.4
79.2
70
60
55.0
50
40
29.6
55.0
50
53.9
40°26'
74°15'
74°00'

Figure 19. Surface distributions of nitrite plus nitrate concentrations combined in $\mu M/\ell$.

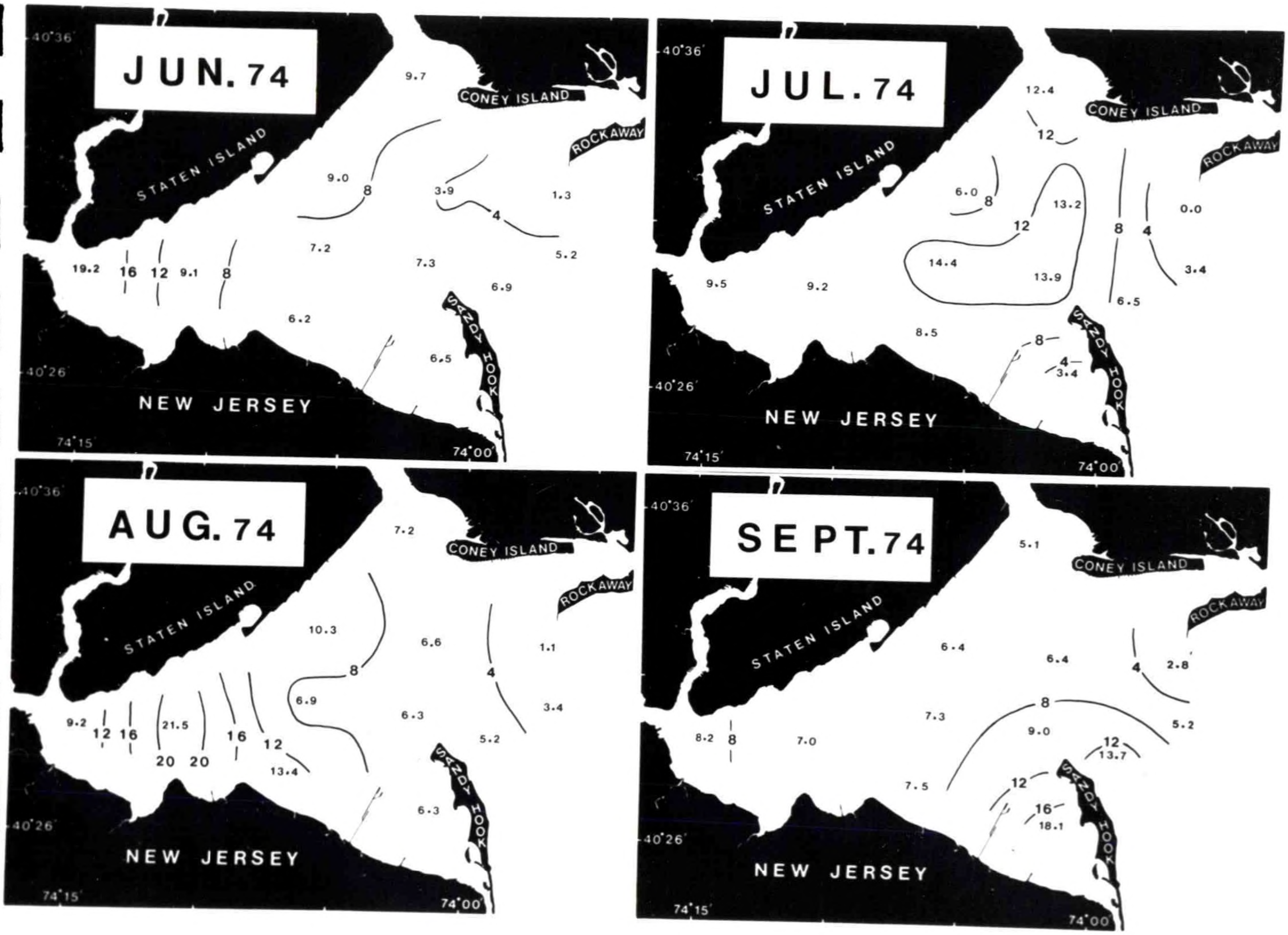
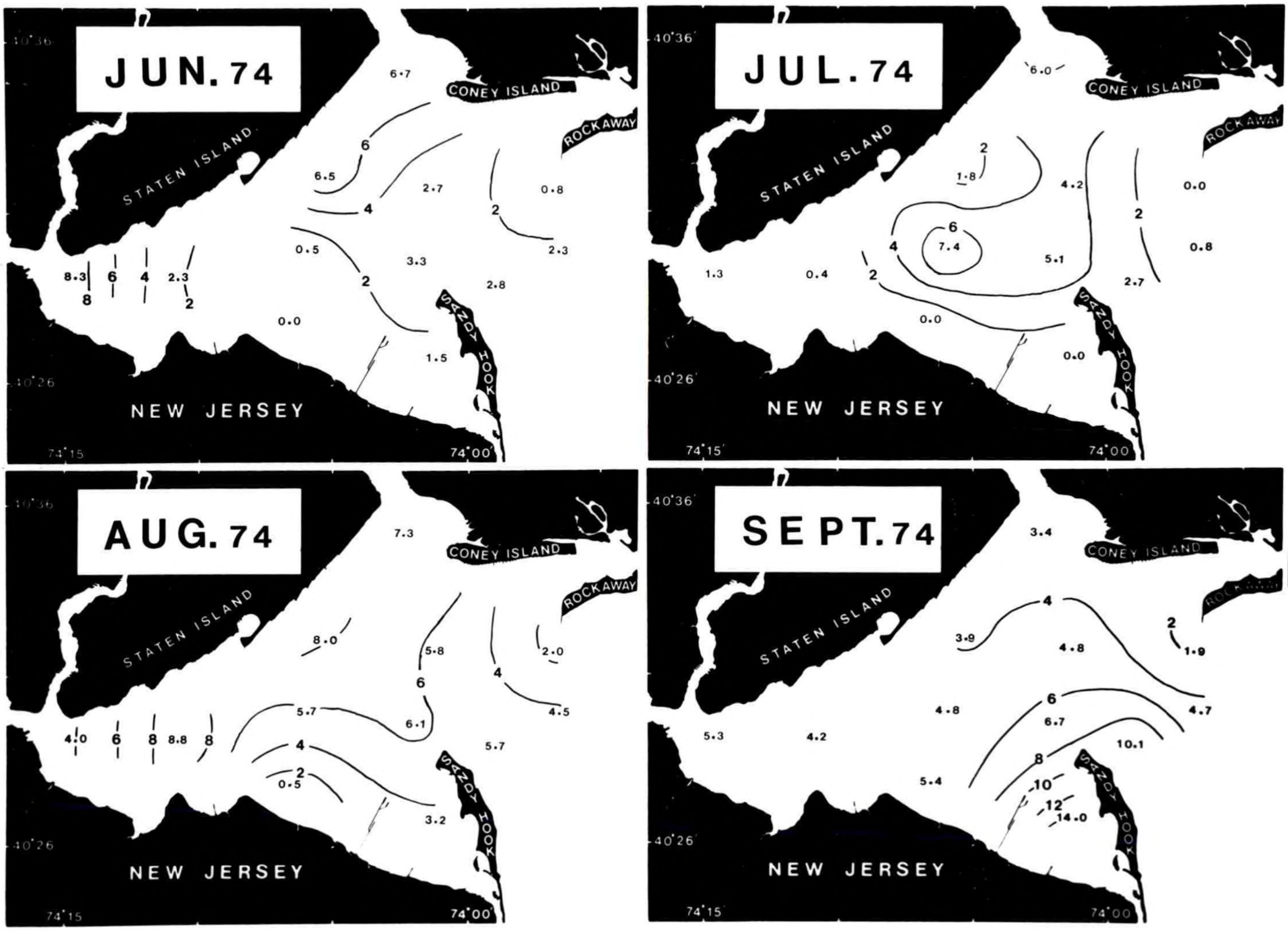

JUN. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
SANDY HOOK
NEW JERSEY
40°36'
40°26'
74°15'
74°00'
9.7
9.0
8
3.9
4
1.3
5.2
7.2
7.3
6.9
19.2
16
12
9.1
8
6.2
6.5
JUL. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
SANDY HOOK
NEW JERSEY
40°36'
40°26'
74°15'
74°00'
12.4
12
6.0
8
13.2
12
8
4
0.0
14.4
13.9
3.4
9.5
9.2
6.5
8.5
8
4
3.4
AUG. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
SANDY HOOK
NEW JERSEY
40°36'
40°26'
74°15'
74°00'
7.2
10.3
6.6
1.1
8
4
6.9
3.4
6.3
9.2
12
16
21.5
16
12
5.2
20
20
13.4
6.3
SEPT. 74
CONEY ISLAND
ROCKAWAY
STATEN ISLAND
SANDY HOOK
NEW JERSEY
40°36'
40°26'
74°15'
74°00'
5.1
6.4
6.4
4
2.8
8
7.3
9.0
5.2
8.2
8
7.0
12
13.7
7.5
12
16
18.1

Figure 20. Surface distributions of silicate concentrations in $\mu M/\ell$.



JUN. 74
40°36'
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
40°26'
74°15'
74°00'
6.7
6
6.5
2.7
0.8
4
2
2.3
0.5
3.3
8.3
6
4
2.3
8
2
2
2.8
0.0
1.5
JUL. 74
40°36'
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
40°26'
74°15'
74°00'
6.0
2
1.8
4.2
0.0
2
6
7.4
4
5.1
0.8
1.3
0.4
2
2.7
0.0
0.0
AUG. 74
40°36'
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
40°26'
74°15'
74°00'
7.3
8.0
5.8
2.0
6
4
4.5
5.7
6.1
4.0
6
8
8.8
8
4
5.7
2
0.5
3.2
SEPT. 74
40°36'
STATEN ISLAND
CONEY ISLAND
ROCKAWAY
SANDY HOOK
NEW JERSEY
40°26'
74°15'
74°00'
3.4
4
3.9
4.8
2
1.9
6
4.8
6.7
4.7
5.3
4.2
10.1
8
5.4
10
12
14.0

Figure 21. Ozone treatment apparatus for seawater contaminated by Gonyaulax tamarensis. Ozone enters the static mixer and is mixed with seawater contaminated by Gonyaulax tamarensis, flowing up the mixer column. Ozonized seawater leaves the top of the column, is collected in a head tank, and gravity-fed to a series of fiberglass trays containing shellfish.

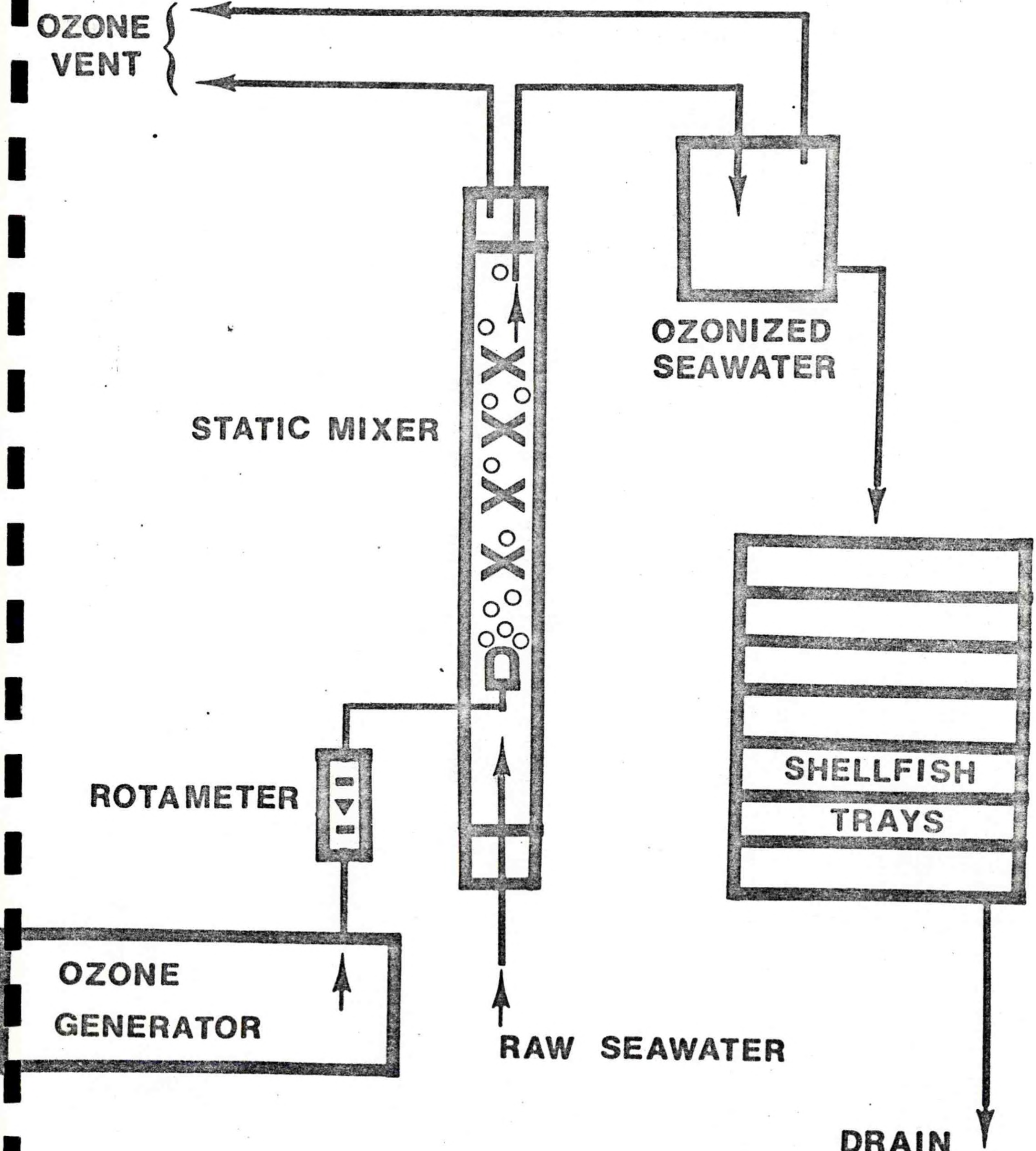

OZONE VENT
OZONIZED SEAWATER
STATIC MIXER
ROTAMETER
SHELLFISH TRAYS
OZONE GENERATOR
RAW SEAWATER
DRAIN

Table 1. Ozone-inactivation of dinoflagellate toxins as determined by mouse bioassay.

ml O_3/min	No. Mice	Death Time (min)	% Survival (48 hr)
		Gonyaulax tamarensis	
220	5	-	100
110	10	-	100
55	10	12	90
27	10	12-14	20
0	20	5-6	0
		Gonyaulax catenella	
110	15	-	100
55	15	-	100
27	10	5-7	0
0	20	5-7	0

GLOSSARY OF TERMS

Bio-accumulation, PSP. The concentration and retention of paralytic shellfish poison by shellfish when they filter-feed on toxic dinoflagellates.

Bloom, phytoplankton. A seasonal dense phytoplankton.

Depuration. The process of purification, freeing from impurities, cleansing.

Essential nutrient. A nutrient which is indespensible in the metabolism of an organism.

Euphotic layer. The layer of water in which there is sufficient light for photosynthesis to occur.

Eutrophication. The natural or artificial addition of nutrients to bodies of water and the effects of added nutrients.

Flagellum. A lashlike appendage serving as an organ of locomotion in certain reproductive cells, bacteria, protozoa, etc.

Food chain. A sequence of organisms in which each is, in turn, food of the latter member of the sequence.

Heterotrophy. Utilization by plants or animals of organic nutrients in their nutrition.

Hormone. A chemical substance which regulates the functioning of cells.

Humic substance. Organic material produced by the decomposition of vegetable or animal matter.

Incidence. The range of occurrence or influence of a thing, or the extent of its effects.

Limiting nutrient. An essential nutrient which because of its scarcity limits growth of one or a group of organisms.

Locus, red tide. The locality of its occurrence.

Nutrient. A substance that can be used as a food.

Organic nutrient. Organic compound which may be used as a sole or supplementary source of its constituents.

Ozone. An allotropic form of oxygen having the formula O_3.

Patch. An area in the sea rich in plankton.

Photoassimilation. Incorporation of a nutrient as a unit into living material during photosynthesis.

Phototaxis. Migration of organisms towards or away from light.

Phytoplankton. Collectively, the microscopic photosynthetic plants which either swim or float in a body of water.

Pollution, water. Any impairment of its quality that has serious adverse effects on the subsequent beneficial uses of the water.

Primary productivity. The amount of carbon fixed (incorporated into living material) by plants per unit area per unit time.

PSP. Paralytic shellfish poison; a highly toxic substance produced by certain species of dinoflagellates.

Red Tide. A discoloration of natural waters caused, usually, by an abundance of microscopic plants.

Regeneration, nutrient. The process of mineralization of organic material to inorganic material which can again be utilized by plants in photosynthesis.

Spring tide. The large rise and fall of the tide at or soon after the new or the full moon; any great flood or swelling rush.

Uptake, nutrient. Absorption or transfer of materials into cells for metabolic utilization.

Upwelling. A movement of deeper waters towards the surface along coasts to replace surface water moving away from the coasts.

Zooplankton. Collectively, the community of small animals in a body of water.