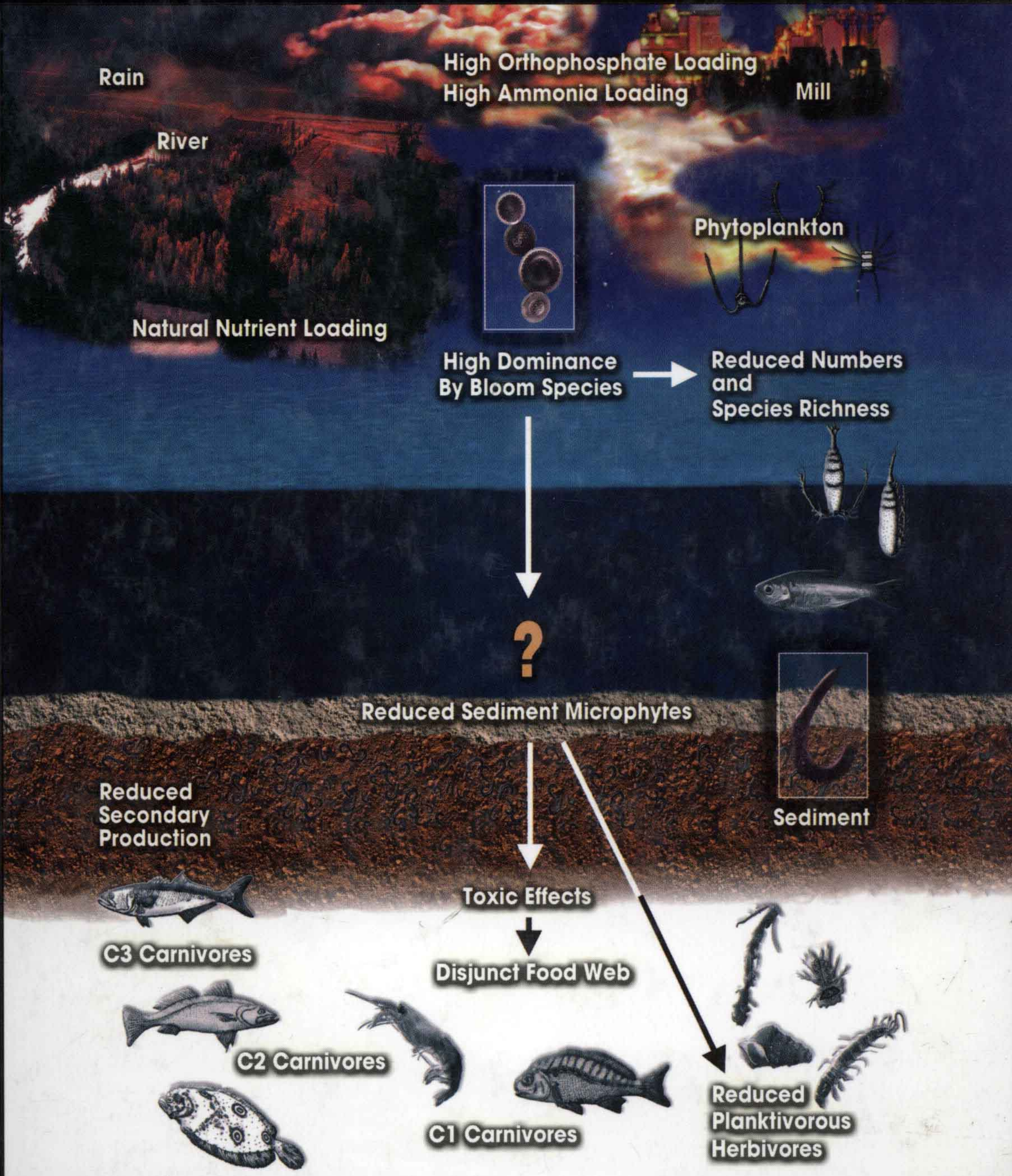
EUTROPHICATION PROCESSES

IN COASTAL SYSTEMS



ROBERT J. LIVINGSTON

COVER ART

The cover represents a pictorial metaphor for the chief findings of the book. Anthropogenous alterations of nutrient loading to coastal systems initiates complex changes of associated phytoplankton communities. Temporal progressions of bloom species lead to reduced phytoplankton species richness and altered dominance relationships. These changes are passed along to associated food webs which, through basic alterations in the response of key trophic groups, lead to major reductions of secondary production.

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EUTROPHICATION PROCESSES
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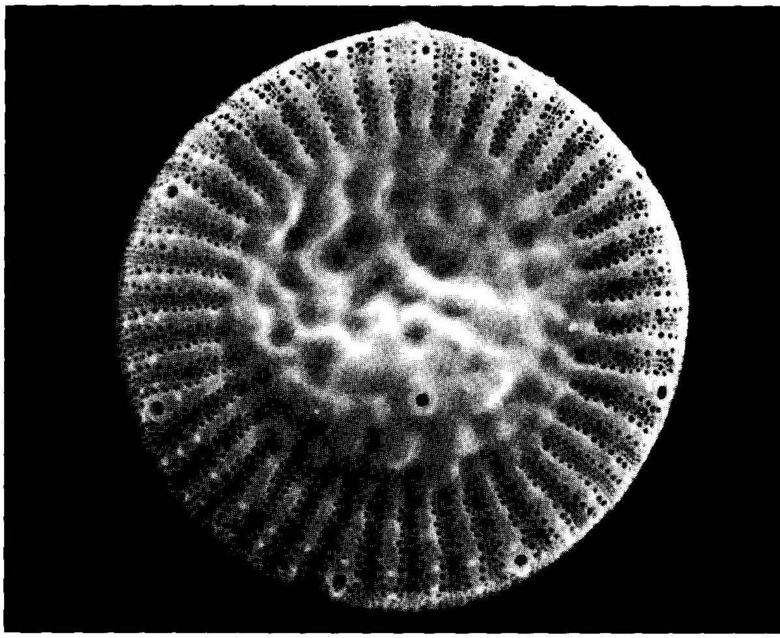
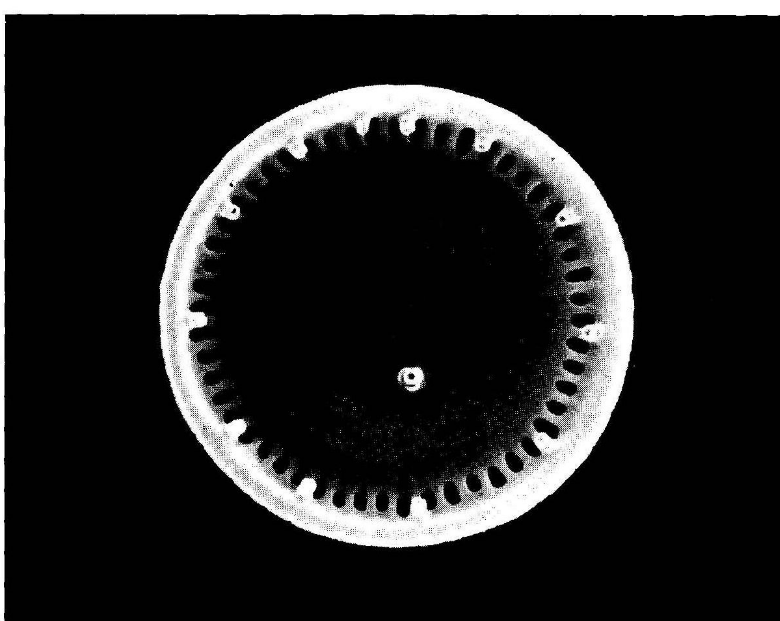
Origin and Succession of Plankton Blooms and Effects on Secondary Production in Gulf Coast Estuaries

Frontispiece





Cyclotella choctawhatcheeana Prasad, a bloom-forming, planktonic diatom from Perdido Bay system. Top: External view of the valve. Diameter of the valve = 6 μm. Acid-cleaned material. Bottom: Internal view of the valve. Diameter of the valve = 7 μm. Acid-cleaned material. (Scanning electron micrographs courtesy of A. K. S. K. Prasad, Florida State University.)

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Preface

The research effort on which this book is based has involved continuous analyses of various river–estuarine and coastal systems in the northeastern Gulf of Mexico since 1970. Multiyear studies (over 60 field-years of data in coastal areas) have been carried out using a combination of field descriptive and experimental (laboratory and field) approaches. The research team for this work has included field collection personnel, chemists, taxonomists, experimental biologists, physical oceanographers, hydrological engineers, statisticians, computer programmers, and modelers. A long-term, interdisciplinary, comparative database has been created that is currently being published in a series of books and peer-reviewed scientific journals. This field program has been used to evaluate system-level processes that determine the relationships of nutrient loading/nutrient dynamics, primary productivity and eutrophication processes, and associated food web responses. Efforts have been made to determine how human activities affect these processes. The emphasis of the research has been on seasonal and interannual trophic response to habitat changes and an evaluation of the interrelationships of natural and anthropogenous nutrient loading, primary and secondary production, and the effects of toxic substances. This research is currently being used to develop realistic indices of ecosystem condition.

This book includes several features that have been integrated into an ecosystem evaluation of the role of eutrophication in shaping primary and secondary production in coastal systems. Detailed, long-term, species-specific analyses of column phytoplankton and benthic microalgae were analyzed relative to long-term changes of nutrient loading and the response of the food webs in Perdido Bay. The food web data were based on a long-term stomach content program whereby data concerning invertebrates and fishes taken in a series of coastal systems along the northeastern Gulf of Mexico were organized into ontological feeding units. These data were then translated into a trophic organization. By reviewing detailed changes of the phytoplankton communities over different nutrient loading regimes, it was possible to determine the response of the food webs to such changes. The Perdido Bay data were then compared to similar information taken in a series of other coastal systems in the northeastern Gulf.

Author

Robert J. Livingston is currently Professor of Biological Science and Director of the Center for Aquatic Research and Resource Management at Florida State University (Tallahassee, Florida, U.S.A.). His interests include aquatic ecology, pollution biology, field and laboratory experimentation, and long-term ecosystem-level research in freshwater, estuarine, and marine systems. Past research includes multidisciplinary studies of lakes and a series of drainage systems on the East and Gulf Coasts of the United States. Over the past 31 years, Dr. Livingston's research group has amassed over 70 field-years of data in various freshwater and marine systems. Dr. Livingston has directed the programs of 49 graduate students who have carried out research in behavioral and physiological ecology with individual aquatic populations and communities in lakes, rivers, and coastal systems. Dr. Livingston is the author of more than 140 scientific papers and 4 books on the subject of aquatic ecology, and he has been the principal investigator for over 100 projects since 1970.

The primary research program of the author has been carried out largely in the southeastern United States. The areas studied include the Apalachicola drainage system, the Choctawhatchee drainage system, the Perdido drainage system, the Escambia Bay system, the Blackwater River–estuary, the Escatawpa–Pascagoula drainage system, the Mobile River–estuary, the Winyah Bay system (including the Sampit River), Apalachee Bay (the Econfina and Fenholloway River–estuaries), and a series of north Florida lake systems. This work has included determinations of the impact of various forms of anthropogenous activities on a range of physicochemical and biological processes. A sophisticated computer system has been developed to aid in the analysis of the established long-term databases.

Acknowledgments

There were many people who contributed to the research effort over the past 31 years. It is impossible to acknowledge all of these people. Literally hundreds of undergraduate students, graduate students, technicians, and staff personnel have taken part in the long-term program.

The author is grateful for the astute reviews and editing of this book by Dr. D. M. Anderson, Dr. A. K. S. K. Prasad, Mr. G. C. Woodsum, Dr. M. J. Kennish, and Ms. V. Tschinkel. Dr. A. K. S. K. Prasad carried out phytoplankton taxonomy and systematics. Dr. K. Rhew has provided support in the microalgal analyses. Mr. Robert L. Howell IV ran the field collections. Mr. G. C. Woodsum designed the overall database organization and, together with Mr. P. Homann, ran database management and day-to-day data analysis and presentation. Dr. F. Graham Lewis III was instrumental in the development of analytical procedures and statistical analyses. Dr. D. A. Flemer designed the overall approach for analytical chemistry.

The early Perdido Bay work was carried out with the services of the following individuals: Dr. D. A. Birkholz (toxicology, residue analyses), Dr. G. S. Brush (long-core analysis), Dr. L. A. Cifuentes (nutrient studies, isotope analyses), Dr. R. A. Coffin (nutrient studies, isotope analyses), Dr. W. P. Davis (biology of fishes), Dr. J. H. Epler (aquatic insects), Dr. M. Franklin (riverine hydrology), Dr. T. Gallagher (hydrological modeling), Dr. C. R. Gilbert (fish systematics), Dr. W. C. Isphording (marine geology), Dr. R. D. Kalke (estuarine zooplankton), Dr. C. J. Klein III (aquatic engineering, estuarine modeling), Dr. C. C. Koenig (biology of fishes), and Dr. A. W. Niedoroda (physical oceanography).

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To every thing there is a season,
And a time to every purpose under the heaven.

—Ecclesiastes 3:1

"I weep for you," the Walrus said:
"I deeply sympathize."
With sobs and tears he sorted out
Those of the largest size
Holding his pocket-handkerchief
Before his streaming eyes.
But answer came there none —
And this was scarcely odd, because
They'd eaten every one.

—*Through the Looking-Glass* by Lewis Carroll

A man and what he loves and builds have but a day and then disappear; nature cares not — and renews the annual round untired. It is the old law, sad but not bitter. Only when man destroys the life and beauty of nature, there is the outrage.

—*Grey of Fallodon* by George Macaulay Trevelyan

Contents

CHAPTER 1

Introduction

I. EUTROPHICATION PROCESSES

Eutrophication represents and defines one of the central themes of aquatic ecology: the production of organic matter that forms the basis of aquatic food webs. There is a rich scientific literature concerning many aspects of the eutrophication process whereby nutrients are taken up by aquatic plants (phytoplankton, benthic microalgae, epiphytes, emergent vegetation, and submergent macrophytes) to form organic carbon. The basic process is generally the same for most aquatic systems. However, the ultimate end products exemplified by the resultant food webs vary from system to system depending on the multifold interactions of the nutrient loading process, nutrient limitation characteristics of the receiving system, habitat distribution, and existing biological conditions.

River–estuarine and associated coastal systems are among the most productive areas on earth due to nutrient enrichment from land runoff, the usually shallow nature of the receiving system, and natural energy supplements in the form of wind, tidal currents, and thermohaline circulation. Phytoplankton and benthic microalgae represent one of the primary sources of organic carbon in river-dominated estuaries. Because of high diversity, taxonomic complexity, and rapid reproduction rates, community interactions of coastal microalgae are poorly understood even though such organisms form the basis of many coastal food webs. The food web structure of natural aquatic systems is molded by the eutrophication process, with complex interactions that depend largely on multiple biological processes of the primary producers and highly evolved feeding strategies of the consumers (Livingston et al., 1997). In addition to being highly productive, many temperate, river-dominated estuarine and coastal systems are known for rapid changes in the physical habitat that contribute to stress-induced changes in food web response. The myriad juxtapositions of the eutrophication process in coastal systems reflect varying combinations of nutrient loading and response mechanisms in habitats that change both seasonally and interannually. Variation of the trophic organization of estuarine systems is an important part of the eutrophication process.

Periodic loading of carbon, nitrogen, phosphorus, and other nutrients and organic compounds from allochthonous (land runoff) and autochthonous sources affect river-dominated estuaries. The often shallow, coastal receiving areas are also influenced by mixing characteristics and current patterns that dominate the physical environment. The resulting food webs are based on the combination of high primary production and limitations on species richness imposed by the extremely variable estuarine habitat. It can be argued that this paradigm has been overused since there is a considerable range of variability in overall primary and secondary production both within and between various coastal systems. The processes that determine primary productivity and the resulting food webs vary considerably from one system to the next. This variation depends on factors such as the physiographic structure of the receiving system, temperature, salinity, wind, tides, currents, stratification characteristics, light transmission, nutrient loading events, nutrient concentrations, sediment characteristics, primary and secondary production, and biological processes such as competition and predation. Thus, different combinations of common variables lead to highly variable food web responses from one system to the next that are then translated into major differences in population dynamics, community structure, and overall secondary production. Despite such variation, the basic eutrophication process remains essentially the same, whereby light energy is captured and redistributed into myriad forms of coastal plants and animals.

There is growing evidence that human activities increasingly affect both the quantitative and qualitative aspects of nutrient loading and phytoplankton response (i.e., bloom formation) in coastal systems around the world. Bricker et al. (1999), in a comprehensive review of the extent of the eutrophication problem in the conterminous United States, found that 44 estuaries, representing 40% of the total estuarine surface area studied, suffer "high expressions of eutrophic conditions" with an additional 40 estuaries having "moderate conditions." The primary symptoms on which the survey was based included decreased light availability, high chlorophyll *a* concentrations, high epiphytic/macroalgal growth rates, changes in algal dominance (diatoms to flagellates, benthic to pelagic dominance), and increased decomposition of organic matter due to the high chlorophyll *a* concentrations and macroalgal growth. These effects were most pronounced along the coasts of the Gulf of Mexico and the Middle Atlantic states. Commercial and shellfish fishery use was impaired in 43 and 46 estuaries, respectively. Most of the estuaries studied were affected by human influence although only 14% of the affected estuaries had correspondingly high nitrogen inputs. More than half of these estuaries had a high capacity to retain nutrients. It was projected that eutrophic conditions would worsen in 86 estuaries by the year 2020. The authors emphasized that better data are needed in terms of estimators of anthropogenous forms of nutrient pressure and nutrient inputs by source.

According to Bricker et al. (1999), there is currently little in the way of available "process-oriented data relative to the mechanisms involved in the progressive development of eutrophication." Currently, thresholds of nutrient loading leading to toxic blooms remain largely undetermined and the relationships of nitrogen and phosphorus to such blooms need "further clarification." The influence of climate changes on blooms remains undefined and the combination of nutrient inputs and other anthropogenous stressors remains largely unknown. There has been virtually no information generated concerning the species-specific qualitative and quantitative changes of the phytoplankton communities relative to the generation of the blooms. The authors found little information with regard to the impacts of plankton blooms on coastal food webs. In other words, the causative factors involved in the generation of phytoplankton blooms, the effects of such blooms on plankton community organization, and the impacts of altered plankton assemblages on secondary production through effects on coastal food webs all remain largely undefined (Bricker et al., 1999).

A comprehensive understanding of the effects of cultural eutrophication on diverse coastal systems is complicated by the extreme complexity of the response of dynamic phytoplankton assemblages to background variation. Despite their importance in terms of overall estuarine primary production, water column phytoplankton and benthic microalgae represent one of the most complex and least well understood parts of any given coastal system. The daunting taxonomic problems associated with microalgal associations usually preclude detailed and quantitative determinations of what is basically an ephemeral series of rapidly cycling bursts of production. The cycles of these microalgal populations can be measured in periods ranging from seconds to years. The assimilative capacity of any given coastal system relative to nutrient loading remains a major question in the evaluation of the transformation from natural eutrophication processes to hypereutrophication and postulated deterioration of associated food webs. It is likely that the responses of the microalgae to nutrient loading determine the structure of the estuarine food webs. In turn, food web processes are central to the nature and extent of population distribution. Although these aspects of eutrophication have been subject to extensive research for decades, there is still a considerable lack of understanding concerning how nutrient loading and habitat characteristics affect the quantitative and qualitative aspects of primary production, and how the resulting microalgal associations are related to associated food webs. This fundamental inconsistency of our knowledge of coastal systems is largely the result of the almost complete absence of long-term, interdisciplinary studies that integrate the various aspects of nutrient loading, microalgal response, and food web structure.

Human population increases in coastal areas throughout the world have become an increasingly important source of nutrient loading to estuarine systems. Recent studies indicate that phytoplankton are the single most important factor in eutrophication processes of river-dominated estuaries. It is therefore necessary to understand phytoplankton population and community dynamics if the postulated effects of plankton blooms on the trophic organization of coastal systems are to be understood. Unfortunately, scientific inquiry in this phase of aquatic ecology is still in the early stages of descriptive research. The taxonomy and natural history of coastal phytoplankton populations remain among the least-understood aspects of coastal ecology. The recent increase of destructive plankton blooms due to anthropogenous nutrient loading has led to renewed interest in this discipline. However, information at the ecosystem level relating to the role of microalgal community structure on the eutrophication of estuarine and coastal systems remains poorly developed even though such processes are central to a basic understanding of the origin and succession of plankton blooms.

II. ASPECTS OF EXCESSIVE NUTRIENT LOADING TO ESTUARIES

Kennish (1997) has reviewed the problems associated with anthropogenous loading of nutrients to coastal systems. Resulting hypereutrophication has long been correlated with increased biochemical oxygen demand (BOD), hypoxia and anoxia in receiving estuaries. Chronic hypoxia has been a problem in coastal areas such as Chesapeake Bay, the Florida Keys, the Pamlico River–estuary, Long Island Sound, and broad areas of the northern Gulf of Mexico associated with runoff from the Mississippi and Atchafalaya Rivers. Hypoxia is also considered a problem in estuaries and bays throughout Europe, the Far East, and Australia (Kennish, 1997). Other postulated water quality changes due to excessive nutrient loading include increased turbidity, reduced light penetration, and deterioration of sediment quality. Proliferation of nuisance algal macrophytes and plankton blooms, often associated with losses of productive seagrass beds, are considered major factors in the response of coastal areas to anthropogenous nutrient loading. Toxic agents associated with plankton blooms have been responsible for fish kills and the loss of commercially important species in addition to creating public health problems following consumption of affected sea life.

The primary effects of nutrient loading on shallow estuaries and lagoons have been outlined by McComb (1995). A common aspect in the review of cultural eutrophication in diverse estuaries includes association of nutrient loading with the development of phytoplankton blooms, associated fish kills, and the general decline of fisheries (Hodgkiss and Yim, 1995). Nutrient enrichment also adversely affects seagrass beds through changes associated with stimulation of micro- and macroalgae (Duarte, 1995; Hein et al., 1995; Valiela et al., 1997). The emphasis on shallow systems highlights the importance of sediments in the nutrient loading and accumulation process (McComb and Lukatelich, 1995). Sediment resuspension as a product of water column dynamics can be a factor in nutrient storage and loading processes (de Jonge and Raaphorst, 1995; de Jonge, 1995), although such effects are not always associated with hypereutrophication (Marcomini et al., 1995). The timed release and bioavailability of sediment nutrients, as modified by resuspension, remobilization, and regeneration through biotic activity, remain poorly understood even though such processes could have an important effect on the response of benthic microalgae and macrophytes (Thornton et al., 1995a). The lack of information regarding non-point-source nutrient loading due to urban and agricultural runoff is another consideration when reviewing the causes of hypereutrophication (King and Hodgson, 1995). De Jonge and Raaphorst (1995) reviewed the positive and negative effects of increased nutrient loading. There can be initial increases of secondary production and fisheries output with increased nutrient loading (Streckis et al., 1995; Thornton et al., 1995b). However, prolonged increases often end in plankton blooms and accompanying declines of coastal populations that are often not discovered until there is an advanced state of hypereutrophication. The complex processes associated with the interaction and competition of microphytes and macrophytes often complicate a uniform response of different estuaries to increased anthropogenous nutrient loading (Streckis et al., 1995). However, in most of these studies, there is a general lack of detailed data concerning how phytoplankton blooms are initiated and how changes in the phytoplankton community structure actually affect secondary production. Despite a plethora of studies concerning hypereutrophication in estuarine and coastal systems, the processes involved in nutrient loading that ultimately lead to altered phytoplankton populations and associated food web changes remain largely undefined.

Howarth et al. (2000) conducted a review of the effects of excess nutrients on coastal systems. This worldwide phenomenon has led to increased algal biomass, excessive concentrations of sometimes toxic algae in the form of harmful brown and red tides, reduced seagrass and coral reef habitat, altered marine biodiversity, hypoxia/anoxia, and the loss of commercial fisheries. The authors emphasized that a considerable number of coastal systems in the United States have some of the symptoms of excessive nutrification. The report was designed to make recommendations for the implementation of management efforts to reduce nutrient loading. These recommendations included expansion of monitoring programs, development of ways to reduce non-point sources of nitrogen and phosphorus, an increased federal role in eutrophication issues, development of a classification scheme for management of nutrient overenrichment, improvement of comprehensive assessments of environmental quality and associated modeling efforts, and expansion of our knowledge concerning eutrophication questions. The dimensions of the nutrification problem in the coastal waters of the United States have been generally well established (Bricker et al., 1999). The key to any restoration effort rests on the development of adequate scientific knowledge of the eutrophication process and the determination of how specific changes in anthropogenous nutrient loading affect individual estuaries and coastal systems.

III. PLANKTON RESPONSE TO NUTRIENT LOADING

The response of individual phytoplankton populations to nutrient loading in coastal systems has been extensively studied (Anderson and Garrison, 1997). Short-term studies of bloom species at well-defined taxonomic levels are the rule both in funding of the research and publication of the results. There are studies that go beyond autecological analyses. Squires and Sinnu (1982) addressed the complexity of the response of diatom assemblages in estuarine areas to varying habitat conditions. Currents and salinity were important factors in the determination of diatom assemblages in the study area. Marshall (1982a,b) showed that distributions of marine diatoms in the Gulf of Maine were related to the location of large bay systems and the Georges Bank. Anthropogenous effects on water quality often are evaluated relative to the distribution of marine phytoplankton. According to Reddy and Venkateswarlu (1986), pulp mill effluents caused reduced numbers of phytoplankton in the effluent channel. The Cyanophycean types were dominant in such areas, with an almost total lack of green algae. *Oscillatoria* spp. were dominant in the polluted regions, with *Rhopalodia gibberula* and *Nitzschia palea* as the primary diatom species. Premila and Rao (1977) showed that blue-green algae (*O. nigroviridis*) were indicative of waters affected by sewage relative to less-polluted areas. Low salinity along with the sewage effluents in such areas tended to encourage this species. However, blue-green algae are also abundant in marine areas under natural conditions (Potts, 1980). Chang (1988) described a *Prorocentrum micans* bloom in a New Zealand estuary that was coincident with increased nitrogen from upwelling. The author found onshore–offshore