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3 Impact of Nutrient Inflows on Chesapeake Bay

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ABSTRACT

The purpose of this chapter is to summarize selected research and monitoring conclusions developed in the last decade regarding the sources, fate, and effects of nutrients in Chesapeake Bay. Compared to other estuarine systems, **loading** rates to Chesapeake Bay are moderate to high for nitrogen and low to moderate for phosphorus. While the effects of nutrient additions vary among estuaries, current loads in Chesapeake Bay are sufficient to cause severe seasonal hypoxia and large declines in **seagrass** communities. Diffuse sources of nitrogen and phosphorus are the dominant inputs, but point and atmospheric sources are also important in tributary systems. On an annual basis, nitrogen has been exported to the coastal ocean while phosphorus is imported. Estuarine sediments are capable of large

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releases of phosphorus, especially when dissolved oxygen concentrations near sediments are low ($<2 \text{ mg } L^{-1}$). However, laboratory and field measurements indicate that sediment reserves of labile nitrogen and phosphorus are sufficient to support high sediment nutrient releases for months to a year or so but not for decades. **Mesocosm** and bioassay experiments indicate that, during warm periods of the year, phytoplankton communities are limited by nitrogen while phosphorus limits production in tidal freshwater regions. Field, **mesocosm**, **and** laboratory studies all suggest that Chesapeake Bay and tributary systems are responsive to changes in nutrient loading rates on relatively short time scales.

INTRODUCTION

During the past few decades it has become clear that coastal marine and estuarine systems subject to intense human activities have shown signs of stress or have become degraded to some extent (Nixon, 1990). This loss or impairment of coastal and estuarine resources has spurred research to determine the causes and consequences of impairments and unprecedented monitoring activities to establish the current health of these systems and their responses to management actions. In many cases, the primary cause of ecosystem degradation is related to excessive inputs of nutrients from the land and atmosphere to these systems. The Chesapeake Bay is no exception.

The purpose of this chapter is to summarize some of the important research and monitoring conclusions developed in the last decade regarding the sources, fate, and effects of nutrients in Chesapeake Bay, particularly those related to phosphorus. A variety of references are also provided so those interested in details, techniques, and **more** complete interpretationscan access these primary information sources. Discussion of both phosphorus and nitrogen are included because the dynamics and management of these nutrients are often linked.

IMPORTANT ESTUARINE ECOSYSTEM CHARACTERISTICS

During the last several decades, a great deal has been learned about estuaries and their role as transition zones between the land and the sea. Much of the information gathered from Chesapeake Bay has increased our understanding of the mechanisms and processes that govern the behavior of estuarine ecosystems worldwide. While the Chesapeake Bay is the largest and one of the most studied estuarine ecosystems in the U.S. (Figure 1), there are many other estuarine ecosystems differing in size and geomorphology that have similar characteristics and problems. One feature common to many estuaries is that they are experiencing some degree of eutrophication (an increase in the rate of organic matter production due to nutrient additions), as well as the consequences of this process. The National Oceanographic and Atmospheric

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FIGURE 1 The Chesapeake Bay and basin, showing the states encompassed and major portions of the tributary network. The ratio of drainage basin surface area to estuarine surface area is 28:1, indicating the potentially large impact of the land on this system.

Administration (NOAA) is currently assessing the ecological health and trends in approximately 140 estuaries in the U.S. (S. Bricker, NOAA, personal communication). Most often, the source of this enrichment is related to land-use activities in their basins.

A second important estuarine feature concerns the circulation pattern of the water (**Boicourt**, 1992). A generalized schematic of Chesapeake Bay circulation is shown in Figure 2. Freshwater from the drainage basin (shown on the left) **moves** toward the ocean as a surface water flow. To counter **this** seaward flow of freshwater, seawater moves into the bay as a near-bottom flow. This gravitational circulation is the net result of differences in pressure gradients caused by the lower density of fresh compared to saltwater. This bi-directional flow is characteristic of average **condi**tions, but some degree of mixing occurs between the layers and is more pronounced in some zones of the estuary than in others. While there are many biological consequences related to this circulation pattern, two are of particular importance here. The **first** is that the vertical differences in density result in water-column stratification, which in turn inhibits mixing of deep and surface waters. Despite the

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FIGURE 2 A generalized schematic diagram showing the main features of a two-layered estuarine circulation pattern. (Adapted from **Boicourt**, W.C. 1992. In D.E. Smith, M. Leffler, and G. **Mackiernan**, Eds., Oxygen *Dynamics in the Chesapeake Bay – ASynthesis* of *Recent Results*, A Maryland Sea Grant Book, College Park, MD.)

shallow nature of the bay (mean depth of approximately 10 m), stratification is a very effective barrier, particularly from spring through early autumn of most years. As a result, deeper waters are not exposed to the atmosphere for weeks to months and can become very depleted in dissolved oxygen (DO) (Kemp and Boynton, 1992). An important second feature is that two-layer circulation leads to relatively long retention times — in effect, materials that get into the bay tend to stay in the bay. The freshwater fill times are on the order of a year, and this factor, coupled with the **two**-layer circulation pattern and relatively weak tides (<1 m), results in a generally nutrient-retentive system. As will be shown later, nutrient input rates to the bay are moderate compared to many other estuarine systems, but rates of plant and animal production are very high, in part because **essential** nutrients which support this production are retained in the bay rather than rapidly transported to the coastal ocean.

Finally, the bay ecosystem is characterized by very substantial temporal and spatial variability. Important inputs to the bay such as freshwater, sediments, nutrients, and **terrestrial** organic matter vary strongly throughout the year (~10× greater in spring vs. autumn) and between years (>2×). These pulsing inputs and interannual variations influence both plant and animal production and spatial distributions of these creatures. As a result of these variabilities, it is difficult to clearly separate the influence of normal climatic variability from human-induced changes to these ecosystems resulting from pollutant inputs.

CHARACTERISTICS OF ESTUARINE EUTROPHICATION

Many estuarine processes are linked, either directly or indirectly, to the inputs of nutrients and other materials from the land. A simplified explanation of these

processes and mechanisms is shown in Figure 3, in which inputs of nutrients are linked to plant and fish production. Nitrogen and phosphorus enter the estuarine system, causing an increase in phytoplankton production and a decrease in light penetration due to shading by unicellular algae suspended in the water column. After nutrient supplies are exhausted by phytoplanktonic growth, the resultant blooms die and sink to the bottom, and DO is consumed in the decomposition of the bloom material. Hypoxic (low DO) or anoxic (no DO) conditions result, killing sessile organisms, such as clams and worms, and removing the cooler deep waters as a habitat for fish and shellfish communities.

Another important consequence of this nutrient enrichment is the stress it places on submersed aquatic vegetation (SAV) by reducing the available light reaching SAV leaves. Light reduction occurs because of increased turbidity in the water column as well as from growth of attached algae (epiphytes) on the leaves of SAV. Light reduction has been determined to be the prime factor responsible for very substantial SAV losses in recent decades. The demise of SAV represents another loss of productive habitat in terms of a nursery and spawning area. Both of the habitat losses indicated in Figure 3 impact fisheries, but the quantitative relationships are not yet clearly established.

EXAMPLES OF EUTROPHICATION EFFECTS IN CHESAPEAKE BAY

There is now strong evidence of the effects of increased nutrient (phosphorus and nitrogen) input to the Chesapeake Bay. In fact, during the last decade the cause-and-effect debate has been refocused more on how to achieve nutrient load reductions (Malone et al., 1993).

One of the prime estuarine responses to increased nutrient input is increased growth of phytoplankton, the unicellular plants that comprise the base of the food web. To an extent, enhanced phytoplankton growth is analogous to the response of agricultural crops to fertilization. The most comprehensive (covering four decades) evaluation of phytoplankton abundance in the bay was conducted by Harding (1994), who used both historical records of algal abundance and current aerial remotesensing data. In both the fresher and saltier regions of the bay, increases in phytoplankton abundance paralleled increases in nutrient loading rates. Similar responses have been observed by the Chesapeake Bay Monitoring **Program** and in other estuarine ecosystems (Boynton et al., 1996; Hagy, 1996; Nixon, 1988).

The ecological effects of elevated phytoplankton abundance are a major concern. In the agricultural model, increased fertilization typically leads to greater crop production which is a positive effect. However, in estuarine waters, excessive nutrient input initiates a series of negative impacts, the results of which are propagated to varying degrees throughout the ecosystem. One of the initial effects occurs when abundant phytoplankton communities die and begin to decompose, primarily in deeper **vaters.** Decomposition consumes DO in large quantities, causing hypoxic or anoxic conditions which are **inhibitory** or lethal to resident animal **communities**.



Cooper and Brush (1991) and Boicourt (1992) have concluded that the extent and duration of **hypoxic** conditions in the bay have increased since the 1950s.

Submersed aquatic vegetation communities play an important role in shallow water portions of estuaries. According to recent studies, SAV communities maintain water clarity in shallow areas by binding sediments and baffling near-shore wave turbulence, modulate nutrient, regimes by taking up nutrients in spring and storing these nutrients until autumn, and enhance food-web production by supplying organic matter and habitat conducive for rapid growth and survival of juvenile organisms. In much of Chesapeake Bay, SAV communities, including some 13 to 15 species, started to undergo a major decline during the 1960s in the upper bay and in the early 1970s in the mid bay (Kemp et al., 1983). In the late 1970s, a series of studies investigated potential causes. These included field observations, small (50 to 700 L) and large (400 m³) microcosm exposure tests, and simulation modeling and were conducted using several different SAV species. Results indicated that the decline was primarily the result of nutrient enrichment. It appeared that epiphytic algae (a normal part of the SAV community) were over-stimulated by enhanced nutrient availability, which led to increased shading of SAV leaves. Photosynthetic rates of SAV were depressed below those needed for healthy plant growth, and increased water-column turbidity and adhesion of suspended sediments to SAV leaves further reduced available light. In these studies, herbicides were found to be a relatively small factor in the SAV decline (Kemp et al., 1983). This situation is illustrated in Figure 4 for the Patuxent River estuary, which at one time supported large SAV communities. Since the mid-1980s. nutrient inputs to the Patuxent have been reduced but with little subsequent improvement in SAV, possibly because SAV has been absent so long that local seed sources have been depleted. However, when nutrient loading rates were reduced, SAV communities re-established themselves in other areas of the bay (Stevenson et al., 1993).

COMPARISONS OF NUTRIENT INPUTS AMONG COASTAL SYSTEMS

During the past few years, nutrient **loading** rates for a diverse mixture of ecosystems have appeared in the **literature (e.g., NOAA/EPA, 1989)**. Based on nutrient loading data for both aquatic and terrestrial systems, others have concluded that **coastal** systems have become among the most heavily fertilized of **ecosystems** because. of increasing **anthropogenic** additions of nitrogen and **phosphorus (Nixon et al., 1986a)**.

Estuarine systems respond to increasing nutrient loads with modest increases in primary production rates and increased rates of nutrient recycling, but only slight enhancement in higher food web production. Most additional production appears to be rapidly consumed by bacteria and other microheterotrophs (Nixon et al., 1986b; Norwicki and Oviatt, 1990). Recent investigations in Chesapeake Bay have also reported similar attenuated responses to loading rates (Boynton et al., 1995). However, comparable nutrient loading rates in different ecosystems do not necessarily



FIGURE 4 Decadal-scale trends in nutrient Ioads, algal biomass, water clarity, and seagrass coverage in the Patuxent River estuary. a tributary system of Chesapeake Bay. (Adapted from Kemp, W.M. and Boynton, W.R. 1998. In Fankenmark, M., Ed., *Proc. Stockholm Water Symposium*, Stockholm, Sweden.)

produce the same responses as those observed in the Bay. For example, even though nitrogen loading rates to the Potomac River and Narragansett Bay **are** very similar, water-quality conditions in the mesohaline portion of the Potomac are poor but quite good in mesohaline portions of Narragansett Bay (Magnien et al., 1990; Nixon et al., 1986a). On the other hand, loading rates to the Baltic Sea are lower than those to Chesapeake systems, but hypoxic and **anoxic** conditions are now characteristic of





FIGURE 5 Simplified annual total nitrogen and total phosphorus budgets for entire Chesapeake Bay system, Exchanges of TN and TP with the coastal ocean were calculated as the difference between landside plus atmospheric inputs and internal losses. (Adapted from Boynton, W.R. et al., 1995. *Estuaries*, 18(18):285–314.)

both (Jansson, 1978). Estuarine morphology, circulation, and **regional alimate con**ditions strongly influence the **relative** impact of loading rates (Wulff et al., 1990).

NUTRIENT BUDGETS FOR THE BAY

One of the themes of this conference concerned sources and transport of phosphorus from various land uses to receiving water bodies. In this section, a summary is provided which estimates the magnitude of both phosphorus **and** nitrogen sources to the bay and their eventual fate (Figure 5).



Diffuse sources of nitrogen and phosphorus are the dominant inputs to the Chesapeake system, but both point and atmospheric sources are also important in some of the tributary systems. Overall, nitrogen was exported seaward, and the magnitude of the export was proportional to nitrogen loading rates from terrestrial and atmospheric sources; however, phosphorus was imported from the coastal ocean to the bay. Whatever the direction of **exchange**, all of these systems rapidly converted inorganic nutrient inputs to particulate and dissolved organic forms, clearly indicating that these estuaries are not passive nutrient transport systems. Other coastal systems appear to export larger percentages of nutrient inputs than Chesapeake Bay, but also as organic compounds (Degobbiset al., 1986; Nixon et al., 1986a; Nowicki and Oviatt, 1990). The mechanisms that cause high retention rates and importation of phosphorus in Chesapeake Bay are probably related to estuarine morphology and circulation patterns. Phosphorus imports across the seaward boundary represent a relatively small percentage of terrestrial plus atmospheric sources in the tributary rivers (9 to 31%) and only slightly more for the Maryland mainstem bay (34%). Much of the phosphorus stock in sediments and waters of the bay is not in a form directly available to phytoplankton and might not have much of an influence on water-quality conditions (Keefe, 1994; Magnien et al., 1990). More understanding concerning the biological availability of phosphorus would clarify the importance of imports.

Calculations based on literature values indicate that current nitrogen and phosphorus loading rates are about 5 to 8 and 13 to 24 times higher, respectively, than in the pre-colonial period (Boynton et al., 1995). Since the base years on which these budgets were calculated (1985 to 1986), phosphorus loads have been substantially reduced in several tributary rivers (e.g., Potomac, Patuxent, Back Rivers), and nitrogen loads have been substantially reduced in at least one system (Patuxent River). The differences in loading rates between pristine and current conditions are not so large as to preclude the possibility of reducing **current** loads to a point where the more damaging effects of eutrophication are diminished (Boynton et al., 1995).

PHOSPHORUS DYNAMICS IN CHESAPEAKE BAY

During the last decade, a great deal has been learned about nutrient dynamics in aquatic ecosystems. The dynamics of phosphorus are no exception. The linkage between DO conditions in deep waters and the release of phosphorus from estuarine sediments in Chesapeake Bay is a good example.

One impact of estuarine bottom sediments on water quality is exhibited during warmer periods of the year when phosphorus can be released from sediments. This . phosphorus can then be used by phytoplankton to support additional production of algal material which eventually sinks and again exerts DO deinand when decomposition occurs at or near the sediment surface. In Chesapeake Bay, sediment phosphorus releases are often on the order of 5 to 15 μ mol P m⁻² hr⁻¹, which is an amount sufficient to support 20 to 30% of typical daily algal production (Magnien et al.,



FIGURE6 Sediment phosphorus flux vs. DO concentration in bottom waters in the **mesohaline** portion of the **Potomac** River estuary between **1986** and **1995**. (Adapted from Boynton, W.R. et al., **1996**. *Ecosystem Processes Component, Level 1*, *Interpretive Report No. 12*, CBL Ref. No. **95-039**, Chesapeake Biological Laboratory. University of Maryland, Solomons.)

1990). These rates of sediment phosphorus release are typical of less impacted areas of the bay, particularly those where DO conditions in bottom waters remain above 2 mg L⁻¹. If algal growth reaches bloom proportions, enough organic matter can be created to exhaust DO in deep waters because of the oxygen demand associated with bloom **decomposition**. When DO concentrations near the sediments become low (<2 mg L⁻¹), phosphorus can be released from sediments at very high rates.

An example of this is shown in Figure 6, where many separate measurements of sediment phosphorus flux were plotted against the bottom-water DO conditions at the time of **measurement**. Phosphorus fluxes are almost always below 15 μ mol P m⁻² hr⁻¹ when DO conditions in deep water are above 2 mg L⁻¹ but are often very high (>40 μ mol P m⁻² hr⁻¹) when DO concentrations are low. Another view of sediment phosphorus processes, based on laboratory experiment., is summarized in Figure 7 where estuarine sediment phosphorus exchanges monitored (Jasinski, 1996). Phosphorus releases in the oxic experiment remained low through the entire 20-day period and were similar in magnitude or lower than those shown in Figure 6 when DO concentrations were greater than 2 mg L⁻¹. In the hypoxic experiment, sediment phosphorus exchanges in overlying





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FIGURE7 Time series plots of sediment phosphorus fluxes obtained from intact sediment cores collected from the mesohaline region of Chesapeake Bay. (Adapted from Jasinski, D.A. 1996. Phosphorus Dynamics of Sediments in the Mesohaline Region of Chesapeake Bay, Masters thesis, MEES Program, University of Maryland. College Park.)

waters were reduced. However, the very high sediment phosphorus releases measured 4 to 5 days after the onset of hypoxic conditions were not maintained for long. In fact, after 20 days, fluxes had decreased by a factor of four, and if the observed rate of decline is projected ahead in time, fluxes would have returned to normal after 30 days. The results of observations and experiments such as these suggest that one important thing we can do regarding phosphorus dynamics within the estuary is to make sure that estuarine sediments are exposed to oxygenated water. Also, estuarine sediment phosphorus processes appear to be responsive to alterations in input conditions; if inputs of phosphorus to sediments decrease so will the rates of phosphorus recycling.

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LIMITING NUTRIENT CONTROVERSY IN CHESAPEAKE BAY

There was a long debate concerning nutrient issues in the Chesapeake Bay area. As early as the late **1950s**, evidence was available suggesting that nutrient enrichment was having adverse effects on DO conditions in deep waters of the bay and tributaries. By the **mid-1970s**, the reality of enrichment was more accepted, and plans were made to begin removing phosphorus from various point-source discharges, although progress was slow. The general position of state and federal management agencies at that time was that phosphorus controls at point sources would solve the nutrient enrichment problem. In addition, there was a strong bias against nitrogen control, despite a growing body of evidence suggesting that both nitrogen and phosphorus were important in controlling algal growth in estuarine systems. Nutrient management in the Chesapeake during this period, and into the **1980s**, was dominated by the evidence from freshwater environments that phosphorus control would reduce or eliminate enrichment problems. Both nitrogen control and the importance of diffuse and atmospheric sources of nutrients had been documented by this time but did not make much of an impression on nutrient control programs.

During the early 1980s, some direct evaluations of the influence of nitrogen and phosphorus additions on algal growth and biomass accumulation in Chesapeake Bay were conducted using a mesocosm approach (D'Elia et al., 1986) and later using nutrient bioassays (Fisher et al., 1992). The mesocosm studies, conducted for 2 years in the mesohaline region of the Patuxent River, indicated strong nitrogen limitation during summer and autumn, with weaker but important phosphorus limitation during late winter and early spring and light limitation during the winter. Because the mesocosm study was conducted at a single site in one tributary river, there was concern about applying these results to regions of the bay having lower or higher salinity regimes, different algal communities, and so on. However, the bioassay approach, which involved short-term measurements (days) using small bottle microcosms (300 mL) sampled from many sites in the bay, provided results consistent with the earlier mesocosm experiments (Figure 8). Results such as these were used in formulating policy, and the Chesapeake Bay Program adopted a duel nutrient reduction strategy which called for a 40% reduction in inputs of both phosphorus and nitrogen.

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One of the concerns associated with the nutrient **reduction program** currently underway is that the Bay **will** respond very slowly to load reductions because high rates of **nutrient** inputs during the last 50 years have induced in the Bay a huge "nutrient memory." In other words, the Bay is so nutrient saturated that water quality improvements wilt take decades, even when nutrient inputs have been curtailed, If so, we must be prepared to devote great efforts for years before the fruits of these labors are realized — a difficult social and political task, to say the least.

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FIGURE 8 Summary of nutrient bioassay measurements made in various locations in Chesapeake Bay and tributary rivers. (Adapted from Fisher, **T.R.** et al. 1992. *Progress Report: August 1990 to December 1993 — Nutrient Bioassays in Chesapeake Bay To Assess Nutrients Limiting Algal Growth*, Report to the Maryland Department of the Environment, Baltimore.)

The Chesapeake Bay monitoring program has developed data sets which suggest that the Bay does not have a long "nutrient memory." In other words, the Bay will respond to changes in nutrient inputs on time scales of months to a few years (Boynton et al., 1991). For the Bay to be resistant to changes in nutrient inputs there must be some significant, accessible nutrient storage within the Bay. It would be these nutrients that would support continuing eutrophic conditions when inputs of nutrients from the land and atmosphere are reduced. It is commonly assumed that sediments represent the only important, long-term (>1 year) storage site for nutrients in many estuarine systems, and this seems correct. The water residence time of the mainstem bay and tributary rivers of the Chesapeake are less than one year (Boicourt, personal communication) which would preclude long-term storage in the water column.

Even if nutrient concentrations were to increase in the water column, the increase relative to other storages would be small because the Bay is so shallow — there is just not much water to accumulate nutrients. The mass of nutrient material stored in living biota may be substantial at some times of the year (Holland et al., 1989) but does not appear to accumulate from one year to the next. The material accumulated in the sediment column is substantial, and estimates indicate that this storage is equivalent to between 5 and 20 years of nutrient inputs from the land, even in just the top 10 centimeters of the sediment column. There is indeed a substantial nutrient storage in Bay sediments. The question is how available and accessible are these sediment nutrients?

Field observations and laboratory experiments indicate that nutrients coming from sediments are primarily derived from decomposition of recently deposited labile organic matter. Nutrients buried in the sediments are not readily recycled. These data indicate that the "nutrient memory" is short, from months to a few years,

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In Figure 9, sediment fluxes of ammonium measured at a location in the mesohaline mainstem bay are plotted against temperature at the time of measurement. Sediment releases of ammonium reached a peak in July, prior to the annual temperature maximum, and decreased substantially in August and September. It appears that lower fluxes were observed, even at higher temperatures, because labile organic matter derived mainly from deposition of the spring bloom had been exhausted. Fluxes in August and September were lower, but still substantial, and it seems likely that they were supported by material derived from summer algal blooms. Alternative explanations for this pattern do not seem reasonable under current circumstances. For example, nitrogen is not being temporarily sequestered in benthic biomass, thus reducing the amount of nitrogen available for release as ammonium, because infaunal biomass levels are very low during this time of year (Holland et al., 1989). Nor does it appear that nitrogen is being routed through the nitrification pathway, because hypoxic conditions in sediments inhibit nitrification. Finally, particulate nitrogen concentrations in the top 2 to 3 mm of sediment began to decrease after deposition of the spring bloom in late spring (May or June), indicating rapid use of this material.

Laboratory experiments also indicate a close temporal coupling between sediment respiration and availability of labile organic matter (Figure 9, middle and lower panels). Both sediment oxygen consumption (SOC), an index of aerobic metabolism, and sulfate reduction rates, an index of anaerobic metabolism, decreased sharply in sediment microcosms held under laboratory conditions of constant temperature (18°C) with no additions of labile particulate organic matter to the water overlying the cores. Similarresponses based on microcosm studies have been reported by Kelly **and Nixon** (1984) **and** Boynton et al. (1991). These data suggest that at least in the middle reaches of the **mainstem** bay, sediment resupply of new nutrients would rapidly decrease with decreased nutrient loads.

CONCLUSIONS

Coastal and estuarine eutrophication is a problem of global proportions arising from diverse effects of human activities. In estuaries such as the Chesapeake Bay, diffuse watershed and atmospheric sources of **nutrients** dominate (except in urban areas), and these diffuse sources have increased substantially during the last century. A key consequence of eutrophication is loss of animal habitat in shallow and, deep regions through declines in **seagrasses** and bottom water DO, respectively. Mesocosm and bioassay experiments suggest that during warm portions of the year mesohaline phytoplankton communities are **limited** by nitrogen, while phosphorus limits production in tidal freshwaterregions. Low light availability and short water residence times also limit production in **some** areas, particularly during winter months. Many regions of Chesapeake Bay now appear to be in a eutrophic condition relative to nutrient loading with consequent nuisance algal blooms, loss of SAV, hypoxia, and reduced benthic production. Both field measurements and results of laboratory experiments suggest that water **quality** conditions in the Bay should respond quickly to reduced nutrient inputs.







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