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North and South Carolina Coasts

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This coastal region of North and South Carolina is a gently sloping plain, containing large riverine estuaries, sounds, lagoons, and salt marshes. The most striking feature is the large, enclosed sound known as the Albemarle–Pamlico Estuarine System, covering approximately 7530 km^2. The coast also has numerous tidal creek estuaries ranging from 1 to 10 km in length. This coast has a rapidly growing population and greatly increasing point and non-point sources of pollution. Agriculture is important to the region, swine rearing notably increasing fourfold during the 1990s.

Estuarine phytoplankton communities in North Carolina are well studied; the most important taxonomic groups are diatoms, dinoflagellates, cryptomonads and cyanobacteria. Several major poorly flushed estuaries are eutrophic due to nutrient inputs, and toxic dinoflagellates (*Pfiesteria* spp) can reach high densities in nutrient-enriched areas. Fully marine waters are relatively oligotrophic. Southern species enter in subsurface intrusions, eddies, and occasional Gulf Stream rings, while cool water species enter with the flow of the Labrador Current to the Cape Hatteras region. The Carolinas have a low number of endemic macroalgae, but species diversity can be high in this transitional area, which represents the southernmost extension for some cold-adapted species and the northernmost extension of warm-adapted species. In North Carolina the dominant seagrass, *Zostera marina*, lies at its southernmost extension, while a second species, *Halodule wrightii* is at its northernmost extent. Widgeongrass *Ruppia maritima* is common, growing in brackish water or low-salinity pools in salt marshes. Seagrass meadows are now much reduced, probably due to elevated nitrogen and increased sedimentation.

In sounds, numerically dominant benthic taxa include bivalves, polychaetes and amphipods, many showing gradients in community type from mesohaline areas of the eastern shore to near marine salinities in western parts. The semi-enclosed sounds have extensive shellfisheries, especially of blue crab, northern quahogs, eastern oysters, and shrimp. Problems include contamination of some sediments with toxic substances, especially of metals and PCBs at sufficiently high levels to depress growth of some benthic macroinvertebrates. Numerous fish kills have been caused by toxic *Pfiesteria* outbreaks, and fish kills and habitat loss have been caused by episodic hypoxia and anoxia in rivers and estuaries. Oyster beds currently are in decline because of overharvesting, high siltation and suspended particulate loads, disease, hypoxia, and coastal development. Fisheries monitoring which began in the late 1970s shows greatest recorded landings in 1978–1982; since then, harvests have declined by about a half.

Some management plans have been developed toward improving water quality and fisheries sustainability. Major challenges include; high coliform levels leading to closures of shellfish beds, a problem that has increased with urban development and increasing cover of watershed by impervious surfaces; high by-catch and heavy trawling activity; overfishing which has led to serious declines in many wild fish stocks; and eutrophication. Comprehensive plans limiting nutrient inputs are needed for all coastal rivers and estuaries, not only those that already exhibit problems. There is a critical need to improve management of non-point nutrient runoff through increased use of streamside vegetated buffers, preservation of remaining natural wetlands and construction of artificial wetlands. Improved treatment processes, based on strong incentive programmes, should also be mandated for present and future industrial-scale animal operations.

Physical Setting

This region includes the diverse collection of estuaries along the North and South Carolina coasts, and the continental shelf waters eastward to the Gulf Stream (Fig. 1), located approximately 76°W, 36°30′N in the north, to 80°42′W, 32°17′N in the south. This coastal region is a gently sloping plain, containing riverine estuaries, sounds, lagoons, and salt marshes. Most of it is bordered by barrier islands formed within the past 15 000 years during sea level rise, and these islands play a major role in hydrological and biological estuarine processes. From the barrier islands, the continental shelf

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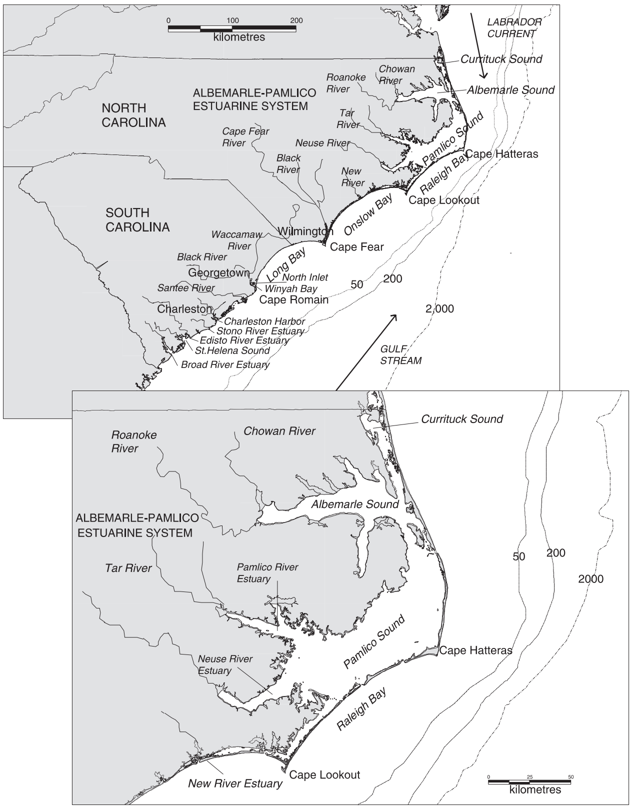

Fig. 1 The North and South Carolina coastal areas, south-eastern United States.

gradually deepens to approximately 50–60 m at the shelf break. The shelf is largely a soft-bottom system consisting of shallow ($\ll$1 m) relict sediments (primarily fine, medium and coarse sands with varying amounts of calcareous sands) overlying a series of sedimentary/calcareous lithofacies, which outcrop to form rock-reef structures with up to 5 m relief. These hard-bottom outcrops, sometimes termed 'live bottoms', support benthic algae and invertebrate communities with a variety of associated fishes (Cahoon *et al.*, 1990a).

From the shelf break seaward there is a rapid deepening, from approximately 50 km seaward of the capes, to about 100 km seaward from bays (Fig. 1). The position of the Gulf Stream roughly marks the shelf break, but this current is highly dynamic. Frictional forcing by the Gulf Stream drives the predominantly counterclockwise circulation in bays, especially Raleigh, Onslow, and Long Bays. Filaments of offshore water sometimes move inshore along the south side of the shoals seaward of Cape Lookout and Cape Fear. Topographic features such as the 'Charleston Bump', a rise in the continental slope off Charleston, and wind forcing drive Gulf Stream meanders up to 30–40 km seaward of the shelf break or onto the shelf itself (Pietrafesa *et al.*, 1985). Intrusions typically reach the mid-shelf, but may reach 10 km from the shore (Atkinson *et al.*, 1980). Meanders are also associated with shelf-edge upwelling, which can advect nutrient-enriched slope water on to the shelf. Upwelled nutrients are a significant portion of total new nutrients entering the shelf ecosystem (Atkinson, 1985). Wind forcing, particularly winds associated with storms, can drive significant flows shoreward (Pietrafesa and Janowitz, 1988).

The most striking feature along this coast is the large, enclosed sound known as the Albemarle–Pamlico Estuarine System (APES) (Fig. 1). Covering an area of approximately 7530 km^2, this is the second largest estuary by surface area in the United States. This system is bounded by the Outer Banks of North Carolina, a series of heavily utilized barrier islands. The Chowan, Roanoke and other rivers feed the northernmost part, the oligohaline Albemarle Sound. The APES is constricted at Roanoke Island and widens to the south into the polyhaline Pamlico Sound which is fed by the Pamlico and the Neuse. South of the APES lies a series of narrow euhaline sounds between the mainland and barrier islands. The most significant estuaries in southern North Carolina are the lagoons that form the New River Estuary, and 65 km to the south of that system lies the Cape Fear Estuary, which drains the largest watershed in North Carolina. This is not constrained by barrier islands. Throughout the North Carolina coastline are numerous tidal estuaries ranging from 1 to 10 km in length.

Rivers originating in the piedmont feed most of the large estuaries in North Carolina. Exceptions are the New River, and the Black and Northeast Cape Fear Rivers, which are blackwater coastal plain rivers. Piedmont soils are largely clays that are reactive and bind with potential pollutants; thus, erosion and sedimentation in the piedmont can affect coastal water quality. Coastal Plain soils are generally less reactive and sandier, but the waters draining swamps here are darkly stained by dissolved organic matter.

In northern South Carolina, the largest estuary is Winyah Bay, fed by the blackwater Waccamaw and Black Rivers and the piedmont-derived PeeDee River. Adjoining it is North Inlet, a salt marsh estuary consisting of a maze of high salinity tidal creeks. To the south lie the North and South Santee River Estuaries, which have drainages arising in the piedmont. The principal urbanized estuarine system in South Carolina is the Charleston Harbor area, fed by the coastal plain-derived Ashley and Wando Rivers, and the piedmont-derived Cooper River. Just to the south lie the lowland Stono River Estuary, and the Edisto River Estuary which receives some drainage from the piedmont. Further south still lie St Helena Sound and the Broad River Estuary, which contain numerous tidal creeks, islands, and salt marshes. In contrast to North Carolina, most of the large estuaries in South Carolina are open to the ocean.

Sources of pollutants

These coasts have rapidly growing populations. The eight North Carolina counties bordering the Atlantic Ocean (Currituck, Dare, Hyde, Carteret, Onslow, Pender, New Hanover, and Brunswick) experienced a population increase of 32% in the period 1977–1997, from 345 200 to 504 700 (US Census Bureau records). Certain coastal counties in South Carolina, especially Horry, Beaufort, and Berkeley Counties, are also growing rapidly (Bailey, 1996). Human and domestic animal wastes are sources of enteric microbes affecting shellfish beds and swimming beaches, while residential land development, commercial landscaping and golf courses are all sources of fertilizers, pesticides, herbicides, sedimentation and turbidity. Thus, urbanization and population growth lead to greatly increased non-point source pollution of coastal waters. Tourism also stresses natural resources and can add to pollutant loads (Bailey, 1996). North Carolina's Outer Banks, barrier island communities along the central and southern coasts of the state, and the Myrtle Beach Grand Strand and the Hilton Head area in South Carolina all experience extensive tourism, especially during warmer seasons (April–October).

In well-populated and/or industrialized areas, point source discharges may be substantial. For example, in the Cape Fear basin alone there are 641 licensed point source discharges (NC DWQ, 1996). Major industrial point sources include the world's largest phosphate mine (Pamlico Estuary), pulp and paper mills (Roanoke, Chowan, Neuse, Cape Fear, and Winyah Bay), a steel mill (Winyah Bay), a metal plating industry (Neuse), and textile manufacturers (Roanoke, Chowan, Pamlico, Neuse, Cape Fear).

Agriculture is important to the region. The 28 counties surrounding the APES include 45% of North Carolina's cropland (Copeland and Grey, 1989). About 24% of the Cape Fear watershed is devoted to cropland or pastureland (NC DWQ, 1996). Agriculture is also a major source of fertilizers, pesticides, sedimentation and faecal bacteria to these coastal waters.

During the 1980s and early 1990s, tobacco farming began to decline, along with an explosive growth in the swine population, from approximately 2.7 million in 1990 to over 10 million head in 1997 (Burkholder *et al.*, 1997; Cahoon *et al.*, 1999a). These hogs are intensively reared. Their wastes are hosed into 'lagoons', to be sprayed onto the surrounding fields, but this system has demonstrated a number of flaws. Accidents have released concentrated wastes into coastal streams and estuaries (Burkholder *et al.*, 1997; Mallin *et al.*, 1997a), while leakage, spray field runoff, and deposition of atmospheric ammonium have all released appreciable quantities of nutrients into coastal waters (Burkholder *et al.*, 1997). In 1998, for example, the North Carolina Division of Air Quality (Raleigh, NC) reported that during the 1990s there had been a 30% increase in ammonia in the airshed of the eastern third of that state, nearly half of which had been contributed by sprayed swine wastes. Vast amounts of nutrients are shipped into eastern North Carolina in feeds (Cahoon *et al.*, 1999a). In 1995 alone, about 90 700 t of nitrogen and 29 930 t of phosphorus were required in the Cape Fear basin (Glasgow and Burkholder, 2000). Over 80% of these nutrients remain in the basin and the watersheds are increasingly acting as nutrient 'sinks', some of which enter coastal waters. Further, an average pig produces the equivalent quantity of waste as three to four people, and swine waste is much richer in BOD materials (Dewi *et al.*, 1994). The availability of excessive animal manure has not driven major changes in use of commercial fertilizers, so that the rise in livestock production has created a concomitant rise in total nutrient loadings within these basins (Cahoon *et al.*, 1999a).

Flora and Fauna of North and South Carolina Coastal Waters

Estuarine phytoplankton

Much is known about estuarine phytoplankton communities in North Carolina (Mallin, 1994), although little has been published for South Carolina. All of the systems studied are characterized by phytoplankton productivity increases that coincide with increasing water temperatures in late spring and summer, and subsequent decreases in productivity as the water cools. Certain North Carolina riverine estuaries, especially the Pamlico and Neuse, often experience additional large productivity pulses and dense algal blooms in late winter–early spring. These blooms consist primarily of the dinoflagellates *Heterocapsa triquetra*, *Prorocentrum minimum*, *Amphidinium* and *Gymnodinium* spp. They occur when elevated winter flows bring large concentrations of nutrients to the lower portions of estuaries. In the Neuse Estuary, for example, phytoplankton productivity has been significantly correlated with river flow which after a lag period, is correlated with rain events in the piedmont (Mallin *et al.*, 1993). In general, riverine estuaries where flushing is constrained by barrier islands support the highest phytoplankton production. Well-flushed sounds or unconstrained rivers (such as the Cape Fear system) maintain much lower phytoplankton biomass and productivity; complex tidal creek/salt marsh systems (i.e., North Inlet) exhibit moderate phytoplankton productivity (Tables 1 and 2) (Mallin, 1994; Bricker *et al.*, 1999).

The most important taxonomic groups as reflected by cell counts are diatoms, dinoflagellates, cryptomonads, and cyanophytes (Mallin, 1994; Fensin, 1997). In euhaline sounds and higher salinity regions, diatoms seasonally dominate, especially the centric diatoms *Thalassiosira* spp, *Skeletonema costatum*, *Cyclotella* spp, and the pennate – diatoms *Nitzschia closterium* and *Navicula* spp. Winter-blooming dinoflagellates such as *H. triquetra*, and other species such as *Ceratium* spp and *Katodinium rotundatum* are often abundant, and dinoflagellates were reported to have been dominant, overall, in the Pamlico Estuary (Copeland *et al.*, 1984). Toxic *Pfiesteria piscicida* and, more recently, P. shumwayae

TABLE 1
Phytoplankton productivity in North and South Carolina estuaries.[a]

Estuarine system	Volumetric (g C m^{-3})	Areal (g C m^{-2})
Beaufort Channel, NC (Williams and Murdoch, 1966)	17	68
Beaufort estuaries, NC (Thayer, 1971)	56	67
Calico Creek, NC (Sanders and Kuenzler, 1979)	315	145
Neuse Estuary, NC (Mallin *et al.*, 1991)	75	280
Neuse Estuary, NC (Paerl *et al.*, 1995)	108	370
Newport River, NC (Williams and Murdoch, 1966)	74	74
Pamlico River Estuary, NC (Kuenzler *et al.*, 1979)	150	500
North Inlet, SC (Sellner *et al.*, 1976)	–[b]	259

[a] Modified from Mallin (1994).
[b] Data not available.

TABLE 2
Phytoplankton abundance and chlorophyll *a* concentrations for North and South Carolina estuaries.[a]

Estuarine system	Cells (no. ml^{-1})		Chlorophyll *a* (μg l^{-1})	
	Mean	Range	Mean	Range
Beaufort Channel, NC				
Williams and Murdoch (1966)	2000	130–5400	4	2–9
Beaufort estuaries, NC				
Thayer (1971)	1700	360–8200	4	2–9
Calico Creek, NC				
Sanders and Kuenzler (1979)	–[b]	1000–1 000 000	–[b]	6–140
Pamlico Estuary, NC				
Hobbie (1971)	–[b]	1000–340 000	11	1–48
Copeland *et al.* (1984)	–[b]	–[b]	–[b]	5–100
Stanley (1992)	4200	630–20 600	17	1–184
Neuse Estuary, NC				
Mallin *et al.* (1991)	1600	210–4200	12	2–23
Mallin and Paerl (1994)	1700	560–4400	14	2–65
Burkholder *et al.* (1996)				
Fensin (1997)	36 500[c]	27 100–46 200[c]	19	6–54
Pinckney *et al.* (1997)	–[b]	–[b]	14	[b]–90
Glasgow and Burkholder (2000)	–[b]	–[b]	23	2–220
New River Estuary, NC				
Mallin *et al.* (1997b) polyhaline	2900	800–10 000	14	3–35
Mallin (this paper) systemwide	–[b]	–[b]	20	1–379
Cape Fear Estuary, NC				
Carpenter (1971)	1700	250–7300	–[b]	–[b]
Mallin *et al.* (1999a)	–[b]	–[b]	7	1–33
Tidal Creeks, NC				
Mallin *et al.* (1999b) summer	7900	1440–26 440	14	1–114
North Inlet, SC				
Sellner *et al.* (1976)	1600	540–3400	–[b]	–[b]

[a] Updated and expanded from Mallin (1994).
[b] Data not available.
[c] These high counts reflect the inclusion of picoplanktonic blue-green algae (cyanobacteria) which were not quantified in previous studies. See text for further explanation.

sponovo, reach highest densities in nutrient-enriched areas during some fish kill/epizootic events – up to 13 000 zoospores ml^{-1}, with gametes and zoospores at densities up to 250 000 cells ml^{-1} in surface water and foam during fish kills (Burkholder *et al.*, 1995; Burkholder and Glasgow, 1997; Glasgow *et al.*, 1995; Glasgow, 2000). Cryptomonads are well represented in North Carolina estuaries, especially *Cryptomonas testaceae*, *Chroomonas minuta*, *C. amphioxiae* and *Hemiselmis virescens*. Other taxa that are sometimes abundant in these systems include the euglenoid *Eutreptia* sp, the chrysophyte *Calicomonas ovalis*, the chlorophytes *Chlamydomonas* spp, and the prasinophytes *Pyramimonas* spp.

Cyanophytes historically were considered rare in these estuaries, except for occasional summer appearances of filamentous *Phormidium* spp and colonial *Microcystis marina*. However, picoplanktonic, cryptic forms (mostly as *Gloeothece* spp, *Lyngbya limnetica*, *Merismopedia punctata* and *Aphanothece microscopica*) in the mesohaline, eutrophic Neuse Estuary are now known to seasonally dominate the estuarine phytoplankton (Fensin, 1997). Cyanophytes were dominant among phytoplankton in cell number throughout the period from June 1994 to October 1995, representing 50–65% of the total phytoplankton cells. On the basis of biovolume, during that period picoplanktonic cyanophytes were dominant except during spring; they comprised *ca* 85% of the total phytoplankton biovolume in summer season, and their average contribution to total biovolume seasonally was *ca* 61%. During winter their biovolume positively correlated with water-column ammonium concentrations. Their maximal cell numbers ($2.3–3.0 \times 10^5$ cells ml^{-1}, depending on the station sampled) were attained during spring, and were positively correlated with soluble reactive phosphate concentrations. Other studies also have now documented cyanophytes as being abundant (Pinckney *et al*., 1997), and it is likely that this group was previously overlooked because of their size and cryptic appearance (Burkholder and Cuker, 1991).

Phytoplankton typically reach maximum values during summer, although late winter or spring blooms can occur. Several North Carolina estuaries can be considered moderately to highly eutrophic (Tables 1 and 2); these include the Neuse, Pamlico, and New River Estuaries (Mallin, 1994; NOAA, 1996; Bricker *et al*., 1999; Glasgow and Burkholder, 2000). Upper reaches of the smaller urban tidal creek estuaries can host dense algal blooms as well, especially during summer (Table 2). The eutrophic portions of these systems can be characterized by elevated nutrient loading and poor flushing. Well-flushed systems like euhaline sounds, and open rivers like the Cape Fear rarely host algal blooms. In the near-pristine tidal creeks of North Inlet, SC, anthropogenic nitrate loading is very limited, and summer phytoplankton abundance is limited by microzooplankton grazing, rather than nitrogen loading, while diatom growth in winter is stimulated by ammonium inputs (Lewitus *et al*., 1998).

Estuaries contain various microalgal taxa that have caused fin- or shellfish kills or impaired fish health in other regions, such as the dinoflagellates *Gymnodinium sanguineum*, *Gyrodinium galatheanum*, and *P. minimum*; the chrysophyte *Phaeocystis*; the diatom *Pseudo-nitzschia australis*; and the raphidophytes *Heterosigma akashiwo* and *Chattonella antiqua* (Burkholder *et al*., 1997; Hallegraeff, 1993; Burkholder, 1998). The two known species of ichthyotoxic *Pfiesteria* also occur in Carolina estuaries (Burkholder *et al*., 1997; Glasgow, 2000). Aside from the latter two *Pfiesteria* species, noxious algal blooms have not been reported in Carolina waters with exception of a bloom of the chrysophyte, *Phaeocystis globosa,* following a major swine effluent lagoon rupture (Burkholder *et al*., 1997). Elsewhere, *Phaeocystis* blooms also have been related to major inputs of raw sewage wastes into lower rivers and estuaries (Hallegraeff, 1993).

Only a little information is available on phytoplankton of North Carolina's expansive enclosed sounds (e.g., Copeland *et al*., 1983). Dinoflagellates were reported as dominant in the low-salinity Albemarle Sound (chlorophyll *a* range of 3–40 μg l^{-1}; Copeland *et al*., 1983). Salinity in Pamlico Sound is typically at 25–30 ppt salinity or higher (Epperly and Ross, 1986). Seasonal sampling over the past two years (Burkholder *et al*., unpub.) indicates that the phytoplankton of Pamlico Sound are dominated by estuarine and marine taxa (Marshall, 1976), predominantly diatoms.

Marine phytoplankton

The marine waters are relatively oligotrophic, with low phytoplankton abundance except in a narrow inshore zone. Chlorophyll *a* concentrations are typically *ca* 1 μg l^{-1} inshore, declining to 0.1–0.01 μg l^{-1} in the Gulf Stream (Cahoon and Cooke, 1992). The nearshore assemblage is dominated by small centric diatoms and flagellates, along with occasional blooms of larger centric diatoms (Marshall, 1969, 1971, 1976, 1978). These surveys have not yet been repeated to identify trends over the past 20–30 years. Available information indicates that warmer-water neritic associations often contain abundant diatom genera such as *Rhizosolenia, Hemiaulus*, and *Coscinodiscus*, together with *Skeletonema costatum* and *Thalassiosira* spp (e.g., Marshall, 1978). Moving seaward, dinoflagellates and coccolithophorids tend to dominate. Winter assemblages also typically include various colder-water forms including diatoms such as *Amphiprora hyperborea*, *Biddulphia aurita*, *Chaetoceros* spp; dinoflagellates such as *Ceratium* spp, *Dinophysis* spp, and certain gonyaulacoids, mixed with coccolithophorids such as *Cyclococcolithus leptoporus* and *Emeliana huxleyi*.

These trends are believed to rise, in part, because nearshore currents carry 'seed' populations of various taxa into Carolina coastal areas. Gulf Stream phytoplankton enter Gulf Stream rings or eddies, and through this mechanism, tropical species may occur throughout an annual cycle in this area. Moreover, cool water species tend to move southward in a temporal pattern that follows the flow of the cold, offshore Labrador Current to the Cape Hatteras region. A major portion of the shelf water that flows south-west of New England originates in the Gulf of Maine and Georges Bank area, thus favouring transport of phytoplankton into neritic areas southward. In late spring as winter winds lessen and warmer water temperatures develop, successional patterns and seasonal assemblages re-establish along a gradient from Cape Hatteras northward. Cape Hatteras is thus a natural coastal feature associated with a geographic division of many phytoplankton (Marshall, 1978). Intrusions of nutrient-enriched slope water also occur, which can stimulate blooms and sometimes create a near-bottom chlorophyll *a* maximum.

High-clarity and low-nutrient concentrations of coastal waters along the Carolinas prevail under normal conditions, and incidences of harmful marine algal blooms have been rare. An exception was an incursion of the toxic dinoflagellate, *G. breve* (formerly called *Ptychodiscus brevis*), in the fall of 1987 which persisted through winter 1988, following transport of bloom-containing eddies from the Gulf Stream into shore (Tester *et al.*, 1991). This event is believed to have occurred because extremely unusual and persistent weather conditions (warm, dry, calm with very little wind) allowed the eddies to maintain integrity and the dinoflagellate populations to grow. The *G. breve* outbreak caused major losses to the commercial shellfish industry (NC DMF records, Morehead City, NC), and was strongly correlated with a catastrophic decline in bay scallop (*Argopecten irradians concentricus*) recruitment in succeeding years (Summerson and Peterson, 1990).

Macroalgae

In biogeographical terms, North Carolina's macroalgal communities lie along the border of the cold temperate North Atlantic and warm temperate Carolina regions of species distributions, delineated at Cape Hatteras; South Carolina's macroalgae occur entirely within the latter region (Lüning, 1990). At the general confluence of these two regions, the North Carolina coast is a transition zone for macroalgal communities (Schneider and Searles, 1991). The Carolinas have a low number of endemic macroalgae relative to the well-developed cool temperate flora to the north, and the rich tropical flora to the south. Species diversity can nonetheless be high in this transitional area, which represents the southernmost extension for certain cold-adapted species and the northernmost extension of some warm-adapted species. The latter influence appears to be more important in contributing to species diversity. At Cape Hatteras the Gulf Stream turns eastward, allowing many deep-water, warm-adapted macroalgal species to thrive (e.g., *Caulerpa* spp, *Dictyota dichotoma*, *Botryocladia occidentalis*, and many others of the *ca* 800 macroalgal species of the western Atlantic tropical region (Lüning, 1990). Thus, macroalgal diversity increases from *ca* 100 species along coastal Maryland and Virginia to *ca* 300 on the North Carolina coast, because of this northern extension of the sublittoral Caribbean algal flora. The benthic macroalgal flora of the continental shelf of the Carolinas may represent the only truly subtropical biogeographic region in Atlantic North America (Kapraun, 1980).

The littoral macroalgal flora has pronounced seasonality, especially in North Carolina. In warmer seasons, tropical species of Caribbean affinity predominate, while in colder seasons species of cool temperate (New England) affinity are dominant. A third, less conspicuous assemblage is comprised of warm temperate species along with certain cosmopolitan species that have become adapted to warm temperate conditions. These species generally attain highest abundance in spring and fall (Kapraun, 1980).

Macroalgal colonization in the Carolinas is limited by a paucity of solid substrata; indeed, most intertidal collections are made along artificial rock jetties. Water temperatures in the salt marshes can exceed 35°C, and a limited number of cyanophyte mat formers and rapidly growing forms such as *Enteromorpha* spp and *Ectocarpus* spp tend to predominate; these species, along with *Cladophora* spp, can show undesirable growth in rapid response to nutrient enrichment (Burkholder *et al.*, 1992a). Brackish *Chara* species can sometimes become abundant in salt marshes as well; and the vascular salt marsh macrophytes can be heavily colonized by small macroalgal taxa such as *Porphyra*, *Polysiphonia*, *Bryopsis*, and *Ulva* species.

The rich subtidal macroalgal communities occur mainly on rocky outcrops, stones, and organic concretions such as those 10–20 km off Cape Hatteras. These habitats have relatively clear water at 15–60 m depths – temperature range *ca* 10–24°C (Lüning, 1990), with most species restricted to depths of less than 40 m (Schneider, 1976). Macroalgae are important members of these 'live bottom' communities (Cahoon *et al.*, 1990a; Thomas and Cahoon, 1993; Mallin *et al.*, 1992).

Benthic microalgae

Benthic microalgae are important primary producers in estuarine ecosystems, where these flora are exposed to high nutrient availability and light fluxes in shallow waters (Mallin *et al.*, 1992; Cahoon *et al.*, 1999b). This is certainly true in Carolina estuaries (e.g., Zingmark, 1986; Freeman, 1989; Pinckney and Zingmark, 1993; Coleman and Burkholder, 1995; Nearhoof, 1994; Cahoon *et al.*, 1999b). Benthic microalgal biomass frequently exceeds phytoplankton biomass in estuarine water columns by factors of 10–100 (Cahoon and Cooke, 1992), and is often inversely related to integrated phytoplankton biomass (Fig. 2).

Seagrass epiphytes can contribute a significant proportion of total community production. Epiphytes on the historically dominant seagrass, *Zostera marina*, exhibit a bimodal curve in productivity with maxima during spring and fall (Penhale, 1977). Generally, however, little is known of the species composition and species-specific productivity of seagrass epiphyte communities. Their composition has been characterized in mesocosm (Burkholder *et al.*, 1992a; Coleman and Burkholder, 1994) and field studies (Coleman and Burkholder, 1995). Depending on the nutrient regime, epiphyte communities in spring were found to consist primarily of diatoms and cyanophytes, shifting to abundant cyanophytes, dinoflagellates, and cryptomo-

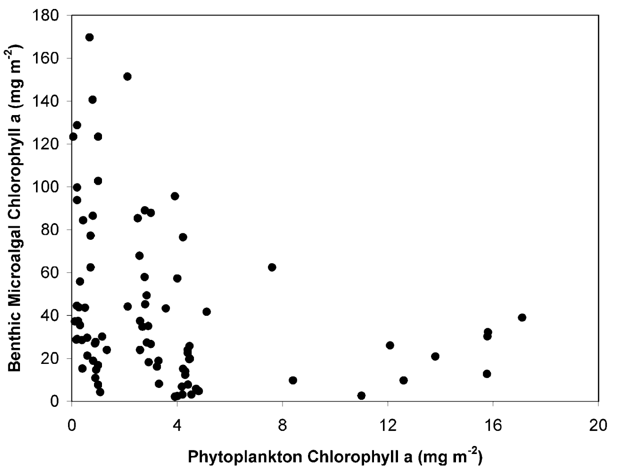

Fig. 2 Relationship between benthic microalgal chlorophyll *a* and chlorophyll *a* content of the overlying water column in North Carolina coastal waters.

nads in warmer months. During autumn the epiphytes of field communities were dominated by the crustose adnate red alga *Sahlingia subintegra,* with dinoflagellates (especially mixotrophic or heterotrophic *Amphidinium* sp, *Polykrikos* sp, and *Cochlodinium* sp) co-dominant in biovolume contribution (Coleman and Burkholder, 1995). Nitrate enrichment stimulated production of the adnate diatom *Cocconeis placentula*, several other diatoms, and cyanophytes.

The clear waters of the continental shelf also support significant benthic microalgal production (Cahoon and Cooke, 1992) dominated by diatoms (Cahoon and Laws, 1993). As in estuarine waters, benthic microalgal biomass can exceed integrated phytoplankton biomass (Cahoon *et al.*, 1990b); but benthic microalgal production in deeper shelf waters is more light-limited, and is approximately equal to phytoplankton production (Cahoon and Cooke, 1992). Benthic microalgae support production of fishes that forage over soft-bottom habitats (Thomas and Cahoon, 1993).

Seagrasses and other rooted submersed aquatic vegetation (SAV)

Along the North Carolina coast the dominant seagrass, eelgrass (*Z. marina*), lies at the southernmost extension of its geographic range on the US Atlantic seaboard, where its growth is stressed in summer from the high water temperatures (den Hartog, 1970; Thayer *et al.*, 1984a), Maximum shoot length of eelgrass in this region averages only about 40 cm. Temperatures above 30°C are detrimental to eelgrass from northern regions (Zimmerman *et al.*, 1989). However, shallow water temperatures along the North Carolina coast typically reach 31–33°C (Burkholder *et al.*, 1992a, 1994), and the populations inhabiting these waters are believed to be a separate ecotype from more northern populations (Touchette, 1999). Primary productivity of eelgrass in this region is regarded as comparatively low: aboveground, 0.59–1.23 g C m^{-2} d^{-1}; below-ground, 0.15–0.28 g C m^{-2} d^{-1} (Penhale, 1977; Thayer *et al.*, 1984b). Eelgrass in North Carolina has one growing season in winter-spring, and another in autumn when production of new shoots is higher (Burkholder *et al.*, 1992a, 1994). The warm summer season is a time of reduced growth or dehiscence, in which *Z. marina* uses carbon stored in its rhizomes for sustenance. Metabolism is reduced and most leaves are sloughed (Burke *et al.*, 1996; Touchette, 1999). Shoot production is especially pronounced during the fall, whereas leaf production and carbon reserves are more important in spring, apparently in preparation for the warm summer season (Burkholder *et al.*, 1992a, 1994; Touchette and Burkholder, 2000).

North Carolina is the northernmost extension for a second seagrass species, shoalgrass (*Halodule wrightii*) (Thayer *et al.*, 1984a). The two species co-occur to some extent, but tend to be temporally separated with *Z. marina* attaining maximal production in winter to early summer, and *H. wrightii* in late summer–early fall (Kenworthy, 1981; Burkholder *et al.*, 1994). The latter species extends into the upper intertidal zone. In North Carolina it generally is found in euhaline regimes, although it is strongly influenced by the high turbidity and freshwater flow (Steel, 1991). *Zostera marina* tends to be dominant or co-dominant in euhaline environments (Thayer *et al.*, 1984a).

A third estuarine/marine SAV species that is sometimes called a seagrass is the euryhaline angiosperm, widgeon-grass (*Ruppia maritima*). This species responds most favourably to nutrient pollution (especially nitrate; Burkholder *et al.*, 1994). It is widespread, and grows in brackish water or low-salinity pools in salt marshes (Thayer *et al.*, 1984a). Shoalgrass and widgeon-grass are sometimes exposed to air during low tide, whereas eelgrass is only rarely exposed (Thayer *et al.*, 1984a, Touchette, 1999).

At present, the remaining seagrass meadows in North Carolina occur mostly in sandy or muddy sediments on the landward side of the Outer Banks, with sparse cover along most of the mainland (Ferguson *et al.*, 1988). Yet, elderly fishermen and fishermen's journal accounts from the late 1800s describe extensive beds of such vegetation in many embayments along the mainland where it is now absent (Burkholder, pers. comm.). Several large eelgrass beds have disappeared within the past decade in the Intracoastal Waterway (Morehead City area, following extensive use of herbicides to control macroalgal growth) and near Harkers Island along the mainland (following construction activity; Burkholder, unpub. data). Early data to resolve historical trends in seagrass distributions are sparse; the only complete maps in existence for this coast were compiled during the late 1980s (Ferguson *et al.*, 1988).

Light availability has been considered a primary factor limiting seagrass distribution (Stevenson, 1988), effected partly through turbidity. Nutrient enrichment can stimulate epiphytic algal growth, but more recently nitrate enrichment has been related to declines in eelgrass as a direct physiological response (Burkholder *et al.*, 1992a). The ability of *Z. marina* to take up nitrate through its leaves during periods of light or darkness (Touchette and Burkholder, 2000), and the apparent inability of plants grown in sandy nearshore sediments to 'shut off' water-column nitrate uptake leads to severe internal imbalances in carbon metabolism (Touchette and Burkholder, 2000). Although *Z. marina* shows this response in both its spring and fall growing seasons, water-column nitrate inhibition appears more pronounced during warm spring seasons, when the plants would otherwise allocate more of their carbon to storage in below-ground tissues (Burkholder *et al.*, 1992a,b). Elevated N can also render the plants more susceptible to pathogens such as the marine slime mould, *Labrynthula zosterae* (Muehlstein, 1992; Short and Wyllie-Echeverria, 1996).

Accelerating coastal development in North Carolina has been associated with increased nutrient (nitrate) loading from, among other sources, septic effluent leachate (Stanley, 1992). It is likely that eelgrass meadows along the mainland have disappeared because of reduced light availability in combination with increased water-column nitrate enrichment. The presence of the barrier islands further from mainland influences provides sheltered habitat for seagrass growth (Steel, 1991). Eelgrass appears to be a more 'oligotrophic' indicator, since it is the most sensitive of the three seagrass species to light reduction as well as water-column nitrate enrichment, while shoalgrass is sensitive to higher nitrate loading, and widgeon-grass is stimulated by high nitrate (Touchette and Burkholder, 2000). The state's remaining seagrass beds are classified by the North Carolina Marine Fisheries Commission as critical habitat for many finfish and shellfish species, with *Z. marina* considered the most valuable (Thayer *et al.*, 1984a).

Abundant meadows of freshwater/brackish SAV such as tapegrass or freshwater eelgrass (*Vallisneria americana*) historically were a prominent feature of the Pamlico Estuary (Copeland *et al.*, 1984) and, to a lesser extent, the Neuse, with pondweeds (*Potamogeton* spp) and widgeon-grass as subdominants (Steel, 1991). This submersed vegetation significantly declined from the mid-1980s under excessive sediment loading, then experienced a resurgence as modest improvements in erosion control promoted an increase in water clarity (Steel, 1991; NC DEHNR, 1994). This information is derived mostly from many recent complaints about abundant SAV around dock areas (Neuse) and from visual observations and fishermen's anecdotal accounts (Pamlico).

Estuarine zooplankton

The most common and abundant estuarine zooplankter in the region is the calanoid copepod *Acartia tonsa*, followed by the calanoid *Paracalanus crassirostris* and the cyclopoid copepod *Oithona colcarva* (Thayer *et al.*, 1974; Lonsdale and Coull, 1977; Fulton, 1984; Mallin, 1991; Mallin and Paerl, 1994; Houser and Allen, 1996). Harpacticoid copepods can be abundant at times (i.e., *Microsetella norvegica*, *Euterpina acutifrons*, and others), and cladocerans (i.e., *Evadne nordmandii*, *Podon polyphemoides*, and *Penilla* spp) are either rare or appear in periodic blooms. Species richness of copepods is low in mesohaline systems such as the Pamlico and Neuse estuaries. However, euhaline systems such as the Beaufort, NC area and North Inlet, SC also yield calanoids such as *Centropages* spp, *Labidocera aestiva* and *Psuedodiaptomus coronatus*, and cyclopoids such as *Corycaeus* spp, *Oncaea venusta* and *Saphirella* sp (Thayer *et al.*, 1974; Lonsdale and Coull, 1977; Fulton, 1984).

In North Carolina, copepods display highest densities in late spring–early summer in euhaline areas and in mid-to-late summer in mesohaline estuaries, while abundances are generally lowest in late winter. There is a positive correlation between zooplankton abundance and water temperature in North Carolina estuaries (Fulton, 1984; Mallin, 1991; Mallin and Paerl, 1994). Seasonal differences were less pronounced in North Inlet compared with the more northerly estuaries. Mesh size of nets is important (Table 3). Diel periodicity is evident; post-naupliar stages of several copepods, particularly *Acartia tonsa*, are more abundant in the water column at night than during the day (Fulton, 1984, Mallin and Paerl, 1994). However, copepod nauplii display no such periodicity. Houser and Allen (1996) also have found a tidal signal in North Inlet in which copepods were most abundant at high tide and least abundant during daytime low tides.

Other organisms can occasionally be abundant. Using small mesh nets, Mallin and Paerl (1994) demonstrated periodic high densities of tintinnid protozoans and the large mixotrophic dinoflagellate *Polykrikos hartmanni* (Table 3). Meroplanktonic organisms, especially barnacle nauplii and polychaete larvae, may be abundant at times (Lonsdale and Coull, 1977; Mallin, 1991; Mallin and Paerl, 1994; Houser and Allen, 1996).

Zooplankton play a key role in transfer of energy through the food chain in these estuaries. Mallin and Paerl (1994) demonstrated that on an annual basis estuarine zooplankton grazed 38–45% of the daily phytoplankton production in the Neuse Estuary, ranging from 2% in winter to $\gg$ 100% in summer. Zooplankton grazing rates were positively correlated with phytoplankton productivity and abundance of centric diatoms and dinoflagellates. Zooplankton, especially copepods, are preyed upon extensively by larval and juvenile fish in these waters and their abundance patterns likely are controlled, in part, by such predation (Thayer *et al.*, 1974; Kjelson *et al.*, 1975; Fulton, 1985). In the mesohaline Neuse Estuary, zooplankton abundance and planktonic trophic transfer are greatest in late spring through summer, when fish larvae migrating from the open ocean reach these estuarine nursery areas (Mallin and Paerl, 1994). Most larval fish arrive when plank-

TABLE 3

Comparison of mean zooplankton abundance and biomass for estuaries in North and South Carolina.[a]

Estuary	Net mesh (μm)	Density (number m^{-3})	Biomass (mg dry wt m^{-3})
Beaufort area, NC			
Thayer *et al.* (1974)	156	4000 (1970)	14.0
		8400 (1971)	21.0
Fulton (1984)[b]	76	21 900 (30 mo.)	47.8
Neuse, NC			
Mallin (1991)	76	34 530 (20 mo.)	15.3
		31 224 (1989)	17.2
Mallin and Paerl (1994)	60	137 150 (22 mo.)	38.7
North Inlet, SC			
Lonsdale and Coull (1977)	156	9257 (20 mo.)	16.1
Houser and Allen (1996)	153	21 555 (6 mo. summer)	–[c]

[a] Updated from Mallin (1991).
[b] Post-naupliar copepod data only.
[c] Data not available.

tonic trophic coupling is strongest and depart in fall, when planktonic trophic transfer, zooplankton abundance, and phytoplankton productivity all decrease. Thus, in spring and summer there appears to be high trophic efficiency and tight planktonic food chain coupling in these waters.

Marine zooplankton

The composition of the zooplankton community in coastal ocean waters is heavily influenced by the mixing of inshore waters with Gulf Stream waters. The inshore zooplankton community is dominated by small copepods, chaetognaths, ctenophores, and larval fishes with estuarine affinities. Offshore zooplankton assemblages include many species of both large and small copepods, gelatinous forms of several taxa, and larval fishes advected by the Gulf Stream with more tropical affinities (Bowman, 1971; Fahay, 1975; Paffenhofer, 1980). Some of the more abundant taxa found include the cyclopoid copepods *Oncaea* spp, *Oithona* spp, and *Corycaeus* spp; the calanoid copepods *Paracalanus* spp and *Eucalanus pileatus*; and the ostracod *Conchoecia* spp.

Demersal forms in North Carolina shelf waters (Cahoon and Tronzo, 1990, 1992) are relatively distinct from the holozooplankton, and are dominated by harpacticoid and cyclopoid copepods, nematodes, amphipods, cumaceans, and others. These organisms are closely associated with benthic substrata, and conventional sampling methods generally have not sampled them adequately, forcing use of other sampling techniques such as re-entry and emergence trapping (Cahoon and Tronzo, 1992). The abundance of demersal zooplankton (as numbers of animals m^{-2}) sometimes approximates the abundance of holozooplankton in the overlying water column (Cahoon and Tronzo, 1992), suggesting that a significant fraction of total zooplankton biomass in these coastal waters is under-sampled and poorly understood.

Coastal benthic invertebrate communities

Many estuarine communities along the North Carolina and South Carolina coasts are separated from adjacent coastal oceans by extensive barrier islands with narrow inlets. These estuaries can be divided into three broad categories: (1) the extensive Pamlico–Albemarle–Currituck Sound system, (2) the smaller, barrier island systems to the south, and (3) the estuarine reaches of the several rivers that empty directly into the coastal ocean.

The key physical characteristics of the APES that structure the benthic communities are inputs from several river systems, a broad, shallow sound, and relatively few, narrow inlet connections to the adjacent coastal ocean that effect a long residency time for waters in the sound. The western portion of Pamlico Sound and much of Albemarle and Currituck Sounds are oligohaline to mesohaline. The northernmost Currituck sound was linked by an inlet to the ocean until 1830, when it closed and the sound began to transform to a fresher system. The APES region, in general, is characterized by low benthic diversity and high seasonality in abundances, especially in the lower reaches of the rivers emptying into the sound (Tenore, 1972; Chester *et al.*, 1983). Numerically dominant taxa include the bivalves *Macoma balthica* and *M. mitchelli*, the polychaetes *Capitella* spp, *Mediomastus californiensis*, *M. ambiseta*, *Heteromastus filiformis*, *Streblospio benedicti*, *Maranzellaria*, and *Nereis* spp, and the amphipods *Ampelisca* and *Corophium*. Such opportunistic taxa are typical of many estuarine systems along the mid-Atlantic coast of North America. Abundances can be high during late winter and early spring, reaching densities of over 3500 per 100 cm^2 in some locations (Posey and Alphin, unpub. data). However, many individuals are relatively small in size, emphasizing the importance of recent recruitment events and annual adult mortality. Abundances decline during mid-to-late summer, especially in deeper areas. This decline has been related to a variety of factors, including influx of predatory fish and decapods and summer bottom-water hypoxia (Tenore, 1972; Epperly and Ross, 1986; Pietrafesa *et al.*, 1986; Lenihan and Peterson, 1998). The Pamlico and Neuse Estuaries support a trawling fishery for blue crabs as well as an extensive and growing blue crab pot fishery. Crab pot fishing and trawling for shrimp occurs throughout much of the eastern Pamlico Sound.

The central Pamlico Sound system provides a gradient in community types from mesohaline areas of the western shore to near marine salinities in some parts of the eastern shore. Abundances are seasonal throughout, but seasonal variations in freshwater input have a greater effect along the west. Water in the Pamlico has a long residency time, which makes it behave as a semi-enclosed system, with larval retention and limited adult loss to the adjacent ocean. There is high internal productivity, but a greater residency of nutrients and pollutants. Albemarle and Currituck Sounds both drain into Pamlico Sound, and are dominated by oligohaline to mesohaline benthic communities with abundance patterns characteristic of low or pulsed planktonic recruitment.

The APES supports extensive shellfisheries. The blue crab fishery is the largest in terms of overall landings, and these sounds contribute almost 80% of North Carolina's catch for this species (Table 4) (McKenna *et al.*, 1998). Shrimp, scallop, clam and oyster fisheries are also important, but most of these fisheries are either in decline or showing signs of stress (McKenna *et al.*, 1998). Reasons include overfishing, eutrophication, sediment loading and other pollution, as well as disturbance to bottom habitats. Major environmental stresses facing the bottom communities of Pamlico and Albemarle Sounds are related to the long flushing time (Epperley and Ross, 1986). Increased inputs of sediment and nutrients from agriculture and development have led to decreased water quality, greater turbidity, and increased sedimentation. This pollution has been linked to declines of SAV and to changes in the benthic composition. About 22% of the Pamlico Sound can currently be classified as significantly impacted (Hackney *et al.*, 1998) but, depending on the estuary, 38–78% of the sediment areas in North Carolina were contaminated with toxic substances (especially nickel, arsenic, mercury, chromium, and PCBs), at sufficiently high levels to depress growth of various benthic macroinvertebrates used as food by commercially valuable finfish. While benthic macroinvertebrates were often present in areas with hypoxia; only areas where appreciable toxic substances occurred, with or without hypoxia, had depleted macroinvertebrates (Hackney *et al.*, 1998).

Most of the other estuarine areas along the Carolina coasts are characterized by narrow barrier island sound systems, interspersed with rivers that empty almost directly into the coastal ocean. These relatively small estuarine areas are often less than 2–3 km in width but extending 10–20 km between inlets. They are exemplified by Masonboro Sound in North Carolina and North Inlet in South Carolina. They have extensive intertidal regions (often greater than 50–70% of the total area), large expanses of *Spartina alterniflora* salt marshes, and relatively high salinities (often reaching 35–37 ppt in the Masonboro Sound area), and are well flushed.

Communities in these areas are relatively diverse, with opportunistic taxa such as capitellid polychaetes, the polychaete *Streblospio*, and *Corophium* amphipods as well as more stable assemblages such as thalassinid shrimp, dense beds of hemichordates, maldanid polychaetes and arenicolids (Fox and Ruppert, 1985; Posey *et al.*, 1995; Dame and Allen, 1996). Low dissolved oxygen is seldom a significant problem here. Seasonal maxima in abundance of many amphipods and polychaetes occur in winter and early spring, with summer

TABLE 4

Stock status of marine fish taxa or habitat groups in North Carolina estuarine and coastal waters with commercial catches worth more than \$500 000 annually (NC DMF, 1999).

Taxa group	Status	Value of 1998 landings (US\$)
Blue crab *Callinectes sapidus*	Concern	\$44 952 300 (72¢/lb)
Shrimp *Peneaus aztecus, P. duorarum, P. seiferus*	Viable	\$10 826 100 (\$2.35/lb)
Southern flounder *Paralichthys lethostigma*	Concern/overfished	\$7 117 300 (\$1.80/lb)
Summer flounder *Paralichthys dentatus*	Stressed/recovering	\$5 427 100 (\$1.82/lb)
Atlantic menhaden *Brevoortia tyrannus*	Viable	\$4 071 000 (7¢/lb)
Atlantic croaker *Micropogonias undulatus*	Concern	\$3 424 800 (32¢/lb)
Reef fish (71 species)	Concern/overfished	\$3 332 000 (\$1.58/lb)
King mackerel *Scomberomorus cavalla*	Viable	\$1 749 400 (\$1.53/lb)
Weakfish/grey trout *Cynoscion regalis*	Stressed/recovering	\$1 694 200 (51¢/lb)
Black sea bass *Centropristis striata*	Concern/overfished	\$1 063 200 (\$1.46/lb)
Striped mullet *Mugil cephalus*	Concern	\$1 061 400 (48¢/lb)
Spot *Leiostomus xanthuris*	Viable	\$1 001 700 (41¢/lb)
Eastern oyster *Crassostrea virginica*	Overfished	\$974 400 (\$4.13/lb)
Bluefish *Pomatomus saltatrix*	Stressed/recovering	\$763 400 (26¢/lb)
Black (gag, grey) grouper *Mycteroperca bonaci*	Overfished	\$742 100 (\$2.50/lb)
Kingfishes (southern, northern, gulf or sea mullet)	Unknown	\$742 100 (\$1.04/lb)
Spiny dogfish (dogfish shark) *Squalus acanthius*	Overfished	\$649 100 (13¢/lb)
Striped bass *Morone saxatilis*	Viable	\$519 400 (\$1.23/lb)

declines related to predation and possibly temperature, and there is relative stability in species composition among years. However, increasing development of terrestrial areas adjacent to the sounds is likely to expose these benthic communities to increased sediment runoff as well as nutrient and organic inputs (Mallin *et al.*, 1999b; Posey *et al.*, 1999a).

Coastal rivers, as exemplified by the Cape Fear in North Carolina, are affected strongly by storms and freshwater runoff. The Cape Fear experiences periodic freshwater flow events related to major fronts and hurricanes, which can lead to significant salinity reductions, increases of agricultural runoff and hypoxic conditions. As a result, opportunistic taxa dominate, such as *Mediomastus*, *Maranzellaria* and *Corophium* (Mallin *et al.*, 1999c). The strong flow and high silt load in these rivers generally reduce effects of chronic nutrient loading on planktonic productivity (Mallin *et al.*, 1999a), but does inhibit many sedentary suspension feeders as well as submerged macrophytes.

Coastal rivers are particularly susceptible to upstream land-use practices. Poor sediment or nutrient retention practices, increasing development, and livestock farms have increased the potential for major effects on the benthic communities when major storms and associated flooding occur. The Cape Fear River can experience 90% declines in species abundances after the passage of a major storm (Mallin *et al.*, 1999c).

Commercially important benthic shellfisheries in the barrier island and coastal river regions include blue crabs, northern quahogs (hard clams), eastern oysters, and shrimp (Table 4). These organisms are affected by loss of seagrass beds south of the central North Carolina coast. Seagrass beds are recognized as a critical juvenile habitat for the blue crab, and there has been increasing interest in identifying alternative juvenile nursery areas for this species; ongoing work (Posey and Alphin, unpub; Posey *et al.*, 1999) has identified oyster beds and salt marshes, as well as lower salinity reaches of coastal rivers. For example, in the Cape Fear Estuary, the highest concentration of small juvenile blue crabs occurs in salinities $\ll$15 ppt, with larger size classes occurring in more saline portions of the estuary (Fig. 3). This distribution indicates habitat segregation along the salinity gradient in the coastal rivers of this region.

Oyster beds are present both in the sounds and near the mouths of rivers. They currently are in decline because of overharvesting, high siltation and suspended particulate loads, disease and coastal development (NC DMF, 1999; Breitburg *et al.*, 2000). Considerable effort has been focused on maintaining the fishery through mariculture and transplant operations. However, oyster beds provide critical habitat for many fish species (Posey *et al.*, 1999) and may have significant impacts on water quality. Therefore, they may need to be managed as an essential habitat, much as seagrass beds are managed. Fishery managers recently have supported efforts to re-establish oyster beds in areas where they have been lost or degraded, as a method of habitat mitigation.

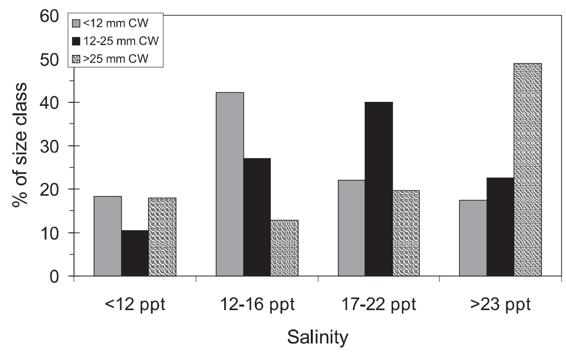

Fig. 3 Distribution of juvenile blue crabs by size class across the salinity gradient in the Cape Fear River estuary (Posey and Alphin, University of North Carolina at Wilmington, unpublished data). Size classes for blue crabs reflect sizes that are thought to rely on seagrass habitat in other estuaries (< 12 mm carapace width (CW); Pile *et al.*, 1996) and the sizes at which they move into lower salinity marsh habitats (> 25 mm CW).

Offshore benthic communities

The benthic shelf habitats include a diverse mix of hard bottoms, hard-bottom veneer (shallow, mobile sands overlying rock) and deeper sand areas. Hard bottoms are productive fisheries habitats. Their benthic communities vary with depth and according to vertical relief (Posey and Ambrose, 1994). Low-relief hard bottoms are subject to periodic sand scour and possibly burial, so they often harbour lower diversity, dominated by a few emergent octocorals and sponges. On high-relief hard bottoms, horizontal surfaces are usually dominated by macroalgae such as *Sargassum* and *Dictyota*, while vertical surfaces and overhangs are dominated by a diverse array of sponges, bryozoans, hydrozoans, and tunicates. Diversity is lowest inshore, where the water is colder in winter and where there are turbidity and salinity effects from adjacent estuaries. Offshore, at depths greater than 35–40 m, the Gulf Stream influence becomes stronger and the community may be dominated by a variety of tropical and subtropical Caribbean taxa. Large areas of offshore bottom habitat are veneer habitats that are often covered by a thin, mobile layer of sand. These areas do not have such a diverse array of encrusting taxa.

Soft-sediment communities are diverse. A recent monitoring study along the southern North Carolina coast found over 500 taxa, with over 20 taxa comprising at least 1% of the individuals. These communities exhibit seasonality, but there is considerable consistency between years. The habitats are dominated by polychaetes as well as a variety of small bivalves. Possible future environmental problems are related to mining or drilling activities, while deeper soft-substrate deposits have been targeted in some areas for beach ‘renourishment’ (Posey and Alphin, 1999), a practice which could cause habitat disruption.

Estuarine and coastal finfish communities

The Carolinas support diverse populations of fishes, ranging from estuarine assemblages to pelagic species. Estuarine communities consist of a mix of species with three types of life history strategy, including anadromous species that spend most of their lives in saltwater but return to freshwater streams to spawn (e.g., river herrings, shad), resident 'estuarine-dependent' species that spend their entire life in the estuary (e.g., white perch, catfish), and estuarine migratory species that spawn in the open ocean, around inlets, or near shore (e.g., spot, Atlantic menhaden, Atlantic croaker, weakfish, and flounders) (Table 4). These species dominate the estuarine finfisheries, and also emigrate to join nearshore stocks that migrate seasonally along the Atlantic Coast (NC DMF, 1993). Coastal populations also include migratory marine fishes (mackerels, bluefish); rock/reef-associated fishes (the snapper–grouper complex, sea basses, haemulids), and larger pelagic fishes such as wahoo, swordfish, marlins and sharks (NOAA, 1992).

Commercial and recreational fisheries are economically important (Table 4). Considerable effort has been devoted to their management and enhancement, including construction of artificial reefs in estuarine and coastal ocean waters. North Carolina historically has had, and still maintains, one of the richest fishery resource bases in the nation, attributed in part to the mix of northern and southern species that tend to overlap in the Cape Hatteras area, and to the more extensive, dissected coastline and expansive habitats afforded by the Albemarle–Pamlico Estuarine System. South Carolina has a similar mix of warm-water species (Sedberry and Van Dolah, 1984) but is lacking species of northern origin. North Carolina's blue crab fishery is among the three largest in the nation, along with the blue crab fisheries in Chesapeake Bay and Louisiana (SC DNR, 1999). North Carolina also has the northernmost major shrimp fishery in the country in Pamlico Sound (SC DNR, 1999). Shrimp (brown and white: *Panaeus aztecus* and *P. setiferus*, respectively) are the most important commercial fishery in South Carolina, with blue crabs secondary. Unlike the major inshore shrimp trawling activity allowed in North Carolina, shrimp trawlers in South Carolina are restricted to ocean waters except for limited periods during fall, when trawlers work the lower areas of Winyah and North Santee Bays (SC DNR, 1999).

Most fisheries monitoring programmes began in the late 1970s–1980s, although some commercial landings data for North Carolina extend back to the 1880s. The five-year period with the greatest recorded landings was 1978–1982, with average landings of 1.62×10^8 kg (357 million pounds), and a maximum of 196×10^8 kg (NC DMF, 1993). Atlantic menhaden, flounders, weakfish, Atlantic croaker, and white perch, as well as shellfish such as northern quahogs, blue crabs, and shrimp established all-time records or reached levels not seen for many years. Since that period, total finfish and shellfish harvests have declined by about half, down to 9×10^7 kg by the early 1990s (NC DMF, 1993).

Twenty-eight individual species and five other species groupings are listed as commercially valuable (NC DMF, 1999). The species groupings consist of reef fish (71 species); sharks (two dominant species, with an unknown number of other common to rare species); shrimp (three species), kingfish (three species), catfish (four species), and river herrings (two species), for a total of 107 species plus sharks. The most valuable fishery in North Carolina is the blue crab fishery, followed by shrimp, southern flounder, summer flounder and Atlantic menhaden (Table 4). In 1998 these fisheries yielded a dockside value of more than $72 million. Populations of shrimp and Atlantic menhaden are evaluated by NC DMF (1999) as viable or in good condition; however, summer flounder has been seriously overfished and is listed as 'stressed but recovering'. Two species, blue crab and southern flounder, have been evaluated as stressed populations of 'concern' with clear signs of overfishing.

Fisheries that, as of 1998, remained viable with healthy stocks included shrimp, Atlantic menhaden, king mackerel, striped bass, spotted seatrout, bay scallops, Spanish mackerel, dolphin, spot, and five reef fish, for a total of 15 viable species. Three species: weakfish, bluefish, and summer flounder are 'stressed but recovering,' following additional regulations to reduce recruitment overfishing. A total of 56 species were listed as stressed populations of 'concern,' including blue crab and southern flounder as mentioned, 1 major stock of black sea bass, Atlantic croaker, 51 reef fish, and striped mullet. Ten species were listed as depressed, 'overfished' populations, including 1 stock of black sea bass, eastern oyster, black grouper, red drum, river herring (two species, one stock), spiny dogfish, monkfish, Atlantic sturgeon, scup, tautog, 15 reef fish, and 'sharks.' Ten species were listed as 'unknown' in status. A total of 26 species, including most of the commercially important fishes with the exception of the reef fish category, are strongly dependent on estuarine habitats during critical periods such as spawning or recruitment. Fish management plans have been developed at the federal and/or state levels within the past *ca* 15 years toward improving their protection and sustainability (NC DMF, 1999).

Environmental Concerns in Estuarine and Coastal Systems

The majority of estuaries in this region show low-to-moderate eutrophic conditions (Bricker *et al.*, 1999). However, three estuaries in North Carolina (the Pamlico River, Neuse River, and New River) ranked as highly eutrophic, and are showing symptoms including phytoplankton blooms, bottom-water hypoxia and anoxia, fish kills, and loss of SAV (e.g., Ferguson *et al.*, 1988; NOAA, 1996; NC DENR, 1997; Bricker *et al.*, 1999).

TABLE 5

Average inorganic nutrient (dissolved inorganic nitrogen, DIN, and dissolved inorganic phosphorus, DIP, μg l^{-1}) and chlorophyll *a* concentrations (μg l^{-1}) in the most productive areas of four North Carolina estuaries (the first three, eutrophic), 1993–1998.[a,b]

Estuary	DIN	DIP	Chlorophyll *a*	Chlorophyll *a* range	*k*
Pamlico	125	28	32	4–360	–
Neuse	86	46	21	1–210	1.80
New River	370	64	70	1–380	3.10
Cape Fear	360	36	9	1–33	4.04

[a] Data records from Burkholder, North Carolina State University; the North Carolina Division of Water Quality; and Mallin and Cahoon, University of North Carolina at Wilmington.
[b] Light attenuation coefficient (*k*) values are given in the last column.

Inorganic nutrient concentrations in the most productive areas of eutrophic estuaries in North Carolina are little different compared to those of a nearby non-eutrophic system (the Cape Fear River Estuary) (Table 5). However, chlorophyll *a* concentrations in the eutrophic systems far exceed those of the Cape Fear (Table 5). The major difference between the systems is morphometric, with the open Cape Fear Estuary well flushed by tidal action. This flushing suppresses phytoplankton bloom development. Light is more strongly attenuated in the Cape Fear, relative to the Neuse, Pamlico, and New River Estuaries (Table 5). Tidal dampening in the eutrophic systems allows turbidity to settle out, so the slower flowing waters provide an ideal environment for bloom formation. Estuaries in South Carolina all show either low or moderate eutrophication symptoms (NOAA, 1996; Bricker *et al.*, 1999), and most are more geomorphologically similar to the Cape Fear than the Neuse or Pamlico systems.

The eutrophic environment has led to numerous estuarine fish kills in recent years (Table 6). The Neuse and Pamlico Estuaries in particular have suffered kills of more than one billion fish (Burkholder *et al.*, 1995). The ichthyotoxic dinoflagellate, *P. piscicida*, was discovered in these waters in the early 1990s (Burkholder *et al.*, 1992b), and its lethality to over 30 species of finfish and shellfish has been documented (Burkholder *et al.*, 1995; Burkholder and Glasgow, 1997). Blooms of *P. piscicida* and a second toxic *Pfiesteria* species, *P. shumwayae* sp. nov., have accounted for up to 50% of the estuarine fish kills in the Pamlico, Neuse, and New River Estuaries on an annual basis in the past decade (Table 6). Many other fish kills are primarily caused by low dissolved oxygen, and occasionally by temperature shock and toxicant (e.g., pesticide) exposure (NC DWQ fish kill database, Raleigh, NC). The extent to which these and other factors act in concert to impair fish health is beginning to be examined, especially for *Pfiesteria* and low dissolved oxygen (Burkholder *et al.*, 1999; Glasgow and Burkholder, 2000). In contrast, the well-flushed Cape Fear system suffers few fish kills, with none attributed to *Pfiesteria* (Table 6). Many of the South Carolina estuaries are similar hydrologically to the Cape Fear.

TABLE 6

Total fish kills and *Pfiesteria*-induced fish kills in four North Carolina estuaries, 1991–1998.[a]

Estuary	Fish kills	Toxic Pfiesteria-related fish kills
Pamlico	26	13
Neuse	124	65
New River	6	2
Cape Fear	3	0

[a] Data records from Burkholder, North Carolina State University; the North Carolina Division of Water Quality; and Mallin, University of North Carolina at Wilmington.

In the eutrophic systems discussed above, bacterial decay of dead algal biomass creates a high BOD, leading to hypoxia/anoxia (Lenihan and Peterson, 1998; Burkholder *et al.*, 1999). Hypoxia and anoxia can also be caused by BOD loads from runoff from poorly treated swine waste (Burkholder *et al.*, 1997; Mallin *et al.*, 1997a; Mallin *et al.*, 1999c). Such incidents have caused massive fish and benthic invertebrate kills.

The Carolinas have experienced frequent hurricanes in recent years, including Hugo which primarily struck South Carolina (1988); Bertha and Fran (1996), Bonnie (1998) and Dennis and Floyd (1999) that struck North Carolina. These events caused power outages in wastewater treatment facilities that led to rerouting of untreated or partially treated sewage into rivers and estuaries. Also, the storms caused breaching of the walls and flooding of swine-waste lagoons. The BOD loads after Fran and Bonnie combined to cause anoxia and large-scale fish kills in the Cape Fear and Neuse River estuaries (Mallin *et al.*, 1999c; Burkholder *et al.*, 1999). Dennis and Floyd combined to produce the wettest September on record at several observing stations. The high volume of freshwater apparently pushed many fish populations down-estuary into the sounds and coastal ocean, so that major fish kills were not reported. Additionally, prolonged standing water on the floodplain likely allowed smaller fish access to food-rich refuge areas in riparian wetlands. The large volume of floodwaters apparently diluted inputs, so that nutrients, BOD and faecal coliform bacterial concentrations were much lower following Floyd compared to levels recorded after Fran and Bonnie.

Following Hurricane Floyd, there were erroneous press reports of a massive 'dead zone' in Pamlico Sound on the basis of a relatively small area extending out from the mouth of the Neuse, where hypoxic conditions were found in the lower 1–2 m of a 6–7 m water column. There was no reported fish kill, and only a few dead blue crabs were found (NC DWQ records, Raleigh, NC). Within seven days, this bottom-water oxygen sag had recovered to $\gg$5 mg DO l^{-1}, and a 60 km transect across the sound from north to south indicated that DO was $\gg$5 mg l^{-1} throughout (Burkholder, unpub. data). However, the massive flooding did inundate agricultural and industrial sources of numerous pollutants including nutrients, petrochemicals, metals, animal decomposition products, BOD, and microbial pathogens. Some of this material was likely transported into the sounds and adjacent marine coastal waters, as evidenced by obvious darkly coloured plumes of turbid material. Some fish populations in the Pamlico Sound developed obvious signs of disease for 6–8 weeks after the hurricane (NC DMF records; L.B. Crowder, Duke U., pers. comm.). The high volume of freshwater that was delivered into the sounds would have caused salinity stress which is known to weaken fish and render them more susceptible to attack by opportunistic pathogens (Couch and Fournie, 1993). The recent storm events have given notice that the sounds, while more distant from terrestrial pollution sources, are not immune to degradation and need to be monitored more closely.

Research in the Cape Fear River and Estuary indicates that much of its chronic BOD load comes from non-point runoff. These sources can include riparian forests, swine lagoon sprayfields and poultry litterfields, and manure from livestock grazing areas. We performed correlation analyses among physical and biological parameters at a sampling station representing inputs to the lower river/upper estuary, using 41 consecutive months of data (Table 7). There was a highly significant correlation between five-day BOD and faecal coliform counts, indicating that much of the material contributing to these parameters was derived from the same sources. However, there was a very strong correlation between turbidity and both faecal coliforms and river flow on the day of sample collection, and a significant correlation between turbidity and BOD (Table 7). Turbidity is often a strong signal of non-point source runoff.

TABLE 7

Correlation analyses among various physical and biological parameters at a station on the mainstem lower Cape Fear River ($n = 41$ data points; correlation coefficient (r)/probability (p); ns = not significant at $p < 0.05$).

	Faecal coliforms	Turbidity	Daily flow
BOD_5	0.518 0.001	0.444 0.005	ns
Turbidity	0.858 0.001	1.000 0.0	0.736 0.001
Faecal coliforms	1.000 0.0	0.858 0.001	0.469 0.005

Since river flow is correlated with both turbidity and faecal coliforms, non-point source runoff appears to be important to both BOD and faecal coliform pollution of the estuary.

Closures of shellfish beds due to high bacterial counts are a widespread problem in North Carolina waters. The most productive clam and oyster harvest waters in North Carolina are located from lower Pamlico Sound south to the South Carolina border, an area undergoing rapid urbanization (Preyer, 1994). Approximately 18% of these waters are permanently closed due to high coliform counts, and much of the remaining area becomes temporarily closed following rain events (P.K. Fowler, pers. comm.). Most urban areas of this coast were brought into centralized sewer systems in the 1970s and early 1980s; thus, most closures result from non-point pollution. In South Carolina, shellfish grounds in urbanized estuaries such as Charleston Harbor and Winyah Bay are closed to harvest, whereas much of the non-urbanized North Inlet is approved for shellfishing (DeVoe *et al.*, 1992).

The rapid urbanization of these coastal areas is an important factor leading to shellfish bed closures. Increasing cover of impervious surfaces concentrates pollutants during dry periods, and then serves as a rapid conduit of these pollutants into water bodies during and following rain. In many coastal locations, stormwater runoff directly enters sensitive shellfishing beds without any pre-treatment. In a four-year study of five urbanized tidal creeks in southeastern North Carolina, Mallin *et al.* (2000) found a strong correlation ($r = 0.945$, $p = 0.015$) between average estuarine faecal coliform counts and percent of developed land in the watershed, and an even stronger correlation ($r = 0.975$, $p = 0.005$) between average counts and percent of the watershed covered by impervious surfaces. In this study, as with the Cape Fear River study, faecal coliform counts for the creeks showed a highly significant correlation with turbidity levels.

Turbidity not only serves as a carrier of pollutants, but also can be directly harmful to estuarine functioning. Turbidity can interfere with fish and shellfish feeding, can block solar irradiance and lead to boating problems through sedimentation. Upstream of Charleston, SC, two reservoirs were created in the 1940s for power generation purposes. Water was diverted from the Santee River through these reservoirs into the Cooper River, then to Charleston Harbor. This increased the average monthly flow of the Cooper River from 12 to 455 m^3 s^{-1} (DeVoe *et al.*, 1992). This flow dramatically increased the sedimentation (and shoaling) rates in Charleston Harbor, and dredging costs to maintain open ship channels became prohibitive. In the 1970s, rediversion of the water back to the Santee River was proposed and eventually completed, reducing the Cooper River's flow to 122 m^3 s^{-1}. With the rediversion, the lower Santee River is again experiencing fresh and oligohaline conditions, and the lower Cooper River is undergoing resalinization to more normal conditions (Hackney and Adams, 1992).

Along with environmental degradation, the destructive nature of certain fishing practices on fish health and population viability is also an important issue. By-catch continues to be an extremely serious problem, with some of the highest wastes associated with shrimp trawling and the flynet fishery (NC DMF, 1993). The shallow estuaries of North Carolina, especially the Pamlico and the New River, sustain heavy trawling activity which disrupts and damages benthic habitats (Watling and Norse, 1998) while also resuspending sediments. Although certain fishing practices are not allowed in primary fish nursery areas, they are used immediately adjacent to them as well as in secondary fish nursery areas. The extent to which trawling and other destructive fishing practices contribute to the degradation and loss of critical habitats has not been quantified. These important fish nursery grounds need to be critically evaluated, so that effective management strategies can be imposed.

Another component of the fisheries issue that needs to be strengthened is the economic assessment and valuation of both the fish and the natural habitat resources that sustain them. Both fish and water are greatly undervalued in North Carolina, as elsewhere in the nation. The present-day commercial fishing industry is, in fact, made possible largely through federal subsidies (Safina, 1995). Fishermen obtain remarkably little compensation for many of the fish species they sell dockside (Table 4), relative to the lucrative gains made by many other components of the seafood industry who use those fish. Public understanding of the underlying value of fish and supporting aquatic habitat, and the critical need to move toward increased sustainability of these resources, will be greatly improved when more realistic and effective means of economic valuation are practised and conveyed (Safina, 1995).

Offshore environmental concerns

Environmental issues in the coastal ocean off North and South Carolina may arise from utilization of economic resources in the US EEZ, including hydrocarbons, sand and gravel, and phosphorite deposits (Cahoon *et al.*, 1996). Proposals by Mobil Oil (in consortium with other companies) and Chevron to explore for oil and/or natural gas off the North Carolina coast have been withdrawn as of this writing, but several active lease blocks remain off this coast. It is likely that interest in this area will remain high, particularly as pressure increases to develop new oil and gas sources in the US. A more novel hydrocarbon resource, methane gas hydrates, is believed to be present in high and potentially extractable quantities in the surface sediments of the Blake Plateau. Demand for beach renourishment sand is likely to continue to rise, since beach erosion from hurricanes has become severe. Consequently, commercial extraction of sands and gravel from offshore sources is likely to begin soon, with environmental assessments and impending lease sales. A high-grade phosphorite ore deposit is also present in the surface sedimentary layers of Onslow Bay in quantities on the order of 10^9 t. Extraction of any of these resources poses challenges to the integrity of benthic communities, and may also affect downstream plankton and fish populations. Possible impacts on other organisms, particularly protected seabird, sea turtle, and mammal species, remain to be assessed.

Prognoses for the Future

Several major critical habitat and resource issues remain to be resolved in the Carolinas. For example, until recently there were no personnel in the Carolinas' environmental agencies who are responsible for tracking and periodically remapping critical seagrass habitat. Moreover, unlike management practices in the Chesapeake Bay region (Dennison *et al.*, 1993), the Carolinas lack water quality regulations for sediment and nutrient loadings to protect seagrass habitat. In addition to pollution stressors on seagrass meadows in North Carolina, destructive fishing practices such as clam-tonging and clam-raking (which destroy the perennating root/rhizome complex) are legally permitted in seagrass beds (Peterson *et al.*, 1983, 1987; NC MFC, 1998). For many years sediment was allowed to be dredged *ca* 6 m in depth, and several hectares in extent at each taking, from areas within the seagrass meadows on the landward side of the barrier islands. The affected area, called the 'Canadian Hole', yielded sediment that has been used to 'nourish' or build the land supporting roads along the barrier islands as it is continuously and seriously eroded by storms. Most of these finely particulate sediments are removed from the 'nourished' areas by winds within a year or less, so that the process must be repeated. Such practices destroy seagrass habitat and should be prevented, for the protection of this critical habitat and the fisheries that depend upon them.

Like many regions worldwide, overfishing has led to serious declines in many wild fish stocks of the Carolinas (NC DMF, 1993, 1999). For some stocks, certain practices leading to recruitment overfishing are still allowed (Table 4), and need to be reduced or restricted. Certain North Carolina fish populations, previously severely overfished, are now showing signs of recovery following strengthened regulations to reduce the fishing pressure (Table 4) (NC DMF, 1999). The same cannot be said for many fish habitats that continue to be degraded by water pollution. For some commercially valuable wild fish stocks that will require a decade or more to recover, there is increasing interest in aquaculture (Defur and Rader, 1995), though this also requires good water quality and, in some cases (e.g., striped bass aquaculture in the Pamlico Estuary watershed) requires substantial use of freshwater aquifers. The Castle Hayne aquifer is already experiencing a cone of depression of more than 2 m per year from this and other increased uses, accompanied by saltwater intrusion that is damaging certain fish habitats.

Constructive measures have been taken to reduce eutrophication in North Carolina estuaries over the past decade. A 1988 statewide ban on phosphate-containing detergents led to decreased P loading from point sources, particularly in the Neuse (NC DEM, 1991). Blue-green algal blooms have shown a concurrent decrease in the Neuse River as well (Mallin, 1994). After 25 years, in 1992 the world's largest phosphate mine installed a waste treatment system that reduced effluent phosphate concentrations by 90% to the Pamlico Estuary (NC DEHNR, 1994). However, algal blooms and fish kills still commonly occur (Tables 5 and 6). As an example, the authors of this paper witnessed a slow but continuous (weeks long) kill on the Pamlico Estuary in July 1997, during which numerous dead fish bearing lesions floated to the surface while dissolved oxygen conditions and other factors were adequate to protect fish health (6.9 mg l^{-1}). *Pfiesteria* concentrations in the water were at levels known to cause death of fish under laboratory conditions; and the presence of an actively toxic population of *P. piscicida* was verified using fish bioassays (Burkholder and Glasgow, 1997; Burkholder *et al.*, 1999).

In the New River estuary, major improvements to wastewater treatment facilities in 1997–1999 appear to be having positive effects, with generally lower nutrient and chlorophyll levels recorded in 1998–1999 compared with the previous four years (Mallin *et al.*, UNC Wilmington unpub.). An intensive five-year study in the Neuse Estuary (Glasgow and Burkholder, 2000) found that total P significantly decreased (by 14% from 1993–1998), but inorganic nitrogen (as nitrate + ammonia) increased by 38% while total N also increased significantly (by 16%). Management strategies for the Neuse Estuary are now targeting a 30% reduction in nitrogen loading (NC DEHNR, 1997), but without consideration for additional management of phosphorous which can be critically important to minimize algal blooms (Fisher *et al.*, 1992; Paerl *et al.*, 1995; Mallin *et al.*, 1999a). While this action will probably yield some improvement, more stringent N reductions coupled with P reductions will be needed to effect a reversal of the eutrophication process, and to hold the problem in check as human population growth and related impacts increases in that basin (Glasgow and Burkholder, 2000).

As previously mentioned, the recent rise in the concentrated swine industry represents a massive potential nutrient source that will remain a significant threat to North Carolina's rivers and estuaries for the foreseeable future. Recent hurricane-induced pollution resulted in a 30-month moratorium on licensing of new industrial hog farms in North Carolina, and a ban on future hog houses and waste lagoons on the 100-year floodplain. However, political factors and the sheer size of this industry suggest that nutrient imports to coastal regions will continue at very high levels (>10^5 metric tons of N and 10^4 metric tons of phosphrous per year; Cahoon *et al.*, 1999a). Atmospheric transport of nitrogen and runoff enriched in both nutrients are thus also likely to continue at high levels from this industry and from human wastewater inputs, with associated environmental impacts on rivers, estuaries and the coastal ocean. For example, experiments by Mallin and Cahoon UNC Wilmington using water from coastal plain blackwater streams (common in the US south Atlantic region) show that nutrient loading can cause direct increases in BOD without stimulating algal bloom formation first (Fig. 4). Thus, even if traditional eutrophication symptoms do not presently affect such systems, hypoxia/anoxia may be a future problem that is caused or exacerbated by excessive nutrient inputs. Comprehensive plans limiting nitrogen and phosphorus inputs are needed for all of the Carolinas' coastal rivers and estuaries. As a proactive measure, such planning should be extended to estuaries that currently do not sustain noxious algal blooms, rather than considering only estuaries that already have developed these characteristic signals of nutrient over-enrichment (e.g., Preyer, 1994). These plans should include discharge limits on total N and P for all municipal and private wastewater treatment systems, and phase-in of biological nutrient removal for all major wastewater treatment plants. Besides these point sources, there is a critical need to improve management of non-point nutrient runoff through increased use of streamside vegetated buffers, water level control structures, preservation

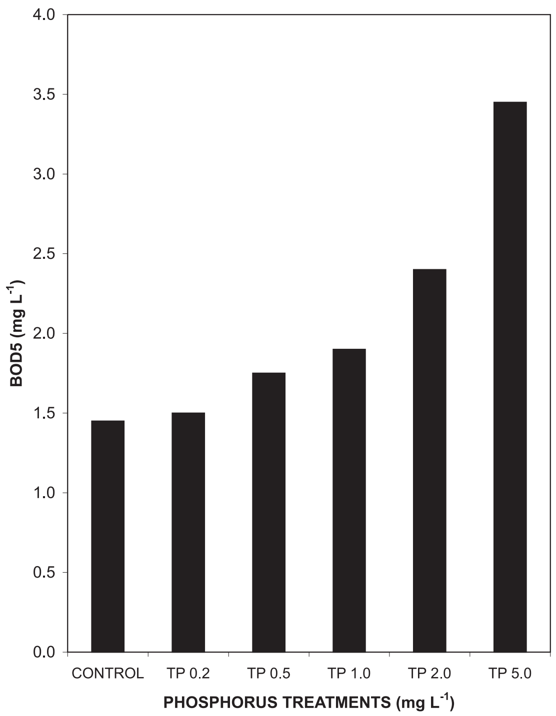

Fig. 4 Response of water samples from the Northeast Cape Fear River, a coastal blackwater stream, to additions of total phosphorus (50% orthophosphate + 50% glycerophosphate) over a gradient from zero to 5.0 mg l^{-1}, as measured by five-day biochemical oxygen demand.

of remaining natural wetlands and construction of artificial wetlands. Improved treatment processes, along with strong incentive programmes, should also be mandated for present and future industrial-scale animal operations.

Since estuaries reflect the impact of pollutant loading from distant sources as well as nearby sources, control measures that account for all contributing sources should be initiated on a watershed basis. Eutrophication symptoms are also manifested in small urbanized tidal creek estuaries that are common along the Atlantic Intracoastal Waterway. General watershed management strategies have been assessed as inadequate to protect such environmentally sensitive coastal resources unless accompanied by additional, localized coastal area-specific plans (Preyer, 1994). For example, tidal creeks in urbanized south-eastern North Carolina sustain dense algal blooms in spring and summer, summer hypoxia, and the presence of *Pfiesteria* in nutrient-enriched areas (Mallin *et al.*, 1999b). These systems generally are not impacted by point source inputs, but receive nutrient loading from urban and suburban lawns, gardens, and golf courses. Thus, non-point source runoff especially needs to be managed better in these smaller, urbanized watersheds. With steadily increasing urbanization along the South Atlantic seaboard, we predict that eutrophication symptoms in both large and small systems will significantly worsen unless aggressive steps are taken to alter current land development and nutrient management practices.

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Atkinson, L. P. (1985) Hydrography and nutrients of the southeastern US continental shelf. In *Oceanography of the Southeastern US Continental Shelf*, eds. L. P. Atkinson, D. W. Menzel and K. A. Bush, pp. 77–92. American Geophysical Union, Washington DC.

Atkinson, L. P., Singer, J. J. and Pietrafesa, L. J. (1980) Volume of subsurface intrusions into Onslow Bay, North Carolina. *Deep-Sea Research* **27**, 421–434.

Bailey, W. P. (1996) Population trends in the coastal area, concentrating on South Carolina. In *Sustainable Development in the Southeastern Coastal Zone*, eds. F. J. Vernberg, W. B. Vernberg and T. Siewicki, pp. 55–73. University of South Carolina Press, Columbia, SC.

Breitburg, D., Coen, L., Luckenbach, M., Mann, R., Posey, M. and Wesson, J. (2000). Oyster reef restoration: convergence of harvest and conservation strategies. *Journal of Shellfish Research* **19**, 371–377.

Bricker, S. B., Clement, C. G., Pirhalla, D. E., Orlando, S. P. and Farrow, D. R. G. (1999) National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD, 71 pp.

Bowman, T. E. (1971) The distribution of calanoid copepods off the southeastern United States between Cape Hatteras and southern Florida. *Smithsonian Contributions in Zoology*, #96.

Burke, M. K., Dennison, W. C. and Moore, K. A. (1996) Non-structural carbohydrate reserves of eelgrass *Zostera marina*. *Marine Ecology Progress Series* **137**, 195–201.

Burkholder, J. M. (1998) Implications of harmful microalgae and heterotrophic dinoflagellates in management of sustainable marine fisheries. *Ecological Applications* **8**, S37–S62.

Burkholder, J. M. and Cuker, B. E. (1991) Response of periphyton communities to clay and phosphate loading in a shallow reservoir. *Journal of Phycology* **27**, 373–384.

Burkholder, J. M. and Glasgow, H. B. Jr. (1997) *Pfiesteria piscicida* and other *Pfiesteria*-like dinoflagellates: behavior, impacts, and environmental controls. *Limnology and Oceanography* **42**, 1052–1075.

Burkholder, J. M., Glasgow, H. B. Jr. and Cooke, J. E. (1994) Comparative effects of water-column nitrate enrichment on eelgrass *Zostera marina*, shoalgrass *Halodule wrightii*, and widgeongrass *Ruppia maritima*. *Marine Ecology Progress Series* **105**, 121–138.

Burkholder, J. M., Glasgow, H. B. Jr. and Fensin, E. E. (1996) Physical, Chemical, and Biological Characteristics of Water Samples Collected from the Neuse Estuary in the Vicinity of Cherry Point, North Carolina, 1993–1995. Final report to the US Marine Air Station, Cherry Point, NC.

Burkholder, J. M., Mason, K. M. and Glasgow, H. B. Jr. (1992a) Water-column nitrate enrichment promotes decline of eelgrass *Zostera marina* L.: evidence from seasonal mesocosm experiments. *Marine Ecology Progress Series* **81**, 163–178.

Burkholder, J. M., Noga, E. J., Hobbs, C. W., Glasgow, H. B. Jr. and Smith, S. A. (1992b) New 'phantom' dinoflagellate is the causative agent of estuarine fish kills. *Nature* **358**, 407–410; **360**, 768.

Burkholder, J. M., Glasgow, H. B. Jr. and Hobbs, C. W. (1995) Distribution and environmental conditions for fish kills linked to a toxic ambush predator dinoflagellate. *Marine Ecology Progress Series* **124**, 43–61.

Burkholder, J. M., Mallin, M. A., Glasgow, H. B. Jr., Larsen, L. M., McIver, M. R., Shank, G. C., Deamer-Melia, N., Briley, D. S., Springer, J., Touchette, B. W. and Hannon, E. K. (1997) Impacts to a coastal river and estuary from rupture of a swine waste holding lagoon. *Journal of Environmental Quality* **26**, 1451–1466.

Burkholder, J. M., Mallin, M. A. and Glasgow, H. B. Jr. (1999) Fish kills, bottom-water hypoxia, and the toxic *Pfiesteria* complex in the Neuse River and Estuary. *Marine Ecology Progress Series* **179**, 301–310.

Cahoon, L. B. and Cooke, J. E. (1992) Benthic microalgal production in Onslow Bay, North Carolina. *Marine Ecology Progress Series* **84**, 185–196.

Cahoon, L. B. and Tronzo, C. R. (1990) New records of amphipods and cumaceans from Onslow Bay, North Carolina, in demersal zooplankton collections. *Journal of the Elisha Mitchell Scientific Society* **106**, 78–84.

Cahoon, L. B. and Tronzo, C. R. (1992) Quantitative estimates of demersal zooplankton abundance in Onslow Bay, North Carolina. *Marine Ecology Progress Series* **87**, 197–200.

Cahoon, L. B. and Laws, R. A. (1993) Benthic diatoms from the North Carolina continental shelf: Inner and mid shelf. *Journal of Phycology* **29**, 257–263.

Cahoon, L. B., Lindquist, D. G. and Clavijo, I. E. (1990a) 'Live bottoms' in the continental shelf ecosystem: A misconception? In *Diving for Science*, ed. W. Jaap, pp. 39–47. American Academy of Underwater Sciences, Costa Mesa, CA.

Cahoon, L. B., Redman, R. L. and Tronzo, C. R. (1990b) Benthic microalgal biomass in sediments of Onslow Bay, North Carolina. *Estuarine and Coastal Shelf Science* **31**, 805–816.

Cahoon, L. B., Clark, W. F. and Crawford, K. P. (1996) North Carolina's Ocean Resources Plan. In *Proceedings of the Coastal Society's 15th International Conference*, eds. T. E. Bigford and R. H. Boyles Jr., pp. 359–365. The Coastal Society, Alexandria, VA.

Cahoon, L. B., Mickucki, J. A. and Mallin, M. A. (1999a) Nutrient imports to the Cape Fear and Neuse River basins to support animal production. *Environmental Science and Technology* **33**, 410–415.

Cahoon, L. B., Nearhoof, J. E. and Tilton, C. L. (1999b) Sediment grain size effect on benthic microalgal biomass in shallow aquatic ecosystems. *Estuaries* **22**, 735–741.

Carpenter, E. J. (1971) Annual phytoplankton cycle of the Cape Fear River Estuary, North Carolina. *Chesapeake Science* **12**, 95–104.

Chester, A. J., Fergesun, R. L. and Thayer, G. W. (1983) Environmental gradients and benthic macroinvertebrate distributions in a shallow North Carolina estuary. *Bulletin of Marine Science* **33**, 282–295.

Coleman, V. L. and Burkholder, J. M. (1994) Community structure and productivity of epiphytic microalgae on eelgrass (*Zostera marina* L.) under water-column nitrate enrichment. *Journal of Experimental Marine Biology and Ecology* **179**, 29–48.

Coleman, V. L. and Burkholder, J. M. (1995) Response of microalgal epiphytes to nitrate enrichment in an eelgrass (*Zostera marina* L.) meadow. *Journal of Phycology* **31**, 36–43.

Copeland, B. J. and Grey, J. (1989) Albemarle-Pamlico Estuarine System: Preliminary Analysis of the Status and Trends. Albemarle-Pamlico Study Report 89-13A. North Carolina Department of Environment and Natural Resources, Raleigh, NC.

Copeland, B. J., Hodson, R. G. and Riggs, S. R. (1984) The Ecology of the Pamlico River, North Carolina: An Estuarine Profile. US Fish and Wildlife Service, Office of Biological Services (Technical Report) FWS/OBS FWS/OBS/82-06, pp. 1–83.

Copeland, B. J., Hodson, R. G., Riggs, S. R. and Easley, J. E. Jr. (1983) The Ecology of Albemarle Sound, North Carolina: An Estuarine Profile. US Fish and Wildlife Service, Office of Biological Services (Technical Report) FWS/OBS FWS/OBS/83-01, pp. 1–68.

Couch, J. A. and Fournie, J. W. (1993) *Pathobiology of Marine and Estuarine Organisms*. CRC Press, Boca Raton, FL.

Dame, R. F. and Allen, D. M. (1996) Between estuaries and the sea. *Journal of Experimental Marine Biology and Ecology* **200**, 169–185.

Defur, P. L. and Rader, D. N. (1995) Aquaculture in estuaries: feast or famine? *Estuaries* **18**, 2–9.

den Hartog, C. (1970) *The Sea-Grasses of the World*. North-Holland, Amsterdam, The Netherlands.

Dennison, W. C., Orth, R. J., Moore, K. A., Stevenson, J. C., Carter, V., Kollar, S., Bergstrom, P. W. and Batiuk, R. A. (1993) Assessing water quality with submersed aquatic vegetation – habitat requirements as barometers of Chesapeake Bay health. *Bioscience* **43**, 86–94.

DeVoe, M. R., Davis, K. B. and Van Dolah, R. F. (1992) *Characterization of the Physical, Chemical and Biological Conditions and Trends in Three South Carolina Estuaries, 1970–1985*. South Carolina Sea Grant Consortium, Charleston, SC.

Dewi, L. A., Axford, R. F. E., Fayez, I., Marai, M. and Omed, H. (1994) *Pollution in Livestock Production Systems*. CAB International, Wallingford, UK.

Epperley, S. P. and Ross, S. W. (1986) Characterization of the North Carolina Pamlico-Albemarle Estuarine Complex. NOAA Technical Memorandum NMFS-SEFC-175. NOAA, Washington DC, USA.

Fahay, M. P. (1975) An Annotated List of Larval and Juvenile Fishes Captured with a Surface-Towed Meter Net in the South Atlantic Bight During Four DOLPHIN Cruises Between May 1967 and February 1968. NOAA Technical Report NMFS SSRF-685.

Fensin, E. E. (1997) Population Dynamics of *Pfiesteria*-like Dinoflagellates, and Environmental Controls in the Mesohaline Neuse Estuary, North Carolina. Master of Science thesis, Department of Botany, North Carolina State University, Raleigh, NC.

Ferguson, R. L., Rivera, J. A. and Wood, L. L. (1988) Submerged Aquatic Vegetation in the Albemarle-Pamlico Estuarine System. Report No. 88-10 to the Albemarle-Pamlico Estuarine Study. NC DEHNR and the US Environmental Protection Agency – National Estuarine Program, Raleigh, NC.

Fisher, T. R., Peele, E. R., Ammerman, J. W. and Harding, L. W. Jr. (1992) Nutrient limitation of phytoplankton in Chesapeake Bay. *Marine Ecology Progress Series* **82**, 51–63.

Fox, R. S. and Ruppert, E. E. (1985). *Shallow-Water Marine Benthic Macroinvertebrates of South Carolina*. University of South Carolina Press, Columbia, SC, 329 pp.

Freeman, D. B. (1989) The Distribution and Trophic Significance of Benthic Microalgae in Masonboro Sound, North Carolina. Master of Science thesis, Department of Biology, UNC-Wilmington, Wilmington, NC.

Fulton, R. S. III (1984) Distribution and community structure of estuarine copepods. *Estuaries* **7**, 38–50.

Fulton, R. S. III. (1985) Predator–prey relationships in an estuarine littoral zooplankton community. *Ecology* **66**, 21–29.

Glasgow, H. B. Jr. and Burkholder, J. M. (2000) Water quality trends and management implications from a five-year study of a eutrophic estuary. *Ecological Applications* **10**, 1024–1046.

Glasgow, H. B. Jr. (2000). The Biology of the Toxic Pfiesteria Complex in the Neuse Estuary, North Carolina, Ph.D. dissertation, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC.

Glasgow, H. B. Jr., Burkholder, J. M., Schmechel, D. E., Tester, P. A. and Rublee, P. A. (1995) Insidious effects of a toxic dinoflagellate on fish survival and human health. *Journal of Toxicology and Environmental Health* **46**, 101–122.

Hackney, C. T., Grimley, J., Posey, M., Alphin, T. and Hyland, J. (1998) Sediment contamination in North Carolina's estuaries. Center for Marine Sciences Research Publication #198. University of North Carolina at Wilmington, Wilmington, NC.

Hackney, C. T. and Adams, S. M. (1992) Aquatic communities of the Southeastern United States: past, present, and future. In *Biodiversity of Southeastern United States Aquatic Communities*, eds. C.T. Hackney, S. M. Marshall and W. M. Martin, pp. 747–760. Wiley, New York.

Hallegraeff, G. M. (1993) A review of harmful algal blooms and their apparent global increase. *Phycologia* **32**, 79–99.

Hobbie, J. E. (1971) Phytoplankton species and populations in the Pamlico River Estuary of North Carolina. Report No. 56, Water Resources Research Institute, University of North Carolina, Raleigh, NC.

Houser, D. S. and Allen, D. M. (1996) Zooplankton dynamics in an intertidal salt-marsh basin. *Estuaries* **19**, 659–673.

Kapraun, D. F. (1980) *An Illustrated Guide to the Benthic Marine Algae of Coastal North Carolina. I. Rhodophyta*. The University of North Carolina Press, Chapel Hill, NC.

Kenworthy, W. J. (1981) The Interrelationship Between Seagrasses *Zostera marina* and *Halodule wrightii*, and the Physical and Chemical Properties of Sediments in a mid-Atlantic Coastal Plain Estuary Near Beaufort, North Carolina (USA). Master of Science thesis, University of Virginia, Charlottesville, VA.

Kjelson, M. A., Peters, D. S., Thayer, G. W. and Johnson, G. M. (1975) The general feeding ecology of postlarval fishes in the Newport River Estuary. *Fishery Bulletin* **73**, 137–144.

Kuenzler, E. J., Stanley, D. W. and Koenigs, J. P. (1979). Nutrient Kinetics in the Pamlico River, North Carolina. Report No. 139. UNC Water Resources Research Institute, Raleigh, NC.

Lenihan, H. S. and Peterson, C. H. (1998) How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. *Ecological Applications* **8**, 128–140.

Lewitus, A. J., Koepfler, E. T. and Morris, J. T. (1998) Seasonal variation in the regulation of phytoplankton by nitrogen and grazing in a salt-marsh estuary. *Limnology and Oceanography* **43**, 636–646.

Lonsdale, D. J. and Coull, B. C. (1977) Composition and seasonality of zooplanktion of North Inlet, South Carolina. *Chesapeake Science* **18**, 272–283.

Lüning, K. (1990) *Seaweeds – Their Environment, Biogeography, and Ecophysiology*. Wiley, New York.

Mallin, M. A. (1991) Zooplankton abundance and community structure in a mesohaline North Carolina estuary. *Estuaries* **14**, 481–488.

Mallin, M. A. (1994) Phytoplankton ecology of North Carolina estuaries. *Estuaries* **17**, 561–574.

Mallin, M. A. and Paerl, H. W. (1994) Planktonic trophic transfer in an estuary: seasonal, diel, and community structure effects. *Ecology* **75**, 2168–2185.

Mallin, M. A., Paerl, H. W. and Rudek, J. (1991) Seasonal phytoplankton composition, productivity, and biomass in the Neuse River Estuary, North Carolina. *Estuarine, Coastal and Shelf Science* **32**, 609–623.

Mallin, M. A., Burkholder, J. M. and Sullivan, M. J. (1992) Benthic microalgal contributions to coastal fishery yield. *Transactions of the American Fisheries Society* **121**, 691–695.

Mallin, M. A., Paerl, H. W., Rudek, J. and Bates, P. W. (1993) Regulation of estuarine primary production by rainfall and river flow. *Marine Ecology Progress Series* **93**, 199–203.

Mallin, M. A., Burkholder, J. M., McIver, M. R., Shank, G. C., Glasgow, H. B. Jr., Touchette, B. W. and Springer, J. (1997a) Comparative effects of poultry and swine waste lagoon spills on the quality of receiving streamwaters. *Journal of Environmental Quality* **26**, 1622–1631.

Mallin, M. A., Cahoon, L. B., McIver, M. R., Parsons, D. C. and Shank, G. C. (1997b) Nutrient Limitation and Eutrophication Potential in the Cape Fear and New River Estuaries. Report No.

313. Water Resources Research Institute of the University of North Carolina, Raleigh, NC.
Mallin, M. A., Cahoon, L. B., McIver, M. R., Parsons, D. C. and Shank, G. C. (1999a) Alternation of factors limiting phytoplankton production in the Cape Fear Estuary. *Estuaries* **22**, 985–996.
Mallin, M. A., Esham, E. C., Williams, K. E. and Nearhoof, J. E. (1999b) Tidal stage variability of fecal coliform and chlorophyll *a* concentrations in coastal creeks. *Marine Pollution Bulletin* **38**, 414–422.
Mallin, M. A., Posey, M. H., Shank, G. C., McIver, M. R., Ensign, S. H. and Alphin, T. D. (1999c) Hurricane effects on water quality and benthos in the Cape Fear watershed: natural and anthropogenic impacts. *Ecological Applications* **9**, 350–362.
Mallin, M. A., Williams, K. E., Esham, E. C. and Lowe, R. P. (2000) Effect of human development on bacteriological water quality in coastal watersheds. *Ecological Applications* **10**, 1047–1056.
Marshall, H. G. (1969) Phytoplankton distribution off the North Carolina coast. *American Midland Naturalist* **81**, 241–257.
Marshall, H. G. (1971) Composition of phytoplankton off the southeastern coast of the United States. *Bulletin of Marine Science* **21**, 806–825.
Marshall, H. G. (1976) Phytoplankton distribution along the eastern coast of the US I. Phytoplankton distribution. *Marine Biology* **38**, 81–89.
Marshall, H. G. (1978) Phytoplankton distribution along the eastern coast of the USA. Part II. Seasonal assemblages north of Cape Hatteras, North Carolina. *Marine Biology* **45**, 203–208.
McKenna, S. K., Henry, L. T. and Diably, S. (1998) *North Carolina Fishery Management Plan – Blue Crab*. North Carolina Department of Environmental Protection and Natural Resources, Division of Marine Fisheries, Morehead City, NC.
Muehlstein, L. K. (1992) The host-pathogen interaction in the wasting disease of eelgrass *Zostera marina*. *Canadian Journal of Botany* **70**, 2081–2088.
NOAA (National Oceanic and Atmospheric Administration) (1992) Status of Fishery Resources off the Southeastern United States for 1991. NOAA Technical Memorandum NMFS-SEFSC-306, Silver Spring, MD.
NOAA (National Oceanic and Atmospheric Administration) (1996) *NOAA's Estuarine Eutrophication Survey*, Vol. 1: South Atlantic Region. NOAA, Office of Ocean Resources Conservation Assessment, Silver Spring, MD, 50 pp.
Nearhoof, J. E. (1994) Effects of Water Depth and Clarity on the Distribution and Relative Abundance of Phytoplankton and Benthic Microalgae in North Carolina Estuaries. Master of Science thesis, Department of Biology, UNC-Wilmington, Wilmington, NC.
NC DEHNR (North Carolina Department of Environment, Health and Natural Resources now NC DENR) (1994) Water Quality Progress in North Carolina: 1992–1993 305(b) Report. NC DEHNR, Raleigh, NC.
NC DEM (North Carolina Division of Environmental Management) (1991) An Evaluation of the Effects of the North Carolina Phosphate Detergent Ban. Report No. 91-04. NC DEM, Raleigh, NC.
NC DENR (North Carolina Department of Environment and Natural Resources) (1997) *Neuse River Nutrient-Sensitive Waters (NSW) Management Strategy*. NC DENR, Raleigh, NC.
NC DMF (North Carolina Division of Marine Fisheries) (1993) *Description of North Carolina's Coastal Fishery Resources, 1972–1991*. NC DEHNR–DMF, Morehead City, NC, 213 pp. and appendices.
NC DMF (North Carolina Division of Marine Fisheries) (1999) *Stock Status of Important Coastal Fisheries in North Carolina, 1999*. Available at website www.ncdmf.net/stocks. NC DMF, Morehead City, NC.
NC DWQ (North Carolina Division of Water Quality) (1996) *Cape Fear River Basinwide Water Quality Management Plan*. North Carolina Department of Environment, Health and Natural Resources, Division of Water Quality, Raleigh, NC.
NC MFC (North Carolina Marine Fisheries Commission) (1998) *North Carolina Fisheries Rules for Coastal Waters 1998–1999*. NCMFC and NC DENR-DMF, Morehead City, NC.
Paerl, H. W., Mallin, M. A., Donahue, C. A., Go, M. and Peierls, B. J. (1995) Nitrogen Loading Sources and Eutrophication of the Neuse River Estuary, North Carolina: Direct and Indirect Roles of Atmospheric Deposition. Report 291. UNC Water Resources Research Institute, Raleigh, NC.
Paffenhofer, G. -A. (1980) Zooplankton distribution as related to summer hydrographic conditions in Onslow Bay, North Carolina. *Bulletin of Marine Science* **30**, 819–832.
Penhale, P. (1977) Macrophyte-epiphyte biomass and productivity in an eelgrass (*Zostera marina* L.) community. *Journal of Experimental Marine Biology and Ecology* **26**, 211–224.
Peterson, C. H., Summerson, H. C. and Fegley, S. R. (1983) Relative efficiency of two clam rakes and their contrasting impacts on seagrass biomass. *Fishery Bulletin* **81**, 429–434.
Peterson, C. H., Summerson, H. C. and Fegley, S. R. (1987) Ecological consequences of mechanical harvesting of clams. *Fishery Bulletin* **85**, 281–298.
Pietrafesa, L. J. and Janowitz, G. S. (1988) Physical oceanographic processes affecting larval transport around and through North Carolina inlets. *American Fisheries Society Symposium* **3**, 34–50.
Pietrafesa, L. J., Janowitz, G. S. and Wittman, P. A. (1985) Physical oceanographic processes in the Carolina Capes. In *Oceanography of the Southeastern US Continental Shelf*, eds. L. P. Atkinson, D. W. Menzel and K. A. Bush, pp. 23–32. American Geophysical Union, Washington DC.
Pietrafiesa, L. J., Janowitz, G. S., Miller, J. M., Noble, E. B., Ross, S. W. and Epperly, S. P. (1986) Abiotic factors influencing the spatial and temporal variability of juvenile fish in Pamlico Sound, North Carolina. In *Estuarine Variability*, ed. D. A. Wolfe, pp. 341–353. Academic Press, New York.
Pile, A. J., Lipcius, R. N., van Montfrans, J. and Orth, R. J. (1996) Density-dependent settler–recruit–juvenile relationships in blue crabs. *Ecological Monographs* **66**, 277–300.
Pinckney, J. L. and Zingmark, R. G. (1993) Modeling the annual production of intertidal benthic microalgae in estuarine ecosystems. *Journal of Phycology* **29**, 396–407.
Pinckney, J. L., Millie, D. F., Vinyard, B. T. and Paerl, H. W. (1997) Environmental controls of phytoplankton bloom dynamics in the Neuse River Estuary, North Carolina, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 2491–2501.
Posey, M. H. and Ambrose, W. G. Jr. (1994) Effects of proximity to an offshore hard-bottom reef on infaunal abundances. *Marine Biology* **118**, 745–753.
Posey, M. H. and Alphin, T. D. (1999) Monitoring of benthic faunal responses to sediment removal associated with the Carolina Beach and vicinity – area south project. Final Report submitted to NOAA Sanctuaries and Reserves Division, pp. 24.
Posey, M. H., Powell, C., Cahoon, L. and Lindquist, D. (1995) Top down vs. bottom up control of benthic community composition on an intertidal tideflat. *Journal of Experimental Marine Biology and Ecology* **185**, 19–31.
Posey, M. H., Alphin, T. D., Cahoon, L., Lindquist, D. and Becker, M. E. (1999) Interactive effects of nutrient additions and predation on infaunal communities. *Estuaries* **22**, 785–792.
Preyer, L. R. (chair) (1994) *Charting a Future for Our Coast – A Report to the Governor of North Carolina*. North Carolina Coastal Futures Committee. North Carolina Department of Environment, Health and Natural Resources, Raleigh, NC, 106 pp.
Safina, C. (1995) The world's imperiled fish. *Scientific American* 273, 46–53.
Sanders, J. G. and Kuenzler, E. J. (1979) Phytoplankton population dynamics and productivity in a sewage-enriched tidal creek in North Carolina. *Estuaries* **2**, 87–96.
Schneider, C. W. (1976) Spatial and temporal distributions of benthic marine algae on the continental shelf of the Carolinas. *Bulletin of Marine Science* **26**, 133–151.
Schneider, C. W. and Searles, R. B. (1991) *Seaweeds of the Southeastern United States – Cape Hatteras to Cape Canaveral*. Duke University Press, Durham, NC, pp. 553.
Sedberry, G. R. and Van Dolah, R. F. (1984) Demersal fish assemblages associated with hard bottom habitats in the South Atlantic Bight of the USA. *Environmental Biology of Fishes* **11**, 241–258.
Sellner, K. G., Zingmark, R. G. and Miller, T. G. (1976) Interpretations of the ^{14}C method of measuring the total annual production of phytoplankton in a South Carolina estuary. *Botanica Marina* **19**, 119–125.
Short, F. T. and Wylle-Echeverria, S. (1996) Natural and human-induced disturbance of seagrasses. *Environmental Conservation* **23**, 17–27.

Stanley, D. W. (1992). Historical Trends: Water Quality and Fisheries, Albemarle-Pamlico Sounds, with Emphasis on the Pamlico River Estuary. North Carolina Sea Grant College Program Publication UNC-SG-92-04. Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC, 215 pp.

SC DNR (South Carolina Department of Natural Resources) (1999) Marine Fisheries publications website: http://www.dnr.state.sc.us/marine/index.html.

Steel, J. (1991) Status and Trends Report of the Albemarle-Pamlico Estuarine Study. Albemarle-Pamlico Estuarine Study, US Environmental Protection Agency National Estuarine Program and the North Carolina Department of Environment, Health and Natural Resources, Raleigh, NC.

Stevenson, J. C. (1988) Comparative ecology of submersed grass beds in freshwater, estuarine, and marine environments. *Limnology and Oceanography* **33**, 867–893.

Summerson, H. C. and Peterson, C. H. (1990) Recruitment failure of the bay scallop, *Argopectin irradians concentricus,* during the first red tide, *Ptychodiscus brevis,* outbreak recorded in North Carolina. *Estuaries* **13**, 322–331.

Tenore, K. R. (1972) Macrobenthos of the Pamlico River Estuary, North Carolina. *Ecological Monographs* **42**, 51–69.

Tester, P. A., Stumpf, R. P., Vukovich, F. M., Fowler, P. K. and Turner, J. T. (1991) An expatriate red tide bloom: Transport, distribution, and persistence. *Limnology and Oceanography* **36**, 1053–1061.

Thomas, C. J. and Cahoon, L. B. (1993) Stable isotope analyses differentiate between different trophic pathways supporting rocky-reef fishes. *Marine Ecology Progress Series* **95**, 19–24.

Touchette, B. W. (1999) Physiological and developmental responses of Eelgrass (*Zostera marina* L.) to increases in water-column nitrate and temperature. Ph.D. Thesis, Department of Botany, North Carolina State University, Raleigh, NC.

Touchette, B. W. and Burkholder, J. M. (2000) Review of nitrogen and phosphorus metabolism in seagrasses. *Journal of Experimental Marine Biology and Ecology* (in press).

Thayer, G. W. (1971) Phytoplankton production and distribution of nutrients in a shallow unstratified estuarine system near Beaufort, NC. *Chesapeake Science* **12**, 240–253.

Thayer, G. W., Hoss, D. E., Kjelson, M. A., Hettler, W. F. Jr. and Lacroix, M. W. (1974) Biomass of zooplankton in the Newport River Estuary and influence of postlarval fishes. *Chesapeake Science* **15**, 9–16.

Thayer, G. W., Kenworthy, W. J. and Fonseca, M. S. (1984a) The Ecology of Eelgrass Meadows of the Atlantic Coast: A Community Profile. US Fish and Wildlife Service, Office of Biological Services (Temporary Report) FWS/OBS FWS/OBS/84-02, pp. 1–147.

Thayer, G. W., Bjorndal, K. A., Ogden, J. C., Williams, S. L. and Zieman, J. C. (1984b) Role of larger herbivores in seagrass communities. *Estuaries* **7**, 351–376.

Watling, L. and Norse, E. A. (1998) Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conservation Biology* **12**, 1180–1197.

Williams, R. B. and Murdoch, M. B. (1966) Phytoplankton production and chlorophyll concentration in the Beaufort Channel, North Carolina. *Limnology and Oceanography* **11**, 73–82.

Zimmerman, R. C., Smith, R. D. and Alberte, R. S. (1989) Thermal acclimation and whole-plant carbon balance in *Zostera marina* L. (eelgrass). *Journal of Experimental Marine Biology and Ecology* **130**, 93–109.

Zingmark, R. G. (1986) Production of microbenthic algae. In *South Carolina Coastal Wetlands and Impoundments: Ecological Characteristics, Management, Status, and Use. Vol. II: Technical Synthesis*, eds. R. Devoe and D. Baughman, pp. 179–194. SC Sea Grant Publication #SC-SG-TR-86-2, Charleston, SC.