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Estuaries of the Northeastern United States: Habitat and Land Use Signatures

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ABSTRACT: Geographic signatures are physical, chemical, biotic, and human-induced characteristics or processes that help define similar or unique features of estuaries along latitudinal or geographic gradients. Geomorphologically, estuaries of the northeastern U.S., from the Hudson River estuary and northward along the Gulf of Maine shoreline, are highly diverse because of a complex bedrock geology and glacial history. Back-barrier estuaries and lagoons occur within the northeast region, but the domiant type is the drowned-river valley, often with rocky shores. Tidal range and mean depth of northeast estuaries are generally greater when compared to estuaries of the more southern U.S. Atlantic coast and Gulf of Mexico. Because of small estuarine drainage basins, low riverine flows, a bedrock substrate, and dense forest cover, sediment loads in northeast estuaries are generally quite low and water clarity is high. Tidal marshes, seagrass meadows, intertidal mudflats, and rocky shores represent major habitat types that fringe northeast estuaries, supporting commercially-important fauna, forage nekton and benthos, and coastal bird communities, while also serving as links between deeper estuarine waters and habitats through detritus-based pathways. Regarding land use and water quality trends, portions of the northeast have a history of over a century of intense urbanization as reflected in increased total nitrogen and total phosphorus loadings to estuaries, with wastewater treatment facilities and atmospheric deposition being major sources. Agricultural inputs are relatively minor throughout the northeast, with relative importance increasing for coastal plain estuaries. Identifying geographic signatures provides an objective means for comparing the structure, function, and processes of estuaries along latitudinal gradients.

Introduction

Estuaries have been classified as drowned-river valleys or coastal plain, bar-built, lagoons, fjords, and tectonically-caused (Pritchard 1967a). Within this geomorphic classification, estuaries are defined by a diverse suite of characteristics, including circulation patterns (Pritchard 1967b) and related physical factors (e.g., tidal range, freshwater input, sediment load, etc.), dominant habitat types, and watershed factors, including physiography and land use. These characteristics often vary geographically and can be evaluated to define fundamental signatures of estuaries on a regional basis. Geographic signatures, as defined in this paper, are considered as physical, chemical, biotic, and human-induced characteristics or processes that result in particular, or sometimes unique, ecosystem responses within a region. For example, Chapman (1960) observed that salt marshes in New England are often small in area with organic peat substrates resulting from small drainage basins with relatively low suspended sediment loads. In contrast, southeastern U.S. drainage basins are large with high suspended sediment loads resulting in extensive salt marshes with substrates of high inorganic content. Physiography of the drainage basin and suspended sediment load can be considered as key characteristics, or signatures, that define the variability of salt marshes across regions. Similarly, these factors regulate seagrass distribution and growth along the U.S. Atlantic coast. As the high suspended sediment load of southeast coastal plain estuaries reduces water clarity, seagrass is limited in extent and where present, it is limited to less than 2 m depth (Thayer et al. 1984). Seagrass meadows in New England and Canada can exceed 10 m depth (Harrison and Mann 1975; Dennison and Alberte 1985; Short and Neckles 1999).

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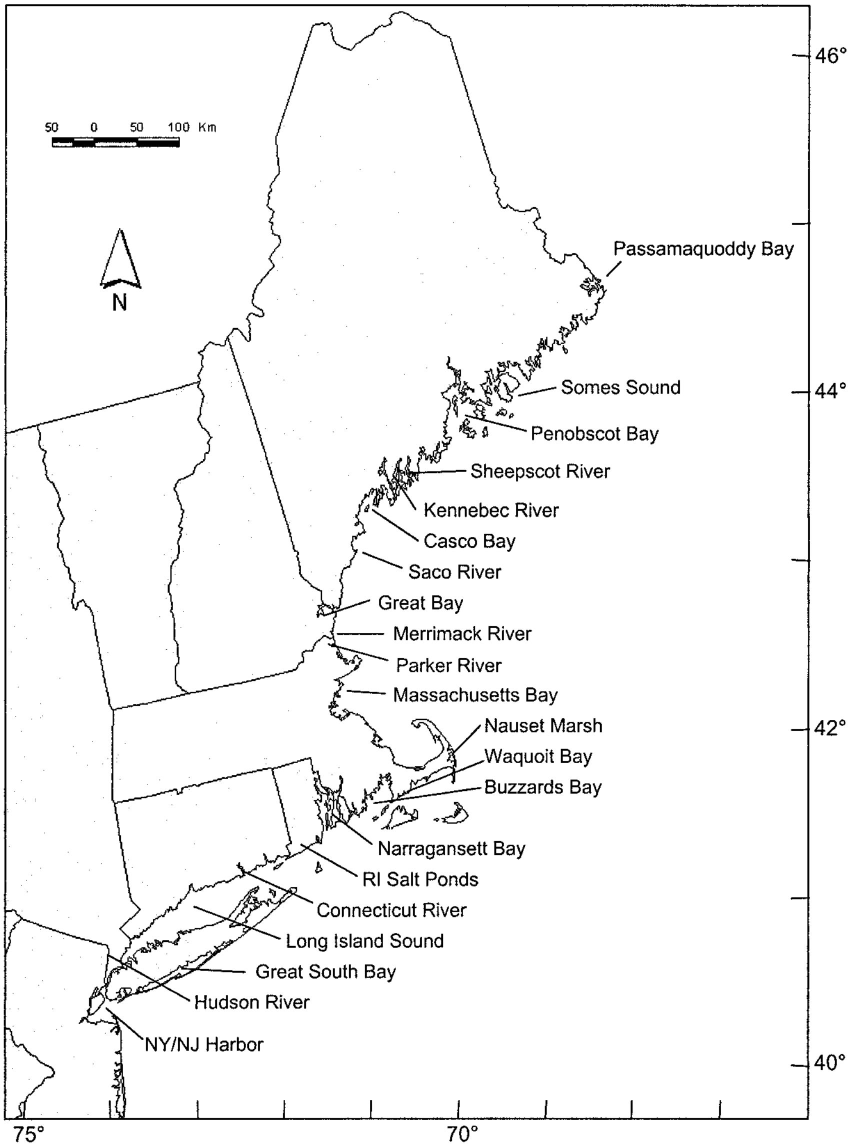

Fig. 1. Geographic extent of northeast estuaries. Many of the estuaries and sub-estuaries discussed in this paper are listed.

This paper will focus on the northeastern United States coastal zone, from the Hudson River and Long Island Sound to the Gulf of Maine (Fig. 1). The region is characterized by a diversity of estuarine types including, glacially-carved (e.g., Penobscot Bay, Maine) and fjord-like systems (Somes Sound, Maine), drowned-river valleys (e.g., Connecticut River, Hudson River) and lagoons (e.g., Rhode Island salt ponds). There is a wide range of development pressure and land use history with some watersheds exposed to over two centuries of intense urbanization (e.g., Lower Hudson River), while others have endured less development (e.g., Maine estuaries). This paper identifies the varied geomorphologies, land use histories, and other signatures that define past and current trends in the structure and function of estuarine habitats within the northeastern U.S.

Estuarine Geomorphology

GEOLOGICAL HISTORY

The shoreline of New England, from the Hudson River and northward is extremely diverse when compared to the barrier island-lagoon dominated coast that prevails from the south shore of Long Island, extending along the east coast of the Atlantic and into the Gulf of Mexico. The basic or gross configuration of the New England shoreline is related to the composition of bedrock and its differential weathering (FitzGerald et al. 1994). As an example, the coast of Maine has a diversity of shoreline types that are closely related to bedrock geology (Kelly 1987). The northern coast of Maine is a cliffed shoreline, the only continuous bedrock cliff on the U.S. east coast (FitzGerald et al. 1994), composed of volcanic rock eroding in a somewhat uniform manner resulting in a fairly straight shoreline. To the south, encompassing Penobscot Bay and vicinity, the shoreline is composed of a complex of granitic islands and broad embayments, while further south a highly indented shoreline (Casco Bay region) represents an example of differential erosion between resistent bedrock peninsulas and sedimentary deposits. From southern Maine and extending to the Boston area, a series of broad embayments are separated by erosion resistent headlands or capes (e.g., Cape Ann, Massachusetts).

In southern New England, the bedrock was covered by sediment eroded from uplands and deposited toward the ocean defining the northernmost extent of the Atlantic Coastal Plain. In areas from New Jersey and south, coastal plain sediments can be quite thick and extend far inland; however, in southern New England the coastal plain is not as extensive. The basic shoreline was originally shaped as these coastal plain sediments were eroded by south flowing drainages, integrated within less resistant bedrock. The numerous estuaries, oriented north-south, along the Connecticut (Lewis and Stone 1991), Rhode Island (McMaster 1984), and Buzzards Bay shorelines (FitzGerald et al. 1987), such as the Thames River, Housatonic River, Narragansett Bay, and Westport River estuaries, along with a nearly continuous band of smaller estuaries were formed within this valley-ridge topography.

New England's gross shoreline configuration was basically shaped by bedrock geology and established by the Early Tertiary period, but more recently, during repeated glaciations of the Pleistocene Epoch, river valleys and shorelines were deepened, widened, shaped, and/or sediment-filled. The most recent continental glacier, the Laurentide ice sheet of the late Wisconsin stage, and subsequent changes in sea level, had an extraordinary influence on northeastern U.S. estuaries. The general chronology of glacial processes and sea level fluctuations since the late Wisconsinan stage, and relevant to coastal New England, has been described and interpreted by many (Kelley et al. 1986; FitzGerald et al. 1994; and references therein). About 20,000 years ago the ice sheet reached its maximum southerly position, extending from near the mouth of the Hudson River, through Long Island, Block Island, Martha's Vineyard, Nantucket, and eastward to Georges Bank (Fig. 2). Northward retreat of the ice sheet was rapid, with deglaciation of the coastal Gulf of Maine region occurring from between 17,000 to 13,000 BP (years Before Present). In areas north of Boston land submergence occurred as the ice sheet retreated until rebound of the earth's crust exceeded eustatic sea level rise. During this marine transgression, about 14,000 BP, sea level ranged from 18 m to over 100 m higher than it is today. This high level, or highstand, was brief and with dramatic rebound of the crust relative sea level dropped up to 60 m below present levels, with the lowstand occurring about 12,000 to 11,000 BP. Sea level then rose rapidly from about 9,500 to 6,000 BP (about 6 mm yr^{-1}) and then began to slow toward the current rate of 2–3 mm yr^{-1}. Areas south of Boston did not experience the marine transgression following glacial retreat because crustal rebound exceeded the rate of eustatic sea level rise.

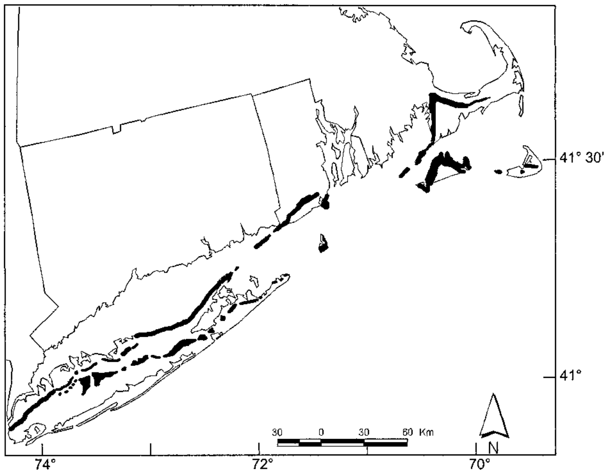

Fig. 2. Extent of Wisconsin glaciation showing end moraines on Long Island, Rhode Island, and the offshore islands (redrawn after Oldale 1992).

Glacial activity served to shape estuaries by carving or scouring bedrock, as evidenced by the fjord-like Somes Sound estuary in Maine (Folger et al. 1972), to re-shape or widen pre-glacial valleys, to deliver large amounts of sediments that are the foundation for barrier beaches, spits and other recent shoreline features, and most importantly, to dramatically influence sea level. The present Cape Cod landscape is defined almost exclusively by sediment deposition associated with the last glaciation, followed by about 15,000 years of reshaping by modern shoreline processes and sea level rise (Fisher 1987; Oldale 1992; Uchupi et al. 1996). When the rate of sea level rise began to slow, about 6,000 BP, barrier spits began to form throughout Cape Cod with subsequent establishment of shallow estuarine embayments (e.g., Pleasant Bay and

Nauset Marsh, Sandy Neck/Barnstable Marsh). The sequence of barrier spit growth and subsequent salt marsh development within the protected embayment is best typified by Redfield's (1965) classic study of Sandy Neck/Barnstable Marsh (Cape Cod, Massachusetts), where growth of the spit and salt marsh began about 4,000 years ago.

Similar to the Cape Cod example, barrier systems and salt marshes that are present today began to form throughout the New England region about 4,000 years ago, under a regime of slowed sea level rise. In southern Maine (Wells, Maine), a basal radiocarbon date of 4,220 BP is reported for back barrier salt marsh peat (Kelley et al. 1988). On Long Island Sound, Orson et al. (1987) describe a scenario of marsh development beginning about 3,800–4,000 years ago that was independent of barrier formation; freshwater marsh was replaced by salt marsh as the Pataguanset River valley was drowned with sea level rise. On the northern coast of Maine, a salt marsh located along the estuarine shore of a major river system dates to 4,095 BP, with salt marsh peat overlying freshwater peat (Kelley et al. 1988), similar to the Pataguanset example.

GEOMORPHOLOGICAL CHARACTERISTICS

Because of this complex of bedrock geology, glacial history, and sea level rise, coupled with factors like sediment supply and wave exposure, the shorelines of New England estuaries and associated habitats are extremely variable. Extensive barrier island shorelines (often extending for 50 km or more) fronting large shallow lagoonal estuaries (e.g., Barnegat Bay, New Jersey; Pamlico Sound, North Carolina) or large salt marsh complexes (e.g., associated with the Georgia and South Carolina coastal barriers) are limited in New England. The Merrimack River barrier system (e.g., Plum Island, Massachusetts; FitzGerald et al. 1994), the outer Cape Cod barrier complex (e.g., Nauset Spit, Monomoy Island, Massachusetts; Uchupi et al. 1996), and the southern shore of Rhode Island (Boothroyd et al. 1985) contain sandy barriers of about 30 km in length that front shallow estuaries dominated by *Spartina* marsh or tidal lagoons. However, most of the barrier shorelines of New England are short, generally less than 1 km, and unlike the sand substrate of barriers to the south, they can be composed of sediment ranging from fine sand to gravel and cobble, reflecting local bedrock and glacial geology (FitzGerald et al. 1994). Shallow estuaries are often associated with these small barriers.

While barrier shorelines are found throughout the region from northern Maine to the Hudson River estuary, back barrier estuaries, lagoons and coastal ponds represent a relatively small percentage of the types of estuaries found in the northeast. For instance, it is estimated that just 25% of the Massachusetts and Connecticut shoreline is composed of barrier systems, despite being the portion of the region with most abundant sediment supplies for barrier formation (FitzGerald et al. 1994). Most of the major estuarine systems in the region are of the drowned-river valley (e.g., Hudson River, Connecticut River, Narragansett Bay, Kennebec River) or drowned-basin type (e.g., Long Island Sound). The bedrock shorelines of the estuaries throughout the region were carved by glacial activity, but just one estuary in the northeast has the typical geomorphology of a fjord-type estuary. Somes Sound is a long (8 km), narrow (< 1 km), U-shaped valley flanked by mountains that rise over 250 m above sea level, with a maximum depth of 50 m and a shallow 10 m sill at the mouth (Pettigrew et al. 1997).

Reflecting the glacial history of the region, northeast estuaries are generally deep, except for the back-barrier systems (Fig. 3). Based on the National Oceanic and Atmospheric Administration National Estuarine Inventory database, the average depth of northeast estuaries (Passamaquoddy Bay, Maine to Hudson River/Raritan Bay, New York/New Jersey) is 13 m, compared to the much shallower coastal plain and back-barrier estuaries to the south (Middle Atlantic, 3 m; South Atlantic, 4 m; Gulf of Mexico, 2 m; National Oceanic and Atmospheric Administration 1990).

PHYSICAL CHARACTERISTICS

Because of high tidal range and relatively low freshwater discharge from riverine sources, tidal mixing is the dominant factor determining circulation patterns in northeast estuaries. Mean range of the semidiurnal tide in Passamaquoddy Bay can approach 6 m and is generally up to 3 m elsewhere throughout Gulf of Maine estuaries (Fig. 3). Tidal range of more southern New England estuaries is less (about 1–2 m), but still greater than in estuaries along the coastal plain to the south. There are obvious exceptions, such as the minimal tidal range of Rhode Island's coastal pond estuaries (< 0.5 m; Isaji et al. 1985), or portions of the Georgia coast exhibiting tidal ranges of 2 m or more. Despite these exceptions, tides of the northeast coast, and especially within the Gulf of Maine, are amplified with the highest recorded tides in the world occurring in the Bay of Fundy (15 m).

With regard to freshwater flow, Fig. 4 clearly illustrates that estuaries in the northeast have significantly lower average daily riverine flow than estuaries of the middle and south Atlantic coastal plain and Gulf of Mexico. In the northeast, watersheds are generally smaller as exemplified by the

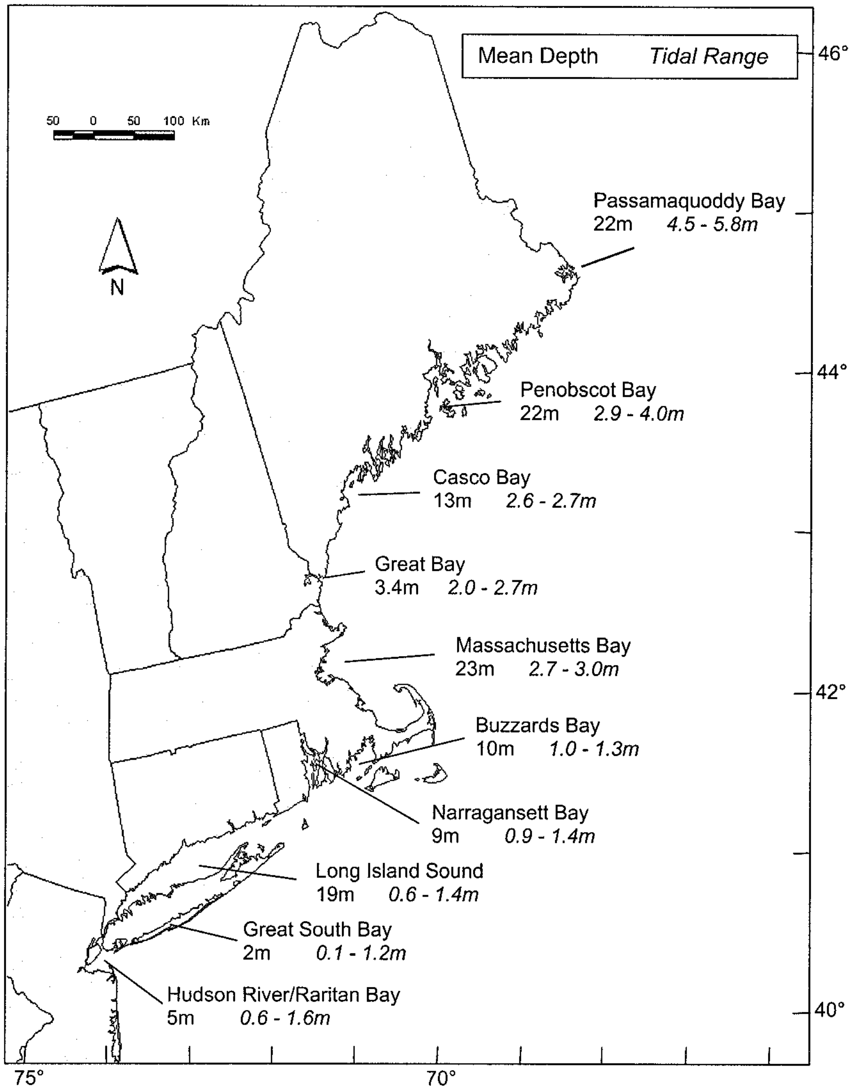

Fig. 3. Maximum depth and mean tidal range of selected estuaries in the northeast (data from National Oceanic and Atmospheric Administration 1990).

ratio of watershed drainage area to estuary water surface area for selected estuaries (Table 1).

Owing to the relatively small drainage basins, low freshwater flows, a bedrock substrate and relatively dense forest cover throughout the northeast region, sediment loads delivered to northeast estuaries are generally lower when compared to more southern coastal plain watersheds. Consequently, water clarity in northeast estuaries is greater than to the south, as reflected by a review of light extinction coefficient data distributed along a geographic gradient (Table 2).

Estuarine Habitats

OVERVIEW

The major nearshore and intertidal habitats of northeastern estuaries include rocky, cobble, gravel, and sandy shores, tidal mudflats, tidal wetlands, and seagrass. It is estimated that salt marshes exist along just 20% of Maine's 5,790 km of tidally influenced coastline (Jacobson et al. 1987), with the remainder presumably occupied by bedrock, gravel/cobble, or sand/mud shores. Similarly, most shorelines of Narragansett Bay are narrow beaches of cobble and gravel and some bedrock shores, with salt marshes being much less conspicuous (Olsen et al. 1980). Estuarine beaches are common throughout the northeast because there is a sufficient supply of sand or gravel and adequate wave and tidal energy to rework the sediments (Nordstrom 1992). Small gravel pocket beaches are common along the shoreline of Maine's estuaries, with the sediment derived from eroding bedrock (Duffy

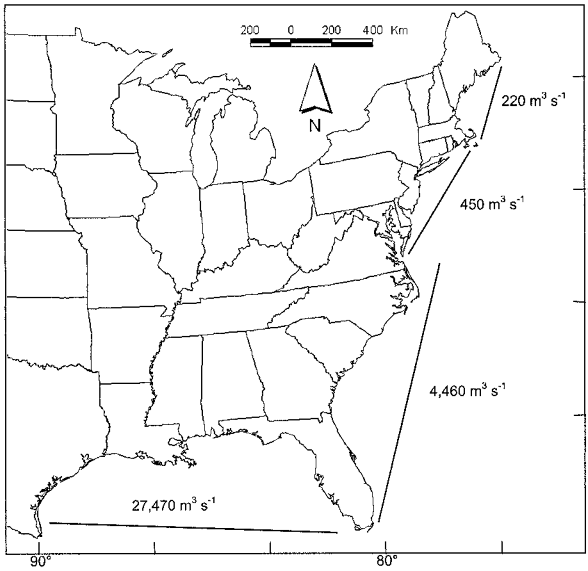

Fig. 4. Average daily freshwater flow to northeast, middle and south Atlantic, and Gulf of Mexico estuaries (data from National Oceanic and Atmospheric Administration 1990).

et al. 1989). In contrast, a coastal plain estuary like Delaware Bay contains a nearly continuous salt marsh border (Daiber and Roman 1988), yet estuarine beaches often front the marshes. Along the South Carolina and Georgia coasts salt marshes are extensive, with these two states containing over 60% of all east coast salt marshes from Maine to Florida (Reimold 1977). The following discussion focuses on signatures of tidal marsh, seagrass, intertidal mudflat, and rocky intertidal habitats of the northeast region.

TABLE 1. Ratio of watershed drainage area to estuary water surface area for selected estuaries along the Atlantic and Gulf of Mexico coasts (data from National Oceanic and Atmospheric Administration 1990).

Estuary	Ratio
Northeast	
Passamaquoddy Bay	20
Penobscot Bay	26
Casco Bay	7
Massachusetts Bay	3
Buzzards Bay	3
Narragansett Bay	11
Long Island Sound	13
Hudson/Raritan, New York/New Jersey	55
Middle Atlantic	
Barnegat Bay	14
Delaware Bay	18
Chesapeake Bay	18
Southeast Atlantic	
Cape Fear River	239
Winyah Bay	603
Altamaha River	947
St. Andrews, St. Simons Sounds	56
Gulf of Mexico	
Apalachicola Bay	96
Mobile Bay	109
Atchafalaya	143
Galveston Bay	45

TIDAL MARSHES

Compared to the signature of salt marshes of the middle and south Atlantic coasts and the Gulf of Mexico, northeast salt marshes are small in spatial extent and often exist as narrow fringing systems. The mean area of discrete marsh polygons in Maine is just 0.26 ha (Jacobson et al. 1987), while

TABLE 2. Light extinction coefficients for estuaries along the Atlantic and Gulf of Mexico coasts of the U.S. As water clarity increases, extinction coefficient decreases.

Estuary	Extinction Coefficient (m^{-1})	Source
Northeast		
Somes Sound, Maine	0.38–0.46	Roman and Doering unpublished data
Damariscotta River, Maine	0.45–0.72	Nixon 1986
Narragansett Bay, Rhode Island	0.58–0.76	Schenck and Davis 1973
Hudson River, New York	1.68–2.80	Sirois and Fredrick 1978
Middle Atlantic		
Delaware Bay, Delaware	0.3–7.0	Biggs et al. 1983
Chesapeake Bay	0.4–>2.0	Flemer 1970
Chesapeake Bay	1–5	Champ et al. 1980
Southeast Atlantic		
Core Sound, North Carolina	1.5–2.0	Thayer 1971
Fort Pierce Inlet, Florida	2.0–4.4	Thompson et al. 1979
Gulf of Mexico		
Charlotte Harbor, Florida	0.46–5.1	McPherson and Miller 1987
Barataria Bay, Louisiana	2.1	Nixon 1986
Sabine-Neches estuary, Louisiana/Texas	0.8–3.4	Bianchi et al. 1997

along the Connecticut shoreline of the Long Island Sound estuary the mean area is larger (39 ha; calculated from data provided in Niering and Warren 1974), but still small when compared to southern latitudes. Marshes in the Hudson River estuary range from saline to freshwater and are spread along the 240 km tidal portion. Like other northeast marshes, they are small with a mean area of just 23 ha. The lack of a broad and relatively flat coastal plain tends to limit the areal extent of marshes in the northeast. While small salt marshes dominate, there are some New England systems of notable size that are associated with barrier island or spit systems (e.g., Scarborough Marsh, Maine; Plum Island/Parker River marshes and Barnstable Marsh, Massachusetts).

The physiography and vegetation of northeast tidal marshes has been described by many, but with most detail provided for southern New England salt marshes (Miller and Egler 1950; Redfield 1972; Niering and Warren 1980; Nixon 1982). Here, a distinct pattern of vegetation is observed, with a narrow band of tall *Spartina alterniflora* occupying the low marsh, areas flooded twice daily by tides, and with high marsh areas flooded less frequently and forming a mosaic of vegetation types that may include, *Spartina patens, Distichlis spicata,* short form *S. alterniflora,* and *Juncus gerardii.* Salt marsh pannes, shallow depressions on the marsh surface often vegetated with forbs, and salt marsh pools can be present throughout the high marsh mosaic.

Descriptions of vegetation patterns on northern New England salt marshes are few, but differences are apparent. The low marsh along the Maine coast, north and east of Penobscot Bay, is dominated by *S. alterniflora,* but the high marsh has a greater diversity of plant species (Calhoun et al. 1993). In addition to *S. patens* and *J. gerardii,* the mosaic pattern of northern Maine salt marshes may include *J. balticus, Festuca rubra, Agrostis gigantea,* and *Carex paleacea,* among others. Along the upland border of salt marshes throughout New England and extending into southern Maine, *Phragmites australis* commonly occurs; it has not been noted in more northern salt marshes of Maine and the Bay of Fundy region (Jacobson and Jacobson 1989; Calhoun et al. 1993; Chmura et al. 1997). The northern region of Maine may represent a transition to Bay of Fundy salt marshes where vegetation zones of *S. alterniflora, Plantago maritima, S. patens, C. paleacea,* and *J. balticus* are noted (Pielou and Routledge 1976; Chmura et al. 1997).

Extensive areas of freshwater and brackish water tidal marshes are a common signature of the upper reaches of river-dominated estuaries throughout the middle and south Atlantic regions, but in the northeast they are rare, except for the major river valley systems of the northeast (Odum et al. 1984). For example, brackish water tidal marshes dominated by *Typha angustifolia* (narrow-leaved cattail) and freshwater tidal marshes with *Zizania aquatica* (wild rice), *Pontederia cordata* (pickerelweed), and *Scirpus pungens* (common three-square) are common along tidal reaches of the Connecticut River (Metzler and Tiner 1992) and Hudson River (Kiviat 1974). The rocky and steep-sided geomorphology of most tidal riverine systems throughout the northeast precludes the formation of extensive fresh and brackish tidal marshes (Odum et al. 1984). Most major rivers throughout the northeast have been dammed and the effect of this altered hydrology and sediment transport on tidal freshwater wetland development remains unstudied. In addition to dams, most of the tidal marshes along the Hudson River occur behind a railroad embankment that runs parallel to the river.

The geographically widespread effects of physical, human-caused, alterations on salt marshes is a fundamental habitat signature in the northeast. These impacts include filling, draining, mosquito ditching, and alteration of tidal exchange by roads, dikes, impoundments, culverts, tide gates, and other structures. Prior to passage of coastal wetland protection legislation by northeast states, beginning in the 1960s, salt marsh losses due to filling were extraordinary. For example, in Connecticut 30–50% of tidal marshes have been lost (Metzler and Tiner 1992; Rozsa 1995). Thirty-five percent of the United State's coastal population (based on census of coastal counties only) resides in the northeast (Maine to Virginia; Culliton et al. 1990) and it is not surprising that a direct relationship between coastal wetland loss and population density has been noted (Gosselink and Baumann 1980).

Mosquito ditches represent one of the most common features on the northeastern salt marsh with an estimated 90% of the marshes from Maine to Virginia being ditched (Bourne and Cottam 1950). In New England, salt marsh ditching began during Colonial times, the 17th century, primarily to drain the marsh and enhance opportunities for salt hay farming, but became most prevalent in the 1930s when ditches were dug in an effort to systematically drain mosquito breeding areas. In the small marshes that dominate the New England coast, ditches were often dug by hand, spanning entire marshes in dense parallel grid patterns, with about 40–50 m spacing. Unditched salt marshes are rarely encountered in the northeast (Fig. 5). Ditching, channelization, and impounding were common practices on marshes of the southeast and Gulf coast, but these practices were not nearly as

Fig. 5. Unditched (Nauset Marsh, Eastham, Massachusetts) and ditched salt marshes (Hammock River, Clinton, Connecticut). Note the extensive network of tidal creeks and marsh pools on the unditched marsh.

all encompassing and extensive as encountered in the northeast. The effects of ditching include a lowering of the marsh water table level, shifts in vegetation, draining of marsh pools and pannes, and subsequent loss of preferred waterfowl and wildlife habitat (Daiber 1986). Today, ditches that have been free from periodic maintenance cleaning for many decades still remain as conspicuous features on the marsh landscape.

Restriction of tidal flow is a significant hydrologic signature of many northeast tidal marshes. Causeways and dikes that cross marshes often have inadequately sized culverts or bridges and tidal exchange is restricted. In addition to transportation corridors, tidal flow was historically restricted to salt marshes throughout the northeast for salt hay farming and mosquito control purposes, and flow restriction was frequently exacerbated by tide gates. More recently, tide gates have been used for flood protection. In New Hampshire, it is estimated that 20% of the state's salt marshes are presently degraded because of inadequate tidal flow (Burdick et al. 1997). Numerous studies throughout New England have documented the hydrologic, vegetation, faunal, and biogeochemical responses of tidal marshes to restriction of tidal flow, and in turn, many successful efforts are underway to reintroduce tidal flow and restore the structure and function of degraded marshes (e.g., Roman et al. 1984; Sinicrope et al. 1990; Fell et al. 1991; Barrett and Niering 1993; Roman et al. 1995; Anisfeld and Benoit 1997; Burdick et al. 1997; Dionne et al. 1999; Portnoy 1999).

Although not a direct human impact, like ditching or tide restriction, rising sea level is a factor that has a strong influence on tidal marsh development processes. Several studies in the northeast report that rates of salt marsh accretion generally exceed rates of sea level rise, and thus, marshes are being maintained (Orson et al. 1987; Bricker-Urso et al. 1989; Wood et al. 1989; Orson and Howes 1992). Conversely, some marshes in the Chesapeake Bay (Stevenson et al. 1985) and large areas associated with the Mississippi delta region (Turner 1997) are becoming submerged and lost. Widespread submergence of northeast marshes is not reported; however, based on long-term trends in vegetation, Warren and Niering (1993) suggest that a Long Island Sound salt marsh may not be keeping up with sea level rise. On Cape Cod, another study found that sedimenation rate and rate of relative sea level rise were nearly similar, and like the Long Island Sound marsh, vegetation patterns indicate that the marsh is getting wetter, representing an initial response to wetland submergence (Roman et al. 1997).

SEAGRASSES

Habitats dominated by seagrass and other submerged aquatic vegetation occur along the estuarine gradient from marine to freshwater tidal portions of northeast estuaries. Seagrass species of northeast estuaries include eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*). Both species have broad salinity tolerances, but *Ruppia* in the northeast commonly occurs in brackish to freshwater estuarine areas or in salt marsh pools (Richardson 1980; Thayer et al. 1984). Within freshwater or brackish water tidal portions of the relatively shallow Hudson and Connecticut River estuaries, submerged aquatic vegetation can be extensive (e.g., *Ruppia, Vallisneria americana, Potamogeton perfoliatus*). In the Hudson River, beds of submerged vegetation, primarily *Vallisneria,* can occupy as much as 20% of the river bottom in areas shallow enough for establishment and growth of these light-limited plants (Harley and Findlay 1994).

Zostera is the dominant seagrass of the northeast

TABLE 3. Percentage of the total area of estuarine habitat types classified as intertidal flat for several states in the northeast and mid-Atlantic coastal plain. Percentages for some specific estuaries or portions of shoreline are also presented. Classifications are according to the National Wetlands Inventory (Cowardin et al. 1979).

Coastal State	% of Total Estuarine Area Classified as Intertidal Flat	Source
Northeast		
Maine	32	Fefer and Schettig 1980
Cobscook Bay/St. Croix estuary	50	Foulis and Tiner 1994a
Mount Desert Island and vicinity	75	Calhoun et al. 1993
Casco Bay estuary	52	Foulis and Tiner 1994b
Maine, New Hampshire, Massachusetts		
Gulf of Maine (York, Maine to Rowley, Massachusetts)	25	Foulis et al. 1994
Gulf of Maine (Plum Island, Massachusetts to Scituate, Massachusetts)	35	Foulis and Tiner 1994c
Rhode Island	41	Tiner 1989
Connecticut	33	Metzler and Tiner 1992
Mid-Atlantic Coastal Plain		
New Jersey	17	Tiner 1985a
Delaware	10	Tiner 1985b

often forming extensive underwater meadows. In terms of supporting detritus-based estuarine food webs, it is estimated that six new leaf crops are produced annually in a Cape Cod eelgrass meadow (Roman and Able 1988). This high turnover contributes to estuarine detritus, including extensive areas of eelgrass wrack that dominate many estuarine shorelines throughout the northeast (e.g., Josselyn and Mathieson 1980; Thorne-Miller et al. 1983).

Historically, eelgrass grew in most of the bays and estuaries of the northeast (e.g., Cottam 1934; Renn 1934; Addy and Aylward 1944; Costa 1988). The historic distribution of eelgrass in estuaries has been poorly documented, although it is likely that eelgrass disappeared in the 19th century from many systems of the northeast as a result of land clearing, deforestation, and industrial development. For example, in Great Bay, New Hampshire extensive logging and operation of saw mills on most rivers entering the estuary created a depositional layer of sawdust that likely eliminated eelgrass from many parts of the estuary (Short 1992). Such losses of eelgrass were generally localized and related specifically to human activity. However, in the 1930s an epidemic disease threatened to eliminate eelgrass from the northeast and elsewhere throughout the North Atlantic and Europe (Rasmussen 1977). This eelgrass decline, known as the wasting disease (Milne and Milne 1951), was a naturally occurring disease event likely caused by the marine slime mold *Labryrinthula zosterae* (Muehlstein et al. 1991). It devastated eelgrass populations, eliminating 90% of North Atlantic eelgrass. Following the extensive wasting disease epidemic of the 1930s, eelgrass populations slowly reestablished in much of their historic habitat throughout the northeast (Conover 1961; Dexter 1985; Costa 1988), although some areas (such as parts of Narragansett Bay) do not appear to have recovered (Short et al. 1993).

A recurrence of the wasting disease occurred in the 1980s (Short et al. 1986), with symptoms similar to those in the 1930s. Localized die-offs occurred along the east coast of the United States in upper Casco Bay, Maine; Great Bay, New Hampshire; Stage Harbor, Massachusetts; and the Niantic River, Connecticut. Although eliminated from the developed parts of estuaries and often fragmented by human activity, eelgrass remains an important and widespread estuarine habitat in the northeast.

With an increasing awareness of the values of eelgrass habitat, every northeast coastal state has initiated restoration, with mixed success. Site selection, insuring sufficient water quality, and appropriate geomorphological conditions are critical to restoration efforts (Fonseca et al. 1998). At a 2.5 ha restoration site in the Great Bay estuary, eelgrass has survived for 6 years with plant and animal populations comparable to natural eelgrass beds (Short et al. 2000). Development and refinement of planting methods (Orth et al. 1994; Davis and Short 1997), coupled with an emerging knowledge of site selection criteria (Fonseca 1992; Davis et al. 1998), will result in the long-term success of eelgrass habitat restoration efforts throughout the northeast.

INTERTIDAL MUDFLATS

Intertidal flats are a common and extensive habitat type in the northeast (Table 3). In some parts of the Gulf of Maine, intertidal flats represent over

50% of the total area of estuarine habitat types. At more southern latitudes, such as along the New Jersey and Delaware estuarine shorelines, intertidal flats are less conspicuous, mainly because of reduced tidal range. Mudflats, the dominant type of unconsolidated intertidal bottom in the Gulf of Maine, occur within protected areas often in association with salt marshes, eelgrass meadows and barrier systems. Over the long-term mudflats are depositional environments responding to rising sea level, but on seasonal or daily time scales they are both depositional and erosional features, responding to tidal currents, waves, ice scour, and bioturbation (Anderson et al. 1981; Pethick 1996).

Mudflats support microalgal production, dominated by benthic diatoms (Whitlatch 1982) and some are dominated by macroalgal mats. Welsh (1980) reports dense mats of the green macroalga, *Ulva lactuca,* in association with a Long Island Sound estuary under a regime of high nutrient loading. In a relatively undeveloped northern Maine estuary, dense mats of the green filamentous macroalga, *Enteromorpha intestinalis,* have been observed on mudflats, but the cause is unknown (Vadas and Beal 1987). These microalgal and macroalgal primary producers, coupled with the input of organic matter from adjacent habitats, play an important role in structuring and supporting a rich benthic fauna. Fefer and Schettig (1980), Whitlatch (1982), and Reise (1985), among others, provide excellent reviews on the role of tidal mudflats in coastal detritus-based food webs. Tidal flats are closely linked to adjacent habitats such as salt marshes, eelgrass meadows, and open water.

Predators are especially important in shaping benthic community structure and abundance in the mudflats. Bertness (1999), based on a literature review, has suggested that large mobile predators, such as blue crab (*Callinectes sapadis*) and spot (*Leiostomus xanthurus*), predominate to the south of Cape Cod. To the north, mobile predators are less abundant (especially blue crab which is absent) and infaunal predators, like polychaete worms, dominate. Comparing the role of predators in controlling benthic community structure and function of the biogeographically distinct regions north and south of Cape Cod deserves further study (Bertness 1999).

ROCKY SHORELINES

Coupled directly to glacial history and geomorphology, rocky shoreline habitats are perhaps the most unique habitat signature of northeast estuaries. This habitat is virtually absent along mid-Atlantic, southeast, and Gulf of Mexico coasts of the U.S. *Ascophyllum nodosum* (knotted wrack) dominates the intertial rocky habitats of protected estuarine shores throughout the northeast (Topinka et al. 1981; Bertness 1999). Productivity of rocky shore algae represents a dominant proportion of total primary production in shallow systems in Nova Scotia, Canada (Mann 1972, 1973). In the Great Bay Estuary, New Hampshire, *Ascophyllum* and other fucoid algae are also reported to be valuable contributors to the estuarine detrital pool (Josselyn and Mathieson 1978; Chock and Mathieson 1983).

Recent species introductions have had a dramatic influence on the ecology of northeastern rocky shorelines, as well as other habitats. Bertness (1984), studying the rocky cobble beaches of Narragansett Bay, found densities of the common periwinkle (*Littorina littorea*) in excess of 1,000 m^{-2} and reports grazing of all algae, except crustose forms. *L. littorea,* introduced in the mid 1800s, has become the dominant intertidal herbivore along the northeast coast. Lubchenco's (1980) classic study clearly documents the role of *L. littorea* in controlling the structure of New England rocky intertidal communities.

Another introduced species, the green crab (*Carcinus maenus*), is a predator on both rocky and soft-substrate habitats of the northeast, and like *L. littorea* has assumed an important role in shaping estuarine intertidal community structure. The issue of introduced species has become a serious concern, to the point that the structure and function of native estuarine communities in the northeast are difficult to define (Bertness 1999).

NURSERY ROLE OF NORTHEAST ESTUARINE HABITATS

Salt marshes and seagrass meadows have long been recognized as providing essential habitat for economically-important species and/or serving as an important nursery for marine species, yet most studies documenting nursery function have been from the mid-Atlantic and south. Young of the year penaeid shrimp (*Penaeus aztecus, Penaeus setiferus*), an economically valuable species, commonly use salt marshes along the southeast Atlantic and Gulf of Mexico coasts and are numerically abundant compared to other nekton using the marsh (e.g., Turner 1977; Boesch and Turner 1984; Zimmerman and Minello 1984; Kneib and Wagner 1994; McIvor and Rozas 1996). In Chesapeake Bay, it is well-documented that *Zostera* beds support high densities of the commercially and recreationally important blue crab (Heck and Thoman 1984). Published quantitative studies for decapod utilization of shallow estuarine systems in the northeast are few; but a comparison of studies from Massachusetts to Texas does demonstrate that commercially-important species, like blue crab and penaeid shrimp begin to be numerically abundant in the middle-Atlantic and south (Table 4). Although not a numerically dominant decapod, American lobster (*Homarus americanus*) was collected from Cape Cod eelgrass meadows (Heck et al. 1989), and in the same estuary it was discovered that salt marsh creek banks are used by American lobster as a nursery area for inshore populations (Able et al. 1988). We acknowledge that sampling methods and sampled habitats varied for the studies presented in Table 4 and direct comparisons should be made with caution; however, a trend does emerge suggesting a greater relative abundance of commercially or recreationally important decapods using southern estuarine habitats when compared to northern latitudes.

Regarding fishes using salt marsh and seagrass habitats as nursery areas, investigations from more southern latitudes have found commercially important species, such as spot (*Leiostomus xanthurus*), mullet (*Mugil curema*), and bay anchovy (*Anchoa mitchilla*), to be ranked as abundant (see references cited in Fig. 6 and Southeast and Gulf of Mexico review by McIvor and Rozas 1996). Fishes with life history strategies classified as nursery, marine, diadromous, or transient visitor appear to represent a much greater percentage of fishes using shallow estuarine habitats from more southern latitudes. In shallow estuarine habitats of the northeast, it is clear that resident fishes, such as mummichogs (*Fundulus heteroclitus*) and sticklebacks (e.g., *Gasterosteus aculeatus, Apeltes quadracus*), and seasonal residents (e.g., *Menidia menidia*) dominate the fauna (Fig. 6). About 90% of fishes collected from northeast estuaries (from Maine to New Jersey) were classified as resident, except for one site in southern Maine where the marine species sand launce (*Ammodytes americanus*) was dominant.

New England and northeast salt marsh and eelgrass habitats serve an important habitat function for commercially and recreationally important nekton species (e.g., menhaden, *Brevoortia tyrannus*; winter flounder, *Pseudopleuronectes americanus*; white hake, *Urophycis tenuis*; herrings, *Alosa aestivalis, Alosa pseudoharengus, Clupea harengus*; American lobster; and tautog, *Tautoga onitis,* among others; Nixon and Oviatt 1973; Teal 1986; Heck et al. 1989; Ayvazian et al. 1992; Dorf and Powell 1997), albeit not as abundant fauna like the blue crab, brown shrimp or spot from more southern systems. In terms of commercial molluscs, eelgrass in the northeast provides settlement substratum for spat and juvenile shellfish as noted for blue mussels (*Mytilus edulis*; Newell et al. 1991; Heck et al. 1995; Grizzle et al. 1996) and bay scallops (*Argopecten irradians*) in Great South Bay (Pohle et al. 1991) and Cape Cod (Heck et al. 1995). Regarding intertidal mudflats in the northeast, commercial harvest of soft-shelled clams (*Mya arenaria*) and baitworms (bloodworm, *Glycera dibranchiata*; sandworm, *Nereis virens*) is prevalent, especially in northern New England (Fefer and Schettig 1980).

Salt marshes, eelgrass beds, and mudflats of the northeast support commercially-harvested estuarine fauna, but they also serve an especially important role in providing habitat for forage species, which in turn support commercial and recreational fishes and coastal bird populations. This brief review of nursery role focuses on the intertidal and shallow water habitats that fringe northeast estuaries. Subtidal and deeper estuarine habitats also serve an important nursery function and support of commercial and recreational fisheries throughout the region, including among others, American lobster, hard clam (*Mercenaria mercenaria*), bay scallop, winter flounder, tautog, and anadromous finfish species. The shallow and emergent habitats of northeast estuaries serve an important link to the deeper estuarine waters and habitats through the estuarine detritus-based trophic structure.

Land Use and Nutrients

HISTORIC TRENDS

There have been over two centuries of intense development pressure within the northeast as evidenced by transformation of the landscape from deforested (1750–1860), extensive agriculture (1790–1860), and then reforestation (1860 to the present; Fig. 7; Foster et al. 1992). This land clearing marked the start of the American Industrial Revolution with the nation's first mill established in 1790 on the Blackstone River, Rhode Island, a tributary to the Narragansett Bay estuary. With land clearing and industry, contaminants were discharged into northeast estuaries, as evidenced in estuarine sediment records. In Narragansett Bay, metals such as lead, chromium, and copper first appeared in the sediment record by the early 1800s, with pronounced increases beginning in the 1850s as industrial activities accelerated (Bricker-Urso et al. 1989; Nixon 1995a).

Regarding the history of nutrient loading to northeast estuaries, estimates were made of the average annual loading of total nitrogen from watersheds, for the period of 1900 to 1994, and included the contribution of various sources, including wastewater, atmospheric deposition, and agricultural runoff. The method for developing these historical reconstructions is presented elsewhere (Jaworski et al. 1997; Hetling et al. 1999) and only briefly described here. The historical wastewater flows were assumed to be proportional to water-

TABLE 4. Relative abundance of decapods collected from shallow estuarine habitats along a gradient from Massachusetts to Texas. Species representing at least 90% of the total decapod catch are presented. Habitats sampled and gear types used are variable as noted.

Estuary	Habitat	Gear	Species	Relative Abundance (% of total catch)	Source
Nauset Marsh Estuary, Massachusetts	Eelgrass	Trawl	*Crangon septemspinosa* (Sand shrimp)	55	Heck et al. 1989
			Carcinus maenas (Green crab)	38	
Connecticut River, Connecticut	Brackish Marsh	Fyke net	*Palaemonetes pugio* (Grass shrimp)	100	Fell et al. 1998
Great Bay-Little Egg Harbor, New Jersey	Salt marsh	Weir	*Palaemonetes vulgaris* (Grass shrimp)	66	Rountree and Able 1992
			Crangon septemspinosa	29	
Great Bay-Little Egg Harbor, New Jersey	Eelgrass	Enclosure trap	*Palaemonetes vulgaris*	35	Sogard and Able 1991
			Crangon septemspinosa	33	
			Hippolyte pleuracantha (Grass shrimp)	30	
York River, Virginia	Eelgrass	Trawl	*Palaemonetes vulgaris*	52	Heck and Thoman 1984
			Crangon septemspinosa	26	
			Callinectes sapidus (Blue crab)	17	
Cape Fear River, North Carolina	Salt marsh	Seine	*Penaeus aztecus* (Brown shrimp)	52	Weinstein 1979
			Callinectes sapidus	25	
			Penaeus duorarum (Pink shrimp)	15	
			Penaeus setiferus (White shrimp)	6	
Sapelo Island, Georgia	Salt marsh	Flume weir	*Palaemonetes pugio*	84	Kneib and Wagner 1994
			Penaeus setiferus	16	
Cocodrie, Louisiana	Salt marsh	Seine	*Palaemonetes* sp.	81	Peterson and Turner 1994
			Penaeus setiferus	9	
			Callinectes sapidus	9	
Galveston Bay, Texas	Salt marsh	Enclosure trap	*Palaemontes pugio*	53	Zimmerman and Minello 1984
			Penaeus aztecus	18	
			Penaeus setiferus	14	
			Callinectes sapidus	14	

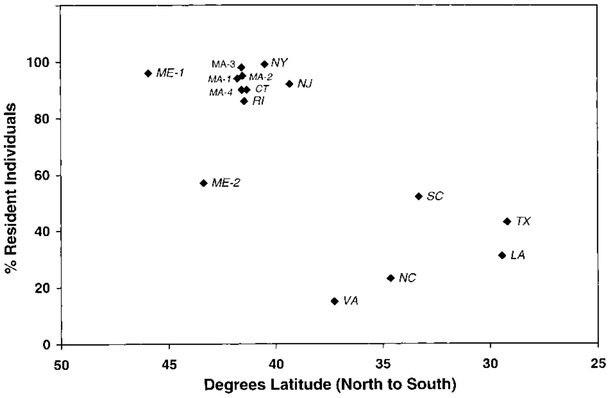

Fig. 6. Percent of total number of fishes that are classified as resident or seasonal resident species (after Ayvazian et al. 1992; Peterson and Turner 1994; Able et al. 1996), collected from several shallow estuarine salt marsh and eelgrass habitats from Maine to Texas. ME-1 = Montsweag Bay (Targett and McCleave 1974); ME-2 = Wells Harbor (Ayvazian et al. 1992); MA-1 = Nauset Marsh (Heck et al. 1989); MA-2 = Waquoit Bay (Ayvazian et al. 1992); MA-3 = Great Sippewissett (Werme 1981); MA-4 = Slocum River (Hoff and Ibara 1977); RI = Pettaquamscutt River and Point Judith Pond (Mulkana 1966); CT = Connecticut River (Fell et al. 1998); NY = Great South Bay (Briggs and O'Connor 1971); NJ = Great Bay-Little Egg Harbor (Rountree and Able 1992); VA = York River (Heck and Thoman 1984); NC = Cape Fear River (Weinstein 1979); SC = North Inlet (Cain and Dean 1976); LA = Cocodrie (Peterson and Turner 1994); TX = Galveston Bay (Zimmerman and Minello 1984).

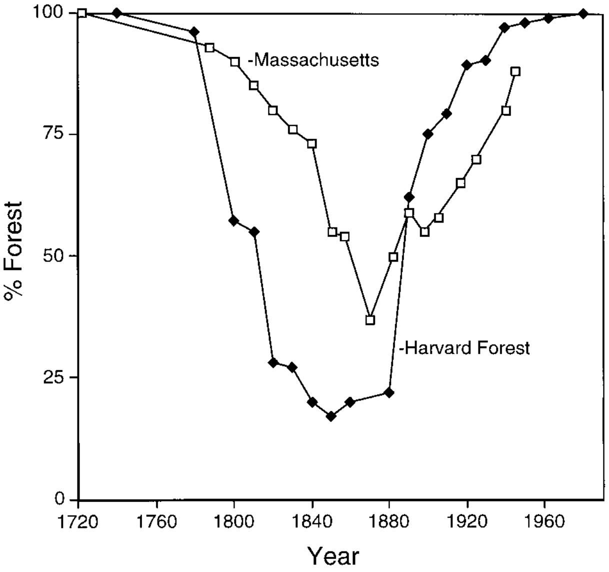

Fig. 7. Historic trends in percent forest cover in the state of Massachusetts and a portion of the Harvard Forest in central Massachusetts (redrawn after Foster 1992).

shed population, and for total nitrogen, the historical wastewater effluent concentrations were set equal to current effluent concentrations. For total phosphorus, wastewater effluent concentrations have changed dramatically because of the changing composition of detergents, thus historical total phosphorus effluent concentrations were estimated from historical sampling data. By assuming the current ratio of emissions to deposition has remained the same since 1900, historical nitrogen deposition loadings were computed from estimates of the historical emissions of nitrogen oxides to the atmosphere. Loadings from agricultural runoff were estimated from animal census and fertilizer use data. Detailed presentations and discussions of nutrient loading data, both historic and current, are being prepared and are summarized here (Hetling and Jaworski in preparation; Jaworski and Hetling in preparation).

The reconstructed riverine source apportionments in Fig. 8 are based on average annual inputs and do not show the considerable variability of average annual loadings calculated from actual monitoring programs. Regardless, the match between observed loadings and average annual estimates is reasonable. Historic trends in total nitrogen for the Merrimack River, Massachusetts show a fourfold increase in atmospheric deposition as a source from 1900–1994 (Fig. 8a). A more urban watershed, such as Massachusetts Bay, revealed that wastewater inputs of total nitrogen dominated over time, as would be expected (Fig. 8b).

An analysis of 10 watersheds along a latitudinal gradient from Maine to Virginia shows that total nitrogen loading increased from about 200 to 1,000 kg N km^{-2} yr^{-1} since 1900, with atmospheric deposition clearly representing the largest anthropogenic source to coastal watersheds (Jaworski et al. 1997). Going back further in historic time to pre-industrial conditions, Nixon (1997) has suggested that atmospheric deposition of nitrogen within the Narragansett Bay watershed was only 5% of present deposition.

The loading of total phosphorus from wastewater discharges has changed dramatically over the past 95 years, as noted for the Merrimack River (Fig. 8c). With the introduction of high phosphorus detergents in the late 1940s phosphorus loading from wastewater facilities increased dramatically. The advent of low phosphorus detergents in the 1970s has resulted in the precipitous decline in recent decades.

In addition to determining historic nutrient loading trends to northeast estuaries, we have reconstructed the historic annual average concentrations of total nitrogen and total phosphorus entering estuaries (i.e., point-of-entry concentrations) as another means of studying the impact of human activity on estuarine nutrient status (Fig. 9). These concentration estimates were derived from average

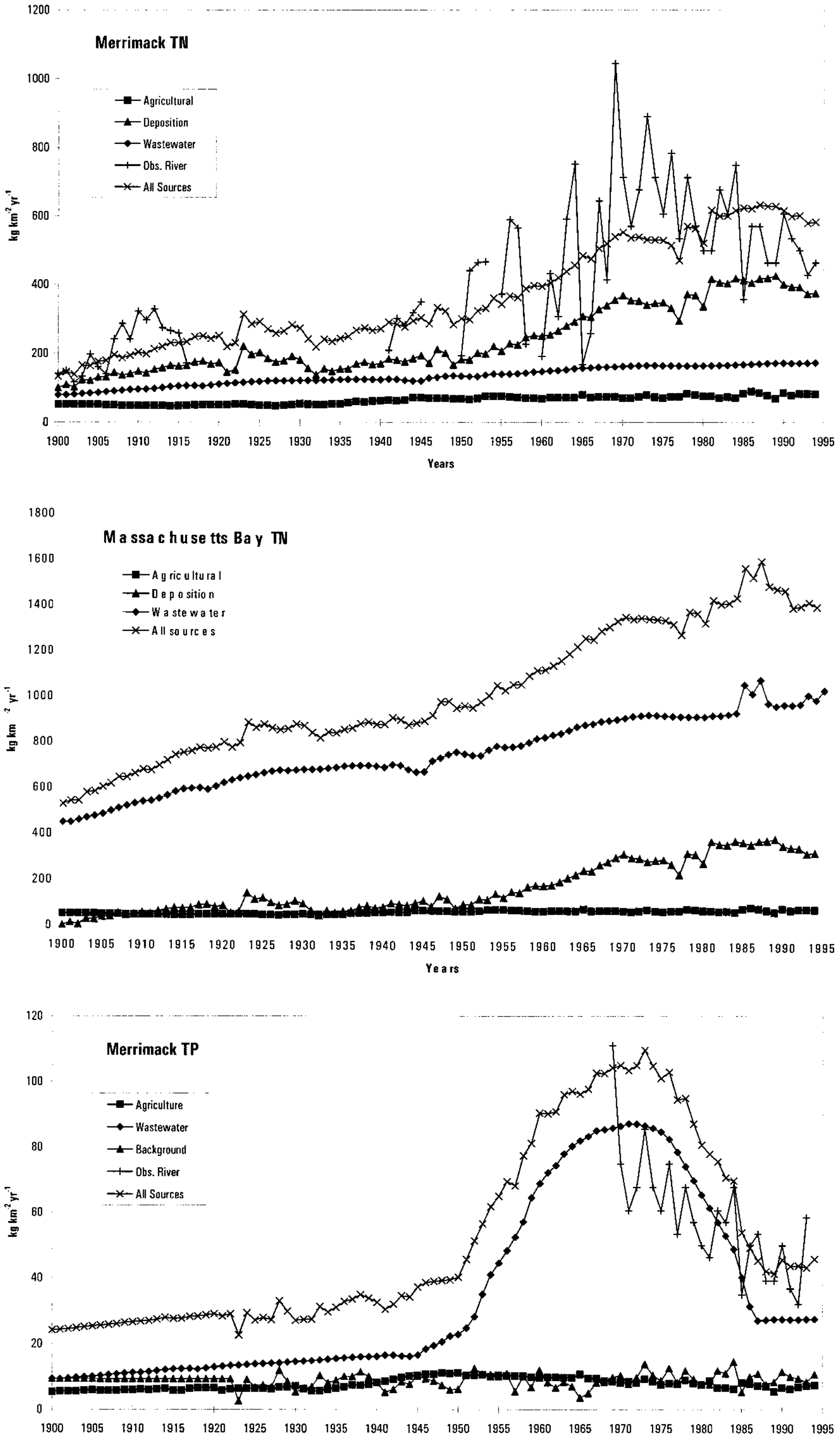

Fig. 8. Average annual nutrient loadings from various sources in kg of nutrient km^{-2} of watershed per year, estimated for the period 1900 to 1994. Top panel: total nitrogen for Merrimack River. Middle panel: total nitrogen for Massachusetts Bay. Bottom panel: total phosphorus for Merrimack River.

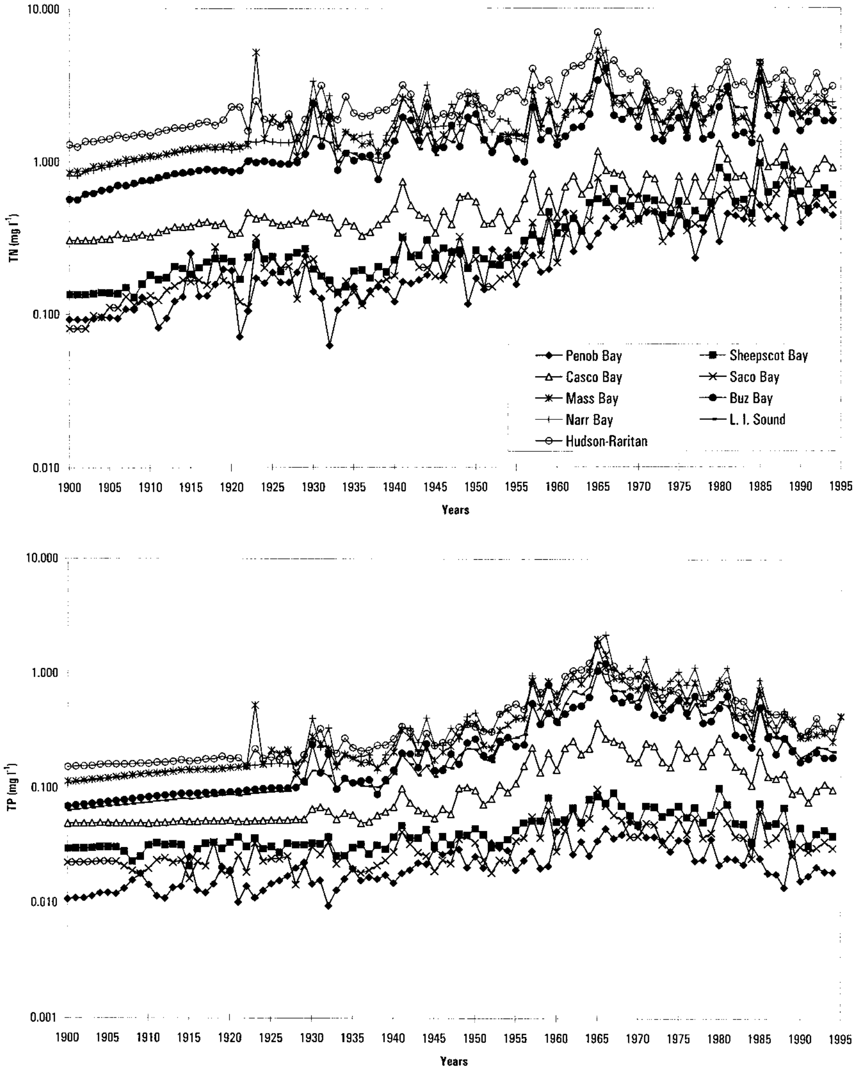

Fig. 9. Average annual concentration of nutrients entering several northeast estuaries, reconstructed for the period 1900–1994. Top panel: total nitrogen. Bottom panel: total phosphorus.

annual loadings, in kg km^{-2} of watershed yr^{-1}, divided by the annual river discharge. The point-of-entry nutrient concentrations do not include any tidal dilution or dispersion. Total nitrogen point-of-entry concentrations in eight northeast estuaries have increased by a factor of over three since 1900 (Fig. 9a). The estuaries to the north, in Maine, have lower average annual concentrations than the more southern systems. It is noted that total nitrogen concentration in the more urban systems of the northeast appears to have leveled in recent decades, while concentration in the more northern systems is increasing, presumably due to increased urbanization and atmospheric deposition. Maine watersheds, with high riverine flows, thin soils, and short growing seasons may be less effective at retaining atmospherically-deposited nitrogen (Jaworski et al. 1997).

Total phosphorus point-of-entry concentrations in the estuarine plumes for the eight northeast systems reached highest levels in the 1960s and have declined since, reflecting detergent bans (Fig. 9b). As with total nitrogen, the more urban estuaries in the southern portion of the region have higher concentrations.

CURRENT TRENDS

Based on an assessment of coastal counties, the northeast (defined from Maine to Virginia by Culliton et al. 1990) is the most densely populated coastal region in the U.S. Sixteen percent of the entire national population resides within this nar-

TABLE 5. Average annual loading (1988–1994) and relative sources (atmospheric, agricultural runoff, wastewater treatment facilities, background) of total nitrogen and total phosphorus loading to northeast estuaries compared to some mid-Atlantic coastal plain estuaries.

Estuary	Total N Loading (kg km^{-2} y^{-1})	% Total N Source			Total P Loading (kg km^{-2} y^{-1})	% Total P Source		
		Atmos	Agri	Waste		Agri	Waste	Backgd
Northeast Less Developed								
Penobscot Bay, Maine	310	82	13	6	12	27	30	43
Sheepscot River, Maine	372	77	12	11	25	25	36	39
Casco Bay, Maine	573	50	6	44	63	8	82	10
Saco River, Maine	387	82	8	10	22	19	35	45
Northeast Urban								
Massachusetts Bay, Massachusetts	1373	24	6	70	198	3	92	5
Buzzards Bay, Massachusetts	1373	33	8	59	139	6	87	7
Narragansett Bay, Massachusetts/Rhode Island	1597	23	4	73	233	2	93	5
Long Island Sound, Connecticut/New York	1571	29	11	61	143	11	83	7
New York/New Jersey Harbor	1882	27	15	58	253	12	84	4
Coastal Plain								
Delaware Bay, Pennsylvania/New Jersey/Delaware	1825	34	22	45	124	31	60	8
Upper Chesapeake, Maryland	1083	48	36	17	44	36	45	18
Potomac River, Maryland	1245	36	36	28	58	72	21	7
Rappahannock River, Virginia	641	60	32	8	69	65	13	22

row fringe of northeast coastal counties. Over 60% of the region's total population, in 1990, lived within coastal counties, representing just 25% of the region's total land area.

Related to the high population density, wastewater strongly influences the current loading of nutrients to northeast estuaries (Table 5). Estuaries to the south, along the mid-Atlantic coastal plain, have a greater agricultural influence. For the period of 1988–1994, sources of total nitrogen and total phosphorus were quantified by combining the source apportionment watershed loading data and wastewater effluent loading data that discharges directly into tidal waters. The average annual total nitrogen loading flux, normalized by watershed area, for the estuaries in Maine was 410 kg km^{-2} yr^{-1}, while the average loading for the more urban estuaries from Massachuestts Bay to New York/New Jersey Harbor was substantially greater, 1,560 kg km^{-2} yr^{-1}. About 65% of total nitrogen loading for the urban estuaries was from municipal wastewater discharges. In contrast, atmospheric deposition represented over 70% of total nitrogen loading to the Maine estuaries. Agricultural runoff represents less that 10% of total nitrogen loading for all of the northeast estuaries, while for the more southern coastal plain estuaries agriculture has a much greater influence on total nitrogen loadings, often exceeding 30% of all sources (Table 5).

As would be expected, total phosphorus loading for the Maine estuaries averaged 30 kg km^{-2} yr^{-1} with about 59% from municipal wastewater discharges, while almost 90% of the total phosphorus loading to the urban northeast estuaries was from wastewater treatment discharges. Agricultural influences dominated total phosphorus loadings to the coastal plain estuaries.

Shallow Estuarine Systems: Nutrients and Habitat Responses

A shift from seagrass to macroalgal-dominated communities appears to be an increasingly recognizable signature within shallow nutrient-enriched estuaries of the urban and urbanizing northeastern U.S. There is a clear relationship between increased housing density and decreased cover of eelgrass at the Ninigret Pond, Rhode Island and Waquoit Bay, Massachusetts shallow estuarine embayments (Fig. 10; Short et al. 1996; Short and Burdick 1996). With increased housing density, corresponding increased nutrient loading, and decreased eelgrass cover, there is an increase in macroalgal biomass at these two southern New England systems (Thorne-Miller et al. 1983; Valiela et al. 1992; Peckol and Rivers 1996). Similarly, Kinney and Roman (1998) have documented the relationship between increased nutrient loading and the conversion of a *Ruppia*-dominated shallow estuary in Maine to green macroalgae, and along Connecticut's Long Island Sound shoreline the green macroalga, *Ulva lactuca,* often dominates in shallow nutrient enriched embayments (Mumford Cove, see Harlin 1995). Competition for light is a key factor responsible for the seagrass declines under nutrient enriched conditions (Short et al.

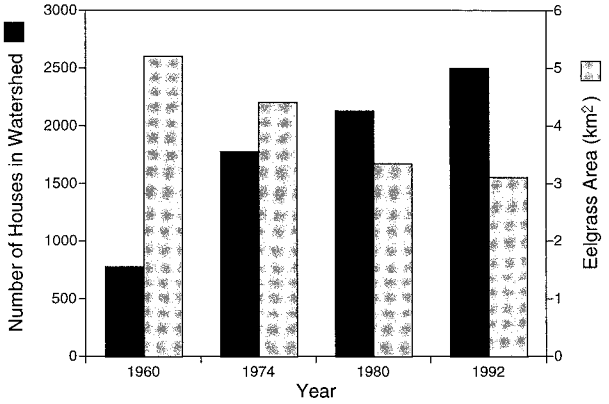

Fig. 10. Relationship between housing density and eelgrass at Ninigret Pond, Rhode Island (data from Short et al. 1996).

1995; Taylor et al. 1995). Light limitation of enriched seagrass communities can also be attributed to phytoplankton blooms and seagrass epiphyte growth (Ryther and Dunstan 1971; Harlin 1995).

Pathways of nitrogen delivery to estuarine systems include atmospheric deposition, river discharge, oceanic fluxes, and groundwater, while most significant sources of nitrogen may include atmospheric contamination, wastewater from treatment facilities or on-site septic systems, and fertilizer use (Nixon 1995b; Jaworski et al. 1997; Valiela et al. 1997). In shallow estuarine systems throughout the northeast, especially within watersheds dominated by highly permeable sand/gravel glacial outwash aquifers, groundwater is a dominant source of freshwater and associated nitrate contamination (Valiela et al. 1990; Short et al. 1996; Portnoy et al. 1998). In some shallow southern New England estuaries, over 80% of total inorganic nitrogen inputs are from groundwater discharge (Table 6). There is minimal removal of nitrate as groundwater discharges from highly permeable watersheds into estuarine shorelines that have sandy and low organic sediments, with little or no fringe of salt marsh (Valiela and Costa 1988; Giblin and Gaines 1990; Nowicki et al. 1999). These shorelines are common from New York to southeastern Massachusetts and concentrations of groundwater-delivered nitrate can be exceptionally elevated within developed watersheds, in excess of 400 μM (Table 6). In contrast to sandy shorelines, as groundwater discharges through highly organic intertidal/subtidal sediments, removal of nitrate by denitrification would be expected before discharge to estuarine waters (Valiela and Teal 1979; Capone and Bautista 1985; Howes et al. 1996).

Summary

Statements that highlight typical characteristics of estuaries for discrete geographic regions should be made with caution because there are always exceptions. For the northeastern U.S. general or common signatures of estuaries are evident, but since the geomorphology is so complex, ranging from bedrock-dominated shores to sand-dominated barriers, there are many exceptions to the typical northeast estuary. Acknowledging this variability, northeast estuaries are relatively deep when compared to more southern systems along the coastal plain, tidal range is high, drainage basins are small and forested, leading to low riverine freshwater flows and low suspended sediment loads. Tidal marshes are small in area and often occur as fringing systems. Resident fishes, including mummichogs, sticklebacks, and silversides, dominate shallow estuarine habitats of northeast estuaries (salt marshes, eelgrass meadows). Related to the high tidal range, intertidal mudflats are extensive in northern New England. Compared to mid-Atlantic, southeast, and Gulf of Mexico coasts, rocky shorelines are a unique feature of northeast estuaries and a direct result of the region's glacial history. Urban land use is a striking feature of northeast estuarine watersheds, especially from Boston to New York. In response, nutrient enrichment is an increasingly recognizable signature, especially within shallow estuarine embayments of the region.

Understanding fundamental characteristics or

TABLE 6. Role of groundwater in delivering nitrate to shallow estuarine systems of southern New England. * denotes average range from several sites.

Estuary	% of Total Freshwater Input by Groundwater	% of Total N Inputs by Groundwater	Groundwater Nitrate Concentration (μM)	Source
Rhode Island Salt Ponds, Rhode Island		88		Lee and Olsen 1985
Buttermilk Bay, Massachusetts		85	0.2–450	Valiela and Costa 1988
			318–431*	Weiskel and Howes 1992
Waquoit Bay, Massachusetts	89			Cambareri and Eichner 1998
			0.3–352	Valiela et al. 1990
Little Pond, Massachusetts	95			Milham and Howes 1994
Nanset Marsh, Massachusetts			6–203*	Portnoy et al. 1998

signatures of estuaries from throughout the U.S. coastal zone, and other areas worldwide, is especially important to recognizing unique processes, trends, or forcing functions that define particular regions. For example, deep estuarine basins are unique to northeast estuaries. What are the ecological linkages between these basins and shallow estuarine habitats, such as seagrass beds, marshes, and mudflats? Rocky shores, dominated by macroalgae, are common throughout the northeast, and in some estuaries may represent the dominant shallow water habitat. The relative contribution of these habitats to total system primary production needs to be quantified. And what is the nekton support function of these rocky habitats? Within the northeast region, Cape Cod is a major biogeographic boundary between boreal species and temperate/southern species. How will global climate change, and associated alteration of physical characteristics of northeast estuaries, influence species composition and abundances along this biogeographic boundary? A major source of nutrient inputs to estuaries of the urbanizing northeastern U.S. is from wastewater sources, whereas agricultural sources are more important in mid-Atlantic and southern coastal plain estuaries. How do these varying sources, when coupled with different watershed characteristics (deciduous forests, thin soils, step topographic gradients to the north; coniferous forests or agricultural, well-developed soils, subtle gradients to the south), influence the processing of nutrients during delivery to the estuary? Knowledge of both unique and common estuarine signatures can be especially useful when designing new research initiatives intended to focus on geographic comparisons.

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