The Ecological Collapse and Partial Recovery of a Freshwater Tidal Ecosystem

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Abstract - European settlement of New England initiated a novel disturbance regime that was prolonged, intensifying through time, and spatially widespread. By the mid-20th century, human commercial and industrial activities had brought about the ecological collapse of several major rivers. Since the mid-1970s, river ecosystems have recovered substantially in response to primary treatment of industrial and municipal wastewaters mandated by the Clean Water Act of 1972. Here we reconstruct an environmental history of a river-estuary complex in mid-coast Maine to examine ecosystem degradation and collapse during three centuries of intensified human disturbance followed by ecosystem recovery over the three decades since the Clean Water Act and the ban on the general use of DDT pesticide in 1972.

Merrymeeting Bay is a large, freshwater tidal ecosystem formed by the confluence of six rivers, 30 km inland from Maine's Atlantic coast. It was once a major stopover for migrating waterfowl and provided vital spawning and nursery habitat for anadromous fish. However, human activities—beginning with overfishing, land clearance, and dam building in the 18th century and culminating in severe industrial and municipal pollution in the 20th century—fully degraded this important ecosystem. By the mid-20th century, summer dissolved oxygen concentrations were routinely depleted resulting in vast fish kills, and poisoning from DDT pesticide eliminated reproduction of Bald Eagles. Since primary treatment facilities began operation and the DDT ban went into effect, dissolved oxygen concentrations have generally been maintained above dangerously low levels, and reproduction has recovered in Bald Eagles and some species of anadromous fish. These improvements notwithstanding, the legacies of past human disturbance continue to impact this important ecosystem. Merrymeeting Bay is permanently shallower, its anadromous fish runs are vestiges of their former abundances, toxic substances remain in its biota and sediments, and it continues to receive excess nutrients from industrial and municipal sources. These legacies are varied and profound. Whereas some physical, chemical, and biological properties recovered rapidly with cessation of the disturbance, others will require considerable more time or may never fully recover.

Introduction

The agricultural, commercial, and industrial development that accompanied European settlement of New England dramatically changed the nature, intensity, and scale of human disturbance in terrestrial and aquatic ecosystems (Foster et al. 1998). The new disturbance regime elicited novel responses from

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the biota, as its intensity and scale had not been experienced previously (Foster et al. 1997, 1998). Much is known about the resulting impacts on terrestrial ecosystems. Over a period of three centuries, much of New England was deforested and converted to agriculture (Foster 1992, Whitney 1994, Williams 1982), and forest ecosystems responded with significant changes in community composition and in temporal and spatial dynamics. For example, at the time of European settlement, the distributions of tree taxa and forest composition in North Central Massachusetts exhibited significant regional variation and strong correspondence with climatic gradients (Foster et al. 1998, Fuller et al. 1998). However, the combination of the altered disturbance regime, ongoing human disturbance, and a short time period for recovery homogenized the forests and disrupted the earlier vegetation–environment relationships (Foster et al. 1998).

Whereas ecologists have learned much about the response of forest ecosystems to broad-scale human disturbance (e.g., Binford et al. 1997, Foster et al. 2002, Gomez-Pampa and Kaus 1992), much remains to be learned about a similar intensification of human disturbance of rivers and estuaries. In addition to land clearance, which accelerated sedimentation into waterways (Cooper 1995, Dearing et al. 1987, Gaillard et al. 1991), "industrial" rivers in New England were also subjected to overfishing, dam-building, and water pollution (Cumbler 2001, Judd 1997, Steinberg 1991). These changes were similarly novel and broad in spatial and temporal scale. Never before had fish species been harvested to local extinction nor had dams altered the flow regime of rivers and prevented anadromous fish from reaching their spawning habitat. Never before had so many chemicals, many not previously occurring in nature, been discharged directly into waterways and the atmosphere.

This intensified disturbance regime largely reflected European settlement and development of natural resource extracting industries. In the early 17th century, pioneer settlers harvested salmon, sturgeon, and fur-bearing animals for commercial markets in Europe. By 1670, several sawmills along Maine's western coast exported lumber to Boston and large *Pinus strobus* L.(white pine) trees to England for ship masts (Churchill 1995). Throughout the 18th and 19th centuries, dams were constructed at key locations on rivers to power ever larger sawmills and eventually textile and shoe factories (Eastman and Rivard 1995). Rivers provided transportation and water power, but also a convenient waste disposal service for escalating levels of industrial development. The advent of Maine's paper and pulp industry during the late-19th century began an era of egregious water pollution. For at least eight millennia, Native Americans had sustainably harvested the seasonally abundant resources of Maine's coastal waterways (Bourque 2001). However, in the three centuries following the arrival of Europeans, commercial and industrial activity fully degraded many of Maine's rivers. The Androscoggin was referenced in Ripley's "Believe It or Not" because fumes emanating from its waters changed the color of painted buildings along its banks (Chase 1949). The Kennebec, Penobscot, and Saco were judged little better. As late as 1994, the Androscoggin was still considered one of the most polluted rivers in the United States (EWG 2005).

The deplorable pollution of Maine's rivers in the mid-20th century eventually catalyzed the political and legislative action that led to the Clean Water Act of 1972. Growing up in Rumford, ME, a paper-mill town on the Androscoggin, Edmund S. Muskie (1914–1996) was well acquainted with industrial pollution. As Governor of Maine, he became frustrated that businesses refused to locate in his state because the rivers were so polluted, and he began a campaign to force industry and municipalities to treat their wastewater. Later as United States Senator, Muskie crafted the bill that became the Clean Water Act and deftly garnered the political support needed to pass the legislation and override a presidential veto. Also in 1972, the new Environmental Protection Agency banned the general use of DDT pesticide in the United States. These landmark environmental regulations were responsible for much of the improvement in the water quality of lakes, rivers, and streams throughout the United States (US Senate Committee on Environment and Pulic Works 2004).

Here we reconstruct an environmental history of Merrymeeting Bay (Fig. 1), the largest freshwater tidal ecosystem on the Atlantic coast north of Chesapeake Bay. Merrymeeting Bay is formed by the confluence of the

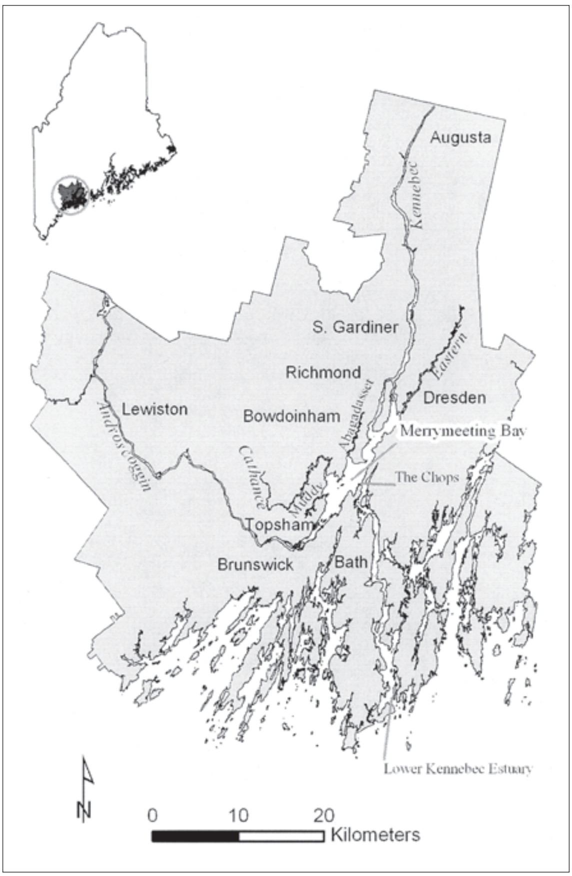

Figure 1. Regional map showing Merrymeeting Bay and the surrounding towns.

Kennebec, Androscoggin, and four minor rivers 30 km inland from the Atlantic coast. It was heavily impacted by human activities along its shores and along its tributaries, and by the 1970s, Merrymeeting Bay was considered "biologically dead" and "an open sewer" (MDEP 1979). The objectives of this historical study were 1) to document the ecological deterioration and collapse of Merrymeeting Bay in response to intensified human disturbance, 2) to examine ecosystem recovery following the implementation of the Clean Water Act and the ban on DDT pesticide use, and 3) to consider the potential legacies of past human disturbance for better understanding and management of the current ecosystem.

To reconstruct an environmental history of Merrymeeting Bay and its tributary rivers, we compiled historical information from a variety of sources documenting change in local land use, water quality, juvenile fish recruitment, and *Haliaectus leucocephalus* L. (Bald Eagle) reproductive success over the last 25 to 70 years. Although these variables represent a limited subset of the important aspects of ecosystem structure and function, they do integrate many of the effects of human disturbance and are good indicators of environmental health in a freshwater, tidal ecosystem. We argue, as have others (e.g., Foster et al. 2003), that to better understand, manage, and conserve an ecosystem, its environmental history and potential legacies of that history must be considered.

Methods

Site description

The Abenaki name for Merrymeeting Bay is "Quabacook," which means duck water place. English settlers named the freshwater tidal ecosystem "Merrymeeting Bay" because it was the place of rendezvous for Abenaki tribes living on the rivers that empty into it, and because its expansiveness appeared as a bay to those traveling by canoe (McKeen 1853). Merrymeeting Bay is formed by the confluence of the Kennebec, Androscoggin, Cathance, Abagadasett, Muddy, and Eastern Rivers approximately 30 km inland from the Maine coast (Fig. 1). The Kennebec and the Androscoggin are Maine's second and third largest rivers, respectively, with a combined discharge ranging between 150 and 600 $m^3 sec^{-1}$ during the ice-free season. Water draining one-third of the area of Maine and part of New Hampshire exits into the lower Kennebec estuary through a relatively narrow (i.e., 215 m wide) channel called "the Chops." The high rate of discharge through this narrow exit channel limits the upstream movement and mixing of seawater. Although seawater does intrude into Merrymeeting Bay during periods of low river flow, salinities generally range below the 5 -ppt threshold that distinguishes freshwater from estuarine ecosystems (Kistner and Pettegrew 2001, Spencer 1959, Wong and Townsend 1999).

Freshwater tidal ecosystems occur in the upper portion of estuaries where river flow is adequate to maintain low salinity, but not sufficient to overcome the force of the tides. Substantial inputs of allochthonous organic matter coupled with rapid decomposition and nutrient turnover make these ecosystems highly productive (Odum et al. 1984, Simpson et al. 1983). In Merrymeeting Bay, emergent plant communities dominated by *Zizania aquatica* L. (wild rice) inhabit expansive areas of intertidal mudflats. Wild rice and other emergent plant species provide forage for the large populations of migrating waterfowl for which Merrymeeting Bay was once renowned (Mendall and Spencer 1961, Noble 1905). Throughout this paper, we refer to Merrymeeting Bay, its four small tributaries, and the freshwater tidal portions of the Androscoggin and the Kennebec Rivers as the Merrymeeting Bay ecosystem (Fig. 1).

Environmental history

To reconstruct a general environmental history of Merrymeeting Bay, we searched the ecological and historical literature including published and internal reports of state agencies charged with natural resource management. There were few published articles in the scientific literature about Merrymeeting Bay or the major rivers. However, historical data were obtained from the Maine Department of Inland Fisheries and Wildlife (MDIFW), the Department of Marine Resources (MDMR), and the Department of Environmental Protection (MDEP). Published histories of the surrounding towns provided background information, and historical information about the anadromous fish runs was obtained from the Reports of the Commissioners of Fish and Game for the State of Maine (1867–1884), the Reports of the Sea and Shore Fisheries (1885–1916), and from various reports of the current MDMR (1974–2003).

Local land use

In 1998, a local conservation organization, *Friends of Merrymeeting Bay*, contracted an engineering firm to conduct aerial photography, mapping, and spatial analysis of Merrymeeting Bay and a 0.8-km strip of the surrounding upland area (Sewall and Co. 2000). The project expanded on previous aerial photographic studies conducted in 1956, 1961, and 1981 (Anderson 1982; Spencer 1959, 1966) and analyzed temporal trends in the spatial extent of emergent plant community types, total vegetative cover, unvegetated sand and silt, and various land-use categories in the upland strip. We used the results of this study to document change in local land use and sedimentation between 1956 and 1998. The history of land use throughout the larger watershed was drawn from various environmental histories of Maine (i.e., Day 1963; Irland 1998, 1999; Judd et al. 1995).

Water quality

To reconstruct a time series describing change in water quality before and after the Clean Water Act of 1972 and the EPA ban on DDT pesticide use, we used intermittent reports dating back to 1930 listing measurements of summer (July through September) dissolved oxygen concentrations and water pH for the tidal portion of the Kennebec River at South Gardiner, upriver of Merrymeeting Bay (Fig. 1). Fecal coliform counts were available during the 1970s. Few data were available for the tidal portion of the Androscoggin or for Merrymeeting Bay proper. Consequently, we relied on the longer time series established for the tidal Kennebec, which supplies, on average, 60% of the water to Merrymeeting Bay. Because the Androscoggin was more heavily polluted than the Kennebec, the time series may under-represent the severity of pollution in the ecosystem. Data were collected during the summer months because rivers are most vulnerable to oxygen depletion during periods of warm temperatures and low flow. For recent years, we obtained water quality data from the MDEP and the MDMR, and contributed our own measurements made with a multi-parameter sonde (Yellow Springs Instruments #6600).

In addition to direct indicators of water quality, we obtained data from chemical analyses of the intertidal soils conducted during the era of raw industrial and municipal pollution. In 1957 and 1966, soil cores were collected to 30-cm depth from widespread locations around Merrymeeting Bay on the intertidal mud flats inhabited by wild rice and other emergent plant species (Spencer 1959, 1966). The samples were analyzed for percent organic C, pH, extractable cations, and extractable orthophosphate-P. We duplicated the methods of laboratory analysis for organic C, pH, and extractable orthophosphate-P as described by Carpenter (1953) from samples collected in the same general sampling locations. This allowed us to document changes in intertidal soil chemistry before and after the Clean Water Act of 1972. The recent soil samples were dried at 60 ºC for five days in a convection oven prior to grinding with a ball mill for C and N analysis (Costech Analytical, ECS 4010). Measurements of soil pH were made with a Brinkmann model #691 pH-meter on subsamples mixed 1:1 by volume with de-ionized water. The orthophosphate concentration was determined colorimetrically in an acetic acid extraction solution as specified by Carpenter (1953) with a Schimadzu UV-1601 spectrophotometer (Clesceri et al. 1998, Method #4500-P); data are given in gP m^{-2}.

Reconstructing a time series of toxic substance pollution was problematic because laboratory analyses for toxic substances have been infrequent. Instead of a detailed time series, we report toxic substances that have been detected in the past based on DEP documents and data stored in the US Environmental Protection Agency's web-based data archive (STORET; USEPA 2005). To detect and quantify the presence of toxic substances in the sediments of Merrymeeting Bay, we conducted a MicroTox® bioassay of soils collected from vegetation survey transects widely spaced around the circumference of Merrymeeting Bay. Each transect started at mean high tide and extended 50 m onto the intertidal mud flat. Soils were sampled to 15-cm depth at distances of 0, 5, 10, 15, 20, 25, 30, 40, and 50 m from the mean high-tide strandline. The Microtox® assay uses luminescent bacteria to measure chronic toxicity in sediments and soils (Bulich et al. 1996).

Juvenile fish surveys

Beginning in 1979 and continuing to the present, the MDMR conducted juvenile fish censuses annually at 14 sites in the Merrymeeting Bay ecosystem (Squiers 2002). A beach seine made of 6.35-mm stretch mesh nylon, 17-m long, and 1.8-m deep with a 1.8-m x 1.8-m bag at its center was held stationary at the shore, and the other end was towed in an upriver arc with a small boat. The sampling area of each tow is approximately 220 m^2. Each of the 14 sites was sampled six times between mid-July and October. The number of juvenile *Alosa pseudoharengus* Wilson (alewives), *Alosa sapidissima* Wilson (American shad), *Alosa aestivalis* Mitchill (blue-back herring), and *Morone saxatalis* Walbaum (striped bass), along with the identification and number of resident fish species, were noted. Data are given as the catch per unit effort (CPUE), calculated by dividing the number of individual fish caught by the number of seine tows.

Bald Eagle surveys

The MDIFW has conducted annual surveys of Bald Eagle nesting and reproductive success since 1962 (Todd 2002). Each year, an inventory of all traditional nest sites and searches for new sites were conducted aerially in late March and April when resident eagles breed. Occupied nests are rechecked in June or July to determine reproductive success. From this database, we reconstructed a 40-year time series showing the number of nesting adult pairs and the number of fledglings utilizing Merrymeeting Bay and the lower Kennebec estuary.

Results and Discussion

Land-use change and sedimentation

Today, much of Merrymeeting Bay's 4330 ha is extremely shallow. Intertidal wetlands comprise approximately 47% of the total area, and much of the subtidal zone is less than 2 m deep at low tide. The tidal portion of the Androscoggin between Merrymeeting Bay and Pejebscot Falls at Brunswick is shallow as well. Historians have suggested that this was not the case during the 17th century, as even the largest vessels of that era were able to navigate the Androscoggin to Brunswick (McKeen 1853, Wheeler and Wheeler 1878). McKeen (1853) explains:

> "This Bay being formerly deep and navigable for any vessels of that day, has long since become shallow; being filled with sand brought down and deposited from the several rivers emptying into it. The channels through the bay from these rivers vary and change from year to year, with almost every freshet."

> "Hundreds of acres of land may be found in and about Merrymeeting Bay, where were formerly deep and navigable waters. To these causes may be attributed great changes at Pejebscot falls and other places on the river. At this early period in the seventeenth century, there can be no doubt that vessels of almost any burden might come to the foot of Pejebscot falls, and that boats might have been towed over the rapids."

McKeen was probably referring to the early settlements at Brunswick and Topsham and to fire within the region during King Phillips War in 1676 when he mentioned "great changes" in the second passage. Homestead development and logging would have also resulted in soil erosion and increased sedimentation (Cooper 1995, Dearing et al. 1987, Francis and Foster 2001, Gaillaird et al. 1991). Widespread land clearance began in the 1720s following the founding of the towns of Brunswick, Topsham, Bath, Richmond, and Dresden. By 1760, much of the land surrounding Merrymeeting Bay was cleared for crops, hayfield, and pasture (Allen 1931). By 1867, the effects of increased sedimentation were apparent. Vessels of 1000 tons destined for Brunswick and Topsham were required to "lighter up" (i.e., unload some of their cargo) five miles downriver because of shifting sands in the mouth of the Androscoggin (Wells 1869). Throughout southern Maine, agricultural area increased to a peak in 1880, then decreased gradually until 1920, after which farms were abandoned due to financial failure (Day 1963, Irland 1998). Reforestation occurred rapidly on the abandoned farm fields.

Aerial photographic studies show that agricultural lands and old fields decreased by 1649 ha (53.5%) between 1956 and 1981, whereas forest area increased by 1020 ha (21.0%). Between 1981 and 1998, agricultural lands and old fields decreased by another 339 ha (23.7%) with forests also declining slightly (i.e., 130 ha, 1.6%). Over the forty-two year period, residential and commercial land use increased with farm abandonment. These local land-use changes were coincident with the broader pattern of farm abandonment and reforestation throughout southern Maine (Day 1963, Irland 1998). As the watershed reforested, the total area of intertidal wetlands stabilized. Examination of the aerial photographs indicates a net gain of 26 ha of intertidal area (i.e., 1.3% of the total area of Merrymeeting Bay) between 1956 and 1981. Field observations in the early 1960s were consistent with increasing intertidal area at the mouth of the Androscoggin (Spencer 1966). The total area of intertidal sand and silt has remained constant since 1981 (Fig. 2), indicating that soil erosion and the extremely high sedimentation rates have stabilized after approximately 50 years of forest recovery within the watershed, despite the concomitant increase in local residential and commercial land use.

Deforestation and enhanced sedimentation may negatively affect aquatic ecosystems for many decades by altering benthic habitat and the physical environment (Harding et al. 1998) as well as by reducing the inputs of coarse woody debris into waterways (Bilby and Likens 1980, Christensen et al. 1996). Submerged aquatic vegetation and benthic organisms make up an important component of the trophic web in freshwater tidal ecosystems (Odum et al. 1984), and coarse woody debris influences habitat structure and biogeochemical cycling in river ecosystems (Foster et al. 2003).

Water pollution

The history of the decline in water quality in Merrymeeting Bay can be traced to industrial and municipal growth along the Androscoggin and Kennebec Rivers. The era of unmitigated water pollution began with the incipient industries that depended on the substantial waterpower of the Androscoggin and Kennebec Rivers. Sawmills at Brunswick and Topsham were constructed soon after the first dam was built across the Androscoggin in 1753 (Wheeler and Wheeler 1878). By 1800, a tannery was in operation at Brunswick, and by 1812, textile mills and a foundry were established. The Topsham Paper Company was founded in 1868 on the Androscoggin and was followed soon by a pulp mill. In 1837, the Kennebec dam at Augusta was constructed, which powered ten sawmills and a textile mill by 1846 (North 1870). Each of these industries disposed of their raw wastes—including great quantities of sawdust, acids, fibers, and dyes—directly into the rivers. By 1893, the Androscoggin already had a reputation for being polluted (Owen 1936).

The most destructive point sources of water pollution were the sulphite pulp mills (Water Improvement Commission 1960). Between 1885 and 1905, three sulphite pulp mills were built on the upriver Androscoggin (Lawrance 1967), and by 1931, six mills were in operation on the Kennebec (Walker 1931). The sulphite pulp process involved heating a mixture of wood chips and sulphurous acid for 20 to 30 hours (Sutermeister 1941), after

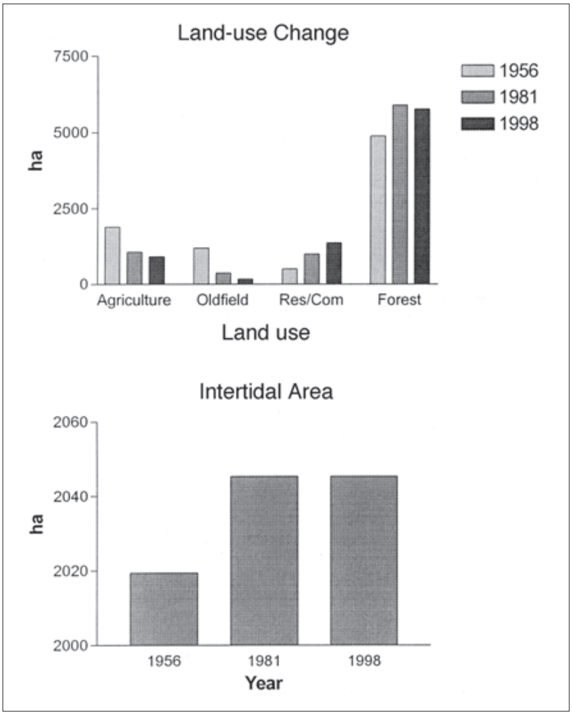

Figure 2. Late 20th-century land-use change in a 0.5-mile strip adjacent to Merrymeeting Bay. Change in total intertidal area reflects change in sedimentation.

which the waste liquor, which contained fibrous and dissolved organic matter and was quite acidic (i.e., lignosulphonic acid, pH ≈ 2), was discharged directly into the river (Lawrance 1967, Water Improvement Commission 1960). The tremendous inputs of organic matter stimulated microbial growth and respiration, which, in turn, depleted dissolved oxygen in the river water. In the 1940s, the Androscoggin frequently went anoxic in the warm summer months of low flow, which resulted in the generation of H_2S gas. H_2S gas emanating from the river caused noxious odors in towns along its banks, most notably in the Lewiston area (Chase 1949, Lawrance 1967). The Kennebec experienced summer anoxia at least as early as 1947 and consistently through the 1960s and early 1970s. Vast fish kills were reported in 1947, 1957, 1963, and 1965 (MDEP 1971, Water Improvement Commission 1966).

The time series of summer dissolved oxygen concentrations shows the tidal portion of the Kennebec emptying into Merrymeeting Bay already polluted with oxygen-depleting organic matter by 1930, and worsening through the early 1970s (Fig. 3). Dissolved oxygen concentrations were lower than 5 ppm in the summer of 1930, and reached complete anoxia during the middle 1960s before rebounding after 1976 to concentrations around 8 ppm. Although the frequency of data collection was sparse before 1976, both the 1930 and 1949 surveys represent intensive studies processing numerous water samples throughout the summer. The rapid recovery of dissolved oxygen concentrations after 1976 was associated with the initial treatment of waste liquor at the upriver pulp mills (MDEP 1979). Acidic waters also prevailed into 1970s, but gradually improved thereafter (Fig. 3). Fecal coliform counts were infrequent, but data gathered during the 1970s indicate large inputs of raw sewage. Most probable number (MPN) counts per 100 ml of river water ranged between 550 and 15,000—substantially higher than the 64 MPN limit specified by current water quality standards for a class B river (i.e., suitable for swimming, fishing, and drinking water supply after treatment; MDEP website).

Our comparison of intertidal soil chemistry shows major changes in pH, orthophosphate-P, and percent C before and after the Clean Water Act of 1972 (Fig. 4). In 1957 and 1966, the soils were quite acidic (pH < 4), whereas measurements in 2003 averaged 6.5 pH units. Extractable orthophosphate was abundant in 1957, but lower in 1966 and 2003. Percent C increased dramatically between 1957 and 1966, then declined back to the 1957 level by 2003.

These patterns can be explained by deposition of suspended solids from industrial and municipal sources. A 1973 engineering report described Merrymeeting Bay's intertidal mud flats as being "… formed mainly by sedimentation of silt and sludge from upstream" (Reed and D'Andrea Co. 1975). Given that the pH of the river water never dropped as low as pH 4 (Fig. 3), suspended solids derived from the acidic pulp wastes and other industrial sources were the likely causes of the low intertidal soil pH. At pH 4, Al and Fe oxides and hydroxides release orthophosphate-P into the soil solution (Vepraskas and Faulkner 2001), where it can be adsorbed to exchange sites and measured as extractable P. Thus, the high levels of extractable P in 1957 correspond to low pH, and

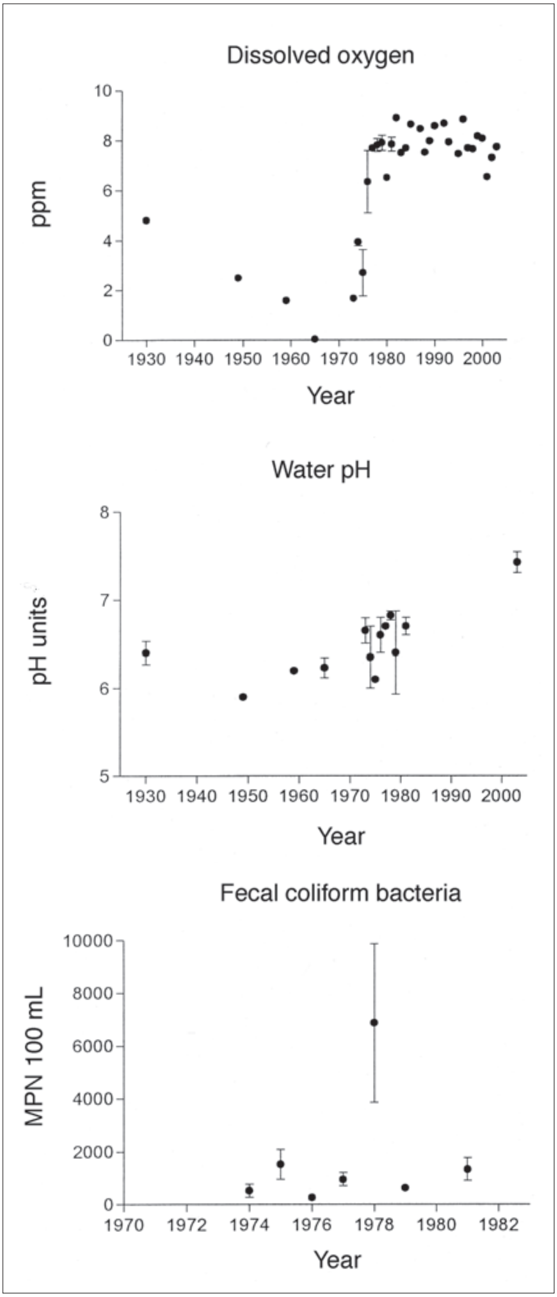

Figure 3. Time series illustrating change in water quality. Summer (July, Aug, Sep) dissolved oxygen concentrations, water pH, and fecal coliform counts.

the low amount of extractable P in 2003 corresponds to high pH (Fig. 4). In this context, the results for 1966 are anomalous. Low pH did not correspond to high extractable orthophosphate. However, the doubling of organic C concentration between 1957 and 1966 would have diluted the amount of mineral soil in the sample from which the orthophosphate derived. Because the acetic-acid extractant will only release weakly bonded orthophosphate-P, organic-P in the sewage would not have been measured.

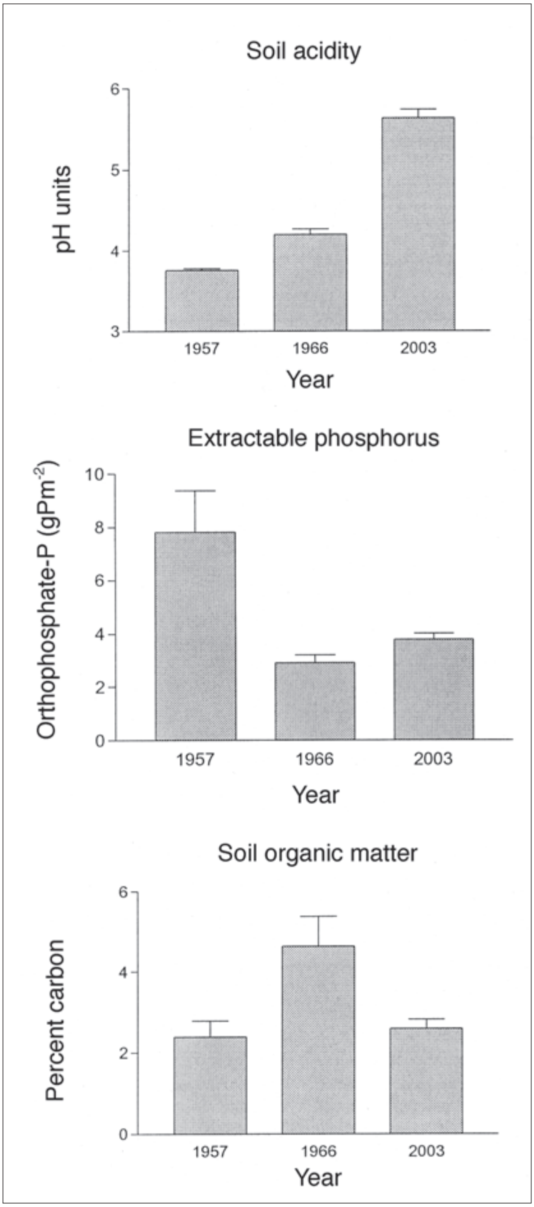

Figure 4. Changes in intertidal soil acidity, extractable phosphorus, and soil organic carbon before and after environmental legislation.

Our MicroTox® bioassay was consistent with earlier studies indicating the presence of toxic substances in the intertidal soils of Merrymeeting Bay. All samples showed some degree of toxicity, which was negatively associated with grain size ($n = 15$, $r = -0.60$, $p = 0.018$). That is, the smaller grain sizes were more likely to have toxic substances adsorbed to them, probably because of their higher organic matter content and surface area. Beginning in the mid-19th century and continuing to the present, the paper industry used chlorine compounds as a bleaching agent to whiten paper pulp (Steinberg 1991). Today, chlorinated hydrocarbons such as dioxin, furan, and polychlorobiphenols (PCBs) are detected in the fish and shellfish of the Androscoggin and Kennebec rivers (Applied Biomonitoring 2004). In addition, numerous trace metals such as Cd, Cr, Cu, Ni, Sn, and Zn occur in the surface sediments throughout Merrymeeting Bay and the tidal Androscoggin and Kennebec Rivers (Larsen and Gaudette 2002).

The anadromous fish runs

Merrymeeting Bay and the upriver Androscoggin and Kennebec watersheds were among the most important spawning and nursery habitats for anadromous fish on the New England coast (Bigelow and Schroeder 1953, Foster and Atkins 1869, Goode 1887, Squiers 1988, Taylor 1951). Historically *Salmo salar* L. (Atlantic salmon), *Acipenser oxyrhynchus oxyrhynchus* Mitchill (Atlantic sturgeon), *Acipenser brevirostrum* Lesueur (short-nosed sturgeon), *Osmerus mordax dentex* Steindachner and Kner (rainbow smelt), American shad, alewive, blue-back herring, and striped bass migrated into the Merrymeeting Bay ecosystem to spawn. Conversely, *Anguilla rostrata* Lesueur (American eel) migrated from the freshwaters of the Merrymeeting Bay watershed out to the North Atlantic to spawn.

By the end of the 18th century, the adverse effects of overfishing and dams on the anadromous fish runs were becoming apparent. Local fish wardens were appointed to make sure dams were opened to allow fish passage during their spawning runs, and a fishing season was defined (Wheeler and Wheeler 1878). In 1788, the town of Brunswick petitioned the Commonwealth of Massachusetts to outlaw weirs, seines, and dip nets and to stiffen the penalties for infractions on Merrymeeting Bay and the Kennebec River. Without government action, the petitioners believed overfishing would result in "… the final ruin of the fish in Merry Meeting Bay and rivers running into the same." (Baxter 1916).

Overfishing was largely responsible for the population collapse of sturgeon in Merrymeeting Bay. In 1628, the first European settler to the Merrymeeting Bay area, Thomas Purchase, began a lifelong career harvesting salmon and sturgeon at Pejebscot Falls in present-day Brunswick for the commercial market in London (Wheeler and Wheeler 1878). Around 1720, a commercial sturgeon fishery employed up to twenty small schooners, but the endeavor was apparently not pursued continuously (Goode 1887). In 1849 and 1850, local fishermen were organized and paid between $0.25 and 0.50 for each sturgeon caught. During the first year, 160 tons of sturgeon were harvested and processed for oil and roe. The following year was also profitable, but in 1851, the business was discontinued because sturgeon were scarce (Goode 1887). Another commercial effort was attempted in 1872, and once again, it was discontinued after a few years because the fish were rapidly harvested to local extinction. Overfishing also contributed to the demise of the salmon and shad runs in Merrymeeting Bay (Taylor 1951).

The effect of dams on the salmon runs was almost immediate. Salmon spawned in the small streams and rivers above the tidal waters of Merrymeeting Bay and its tributaries. Consequently, the construction of a permanent dam at Brunswick-Topsham on the Androscoggin by 1815 and the completion of the Kennebec dam at Augusta in 1837 caused the demise of the famous Kennebec salmon. N.W. Foster and C.G. Atkins (1869), the state fish commissioners, gave this account of the collapse of the Kennebec salmon fishery:

> "At Augusta, Mr. William Kennedy estimates the number of salmon taken in 1820 at 4000. There were twelve drift nets engaged in the fishery. The year that the Augusta dam was built, Mr. K. caught more than usual, namely 500; but from that time the fish immediately fell away, and very soon the yield was only twelve per year. In 1866, fishing with a seine, he took only two salmon."

Pollution was also faulted, but its effects were judged limited at that time. Sawdust, however, was seen as a problem as "Great drifts of it settle down on bottoms that were well peopled with insects and other small creatures, and destroy all life. This deprives the fish of a portion of their feeding ground, and compels them to seek new pastures" (Foster and Atkins 1869).

Throughout the 19th century, Merrymeeting Bay and the Kennebec River also supported the largest shad fishery north of the Hudson River (Taylor 1951). Whereas salmon need cold, running streams with gravelly substrates for spawning, shad are less selective about spawning habitat. Consequently, Merrymeeting Bay and the tidal portions of the Kennebec and the Androscoggin provided suitable spawning habitat for shad. Thus, the dams at Brunswick and Augusta did not entirely obliterate the available spawning habitat for shad, but reduced it by approximately 50% (Foster and Atkins 1869). The commercial shad fishery of the Merrymeeting Bay ecosystem produced at least 500,000 lbs of shad annually for sixty years leading into the 20th century until its eventual collapse around 1930 (Taylor 1951). The combined effects of habitat loss and pollution were blamed. As early as 1884, the tidal Androscoggin was no longer producing fish as "poisonous matter from the Brunswick factories destroyed the spawning grounds of the shad and drove them away" (Stilwell and Stanley 1884). Quantities of sawdust and, in all likelihood, low dissolved oxygen concentrations probably also contributed to the demise of the shad runs.

Alewives, blue-backed herring, and rainbow smelt were also decimated by pollution in the mid-20th century. However, modern restoration efforts beginning in 1983 have stimulated a recovery of juvenile recruitment of some species. Fishways were constructed on the major dams of the

Androscoggin in 1982, and fish pumps were employed where feasible. By the early 1990s, these efforts began to pay off. Juvenile recruitment of alewives in Merrymeeting Bay has increased since 1979, although somewhat episodically, and by 1992, juvenile recruitment of shad, blue-back herring, and striped bass were observed for the first time in fifty years (Fig. 5).

The story is less encouraging for the Atlantic salmon. Although restoration efforts were never as extensive as for alewives and shad in terms of introducing larvae into upriver spawning habitat, fishways were constructed on the Androscoggin dams to allow salmon passage during their spawning runs. The number of adult salmon observed at the Brunswick fishway has varied considerably since 1983, reaching a high of 185 fish in 1990 and a low of one fish in 1997. Over the last several years, fewer than six adult salmon have been observed in the Brunswick fishway during each spawning season (MDMR 2002a). It is possible that climatic warming during the 20th century underlies the failure of salmon recovery in this watershed. Archeological sites scattered throughout New England contain little evidence of salmon harvest by Native Americans until the onset of the Little Ice Age (Carlson 1992), implying that the salmon spawning runs enjoyed by the

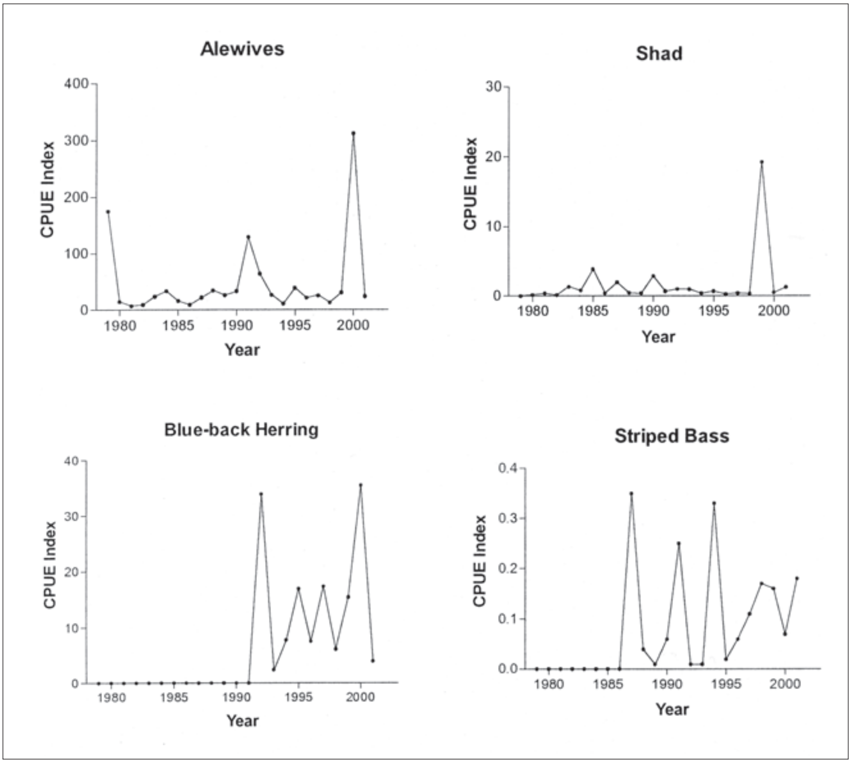

Figure 5. Return of juvenile recruitment of anadromous fish species in Merrymeeting Bay and the lower Kennebec estuary. CPUE index reflects the number of fish caught per tow of the sampling seine.

colonists on the Kennebec and Androscoggin Rivers and rivers further south may have been a consequence of the exceptionally cool climate during the 17^{th} through 19^{th} centuries.

Bald Eagle reproduction

As a teenager in the late 1870s and early 1880s, Herbert L. Spinney "took an interest" in Bald Eagle nesting sites near his home in Georgetown on the lower Kennebec (Spinney 1926). He visited all of the nest sites within an eight to ten square-mile area in Georgetown, Arrowsic, and Phippsburg, frequently climbing the nest tree or a nearby tree to look into the nest. He described thirteen nests, in what can conservatively be described as eight nesting sites, and included details about each nest tree and its locale. Most of the nest trees were second-growth white pine, some of which were cut down during his youth. Later as an adult, Spinney realized that he had witnessed the decline of Bald Eagles and commented about the causes being the destruction of suitable nest trees and the decline of the great spawning runs of anadromous fish. Pesticides and other synthetic organic compounds would be added to the list of causes in the 1950s and 1960s (Carson 1962).

Despite being this country's national symbol, Bald Eagles were routinely shot (Kaiser et al. 1980, Palmer 1949) and their nests robbed of eggs in the 19^{th} century (Spinney 1926). One Maine town even offered a $0.20 bounty on Bald Eagles in 1806 (Lyons et al. 1889). In 1945, DDT pesticide was introduced, and over the next twenty years it nearly exterminated Bald Eagles and other birds of prey. By 1968, eagle-egg shells from Swan Island and other locations along the Kennebec River had the highest concentrations of DDE and DDD residues (byproducts of DDT breakdown) as well as dieldrin, heptachlor, and PCBs among samples collected from Maine, Wisconsin, and Florida (Krantz et al. 1970). Numerous other studies found record levels of DDE, PCBs, and Mirex in eagle carcasses and eggs collected in Maine (Todd 2002). DDT was widely used to control mosquitoes and forest and agricultural pests throughout Maine, whereas the other toxic substances were derived from industry or garbage incinerators.

The Bald Eagle nesting and fledgling success time series shows the decline in the number of nesting pairs in the 1960s to a single pair in 1975 (Fig. 6). Fledgling recruitment was negligible for over 20 years. Then, in the early 1980s, a decade after the ban on DDT pesticide use, the number of fledglings increased to as many as 4 eaglets per year. By 1990, both the number of nesting pairs and fledglings began a sustained recovery. In 2002, there were eighteen active nesting sites in Merrymeeting Bay and the lower Kennebec estuary, and fledgling success rose to an average of 1.2 eaglets per nesting pair per year between 1998 and 2003. This success mirrors the comeback of the Bald Eagle across the continent (Buehler 2000, Grier 1982). Of those eighteen nesting sites, four occur in the towns of Georgetown, Phippsburg, and Arrowsic, where Spinney found eight in the late-19^{th} century. The Merrymeeting Bay ecosystem, therefore, may support only half the nest sites that it did during the late 19^{th} century.

Ecosystem degradation and collapse

Our research findings effectively demonstrate ecosystem degradation exacerbated by the culture of commerce and industry that European settlers brought to the New World (Tables 1 and 2). These settlers greatly expanded and intensified the effects of human activity on ecosystems, in contrast with the prior disturbance regime, which was characterized by episodic wind damage, fire, and pathogen outbreaks with limited impacts by Native Americans (Foster et al. 2004). The rapid changes brought on by European settlement were far-reaching, occurring along several major rivers in New England (Cumbler 2001, Judd 1997, Steinberg 1991). New England waterways, with their abundant natural resources, provided the essentials for growing economies, and simultaneously served as waste disposal systems for the incipient industries.

After more than two centuries of intensifying disturbance, the Merrymeeting Bay ecosystem deteriorated to the point of collapse in the mid-20th century with raw pollution, toxic sediments, widespread fish kills, and only a single successful pair of nesting Bald Eagles. The collapse had

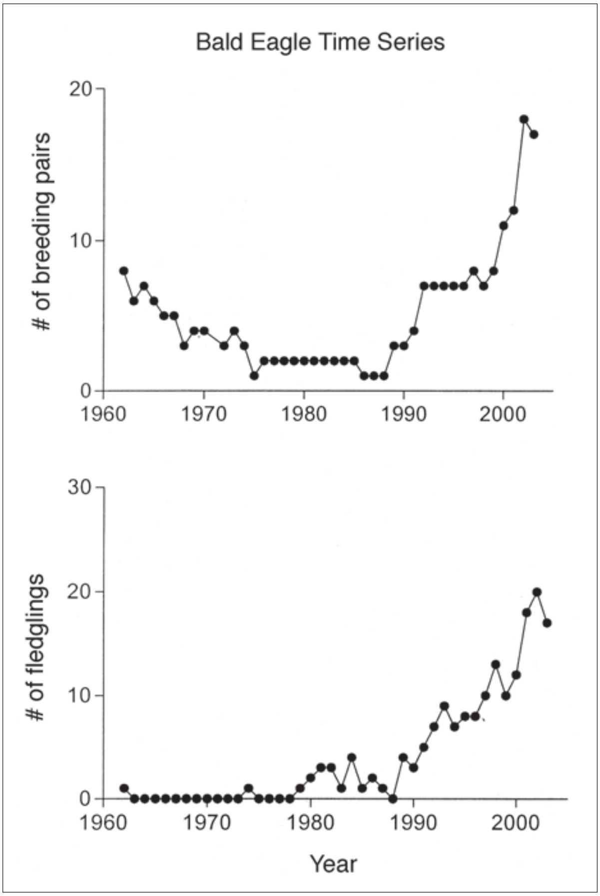

Figure 6. Bald Eagle reproductive success in Merrymeeting Bay and the lower Kennebec estuary. The number of breeding pairs of eagles and the number of successfully fledged eaglets.

been steadily, and one could argue, predictably approaching for years. Concern about overfishing dates back at least to the 1788 petition by the town of Brunswick for regulation of fishing, and perhaps back to the intermittent commercial sturgeon fishery of the 1710s (Table 1). Regional land clearance began no later than the 1720s as the towns of Brunswick, Topsham, Dresden, Richmond, and Bowdoinham were re-settled following

Table 1. Time table of events influencing Merrymeeting Bay and its tributaries.

Year(s)	Events
1628–1676	Thomas Purchase and other pioneer settlers; commercial salmon and sturgeon fishery, lumber, subsistence agriculture, fur trade; beaver depleted throughout Kennebec watershed by 1660.
1676–1720s	King Phillip's War followed by four others between European settlers and the Abenaki constrained European settlement.
1720s	Re-settlement by English, Scotch, and Irish immigrants of Brunswick, Topsham, North Bath, Bowdoinham, Richmond, and Cork (later Dresden). Commercial sturgeon fishery on Kennebec employing 20 schooners. Widespread land clearance begins.
1753	First dam across the Androscoggin at Brunswick-Topsham.
1760	Immigration accelerates following termination of French and Indian Wars. Area surrounding Merrymeeting Bay described as a mixture of farm, field, and forest.
1788	Overfishing evident. Petition by the Town of Brunswick to the Massachusetts government for regulation of use of weirs and seines for commercial fishing.
1800–1812	Tannery, textile mills, sawmills, and foundry established at Brunswick.
1815	Permanent dam at Brunwick-Topsham. Last salmon caught upriver on the Androscoggin at Lewiston.
1837	Kennebec dam completed at Augusta on the Kennebec. Powered ten sawmills and a textile mill by 1846.
1851	Collapse of the commercial sturgeon fishery.
1868	Completion of the Topsham paper mill on Androscoggin.
1880s–1890s	Construction of sulphite pulp mills on both the Androscoggin and Kennebec Rivers.
1880–1920	Peak agricultural land use.
1930	Collapse of the commercial shad fishery. Comprehensive engineering report on the pollution of Maine's industrial rivers.
1940–1970s	Period of peak water pollution. Noxious odors emanating from waterways and widespread fish kills in 1947, 1957, 1963, and 1965.
1972	Clean Water Act and ban on general use of DDT pesticide.
1975	Bald Eagles reduced to a single pair of reproducing adults.
1976	Primary wastewater treatment facilities in operation at pulp mills. Summer dissolved oxygen concentrations rebound.
1986	First juvenile striped bass observed in annual anadromous fish survey that began in 1979.
1989	Initial recovery of reproduction in Bald Eagles.
1991	First juvenile blue-back herring observed in annual anadromous fish survey.
2002	Toxic substances still present in Merrymeeting Bay sediments and biota.

the wars with the Abenaki. The effects of dams and water pollution were also prolonged and far-reaching. Similarly, the era of raw industrial and municipal pollution began in the early 1800s with the numerous sawmills powered by the dams at Brunswick and Augusta and lasted until implementation of the Clean Water Act of 1972.

Many species succumbed to a combination of these human disturbances rather than to the effects of a single one. For example, shad were overfished from the late 18th century on, their spawning habitat was reduced 50 percent by dams, and the remaining spawning habitat was eventually ruined by sawdust and water pollution (Taylor 1951). Deforestation and human attempts to exterminate Bald Eagles probably reduced their population before the widespread dispersal of synthetic pesticides took them to the brink of extinction (Spinney 1926).

Species responded differentially to the novel disturbance regime. For example, the complete blocking of the salmon spawning runs by the head-of-tide dams on the Androscoggin and Kennebec brought about the rapid demise of the salmon population, whereas other anadromous fish species persisted for decades longer because they could spawn in the tidal waters of Merrymeeting Bay. Longevity and reproductive rates also influenced the response of individual species. Populations of the long-lived, slowly

Table 2. Human activities, period of ecosystem degradation, ecosystem effects, length of recovery period, and potential legacies of past human activity.

Human activity	Period of degradation	Effects	Period of recovery	Legacies
Overfishing	1710s–1930s: 220 yrs	Species loss, trophic web effects	≈ 70 yrs	Species loss
Land-use change (Deforestation and agriculture)	1710s–1920s: 210 yrs	Sedimentation, biogeochemistry, habitat structure and diversity, species loss	≈ 80 yrs	Permanently shallower ecosystem, eutrophication, reduced habitat diversity, species loss
Dam building				
Androscoggin	1753–present: 253 yrs	Altered flow regime, geomorphologic changes, spawning habitat loss, species loss	0 yrs	Altered flow regime
Kennebec	1837–1999: 162 yrs		5 yrs	Species loss
Pollution	1753–1975: 222 yrs	Altered biogeochemistry, oxygen depletion, accumulation of toxic substances, species loss	30 yrs	Species loss, eutrophication, toxic substance accumulation

reproducing sturgeon species decreased rapidly during the all-out fishing effort of the mid-19th century, whereas shorter-lived species that reproduced at a younger age—such as shad, alewives, and herring—lasted well into the 20th century. Also, despite the daily discharge of tons of industrial wastes into the Androscoggin and Kennebec rivers, the high flow of water provided enough oxygen to support anadromous fish for decades before the widespread fish kills of the mid-20th century.

Ecosystem recovery

Much as individual species succumbed to the novel disturbance regime at different rates, various ecosystem parameters are recovering at different rates. The rapid recovery of summer dissolved oxygen concentrations in the first few years following the initial treatment of wastewaters discharged by pulp mill and municipalities illustrates the capacity of the rivers for re-oxygenation as well as the efficacy of the Clean Water Act in controlling raw pollution. Whereas dissolved oxygen concentrations and water pH improved rapidly, toxic substances still persist in the sediments and biota, and whereas Bald Eagles and some species of anadromous fish are once again reproducing, recovery of the once famous Kennebec salmon population is questionable, especially in the face of climate warming.

At best, the recovery of Merrymeeting Bay can be described as partial. Paper mills still discharge phosphorus and toxic compounds into the rivers, and N, S, Hg, and other pollutants enter via municipal wastewater treatment facilities, atmospheric deposition, and agricultural runoff. Along with regulatory efforts to improve the water quality of the rivers, anadromous fish restoration has received considerable interest and public support. Shad and alewive fry have been stocked in suitable ponds, lakes, and tributaries within the watershed for the past 20 years (Lary 1999). The apparent return of juvenile fish recruitment in Merrymeeting Bay suggests that these efforts are paying off, and indicates that suitable spawning habitat exists within the ecosystem.

Perhaps the most promising recent change is the removal of the notorious Kennebec dam at Augusta, which wholly prevented fish passage for 162 years. Its removal in 1999 opened 27 km of prime spawning habitat for several species. Although it is too early to tell how much time will be required for the additional habitat to significantly bolster fish populations, evidence of shad spawning, and adult alewives, sturgeon, and striped bass have been observed upstream of the dam location (MDMR 2002b).

Conclusions

Despite the substantial improvement in water quality and the initial recovery of fish and Bald Eagle reproduction, important legacies of past human disturbance continue to influence the ecosystem. Merrymeeting Bay is permanently shallower and more eutrophic than it was prior to European settlement. Toxic substances remain in its biota and sediments. Its diversity of aquatic habitat is probably much reduced, and its flow regime and biogeochemistry have been altered by dams and land use. It almost certainly has fewer species, and once abundant and ecologically important species such as sturgeon and shad are now greatly reduced. After 252 years, the dam at Brunswick-Topsham on the Androscoggin still hinders fish migration, whereas the long-term recovery of aquatic habitat and spawning runs of anadromous fish on the Kennebec is still in question, as the 162 year-old dam was removed only a few years ago.

The ecological consequences of past human activity are long lasting, and must be fully considered to understand and properly manage this important ecosystem (e.g., Foster et al. 2003, Russell 1997). These historical legacies beg the question of whether achieving something tantamount to a restored ecosystem is possible. The additional sediments deposited during the era of land clearance may be continually re-suspended by tidal action, resulting in turbid waters that reduce light penetration to submerged aquatic vegetation and effectively prevent recovery of the benthic food web. Similarly, because phosphorus sequestered in sediments during eutrophication can be released back into the water column, nutrient loading in the past may continue to enhance the productivity, and consequently the turbidity, of rivers and estuaries long after external sources have been reduced (Coelho et al. 2004). Certainly, the loss of key species and the introduction of non-native species have permanent consequences for the ecosystem. Lastly, toxic substances may continue to impair reproduction in birds and other animals for decades (Todd 2002).

These legacies pose a dilemma for conservation and management. How should resources be spent, given that changes to some ecosystem properties are likely to be irreversible, whereas other ecosystem properties may be restored with persistent effort? Applied ecological research coupled with historical insight can identify the conservation and restoration actions that are most likely to succeed given the historical constraints on ecosystem recovery. For example, knowing that the prolific spawning runs of Atlantic salmon during the Colonial Era were most likely the result of the cool climate can forestall the wasted effort and expense that a reintroduction program would incur given the current trend of rapid climate warming. Conversely, recovery of southern species such as American shad may be promoted by warming, and should therefore be given priority in restoration planning. Questions about the efficacy of habitat restoration, the sources of turbid water, the influence of introduced species, and the lingering effects of toxic chemicals can be addressed with field and laboratory studies. Perhaps public understanding of what this ecosystem was once like, and what, given the historical constraints, it might become, can stimulate support for conservation and restoration measures that are likely to be costly over the short term.

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