Estuarine habitat restoration at CAPE COD NATIONAL SEASHORE:

the Hatches Harbor prototype

By

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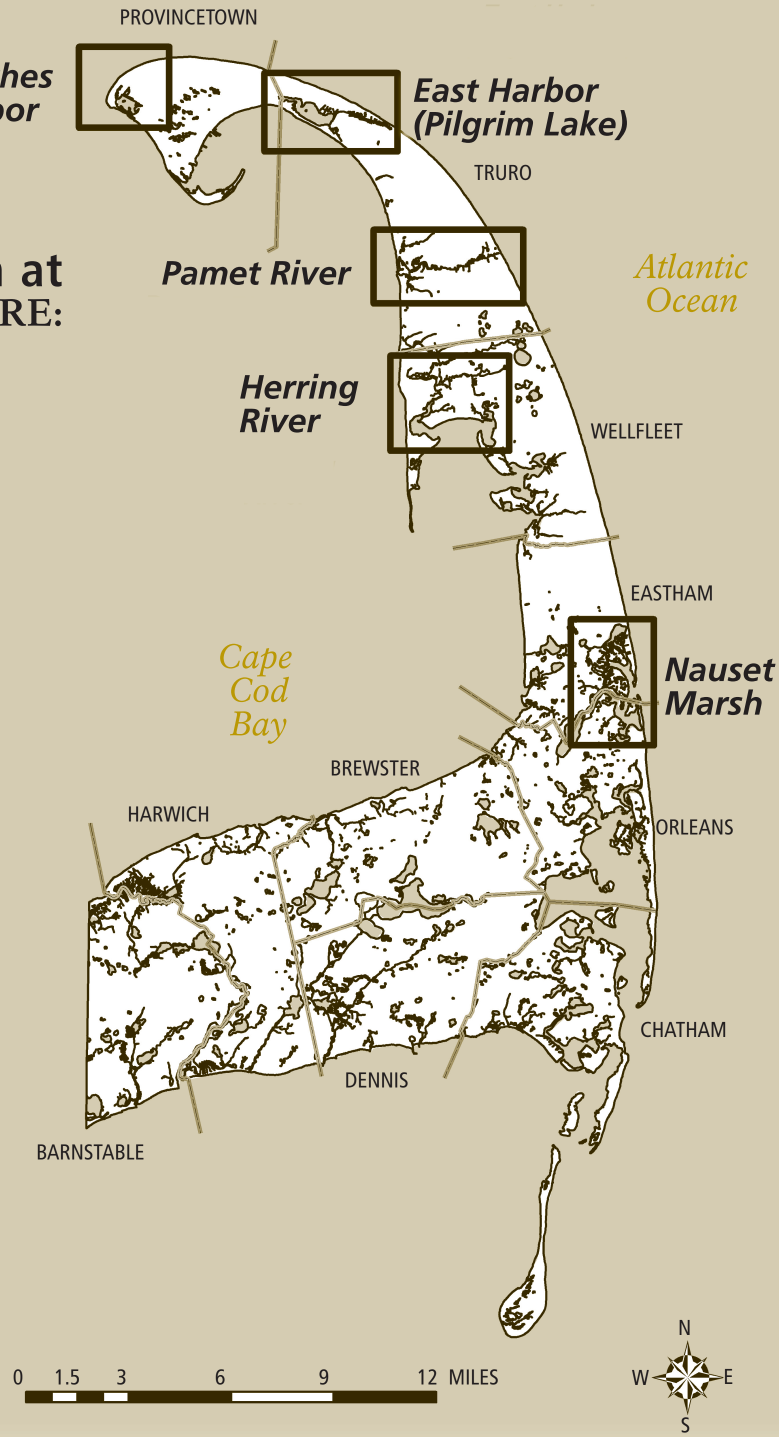


Figure 1. The four largest diked estuaries on Cape Cod occur in three seashore towns on outer Cape Cod: Truro, Wellfleet, and Provincetown. Roads, railways, and dikes restrict large portions of these wetlands. A prototype program for estuarine restoration and monitoring is occurring at Hatches Harbor.

Tidal range (flooding) and salinity are driving forces that define salt marsh ecosystems. Recognizing this, and the degrading effects of human-imposed tidal restrictions, Cape Cod National Seashore and cooperating state and federal agencies have been working for 20 years to restore tidal flow to many diked salt marshes on Cape Cod. Currently scientists from the U.S. Geological Survey-Biological Resources Division, Cape Cod National Seashore, and universities are developing the long-term coastal ecosystem monitoring program for Cape Cod National Seashore, of which estuarine monitoring is an integral component. We report on the status of tide-restricted salt marshes within Cape Cod National Seashore and describe the approach and progress toward habitat restoration at Hatches Harbor (Provincetown, Massachusetts), our prototype for estuarine restoration and monitoring.

The legacy of tidal restrictions

Cape Cod has a 350-year history of coastal wetland loss because of diking, drainage, and filling. An estimated 3,460 acres (1,400 ha) of original salt marsh estuaries remain diked today (Justus 2001). The four largest diked estuaries occur in three seashore towns on outer Cape Cod: Truro, Wellfleet, and Provincetown (fig. 1). With national seashore authorization in 1961, the National Park Service (NPS) received management responsibility for more than 2,100 acres (850 ha) of these diked coastal systems. This acreage represents a loss of 42% of the native salt-marsh habitat present at the time of European settlement (table 1).

Although diking of salt marshes has caused serious estuarine water quality problems on Cape Cod (Soukup and Portnoy 1986, Portnoy 1991, Portnoy and Giblin 1997), the most noticeable effects of diking are changes in vegetation (Roman et al. 1984). Cattails (*Typha* spp.) and, in particular, common reed (*Phragmites australis*) characteristically spread onto tide-restricted marshes, displacing native salt-tolerant grasses. At higher elevations, which are consequently more deeply drained by diking, a large variety of freshwater wetland and upland plants invade diked floodplains once the stresses of salt and waterlogging are removed. Thus, thousands of acres (hundreds of hectares) of original salt-marsh habitat have been converted to freshwater wetlands or upland habitat within four of the five largest tidal marshes in Cape Cod National Seashore (table 1, fig. 1). In response to hydrologic, water quality, and vegetation changes, scientists have documented impacts on fish and decapod crustaceans (Raposa and Roman 2003).

"The most noticeable effects of diking are changes in vegetation."

Although the National Park Service became responsible for stewardship of most of the marshlands, both diked and natural, within the park boundary in 1961, local towns and the Commonwealth of Massachusetts retained ownership and control of the structures (e.g., dikes, culverts, tide gates, and weirs) that restrict tides. Progress in addressing NPS concerns about water management has been slow, but recently successful in Hatches Harbor.

Table 1.

Extent and Duration of Tidal Restrictions in the Major Estuaries of Cape Cod National Seashore

Estuary, township	Total area acres (ha)	Diked area acres (ha)	Year of diking
East Harbor, Truro	719 (291)	719 (291)	1868
Pamet River, Truro	388 (157)	158 (64)	1869
Herring River, Wellfleet	1,100 (445)	1,000 (405)	1909
Hatches Harbor, Provincetown	420 (170)	198 (80)	1930
Nauset Marsh, Eastham	2,334 (945)	<25 (<10)	?
Total	4,961 (2,008)	2,100 (~850)	

Note: The Cape Cod Commission estimates that diked salt marshes total 3,460 acres (1,400 hectares).

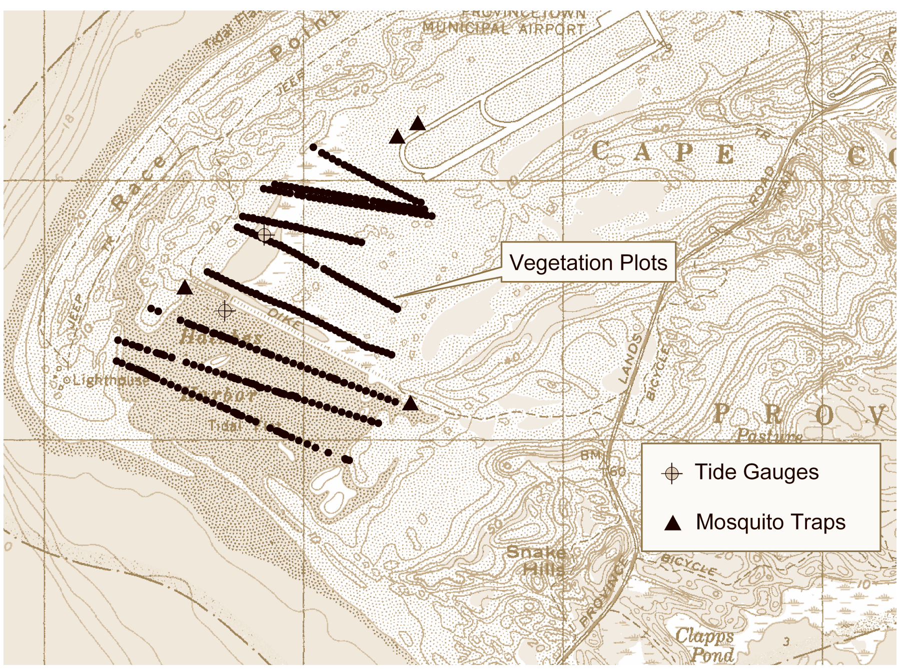


Figure 2. A dike built across the floodplain of Hatches Harbor salt marsh in 1930 isolated about half of the coastal wetland from tidal exchange.

Hatches Harbor, Provincetown

The Hatches Harbor salt marsh developed relatively recently behind the prograding northwestern tip of outer Cape Cod (fig. 1). As such, the peat is sandier and peat depths are shallower than in the older marsh systems to the south. A 1-kilometer-long dike constructed in 1930 for mosquito control essentially bisected the floodplain completely blocking tidal exchange and reducing salinity in the landward half of the wetland (fig. 2). In addition, Provincetown Airport was constructed within the floodplain in the 1940s, about 20 years before park establishment, using the preexisting dike as protection against tidal flooding. As a result by the 1980s, many species of salt-sensitive plants, including 20–25 acres (8–10 ha) of the somewhat salt-tolerant

Phragmites, replaced native salt marsh grasses; relict cover of *Spartina alterniflora* (the dominant species in a natural salt marsh) in the diked marsh amounted to only about 12 acres (5 ha) at lowest elevations nearest the tidal creeks.

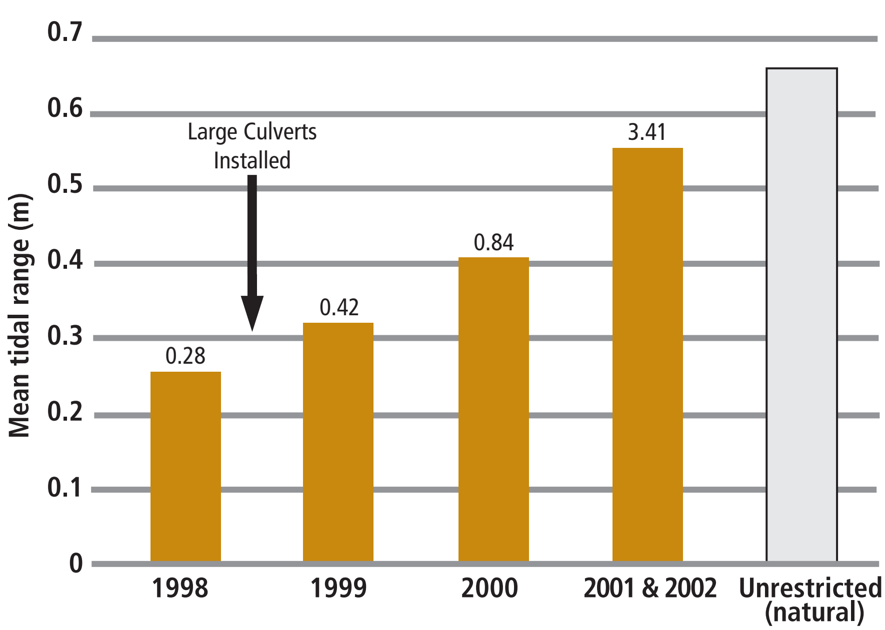
The need for dike repair in 1986 prompted interagency discussions about flood-protection needs of the airport and the possibility of tidal restoration. Engineers from the Federal Aviation Administration determined critical flooding elevations for airport structures, while NPS scientists and cooperators developed a numerical hydrodynamic model of the estuarine system (Roman et al. 1995). The model showed that a wide, low culvert opening (8.5-meters-wide-by-one-meter-high) should provide sufficient seawater flooding to restore between 60 and 90 acres (25–35 ha) of salt marsh and, at the same time, dampen storm tides that may otherwise affect the airport's instrument landing system. In 1997 a planning and regulatory team representing 10 local, state, and federal agencies approved this culvert configuration and a general restoration plan. Pre-restoration monitoring began in summer 1997, with the new culverts installed in winter of 1998–1999 (fig. 3).

Despite model predictions, the new culverts were not fully opened after construction. Opening has been done in small increments (figs. 3 and 4) to build confidence among cooperators—especially airport officials—in the reliability of the model and because of concerns for extensive plant death from waterlogging should the marsh fail to drain during each low tide. Experience since 1999 has allayed most concerns.

Monitoring tide restoration at Hatches Harbor

The NPS monitoring team has used a before-after-control-impact (BACI) approach, selecting physical and biological variables that were judged (based on experience elsewhere) to be most sensitive to changes in the principal governing variables: tidal range (flooding) and salinity. The unrestricted portion of the marsh downstream from the Hatches Harbor dike is the control; restoration of tidal flow above the dike is the impact. The BACI design enables a statistical assessment of

1. The degree of difference between control and diked marsh
2. The degree of difference between diked and restoring marsh as tidal restoration proceeds
3. The degree of difference between the control marsh before and after tidal restoration (important because changes in the control would suggest that factors other than the tidal restoration treatment—that is, factors that are functioning on a regional scale—may have



Figures 3 (photo) and 4 (graph). In 1997, a planning and regulatory team with members from local, state, and federal agencies approved a culvert configuration and general restoration plan for Hatches Harbor. The installation of new culverts occurred in January 1999, following two years of pre-restoration monitoring. The photograph shows four new 7-feet-wide-by-3-feet-high culverts at Hatches Harbor with adjustable tide gates that are about half open. The graph documents how tidal range has increased in diked portions of the Hatches Harbor salt marsh with the installation and incremental opening of large culverts. Numbers above bars are cross-sectional areas (m^2) of culvert openings.

affected the trajectory of changes in the biotic community both upstream and downstream of the dike)

4. Convergence in control versus diked-marsh plant communities

As restoration proceeds, we hypothesize that the restoring marsh will become more like the control marsh.

Physical and chemical variables

Tide heights and salinity are monitored periodically—at least semiannually—with month-long (minimum) deployments of sampling probes in the main creek on either side of the dike structure (fig. 2). These data describe the hydrography of the system and its response to incremental openings of the culverts (fig. 4); they further allow a test of model-predicted tide heights. However, most of the biotic community is dependent on the flooding duration and water quality beyond the major creeks, i.e., within the marsh proper. Therefore, marsh water levels' salinity, and sulfide concentrations are monitored within the root zone along permanent transects. We anticipate that increased salinity will suppress *Phragmites* and allow *Spartina* spp. to reoccupy the wetland surface. Initial concerns that the wetland may not drain adequately during low tides—causing sulfide toxicity that can reduce productivity of salt marsh plants, waterlogging, and low redox potentials—have not borne out as low tides have become lower (fig. 5) at the same time as high-tide heights have increased with increased culvert opening (fig. 4). Meanwhile, root-zone salinity has increased about 790 feet (240 m) from creek banks, while sulfide—an indicator of waterlogging and decreased redox potential—has remained extremely low and comparable to the

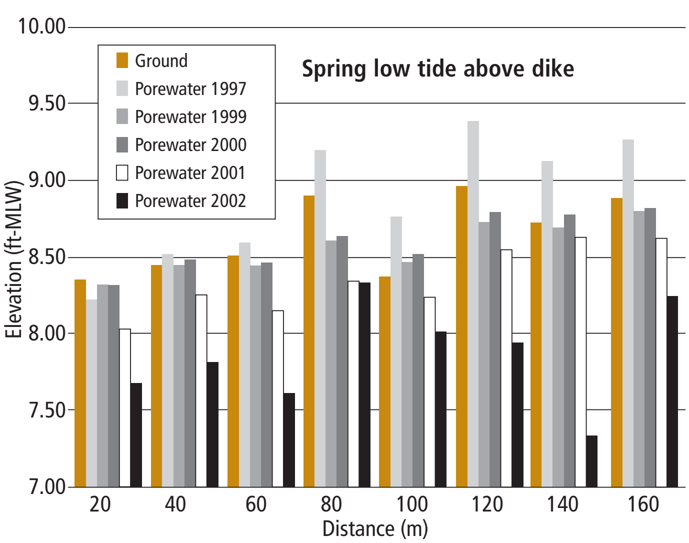


Figure 5. Low-tide porewater levels within the diked marsh at Hatches Harbor before and since incremental culvert openings beginning in 1999. Initial concerns that the wetland might not drain adequately during low tides have not borne out as low tides have become lower at the same time as high tides have increased with increased culvert opening.

unrestricted control marsh seaward of the dike. Low root-zone sulfide is promoted at Hatches Harbor by the high permeability of the sandy peat, allowing efficient drainage and aeration during low tides.

Sediment elevation tables (SETs)

The ability of salt marshes to accrete along with sea level rise is a major issue for wetland managers facing the projected effects of global warming. The topic is especially relevant to the management and restoration of tide-restricted salt marshes that have subsided because of drainage, pore-space collapse, increased decomposition, and blockage of tidally transported sediment (Portnoy 1999). When seawater flooding is returned to marshes that have been diked for many years, will sedimentation compensate for past subsidence or will these marshes become waterlogged and unsuitable for recolonization by salt marsh plants, resulting in mudflat and open water habitats rather than emergent salt marsh?

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We have established sediment elevation tables (SETs) (Boumans and Day 1993, Cahoon et al. 1999) at Hatches Harbor (and at two other wetlands in Cape Cod National Seashore) to monitor both accretion and subsidence and to see if the current six-inch (15 cm) elevation deficit measured above the dike can be balanced now that tidal flow has been restored. SETs provide a stable base from which to monitor marsh surface elevation repeatedly over time at precisely the same locations in the marsh. In conjunction with SETs measurements, we have also established feldspar marker horizons to determine the amount of sediment deposited on the marsh surface. With the SETs and marker horizons we can precisely determine elevation changes within the marsh and understand what processes are contributing to the elevation change. We gathered information on local rates of sea level rise from NOAA tide gauges to determine whether marsh elevation is keeping pace with rising sea level. Because marsh elevation change is minuscule (just a few millimeters) each year, it is difficult to determine trends based on only a few years of monitoring, but at this point it appears that the elevation of the restoring marsh is increasing at a rate that is greater than the unrestricted marsh.

"We gathered information on local rates of sea level rise ... to determine whether marsh elevation is keeping pace with rising sea level."

Salt marsh vegetation

We used the BACI design to make several comparisons aimed at determining, with statistical certainty, the response of vegetation to tidal restoration. We established permanent one-square-meter vegetation plots in a stratified-random manner throughout the unrestricted marsh and tide-restricted marsh to estimate plant species composition and abundance (cover) between groups of community data (e.g., tide-restricted vs. tide-restored) (Roman et al. 2001). Our initial sampling took place in summer 1997. We performed follow-up monitoring in summer 2000 and summer 2002 as tidal restoration proceeded.

Plant diversity is naturally low within the unrestricted salt marsh; *Spartina alterniflora* dominates, but *Spartina patens*, *Salicornia biglovei* and *europea*, *Limonium nashii*, and *Sueada linearis* are also present. In addition, two species of brown macroalgae (*Ascophyllum nodosum* and *Fucus vesiculosus*) contribute substantially to cover within the unrestricted marsh. By comparison, we found more than 80 species of vascular plants within the tide-restricted—tide-restored marsh, strongly pointing to conversion of this once *Spartina*-dominated marsh to a freshwater—brackish water wetland. Following the BACI study design, we made numerous comparisons.

Changes in vegetation are best demonstrated by comparing the 1997 tide-restricted marsh to the same marsh under tide-restored conditions in 2000 and 2002. In 2000, after just two growing seasons of tidal restoration, there were no changes in the vegetation community, probably because of the small initial openings of the new culverts. By 2002, however, vegetation between the tide-restricted marsh and the same marsh was significantly different. We attribute this difference primarily to a decrease in brackish marsh species, such as purple loosestrife (*Lythrum salicaria*) and soft rush (*Juncus effusus*), as well as some woody vegetation (e.g., blackberry, *Rubus* and bayberry, *Myrica pensylvanica*). Increased soil salinity and flooding duration have caused these species to begin to die back. Invasive, exotic common reed (*Phragmites australis*) (Saltonstall 2002) dominates large portions of the diked Hatches Harbor floodplain. Increased salinity and flooding duration, accompanying tidal restoration, should suppress common reed and favor the reestablishment of the salt marsh grasses that originally dominated the wetland (fig. 6).

From 1998 to 2002, *P. australis* cover decreased in plots close to—within 525 feet (160 m) of—the main tidal creek, but increased or changed very little in plots distant from the creek (fig. 6). Thus, zones of high *P. australis* cover shifted up-gradient, away from the influence of high-salinity tide water, i.e., greater than 20 parts per thousand (ppt). In addition, *Phragmites* biomass and stem height were significantly lower in 2002 than in 1998 (fig. 7), with large reductions between 0 and 330 feet (0–100 m) of creeks where root-zone salinity ranged from 25 to 30 ppt.

Phragmites biomass was positively correlated with the depth of low-tide drainage, and negatively correlated with salinity (fig. 7). Because of the sandy composition and good drainage of Hatches Harbor peat, waterlogging and consequent sulfide toxicity did not occur.

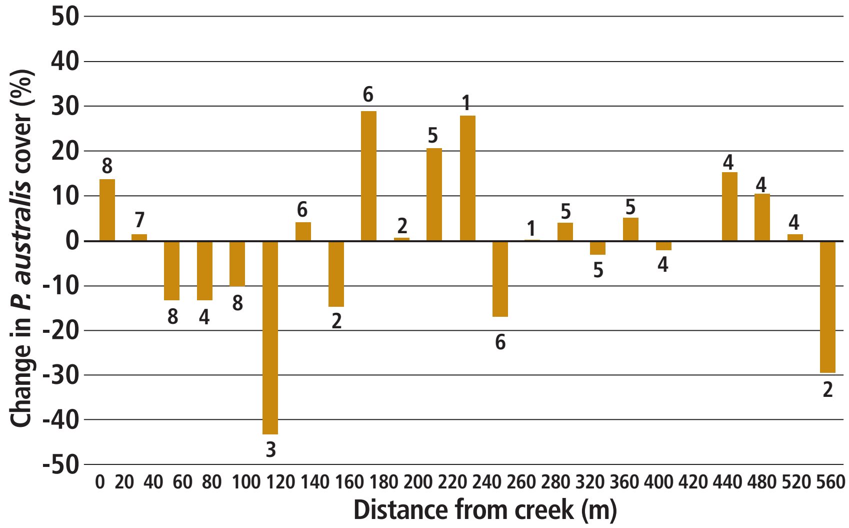

Figure 6. Average percent change from 1998 to 2002 in cover of *P. australis* with distance away from the tidal creek. From 1998 to 2002, *P. australis* cover decreased in plots close to—within 525 feet (160 m) of—the main tidal creek, but increased or changed very little in plots distant from the creek. Thus, zones of high *P. australis* cover shifted up-gradient, away from the influence of high-salinity (> 20 ppt) tidewater. Numbers above and below histograms represent the number of plots in each distance category.

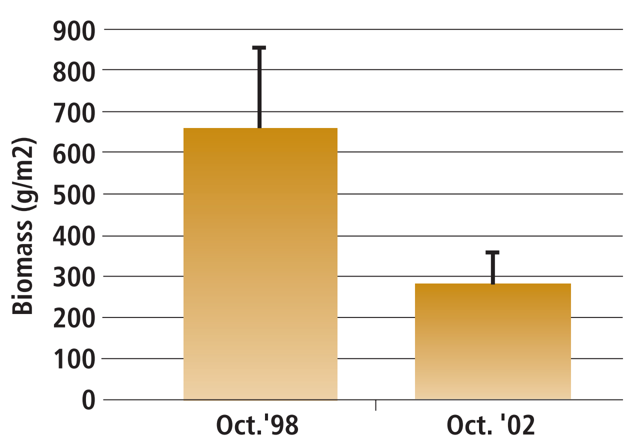

Figure 7. Mean biomass of *P. australis* in 1998 and 2002 (all plots, all transects). *Phragmites* biomass and stem height were significantly lower in 2002 than in 1998, with large reductions between 0 and 330 feet (0–100 m) from creeks where root-zone salinity ranged from 25 to 30 parts per thousand (ppt).

Despite the near absence of sulfides, *Phragmites* in the restoring marsh still has to contend with high salinity (Hartzendorf and Rolletschek 2001), which may explain diminishing aboveground biomass.

Nekton

From 1997 to 1998 and again in 1999, just before and during the initial phases of tidal restoration, we monitored nekton in creek, pool, and marsh-surface habitats on both tide-restricted and natural sides of the Hatches Harbor dike (Raposa and Roman 2001) (fig. 8). We combined and averaged nekton density data with creek and pool data from the period June through September. We collected nine fish species and three decapod crustaceans, with the common mummichog (*Fundulus heteroclitus*) as the dominant species. Before tidal restoration, total nekton density in creeks and pools of the unrestricted control marsh and the tide-restricted marsh was the same. Also, total nekton density did not change, or increase as might be expected, within the tide-restricted marsh after tidal restoration (table 2).

We are also monitoring nekton use of the marsh surface with an enclosure trap method (Raposa and Roman 2001). Nekton, especially the common mummichog, is known to forage and spawn within *Spartina alterniflora* marsh during high tide flooding events. Nekton inhabited only seven acres (3 ha) of *S. alterniflora* marsh in the restricted portion compared to more than 60 acres (25 ha) in the unrestricted marsh; thus, there was much less available habitat in the tide-restricted marsh. With major increases in the openings of culverts and tidal range since April 2001, marsh surface habitat (i.e., flooded during high tide) has greatly increased. We therefore expect to see a commensurate increase in nekton use when this group is resampled in summer 2003.

Mosquitoes

The abundance and species composition of nuisance mosquitoes depend in large part on wetland flooding regimes and salinity. With increased

Figure 8. Investigators monitored nekton (fishes and decapod crustaceans) in salt marsh creeks, pools, and on the marsh surface. The investigator is sweeping the trap with a bar seine. Investigators can attach a skirt of nylon mesh to the top of the trap for sampling deeper habitats.

Table 2.

Nekton Density (per square meter) in the Unrestricted and Restricted Hatches Harbor Salt Marsh in 1997, Before Tidal Restoration, and 1999 with Partially Restored Tides

Species	Restricted 1997 n=90	Restoring 1999 n=90	Unrestricted 1997 n=120	Unrestricted 1999 n=120
Fundulus heteroclitus (mummichog)	22.84	28.38	18.99	14.77
Carcinus maenas (green crab)	0.46	1.47 ***	1.38	1.69
Crangon septemspinosa (sand shrimp)	0.18	0.14	2.16	0.69
Fundulus majalis (striped killifish)	0.10	0.36	0.28	0.58
Menidia menidia (Atlantic silverside)	0.12	0.20	0.65	0.18
Anguilla rostrata (American eel)	0.36	0.12	0.00	0.00
Apeltes quadracus (4-spine stickleback)	0.20	0.09	0.00	0.00
Gasterosteus aculeatus (3-spine stickleback)	0.10	0.10	0.00	0.00
Mugil curema (white mullet)	0.02	0.00	0.04	0.00
Syngnathus fuscus (pipefish)	0.03	0.01	0.00	0.00
Neopanopeus sayii (mud crab)	0.00	0.00	0.00	0.01
Pseudopleuronectes americanus (winter flounder)	0.00	0.00	0.01	0.00
Total Nekton	24.41	30.86	23.50	17.93

Note: Researchers performed two-way analysis of variance to evaluate differences in species density between restricted (1997) and restoring (1999) salt marsh, and then between the unrestricted portion in 1997 and 1999. Nekton density data were log (x+1) transformed. Only one significant difference was noted (***, *Carcinus maenas,* $p<0.01$).

tidal heights and salinity within the floodplain above the Hatches Harbor dike, mosquito breeding habitat in floodwaters may increase or species composition may change, thereby increasing the mosquito nuisance at Provincetown Airport. We trapped adult mosquitoes during two summers (1997 and 1998) before tidal restoration and have continued for four more years (1999–2002) as tidal flow has incrementally increased through the new, enlarged dike culverts. The objective of the monitoring is to represent seasonal abundance and species composition of nuisance mosquitoes over the entire floodplain using repeatable methods as tidal restoration proceeds. Species composition should indicate primary breeding habitats, especially for habitat variables that are most sensitive to changes in tidal flow through the Hatches Harbor dike. We hypothesize that tidal restoration will increase the extent and depth of flooding of the diked wetland surface during high tides; however, improved drainage of freshwater runoff and tidal water through the enlarged culverts during the ebb will limit floodwater mosquito breeding habitat. We further hypothesize that improved access for fish (especially *Fundulus* spp.) to the wetland surface will reduce successful mosquito reproduction. Increased salinity may alter the species composition of nuisance mosquitoes landward of the dike, perhaps favoring salt marsh species (*Ochlerotatus sollicitans* and *Ochlerotatus cantator*).

From 1997 through 2000, mosquito production for all species related directly to summer precipitation. However, we observed large increases in the production of brackish and saline species (*O. cantator* and *O. sollicitans*) in 2001 and 2002 respectively, indicating that habitat for these species is increasing (fig. 9). Continuation of this trend will depend on the persistence of some pools on the wetland surface that are presently poorly flushed or inaccessible to predatory fish. Meanwhile, planning is under way to improve low-tide drainage of the marsh surface by restoring tidal creeks that have filled with vegetation and sediment as a result of diking and its reduction of tidal currents. Over much of the marsh, low-tide drainage may improve without intervention, as radically increased tidal currents are apparently creating a new drainage network across the marsh surface.

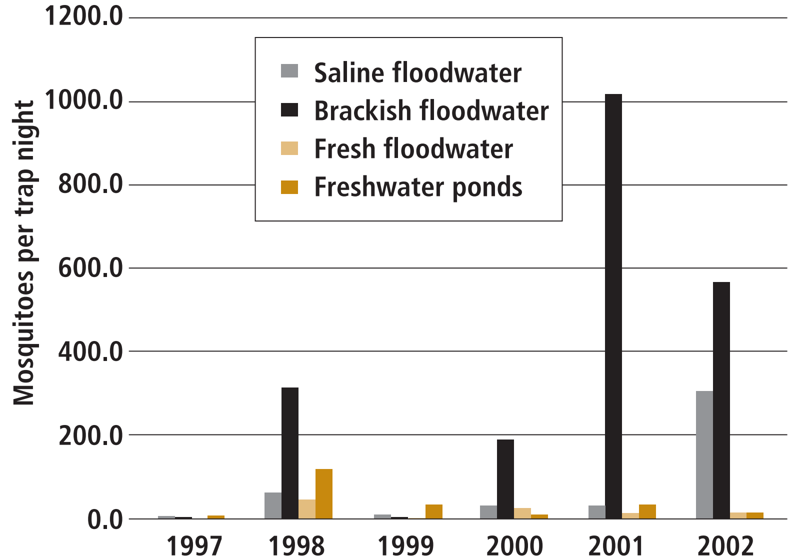

Figure 9. Average numbers of adult mosquitoes captured in combination light-CO_2 traps set biweekly from July–August since 1997 in the Hatches Harbor floodplain.

Conclusions

Salt marsh estuaries are naturally complex systems further complicated by historical alterations to tidal range and salinity; therefore, predicting the ecological effects of restored tidal flow is difficult. Given this uncertainty, the success of salt marsh restoration efforts and informed adaptive management at Cape Cod National Seashore will depend upon our ability to sustain the multidisciplinary monitoring effort. Initial responses of the Hatches Harbor salt marsh to renewed tidal flow show that restoration may continue for several decades. It is therefore important to document changes in physical, chemical, and ecological processes over the long term so that we can better understand the restoration process and improve our predictive capabilities. In parks like Cape Cod with intense public use, adjacent development, and overlapping jurisdictions by agencies with differing management goals, scientifically credible monitoring protocols and results provide a critical basis for improved wetland management.

"The success of salt marsh restoration efforts … will depend upon our ability to sustain the multidisciplinary monitoring effort."

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