THE ECOGEOMORPHOLOGY OF TWO SALT MARSHES IN MIDCOAST MAINE: NATURAL HISTORY AND HUMAN IMPACTS

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INTRODUCTION

Coastline of Maine and Marsh Morphology

The coast of Maine is divided into 4 distinct geomorphologic sections arising from differences in the composition, orientation and structure of the bedrock (Kelley et al., 1988) (Figure 1). The salt marshes located in these 4 sections of the coast are somewhat distinct geomorphologically due to differences in geology, the sediment supply and composition, and the intensity and direction of wave energy. The Arcuate Embayments compartment (in the southwest region of the state) is characterized by resistant bedrock headlands separated by large sandy beaches and large back barrier marshes. Moving further east, the Indented Shoreline compartment is characterized by high grade metamorphic rocks that have been gouged out by glaciers into elongate peninsulas and islands oriented N/S to NE/SW and mudflats and salt marshes. The Island-Bay Complex shoreline is composed largely of igneous rocky shorelines and islands with relatively high exposure to waves and fewer salt marshes. Finally, the Cliffed Shoreline, in downeast Maine, is characterized by cliffs of volcanic rock and few salt marshes.

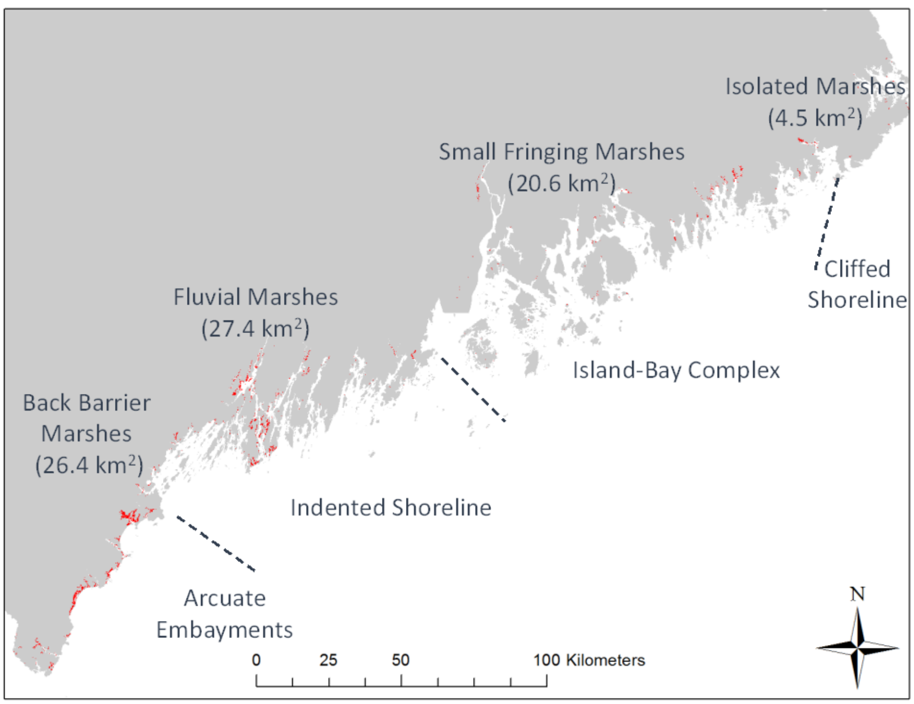


Figure 1. Maine coastal compartments and areas of major types of salt marshes (after Kelley et al., 1988).

Many of New England's salt marshes exist behind barrier beaches, or as individual systems in glacially carved, relatively small drowned valleys (Niering and Warren, 1980; Kelley et al. 1988). In this field trip, we will be looking at two marshes within the Indented Shoreline compartment, Long Marsh and the Sprague River Marsh (Figure 2).

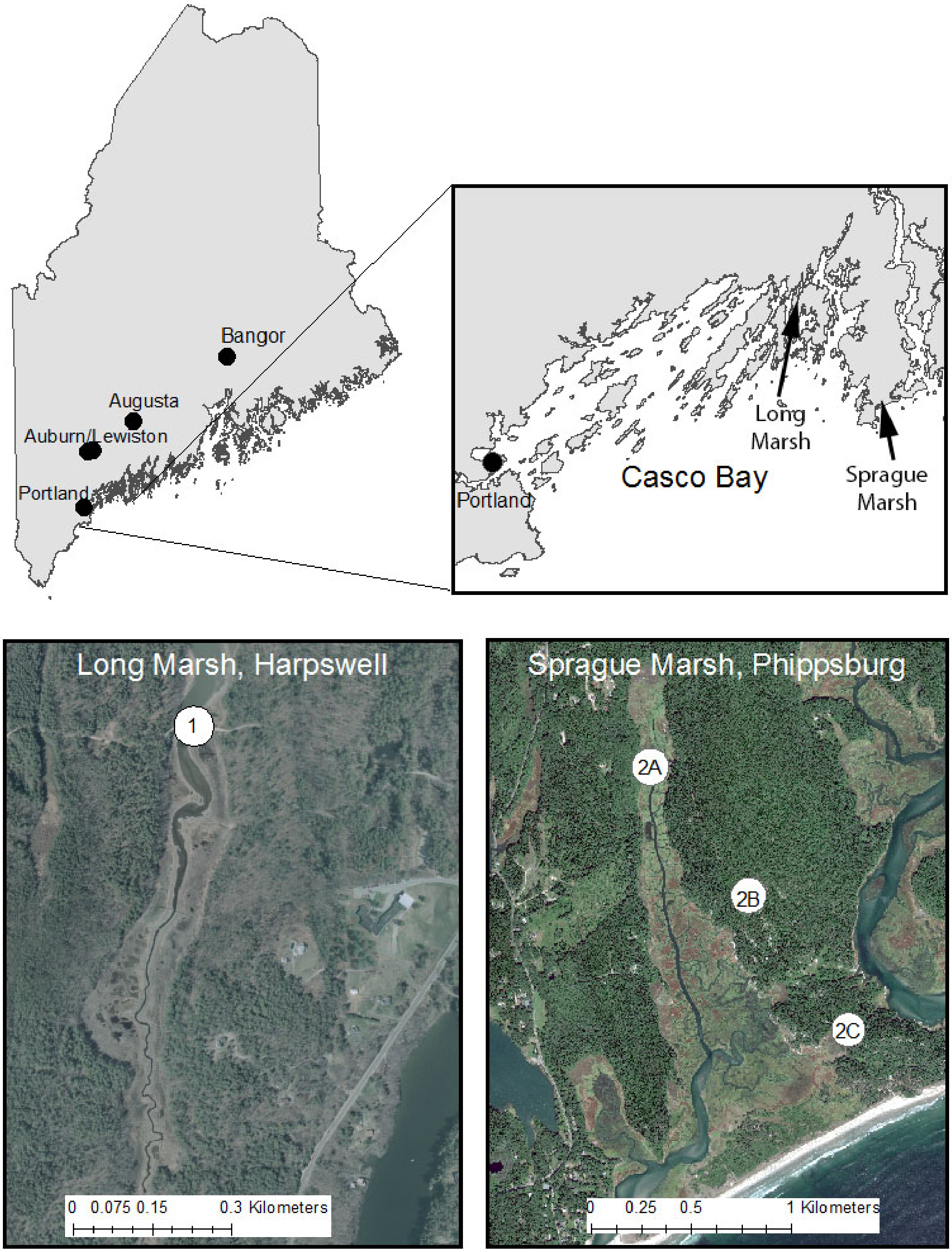


Figure 2. Map of Maine and inset of Casco Bay, with locations of Long and Sprague Marsh, plus satellite images of Long and Sprague Marsh. Fieldtrip stops are designated as 1, 2A, 2B and 2C on the satellite images.

The most common marsh formation within the Indented Shoreline compartment is the fluvial marsh. These are typically found in glacial valleys along streams/rivers (Kelley et al., 1988). There are fluvial major and fluvial minor marshes; the former occupy estuarine sections of large rivers, the latter are found in underfit stream valleys. Fluvial marshes differ from back barrier marshes in that fluvial marshes border tidal streams/rivers, and *Spartina patens* usually grades into *Spartina alterniflora* and mudflats rather than sandy beaches (Kelley et al., 1988).

Long Marsh is classified as a fluvial minor marsh and Sprague Marsh is classified as fluvial minor grading into a back barrier marsh at its southern end. Morphologically, Maine's fluvial minor marshes are characterized by a nearly flat high marsh plateau, bounded above by steep valley walls, and below by tidal channels or tidal flats. In larger marshes, the high marsh plateau often harbors pools that retain water throughout the monthly tidal cycle, or shallow "pannes" that may dry periodically but are characterized by shallow water, bare soils and distinctive vegetation communities.

Salt Marsh Formation

The formation of salt marshes depends on rates of sea level rise, sediment accumulation and vertical accretion. Initially, low marsh plants colonize a tidal flat. The plants reduce the energy of the tide waters which then allows for suspended sediment to settle out. Over long periods of time, thick sequences of peat develop if vegetation and sediment accretion keep pace with sea level rise (summarized in Redfield and Rubin, 1962; Niering and Warren, 1980; Adam, 2002). If sea level rise is greater than sediment accretion, the low marsh plants will be drowned. If sediment accretion is greater than sea level rise, than the marsh surface becomes elevated and is no longer tidal. In Maine, following the rapid post glacial marine transgression and regression, and then the early Holocene rise in eustatic sea level, rates of sea level rise slowed enough to allow colonization of tidal flats by low marsh vegetation between 4000 and 3000 years ago (Figure 3; from Kelley et al,. 2010).

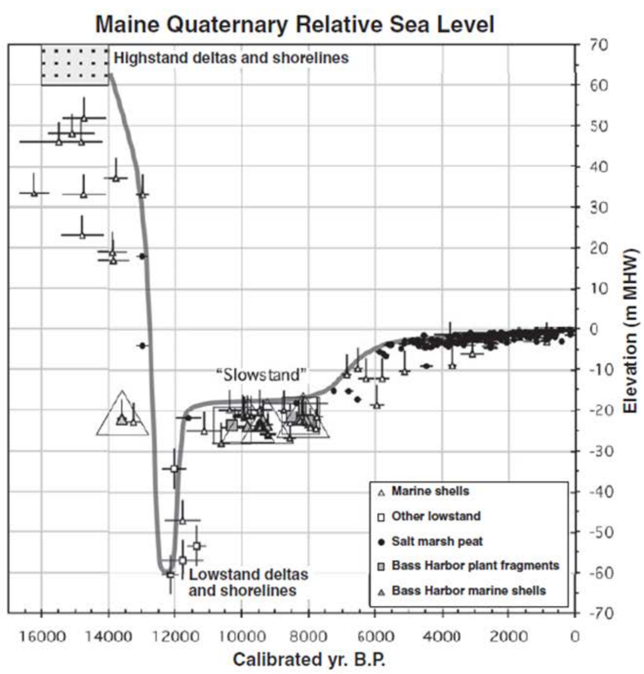


Figure 3. Late Quaternary sea level curve for Maine (from Kelley et al., 2010).

A close feedback process links salt marsh surface elevation with vegetation and tidal inundation. By trapping sediments and increasing accumulation of organic matter on the marsh surface and below ground, vegetation shapes sediment dynamics, which in turn shapes microtopography on which the vegetation grows. The link between vegetation, elevation and inundation is so close that the lower elevation of the high marsh plateau generally occurs within a few centimeters of Mean High Water (MHW), and corresponds to a shift in vegetation from "low marsh", dominated by *Spartina alterniflora* (salt marsh cordgrass) to "high marsh" vegetation, dominated by *Spartina patens* (salt meadow hay) and *Juncus gerardii* (black grass). The characteristic high marsh plateau appears to be the morphological consequence of this feedback process over a period of nearly 4000 years of relatively gradual sea level rise.

Detailed assessment of the elevation of tidal wetlands (Bohlen et al., 2012) show that most of our fluvial minor marshes have room to migrate up valley in response to rising seas. Unless inundation (1) is too rapid or (2) increases subsidence or lateral erosion, total intertidal area would increase with moderate sea level rise (ca. one meter). Sediment accretion rates, especially on the high marsh plateau, will influence the ecological character of the wetlands, with potentially significant implications for birds that nest (salt marsh sparrows; some waterfowl) or feed (wading birds) on the high marsh.

Vegetation Zonation

The zonation pattern of New England salt marshes, as described in numerous textbooks, depicts a relationship between dominant plant species and elevation (Figure 4). The classic model divides the salt marsh into low marsh, dominated by *Spartina alterniflora* and the high marsh dominated by *Spartina patens* and *Juncus garardii*. Permanent pools and periodically flooded pannes in the high marsh harbor distinct plant communities of their own. This zonation reflects the dynamic interplay between the physiological stresses of the salt marsh environment and competition among plant species that are able to survive at a given location on the marsh (Bertness and Ellison, 1987). Generally the plants of the low marsh and the pannes are better able to tolerate stress, while better competitors crowd out the stress tolerant species in the high marsh. The high marsh species, in turn, are crowded out by other species where conditions are more benign.

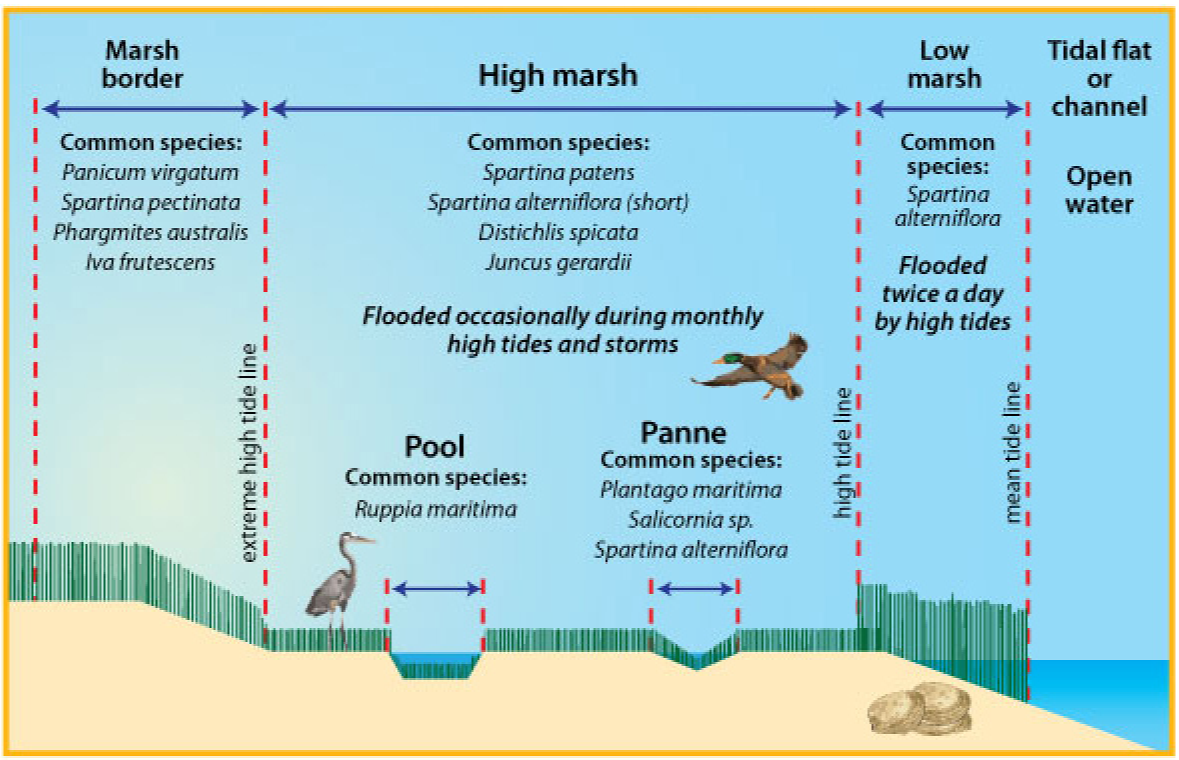


Figure 4: Diagram of classic salt marsh zonation for southern Maine (University of Maine Seagrant. 2016. Coastal Wetlands. http://www.seagrant.umaine.edu/coastal-hazards-guide/coastal-wetlands)

This classic zonation pattern, however, incompletely describes vegetation patterns on the marshes we will be visiting. On our sites, the elevation and inundation gradient interacts with strong latitudinal and lateral gradients in salinity. In these long, narrow wetlands, salt water enters the system at the mouth of the tidal creek, while freshwater enters at the other end of the marsh, via the marsh tributary. Fresh water also enters directly from the surrounding uplands via groundwater and surface runoff. The salt tolerant species of the "salt marsh" are found towards the downstream end of the wetland, grading towards brackish and then freshwater as those freshwater inputs come to dominate. Human alterations of marsh hydrology also result in variable patterns of vegetation, as will be illustrated at the sites we visit today.

<u>Ecosystem Services and Carbon Mitigation</u>

Salt marshes provide a variety ecosystem services (recently summarized in Gedan et al., 2011). They provide nutrients and habitat for many estuarine and marine organisms, buffer against storm surges, reduce coastal erosion and they filter out nutrients and pollutants. Additionally, they are extremely effective at CO_2 drawdown and carbon sequestration (more so than tropical forests) (McLeod et al., 2011). Recent elevation of this fact to the international and national climate policy and science communities has created a renewed focus on the climate mitigation benefits of restoring and conserving salt marsh and other coastal "blue carbon" (i.e., mangroves and seagrass) ecosystems (Nelleman, 2009; McLeod et al., 2011; Murray et al., 2011).

The climate benefits are derived from the fact that functional salt marshes are a carbon sink. In other words, CO_2 is removed from the atmosphere, converted to plant matter, and buried in anoxic sediments for centuries to millennia (Figure 5). Approximately 20% of fixed carbon is released back to the atmosphere as CO_2 via respiration, 70% is exported to the surrounding estuaries, and 10% is buried in the sediments (Bauer et al., 2013). In some cases, greenhouse gases (GHG) are emitted from sections of salt marshes, particularly those who have been subject to human impacts (summarized in Johnson et al., in press). Thus it is important to track GHG emissions and uptake when considering the climate mitigation potential of a salt marsh (Moseman-Valtierra, 2013).

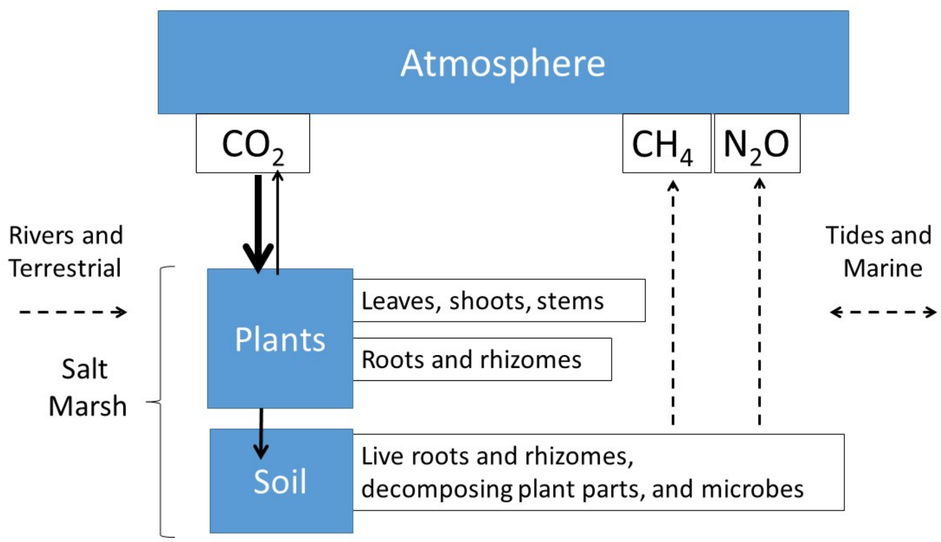


Figure 5. Concept map of carbon and GHG budgets in a salt marsh (from Johnson et al., in press). Boxes = reservoirs of organic matter; arrows = represent fluxes of organic matter and/or GHG. Black solid arrows = dominant fluxes of carbon (photosynthesis, respiration and burial); black dashed arrows = variable, and usually minor fluxes of GHG, green dashed arrows = variable, and often unknown, inputs of organic matter from land and sea.

<u>Human Impacts</u>

Today, when we look at tidal wetlands, we often think if them as natural areas, of value principally because of their visual beauty, water quality benefits or as habitat for juvenile fish or migratory birds. However, Maine's tidal wetlands have a deep and complex history of human use and alteration. In fact, nearly all salt marshes have been impacted by humans; between 24 and 50% of salt marshes have been destroyed over the last couple of hundred years (Gedan et al., 2011). Globally, estimates of salt marsh loss range between 1-2%/yr (Duarte et al., 2008).

For early settlers of Maine, and continuing into the 20th century, tidal wetlands were an important source of forage for livestock. Wetlands were altered to facilitate harvesting or to increase quality and quantity of hay produced. Famers cut perimeter ditches around the edge of the marsh to divert surface and groundwater from the adjacent uplands, or carved drainage ditches to speed drainage of tidal waters. Roads were built on the marsh surface to speed access to the hay. Natural channels and pools were filled, both as convenient locations to dispose of dredged material, and to increase harvesting area.

The importance of salt marsh hay diminished as the uplands were cleared; human uses and alterations of tidal wetlands grew ever more complex. Portions of marshes or entire wetland systems were cut off from the sea to facilitate production of salt-sensitive crops. Ditches were dug in an effort to reduce mosquito populations. Dikes were built to retain water on the marsh surface and increase habitat for waterfowl. Roads and railroads were built across tidal wetlands, blocking fish passage and restricting tidal flow. Dams were constructed across tidal valleys to create freshwater ponds. Wetlands are also altered indirectly by development of adjacent areas.

Tidal restrictions are locations where roads, railroads, dams or other structures cross tidal wetlands, block or restrict movement of tidewater. Tidal restrictions alter system hydrology, cause changes in vegetation, and degrade habitat quality for certain saltmarsh dependent species. By restricting delivery of marine-derived sediments to the marsh surface, they may also reduce marsh resiliency to sea level rise.

Surveys of structures in intertidal areas around the Casco Bay shoreline identified over 128 candidate sites for restoration (Figure 6). Analysis of elevations using LIDAR confirmed that 76 of these structures occur at present-day tidal elevations, and thus qualify as tidal restrictions.

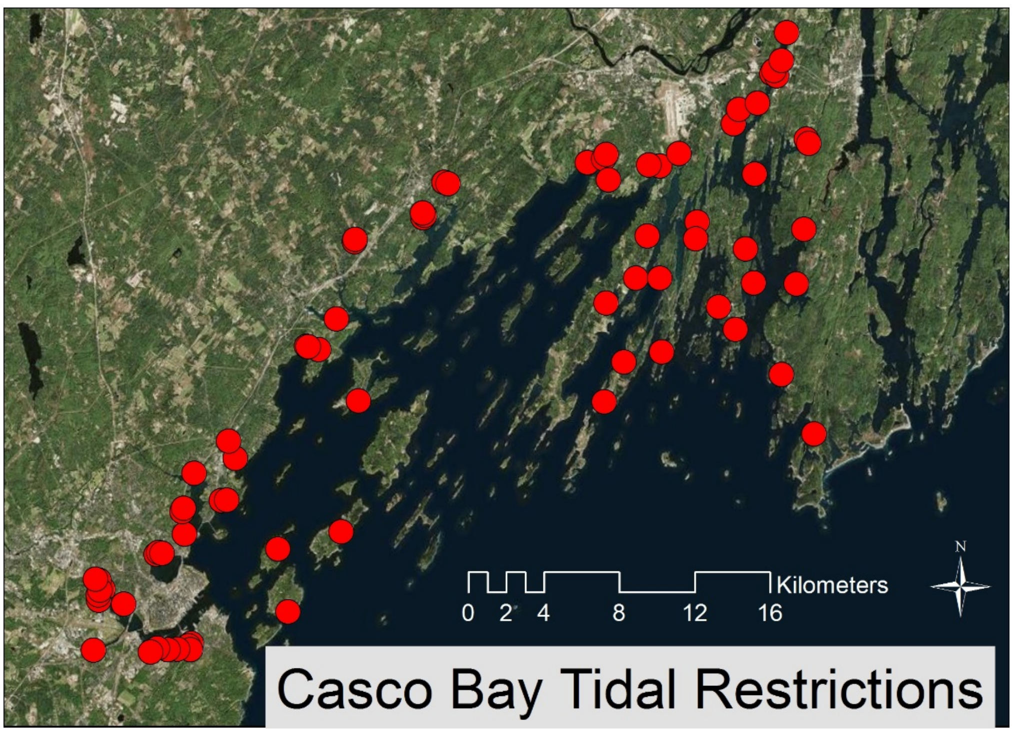


Figure 6. Map of tidal restrictions along the Casco Bay Shoreline (modified from Bohlen et al. 2012).

Restoration is commonly undertaken to repair negative impacts of prior human activities in tidal wetlands. Most salt marsh restoration projects undertaken in Maine in recent years have focused on restoration of hydrologic characteristics of the tidal wetland. In the 1990s, "ditch plugging" projects were undertaken to block flow through linear ditches, to restore what was thought of as more natural hydrology, or to increase shallow surface water to improve habitat for migratory birds. More recently, projects have focused on repairing tidal restrictions by removing tide gates or replacing under-sized culverts at road crossings with larger structures.

Purpose of Fieldtrip

Recent efforts to restore salt marshes have met with mixed results. In this field trip, we explore a success story in-the-making at Long Marsh, Harpswell, where an undersized culvert was recently replaced. Also, we visit a site with mixed restoration results (restoration of the hydrology and ditch plugs) in the Sprague River Marsh, Phippsburg. Participants will (1) explore the geologic history of both marshes by collecting and examining sediment cores, (2) learn about the ecology of the dominant marsh plants, and (3) examine the pros and cons of various restoration methods. While we wait out the tides, we will first go to the beautiful historic and famous Cribstone Bridge on Bailey Island (A6-1 through A6-4 of this field guide), followed by a brief lunch in scenic coastal Maine and then visits to 2 salt marshes in midcoast Maine. Discussions on topics such as carbon sequestration and methane emissions, marsh hydrology, sea level rise and coastal hazards are sure to ensue.

ACKNOWLEDGEMENTS

We thank the Bates Morse Mountain Conservation Area and Laura Sewall for all of the kindness and support received over the years for our work on Sprague Marsh, the Bates Student Research Fund, and the many excellent thesis students who have spent a good part of their senior year studying various aspects of salt marshes with us, including Karen Moore, Erin Beirne, Elyse Judice, Ingrid Knowles, Colin Barry, Margaret Pickoff, Cameron Russ, Cailene Gunn, Dana Cohen-Kaplan, and this year’s crop, Kelsey Chenoweth and Daniel Stames.

ROAD LOG

Due to the timing of the tides (low tide is at 3:30 pm), and our desire to take sediment cores of marsh sediments when the sediments are not fully saturated, we have linked the Ecogeomorphology of Marsh field trip with the Cribstone Bridge fieldtrip described on pages A6-1 through A6-4 of this field guide.

Participants for both the Cribstone Bridge and Ecogeomorphology of Marshes Fieldtrips will meet at the Cooks Corner Shopping Center, Brunswick, on the southwest corner of Route 24 beneath the trees in the TJ Maxx parking lot, near the Subway/Starbucks building at 10:00 am. Due to limited parking, we will consolidate vehicles and follow the ROAD LOG described on pages A6-1 through A6-4 for the Cribstone Bridge trip. After seeing the Cribstone Bridge, we will have lunch and then drive to Long Marsh, arriving there at 12:30 pm.

We will be driving to all fieldtrip stops, but will provide the option for folks to walk between stops at the Sprague Marsh, should they prefer shorter times at the stops and more time walking. (The total walking distance will be between 3-4 miles. It is not technical, but there is a ~200 foot climb up Morse Mountain at the Sprague Marsh site.) No food or water will be available at the marsh stops; please bring all food and drink. Comfortable mid-calf-high waterproof shoes would give you the most flexibility in terms of marsh exploration. Please pack warm clothes and/or rain gear, depending on the forecast.

STOP 1. LONG MARSH (and starting point for Ecogeomorphology for Marshes Part of Fieldtrip)

At Long Marsh, we will examine the marsh stratigraphy/history, vegetation and the impacts of tidal restoration and subsequent response of marsh vegetation and CH_4 emissions. Though this restoration project is only 2.5 years along, all signals suggest it has been a grand success.

General Background.

Long Marsh is located in Harpswell, Maine. It is almost 3 km long and for much of its length has a width of under 200 m. It is confined to east and west by bedrock uplands, which form a narrow valley. Tidewater from Casco Bay enters the marsh through a culvert under Long Reach Lane, to the north. The first kilometer or so of the wetland is predominately salt marsh, but it grades to brackish marsh and to tidal and ultimately non-tidal freshwater wetlands upstream. Much of the marsh is public land, part of the Austin Cary Lot, which is managed by the Baxter State Park Authority. Another lot that includes part of the marsh is protected by a conservation easement held by the Harpswell Heritage Land Trust.

Long Marsh is located in metamorphic sedimentary rocks (middle to late Ordovician) on the western limb of the Hen Cove anticline. Here, the older Cape Elizabeth Formation to the west lies structurally on top of the younger Sebascodegan Formation to the east due to the Boothbay Thrust Fault (Hussey and Berry, 2006). It is important to note that there is some debate about the existence of the Boothbay thrust fault (Eusden, pers com, 2016). The surficial sediments of Long Marsh and surrounding uplands is composed the glaciomarine clay of the Presumpscot Formation and depositional glaciomarine silts and clays. The soils of Long Marsh show considerable spatial heterogeneity and in many areas show interlayering of salt marsh peats with secondary deposits of the glaciomarine silts and clays. Small–scale variation in soil characteristics appears to influence hydrology and vegetation.

<u>History of Human Impacts.</u>

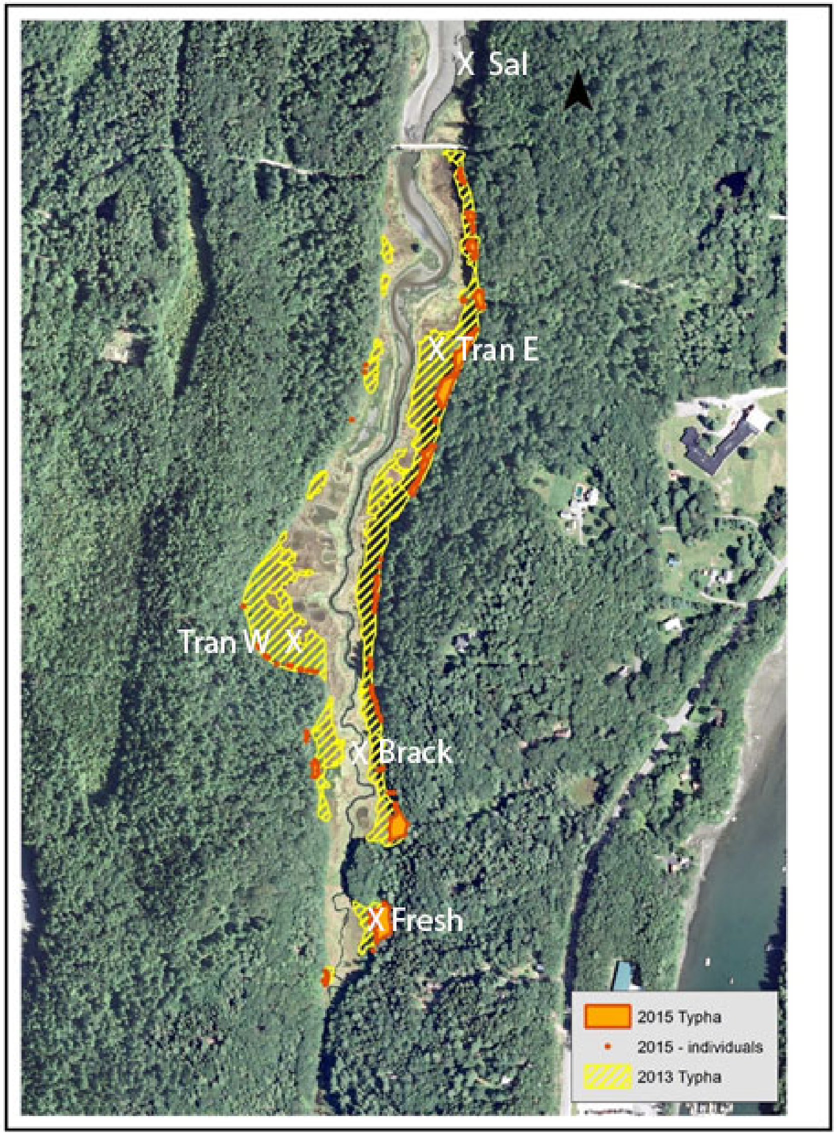
Long Marsh has long been diked at the current location of Long Reach Lane (Coffin, 1934). The exact timing of initial construction is uncertain. Long Reach Lane itself does not show up on USGS topographic maps until the 1940s, but is older than that might suggests. We believe tidal flow to the marsh has been restricted since about 1900. The adjacent land was the site of a coastal farm. “Mash hay” was cut from the marsh surface by hand for livestock, dried on nearby beaver dams, and then carried off by hand. The marsh was described as being ‘too soft for a horse’ (Coffin, 1934). While there is no evidence of grid ditching typical of 20th century efforts at mosquito control, remnants of a perimeter ditch are visible around several portions of the marsh. Perimeter ditches were frequently used to divert runoff from adjacent uplands, to facilitate growth and harvesting of salt hay. If the site was “too soft for horses”, apparently the effort was only partially successful here.

Several other structures are visible in the marsh, but we have so far found little documentary evidence for when they were constructed or why. Lateral berms are prominent in the northern (downstream) portion of the marsh both to the east and the west of the tidal channel. They may have been constructed by resource agencies in the 1960s in an effort to enhance habitat for waterfowl. An abandoned road bed crosses the marsh about 800 m from Long Reach Lane. The road bed leads to the site of one of the first homestead settlements in Harpswell.

<u>Restoration and Vegetation Response.</u>

Several years ago, Maine’s Department of Transportation undertook the replacement of the Martin’s Point Bridge, which crosses the Presumpscot Estuary between Portland and Falmouth. The project resulted in the destruction of tidal flats and wetlands, which triggered an obligation for wetland mitigation under federal and state law. In January of 2014, contractors working for DOT replaced the three foot diameter round culvert that had been in place for decades with a substantially larger box culvert (Figure 7). Not only is the new culvert substantially larger, but its bottom is several feet below the elevation of the bottom of the old culvert. This change has sharply increased the tidal range in the marsh, both lowering the level of water in the marsh at low tide and raising the elevation of water in the marsh during high spring tides. CBEP has sampled pore water salinity at eleven sampling locations since 2013, before the project was completed. At most sites, salinity either increased or significantly increased following the project.

Figure 7. Culvert at northern end of Long Marsh, prior to and after the 2014 restoration.



The vegetation response to the restoration effort has been both significant and dramatic and includes widespread cattail mortality (Figure 8). Prior to replacement of the culvert, cattails (*Typha latifolia* and *Typha angustifolia*) were abundant, present on as much as one quarter of the marsh surface within the primary study area (see Figure 8; yellow hashmarked areas). Within a year of project construction, cattails were gone from most of the former area they had occupied (see Figure 8; orange solid areas). Cattails are sensitive to salt, so this widespread mortality is almost certainly due to increased porewater salinity post restoration.

Figure 8 (to the left). Map of *Typha* spp. on Long Marsh prior to restoration (yellow hashed marks) and after restoration (orange solid area). Also included are location of CH_4 sampling sites, including Sal (Saline), Tran E (Transitional East), Tran W (Transitional West), Brack (Brackish) and Fresh.

Other vegetation changes suggest that changes in salinity have been the primary driver of vegetation change. Results of intensive vegetation monitoring show a significant drop in abundance salt-sensitive plant species throughout the marsh.

<u>Tidal Restoration and Reduced Methane Emissions.</u>

Using static gas chambers, we quantified CH_4 fluxes along a salinity gradient at three sites ranging from the salt marsh platform (salinity of 27 to 31 psu, dominated by *Spartina* spp.), to the salt marsh margins (salinity of 0 to 4 psu, dominated by *Typha* spp.) (Gunn, 2016). Two sites in the *Typha* die-back zone (hereafter referred to as transitional sites) were also measured. Sampling was executed monthly between July and October, 2015, and between April and October, 2016. CH_4 concentrations were determined using a gas chromatograph with a flame-ionization detector in the Environmental Geochemistry Laboratory at Bates College (Figure 9).

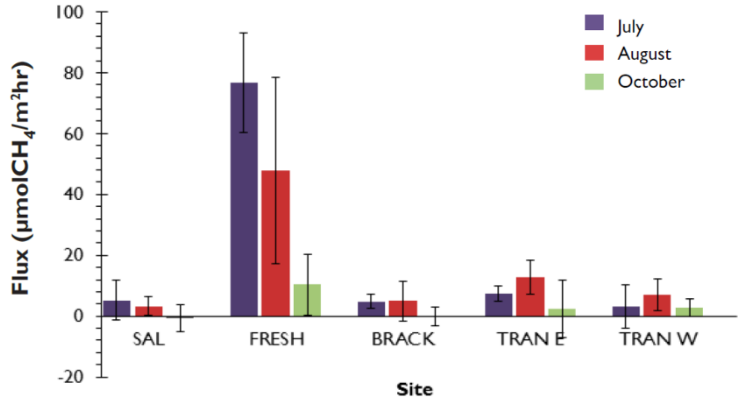


Figure 9. Average methane fluxes for triplicate measurements from five sites in Long Marsh, 2015; error bars represent 1 standard deviation (from Gunn, 2016).

In 2015, the lowest CH_4 fluxes were observed at the most saline and brackish sites (SAL and BRACK). The highest CH_4 fluxes were measured at the marsh margins, where *Typha* dominated (FRESH). CH_4 fluxes at the transitional sites were relatively low (TRAN E and TRAN W). These data agree with those of Poffenbarger et al. (2011), indicating that salinity and CH_4 emissions are inversely correlated. When marine water is not present (and porewater sulfate concentrations are low), methanogens outcompete sulfate reducing bacteria, and methane is released. For all sites, lowest fluxes were observed in October and highest fluxes in July, suggesting seasonal influence on CH_4 emissions. Our 2016 measurements are currently underway.

We used a space-for-time sampling design and assumed that CH_4 emissions at the salt marsh margins (and by the long-lived *Typha* stand), could be used to calculate CH_4 emissions from areas where *Typha* had expanded onto the marsh platform prior to restoration. Based on average CH_4 fluxes from the FRESH site for all sampling periods (61.8 μmol CH_4/m2 hr) and a measured 3.11 ha decrease (92%) in *Typha* area after restoration, we project a decrease in CH_4 emissions of approximately 70 kg CH_4, or 1750 kg CO_2e.

While 1750 kg CO_2e may sound substantial, this corresponds to the amount of CO_2 generated, in terms of global warming potential, by complete combustion of approximately 210 gallons of octane (gasoline). In other words, the reduction in CH_4 emissions at Long Marsh is equivalent to the CO_2 produced from the amount of gasoline burned by one car driven by the average American over a 4 month period of time (assuming 25 mpg and 15,000 miles driven annually). Our CH_4 flux data suggest the reintroduction of healthy tides reduces methane production and emissions; however, the net carbon benefits of the relatively small (~ 5 to 15 Ha) tidal restoration projects in Casco Bay may prove difficult to monetize to support future projects

STOP 2. SPRAGUE RIVER MARSH

Mileage and Directions to STOP 2 (Sprague Marsh) from TJ Maxx parking lot at Cooks Corner Shopping Center

Participants depart Long Marsh at 1:45 pm and will return to the TJ Maxx parking lot at Cooks Corner Shopping Center, Brunswick (on the southwest corner of Route 24) to move vehicles to STOP 2, the Bates Morse Mountain Conservation Area (BMMCA), Sprague Marsh in Phippsburg. The transition at Cooks Corner will be a good time to take a brief bathroom break before continuing onto Sprague Marsh (at the BMMCA). Participants should plan to leave Cooks Corner no later than 2:10 pm so they can arrive at the Bates Morse Mountain Conservation parking lot by 2:45 pm.

Road log is listed in cumulative miles beginning at TJ Maxx/Starbucks parking lot at Cooks Corner.

Mileage and Directions from TJ Maxx/Starbucks parking lot at Cooks Corner to Sprague Marsh (~40 minutes):

00.0	Turn Left/North onto Route 24 out of the parking lot
00.1	Take US-1 N to Bath
07.2	Take Route 209 S (High St) in Bath, heading down the peninsula
18.7	Route 209 S turns sharply left to Popham Beach. <u>Stay straight on Route 216</u>.
19.1	Take left onto Morse Mountain Road (gravel road), and park in parking lot for Bates Morse Mountain Conservation Area about 350 feet from the turnoff onto Morse Mountain Road. (In the summer, there is a gate keeper in the lot.)

In the Parking lot, we will consolidate cars and drive along the Morse Mountain Road to sites 2A, 2B and 2C. (Participants may elect to walk to the sites, but will need to account for walking time between sites.)

<u>General Background.</u>

Sprague Marsh is located in the Bates Morse Mountain Conservation Area (BMMCA) in Phippsburg Maine. It is approximately 2 km long and has an average width of 0.5 km, occupying an area of ~1 km^2 (refer to Figure 2). It is confined by bedrock uplands on the east and western boundaries (Morse Mountain to the east) and the largest undeveloped barrier spit in Maine to the south (Sewall Beach). The dune and backdune area of Seawall Beach is broad and characterized as the largest parabolic dune system in Maine (Nelson and Fink, 1978). BMMCA is listed as a Focus Areas of Statewide Ecological Significance (Maine Natural Areas Program), as part of the Kennebec Estuary.

The bedrock geology of the Sprague Marsh and surrounding uplands includes the metamorphosed sedimentary rocks of the West Marsh Formation (late Ordovician) to the west abutting the Morse Mountain granite (Devonian) along the eastern margin of the marsh (Eusden et al., 2016). The discovery of the granofels and amphibolite members within the nonrusty schists of the West Marsh Formation in this region argues for its correlation to the Scarborough Formation (Eusden et al., 2016). These rocks originated as sediments in a backarc basin during the Taconic Orogeny, and were metamorphosed and deformed in the Salinic through NeoAcadian orogenies. For more detailed information on the bedrock geology of Small Point, Phippsburg, the reader is referred to Dyk Eusden's NEIGC fieldtrip on Oct 15, 2016 and accompanying fieldtrip guide (Eusden et al., 2016), this volume.

The bedrock is draped in a layer of thin layer of till and the Presumpscot Formation (glaciomarine clay), both of which mark the presence and retreat of ice through various stages of sea level. The beach and back barrier dune system is supplied primarily by sand from the Kennebec River and offshore paleodelta deposits. In the marsh, the inorganic sediments are coarser and sandier to the south, indicating the reworking of sediments from the beach and dune system and finer to the north, indicating incorporation of more Presumpscot into the sediments. The marsh peat is thickest in the north and thinnest in the south (Russ, 2013).

<u>History of Human Impacts.</u>

The degree to which BMMCA was inhabited/farmed/deforested/mined and the transfer of lands over its history is detailed up to 1990 in Curi (1990, 1991). The following is a brief account of human activity in the BMMA with a special focus on the Sprague River Marsh. The reader is strongly encouraged to read Curi (1990, 1991) for more details.

Prior to European arrival, archaeological shell middens provide important clues about foods eaten and resources exploited and the technologies used by the region's earliest occupants. A small shell midden located along the SW border of Sprague Marsh (which has yet to be dated) indicates that people were fishing and digging for clams within the marsh and in the surrounding tidal flats at some point over the last few thousand years. Given the sporadic temporal and spatial nature of these deposits around the marsh, the activities of the Native Americans probably did not have any long-term impact.

European settlement of the area began in earnest in 1716 when the Pejepscot Proprieters offered 50 acres of land (5 acres of which would be salt marsh) to the first 50 families who settled in Small Point/Phippsburg (Curi, 1990; Curi, 1991). By 1792, the Sprague River salt marsh was divided into 23 parcels which were used for grazing and salt marsh hay production (Figure 10).

In the mid to late 1800s, a cranberry meadow was created in the backdune area to the SE of Sprague Marsh. Grazing and the harvesting of marsh hay was continued up until the 1920s.

In 1942, the US Army built a lookout at the top of Morse Mountain to surveil the mouth of the Kennebec and protect the Bath Iron Works during WWII. They vacated the premises in 1946, but tarred the road across the northern end of the marsh and the Sprague River (hereafter referred to as the causeway and the troll bridge; STOP 2A) and to the top of Morse Mountain (STOP 2B).

In the 1950s, modifications of the marsh were centered on draining the water from pools and shallow depressions on the marsh surface (to reduce mosquito habitat). Locals dug networks of ditches through the marsh peat from the pools to the tidal channel. Grid-ditching was a common practice at this time; approximately 90% of the marshes in New England were ditched during the 1930s. It is estimated that the ditching of the Sprague marsh continued until the 1960s.

In 1958, Junior Mellen, used a dragline excavator (or bulldozer, the reports are not clear) to straighten the Sprague River channel for rapid draining. As a result, the major channel of the Sprague River still flows in a relatively straight line oriented N-S. The natural stream channel exists as a secondary dead-end feature on the marsh surface.

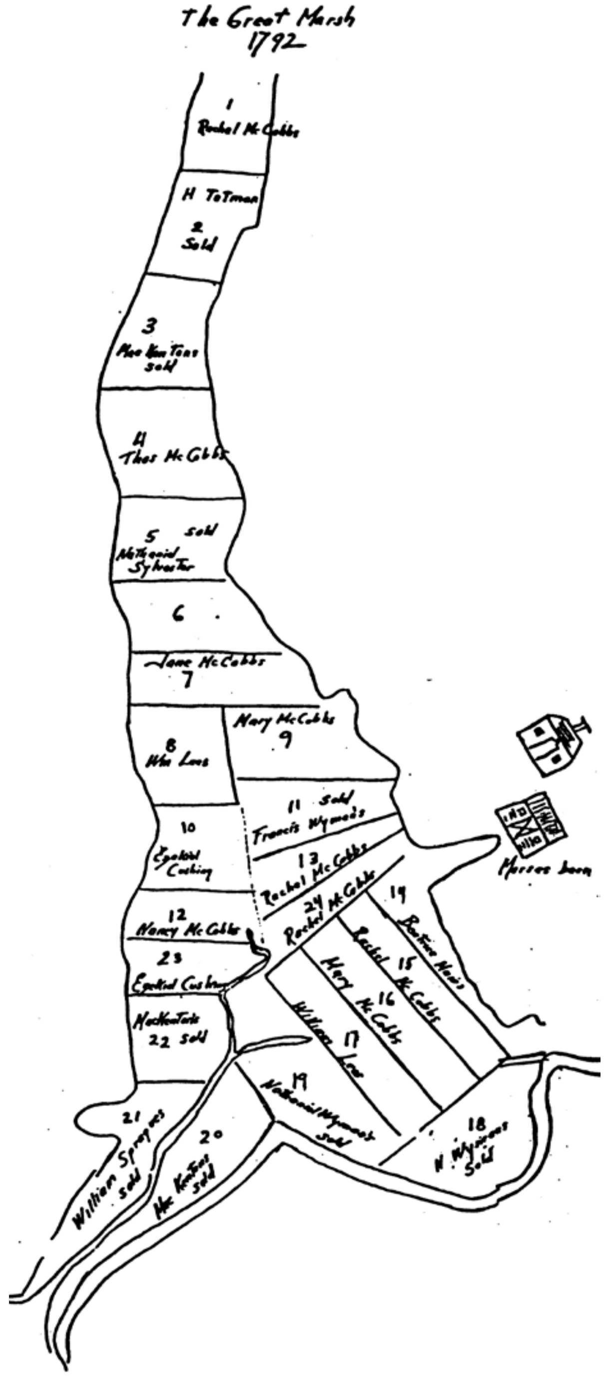


Figure 10 (image to the right). Map of Sprague Marsh (also known as the Great Marsh) drafted in 1792 demonstrating ownership of 23 parcels of the marsh.

Restoration.

Major restoration projects on Sprague Marsh began in January, 2000. Specifically, the goals were to lessen the impacts of tidal restrictions on the marsh north of the causeway and the troll bridge (STOP 2A) and to reintroduce pool habitat to the surface again via ditch-plug restoration (STOPS 2A and 2C). In January, 2000, perimeter ditches were dug around the northern part of the marsh in an attempt to limit freshwater inflow and growth of invasive species such as *Pragmites australis*. Two days into the project, the marsh iced over and this part of the project was abandoned. In June 2002, three ditch-plugs were installed north of the causeway, and the channel was dredged just to the south of the causeway. The dredge spoils were removed from the marsh and used to expand the Shortridge parking lot. In the fall of 2002, 11 ditch-plugs were installed in the southern end of the marsh (STOP 2C). In April of 2006, the troll bridge was widened to improve tidal flow to the northern end of the marsh.

STOP 2A. CAUSEWAY ACROSS THE NORTHERN END OF MARSH (2:45-3:00 pm arrival)

Directions and Background.

From the BMMCA parking lot, follow the Morse Mountain Road to the causeway. The distance from the parking lot to the causeway/STOP 2A is ~ 0.4 miles. The causeway has been in place since at least the 1940s. The original bridge over the Sprague Creek (called "the troll bridge") was undersized; consequently the marsh north of the causeway became fresher, and much of the marsh platform became springy and mushy (called "rotten marsh").

There are multiple points of interest at STOP 2A to investigate, including the marsh stratigraphy south of the causeway, the outcrops of the Morse Mountain granite, the three ditch plugs, and the erosion of the creek bank, which appeared after the troll bridge was modified (Figure 11).

Figure 11. Points of interest for STOP 2A, including the causeway (road across the marsh) and "troll bridge" (eastern side of the causeway), location of ditch plugs (X), and location of cores taken (vc1, vc2) for stratigraphic cross section presented below and in Figure 12. (Satellite image taken 8/15/13.)

Stratigraphy.

To the south of the causeway, the marsh is relatively healthy. The peat has a good firm structure, and the vegetation is healthy. The stratigraphy illustrates the evolution of the marsh as sea level rises (Figure 12; Beirne, 2005). The basal organic layer is derived from a freshwater peat or terrestrial plants. This is overlain by tidal stream channel/tidal flat sediments which were colonized by low marsh plants. Wood fragments 14C-dated at 3700 +- 80 cal yr BP (Johnson et al., 2007) were washed into the system and the initial low marsh failed. The wood may have been derived from the surrounding uplands (perhaps mobilized by firing of the landscape), or washed in from the tides or storm events. Overlying the wood chips is a thick sequence of tidal stream channel/intertidal sandy silt, with some marine shells and no evidence of low marsh plants. Radiocarbon dates of the wood and shells in this unit provide a sedimentation rate of ~0.3 cm/yr for this unit (Johnson et al., 2007). This rapid period of marine sandy silt deposition may correspond to a relative increase in the rate of sea level rise and sediment accretion. Alternatively, these sediments may represent rapid meandering and reworking of the tidal stream across the marsh. Overlying the sandy silt, low marsh plant roots and rhizomes grade into higher marsh plants. There is evidence of a storm deposit at about 50 cm (2-3 cm layer of sand), and perhaps a buried panne near the surface. At STOP 2A, we will take a couple of sediment cores south of the causeway to get a sense of the stratigraphy and history of the marsh.

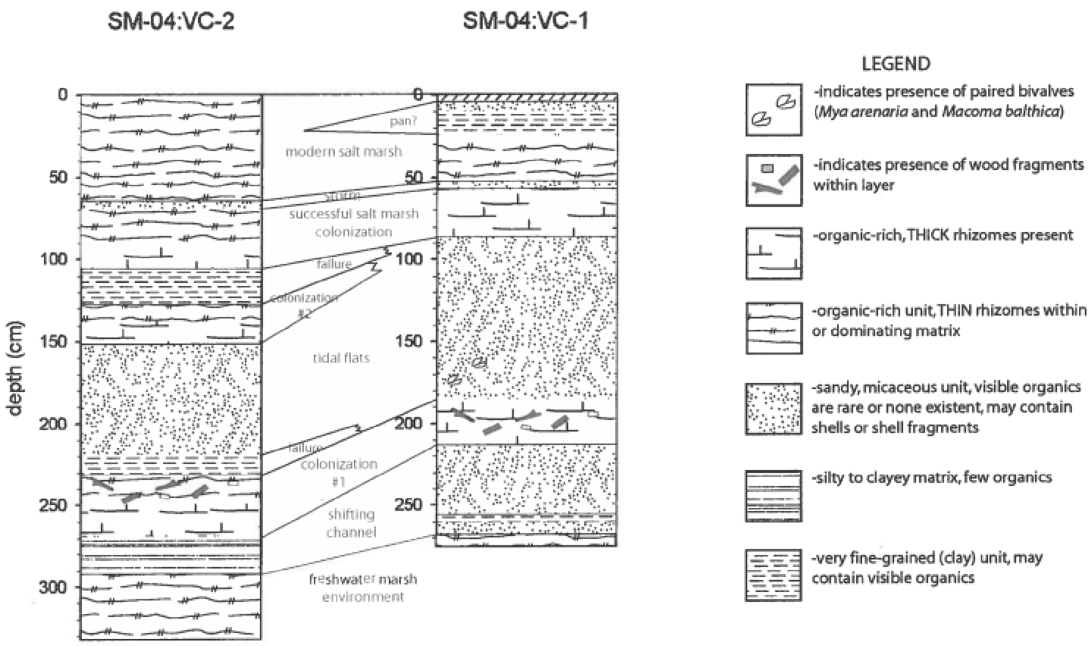


Figure 12. Stratigraphy, correlations and interpretations of 2 vibracores (labeled vc1 and vc2 on Figure 11) collected along a west-east orientation approximately 30 m south of the causeway (from Beirne, 2005).

Three Ditch Plugs.

At STOP 2A, there are three ditch plugs north of the causeway, installed in 2002. The consequent change in hydrology has resulted in a major interconnected water feature on the marsh surface. The pools are shallow and varied in terms of the biogeochemical cycling within, and the marsh platform (which was a healthy high marsh platform prior to ditch plug installation) is now spongy, decomposed and “rotten” in many places. Fresh/brackish water vegetation is encroaching onto the marsh. The plugs are best viewed on the east side of Sprague River. Please say off of the ditch plug/pool surface itself, on the west side of the Sprague River, as it is a fragile system, and the marsh surface is relatively weak.

Morse Mountain Granite.

At STOP 2A, on the south side of the troll bridge, you will see the contact of the Morse Mountain Granite with the West Marsh Formation. Other outcrops of the Morse Mountain Granite can be found within the marsh on the north side of the causeway.

STOP 2B. TOP OF MORSE MOUNTAIN (4:00-4:15 pm arrival).

From the causeway, follow the Morse Mountain Road to the top of Morse Mountain/STOP 2B. The distance from the causeway/STOP 2A to the top of the mountain is ~ 0.5 miles with an elevation gain of approximately 200 feet. Here you will see a lovely view of the marsh, including the original channel and mouth of the Sprague River, the backdune system, the upland forests, Sewall Beach, and Small Point. On a clear day, you will see across Casco Bay to Portland to the southeast, and on a very clear day, Mt Washington to the west. There are two private homes at the top of the mountain, so participants are asked to mind the signs directing visitors to the public outlook on the granite outcrop.

STOP 2C. SOUTHEASTERN END OF SPRAGUE MARSH (4:45-5:00 pm arrival).

From the top of Morse Mountain, follow the Morse Mountain Road to the southeastern area of Sprague Marsh, STOP 2C for approximately 0.75 miles, and an elevation loss of 200 feet. Entry to the marsh here is to the south, AND is very wet. Participants are asked to move carefully along the edges of the marsh here, to minimize impact on an already fragile system, and for safety's sake. Once you get level with the first granite outcrops in the middle of the marsh, it is fine to walk on the marsh platform. At STOP 2C, we will take a look at 4 of the 11 ditch plugs installed in 2002 (Figure 13).

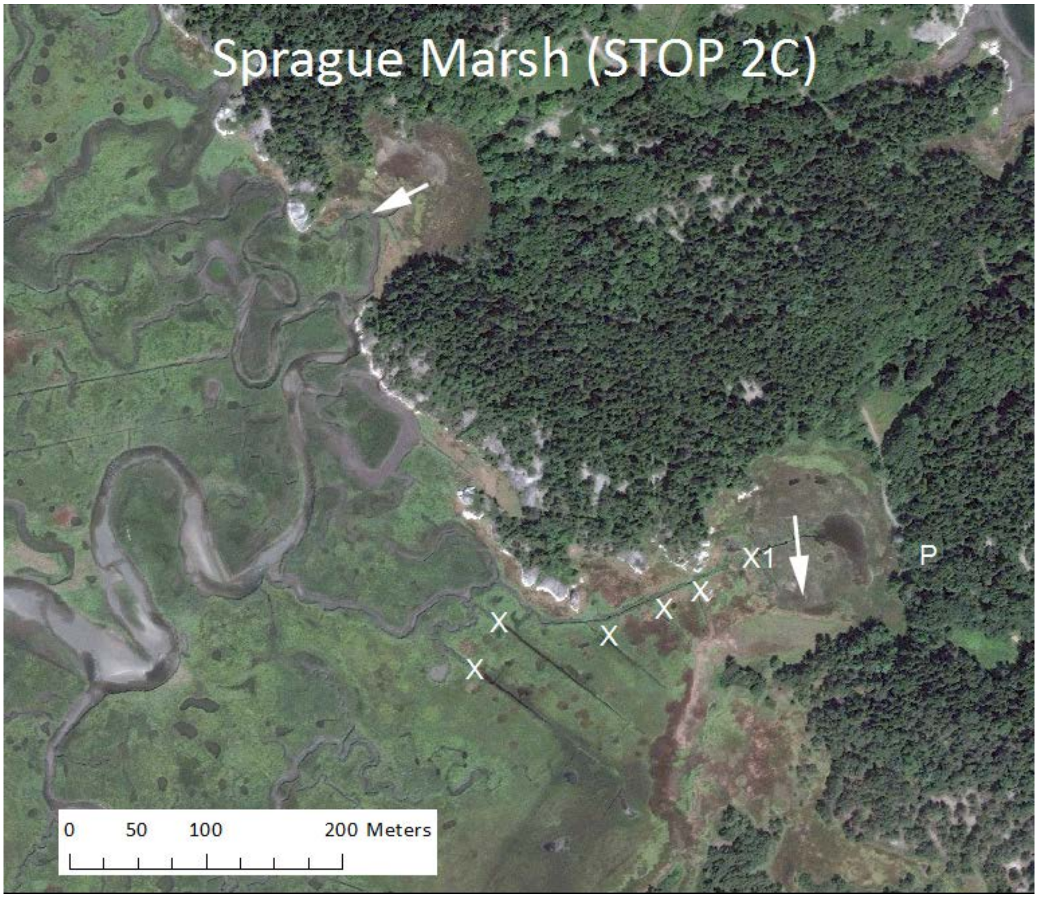


Figure 13. Points of interest at STOP 2C, where P = parking area, X1 = largest ditchplug, other X = other ditchplugs. White arrows represent direction of groundwater flow in two similar alcoves along the margins of the marsh (from Barry, 2012). (Satellite image taken 8/15/13.)

One of the ditch plugs (X1) is located closest to the margins of the marsh, and the barrier to flow combined with proximity to fresh groundwater inputs from the surrounding uplands has created a very interesting set of conditions on this section of the marsh. The hydrology of the marsh is significantly altered here; we now have a massive water feature on the surface and an effective barrier to groundwater flow. Here, ground water flow moves to the south as opposed to towards the tidal channel and center of the marsh, as seen in other marginal areas of the marsh (Figure 13). This may due to the effectiveness of the ditch plug as a dam and the fact that permeable sands lie to the south of the site. The marsh platform is springy, lacks strength, and is breaking down relatively rapidly, such that there is a small basin behind the ditchplug. Changes in vegetation and biogeochemical cycling have occurred, and there is some evidence of sulfide toxicity on the marsh east of ditchplug X1.

Ditch Plug Restoration and Reduced CO_2 Uptake.

Using satellite images, we calculate that the area of salt marsh grasses lost due to the ditch plug restoration in this section of the marsh to be approximately 1 ha. Assuming average annual carbon sequestration rates of 8 tons CO_2e $ha^{-1}yr^{-1}$ in healthy salt marshes (Murray et al., 2011), the loss of CO_2 drawdown by emplacement of this ditch plug corresponds to the amount of CO_2 generated by complete combustion of approximately 970 gallons of octane (gasoline), or the amount of gasoline burned by one car driven by the average American over a period of time of 1.5 years (assuming 25 mpg and 15,000 miles driven annually).

The other ditch plugs are located further away from the marsh margins and more towards the marsh center. The impact of the ditch plugs is minimal here; long linear pools have been created, and in some cases the surrounding marsh is more saturated, but overall, the ditch plugging restoration seems to be going OK. If there is time, participants can explore the backdune system just south of here, where evidence of historical dyking, excavation and farming for cranberries exists.

Restoration, Carbon Benefits and Climate Mitigation.

When comparing and contrasting the carbon benefits associated with restoration of the two marshes we have visited today, we estimate an annual reduction in emissions of ~0.5 tCO2e/ha for the tidal restoration at Long Marsh, and an annual increase in emissions of ~8 tCO2e/ha at the ditch plug restoration in Sprague Marsh. Yes, these two types of salt marsh restoration work against each other, in terms of carbon drawdown and climate mitigation. If carbon sequestration is the most valued ecosystem service in these marshes, these data suggest that hectare-for-hectare, revegetating a pool created from a previously vegetated surface will have a 16x greater impact on carbon drawdown than restoring tidal flow to an area that has become brackish and is emitting CH_4. These are some of the first data generated for cost-benefit analyses of marsh restoration from a carbon perspective.

The reality is, there are often competing interests that drive any type of restoration. Questions about what we value most in our salt marshes (carbon sequestration vs more habitat for fish and shore birds, for example) are not simple to answer in today's rapidly changing world. Answers will require discussion and compromise and flexibility among the various stakeholders over the years to come.

END OF FIELDTRIP, 5:30 pm.

Return to vehicles the way we came in, via the Morse Mountain Road (~1.75 miles), and proceed to Bath for welcoming reception at the Winter Street Center, in Bath (approximately 30 minute drive from the BMMCA parking lot). THANKS FOR JOINING US!

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