DRAFT

REPORT ON SALT MARSH DIEBACK ON CAPE COD (2006)

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Contents

Summary

Salt marsh dieback refers to the rapid disappearance of vegetation, leaving behind areas of barren mudflats interspersed with remnant peat. Dieback has occurred in many different states along the Gulf of Mexico and the mid- and south-Atlantic coastlines. In New England, salt marsh dieback was first reported along the south shore of Cape Cod in 2002. Subsequently, dieback sites have been found in all coastal New England states. However, the most extensive dieback has occurred on the Bay-side of outer Cape Cod, particularly around Wellfleet. In some places within the Cape Cod National Seashore, up to ~12% of emergent marsh has been converted to mudflats. As such, outer Cape Cod seems to be the "epicenter" of salt marsh dieback in the Northeast.

Field observations indicate that wrack deposition, ice scouring, geese grazing, and soil toxicity can be ruled out as primary causes of dieback. However, there is evidence that the loss of high marsh vegetation – *Spartina patens* (salt marsh hay) and *Distichlis spicata* (spike grass) – is linked to elevation. High marsh is dying back along its seaward edge, suggesting that accelerated sea level rise may be impacting these marshes through flooding stress. Low marsh dieback of *Spartina alterniflora* (cordgrass) occurs at many different elevations but may also be the result of sea level rise acting both physiologically and physically (in the form of erosion) in this zone. With respect to the latter, the geographic distribution and severity of low marsh dieback correlates with exposure to prevailing winds and wave energy across Cape Cod Bay. Another hypotheses being investigated is that dieback may be caused by a new or existing pathogen that interacts with some combination of environmental factors. However, pilot greenhouse experiments with cordgrass suggest that any disease organism is highly ephemeral and/or highly dependent upon growing conditions. This idea is based upon the observation that 1) healthy plants can be grown without any problems in soils collected from dieback areas and 2) dying plants can be rehabilitated upon removal from the field. There may be other secondary factors contributing to plant decline as well. These include things like herbivory, drought, salinity, etc.

Regardless of the cause(s), it is imperative to understand how salt marsh landscapes are changing as a result of this process. Three years of monitoring I&M vegetation plots and analyzing photo-point images shows high marsh dying back in some areas and revegetation of old high marsh dieback sites by landward advance of the low marsh. However, the landward edge of *S. alterniflora* began dying mid-summer in an old high marsh dieback area in Middle Meadow (Wellfleet). Other sites have shown neither recovery nor deterioration. Where vegetation has been lost, it is clear that sediment erosion is occurring at a rapid pace. This can have enormous implications for recovery, since hydroperiod increases with decreasing elevation. Furthermore, sediment loss from the marsh and transport to coastal waters can impact nearshore, and potentially offshore, communities. Accordingly, erosion rates are currently being monitored at 48 different locations and initial data show significant losses of elevation are occurring in dieback areas - even during periods of benign weather. Finally, aerial photography has being analyzed to reconstruct the history of vegetation changes throughout the past 60 years and to determine how these changes relate to dieback processes.

Background

What is salt marsh dieback?

Salt marsh dieback is simply the disappearance of salt marsh vegetation. Wile natural vegetation loss occurs from various processes like wrack accumulation, intense grazing by geese, ice rafting, stem boring insects, planthoppers, and human-related causes, "unnatural" dieback refers to vegetation loss on a much larger scale that cannot be explained by the above. Moreover, in areas where natural plant death has occurred, recovery is usually rapid (1-2 years).

Unfortunately, salt marsh dieback on Cape Cod has rarely been observed as it is happening. However, it is usually recognizable by various amounts of remnant shoots/root-rhizome material than remain in the sediment. In the case of *Spartina patens* high marsh dieback, this material, which is considerably finer, tends to decompose and disappear more rapidly than in *Spartina alterniflora* (low marsh). In the latter, erosion of sediments from around the remaining roots/rhizomes often results in a "swiss cheese" or reef-like appearance.

Where has it been found?

Large-scale salt marsh dieback is not a new phenomenon. In the1990s dieback was reported in the Florida Panhandle (Carlson et al. 2001) and in Louisiana (McKee et al. 2004). The dieback attributed to multiple stressors including drought and subsequent attacks of *Fusarium* fungi on stressed plants. In 2001-2002, Georgia and South Carolina marshes suffered from huge diebacks, attributed again to prolonged (~2 years) drought that proceeded the vegetation losses (Ogburn and Alber 2006).. The dieback was further exacerbated by *Littorina irrorata* snails (Silliman et al. 2001).

On Cape Cod, although dieback is evident in aerial photography from as far back as 1977, it first received attention when it was reported by Scott Warren (Connecticut College) and Ron Rozsa (Connecticut Department of Environmental Protection) who noticed dieback in several Nantucket Sound-facing marshes (e.g., Herring River in Harwich, Swan River in Dennis). In 2003, Stephen Smith and John Portnoy independently discovered dieback in a remote Cape Cod National Seashore marsh (Middle Meadow). Over the next couple of years, Smith documented dieback as having occurred in numerous marshes along Cape Cod Bay (from Truro to Brewster) and a few additional sites along the south shore (Chatham, Harwich, Dennis) (Figure 1).

Within individual marshes, dieback is observed in many different locations, including the lower edges and creekbanks, mid marsh, and in the high marsh. Dieback spans a range of elevations – from ~ 0.5 to 1.6 m-MSL (Figure 2). In addition, three species are affected – *S. alterniflora* (cordgrass), *S. patens* (marsh hay), and *Distichlis spicata* (spikegrass).

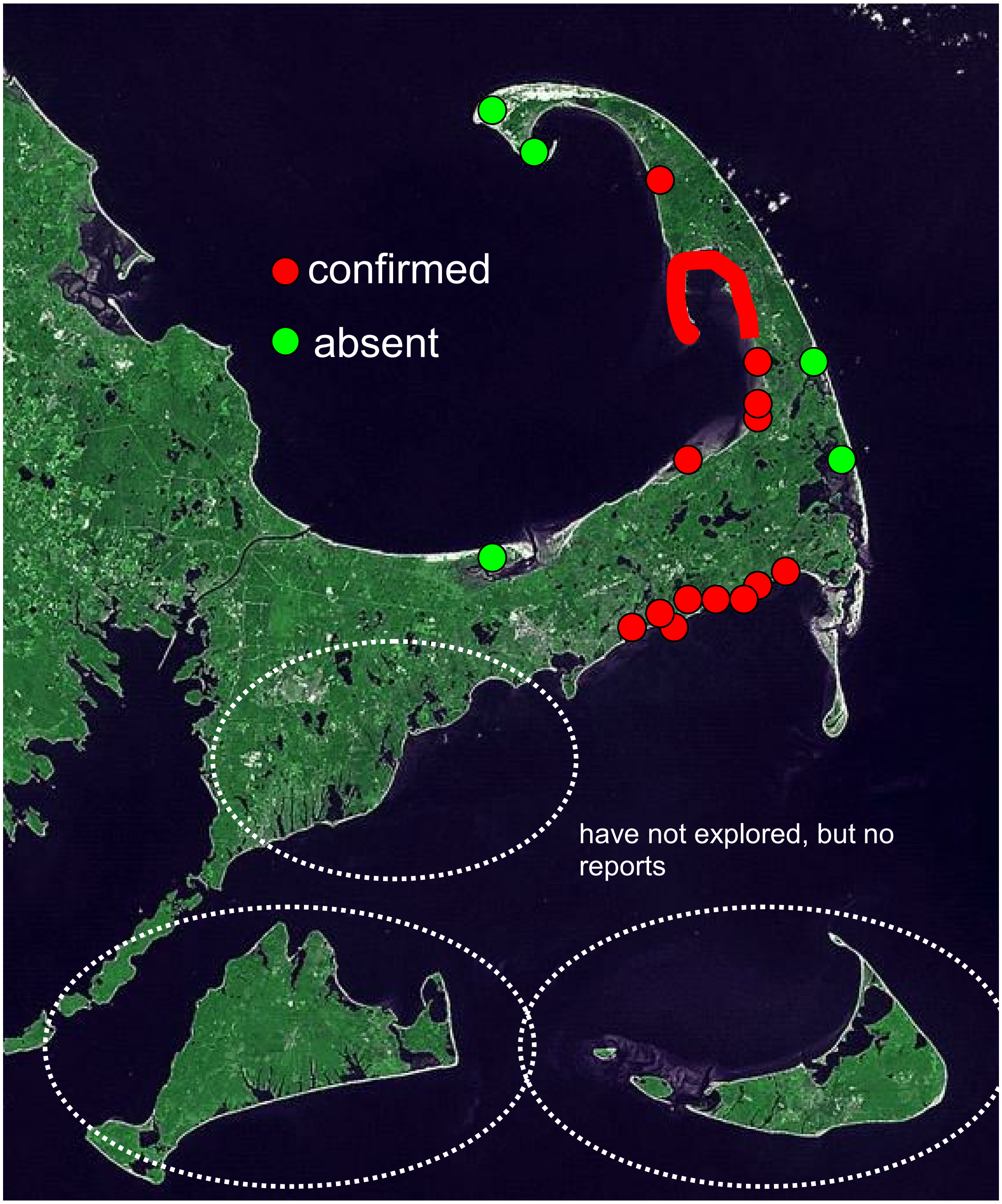


Figure 1. Known salt marsh dieback locations on Cape Cod

Figure 2. Dieback locations within the low (left), mid (middle), and high (right) marsh zones of individual marshes.

Brownmarsh, a term coined by scientists working on Louisiana dieback, refers to large areas of standing dead or dying salt marsh vegetation. Brownmarsh was observed in Middle Meadow (Great Island area) in July 2006 where large numbers of both *Spartina alterniflora* and *S. patens* were either chlorotic or necrotic by the end of July (Figure 3). In general, these symptoms were observed in plants growing in the near vicinity of old high marsh (primarily *S. patens*) dieback areas. A few isolated cases were found in the midst of green, healthy stands. For the first part of the growing season, the plants had apparently grown normally, generally attaining heights of 0.5-1m. At some point, however, they began to decline and had very little or no live foliage by the end of July.

Figure 3. Photos of dying *S. alterniflora* around the edges of an existing high marsh dieback area.

The dead foliage on many of the dying plants was covered with fungus, but when stems were cut open no discoloration of inner vascular tissue was found. In addition, there tended to be high densities of planthoppers on much of the foliage. No evidence of *Sesarma* crab grazing on the dying plants was observed. Dr. Wade Elmer of the Connecticut Agricultural Experiment Station collected tissue samples from dying and healthy plants in early September and incubated them on agar plates. A number of dying stem segments gave rise to much more *Fusarium* biomass than healthy tissue. However, this may simply be case of fungi opportunistically colonizing dead plants, rather than directly causing death.

<u>Possible underlying cause(s)</u>

A number of ideas have been put forth as possible explanations for salt marsh dieback. However, many are contradicted by what is observed in the field or what is known about salt marsh biogeochemistry and ecology.

Drought effects on soil chemistry - Prolonged drought can alter soil chemistry by increasing salinity, acidity, and the mobilization of metals upon rewetting. However, many dieback areas on Cape Cod are inundated daily by alkaline seawater, so these kinds of changes in soil chemistry are not possible. Dieback was witnessed as it was happening in Middle Meadow (Wellfleet) during July-Aug 2006 in the absence of drought.

Toxic constituent(s) in soil – Because dieback occurs in many different settings (from Long Island to Cape Cod to Maine), and presumably ranges across many different soil types/conditions, it is difficult to believe that there is some element or constituent in the soil that is responsible for dieback. Moreover, preliminary soils analyses, transplant experiments, and greenhouse studies seem to discount this theory (see sections below).

Wrack – While wrack deposits can result in vegetation loss, they are usually relatively small in area and the vegetation quickly recovers once the wrack disappears. Moreover, dieback occurs in places where wrack rarely, if ever, accumulates (e.g., creekbanks). Finally dieback is much more extensive than what wrack could possibly cover. Dieback was witnessed as it was happening in Middle Meadow (Wellfleet) during July-Aug 2006 in the absence of wrack.

Grazing by geese – At times, grazing by geese can cause severe damage in marshes. On Cape Cod, however, dieback has occurred in marshes where geese are rarely observed. Conversely, there is no dieback in marshes where geese are abundant (e.g., Nauset marsh, Pleasant Bay). There is a general consensus that dieback area far exceeds the damage that geese could do. Dieback was witnessed as it was happening in Middle Meadow (Wellfleet) during July-Aug 2006 in the absence of geese grazing.

Ice – Ice tends to sheer off aboveground foliage or transport large blocks of peat. It does not often impact roots and rhizomes while leaving the ground in place. Also, if ice were the cause of dieback, we might expect to find the worst dieback in Maine (which is not the case). Dieback was witnessed as it was happening in Middle Meadow (Wellfleet) during July-Aug 2006 in the absence of ice.

Upland development/eutrophication – Perhaps the best evidence against this idea is that dieback occurs in very pristine settings such as on Great Island, Wellfleet, which is surrounded by undeveloped National Seashore.

Pathogen(s) – dieback may be the result of infection by a virus, bacterium, or fungus. The organism may either be an existing agent that is taking advantage of plants under stress or a new organism that has not been described yet. To date, pathologists have not yet been able to identify a likely culprit from many tissue samples collected. In addition, pathogenic symptoms such as blackening of stem vascular tissue or root rot have not been observed in dying plants. However, symptoms of infection can be difficult to diagnose and this remains a viable hypothesis.

Pilot greenhouse studies (July-Sept 2006)

The following text describes a series of preliminary experiments that were conducted on the dieback of *Spartina alterniflora*. The term "experiments" is used somewhat loosely here as these studies were not set up in a statistically rigorous manner. Rather, they are highly descriptive in nature, although there is some quantitative data as well, with the idea that the information generated would help focus our efforts on the most promising aspects of dieback. Many of the plants that were used in these experiments were grown from tillers harvested from the West End marsh in Provincetown – a marsh where no dieback of the type observed elsewhere on Cape Cod has been observed. Each section begins with a key question, followed by a brief description of methods, results, and preliminary conclusions.

Question 1: Are shredded, tattered, leaves on cordgrass found around the edges of dieback areas the result of grazing? Can plants be rehabilitated if removed from grazers and grown in the greenhouse?

Methods: On May 19, 2006, plugs of *S. alterniflora* exhibiting was appeared to be signs of herbivory were collected from around edges of dieback sites in the Lieutenant Island area. At the time of collection, the leaves of the cordgrass were tattered and looked as if they had been grazed. Plugs were placed in containers filled with either full-strength seawater (n=4) or freshwater (n=4) and maintained for 3 months under these conditions.

Results: All plants survived and grew rapidly (Figure 4).

Figure 4. Shredded leaves of a plant collected from the edge of a dieback area (left) and the same plants after growth in the greenhouse ~ 1 month later (right).

Preliminary conclusions: Plants around the edges of dieback areas with the kind of leaf damage described above can be rehabilitated and are probably being grazed by an herbivore (possibly *Sesarma reticulatum*), rather than suffering from any physiological decline. (Note: Dr. Mark Bertness is currently investigating this hypothesis).

Question 2. If dieback is caused by a soil organism (e.g., root knot nematodes), can pretreatment by prolonged flooding of the soil prevent dieback? Note: flooding is commonly used in agriculture for soil pest control.

Methods: On July 14, 2006, healthy cordgrass seedlings grown from tillers collected from West End marsh (Provincetown) were put into containers filled with dieback soil that had undergone two different treatments. In one treatment, dieback soil was subjected to constant flooding with full-strength seawater for 4 weeks. In the other, dieback soil was kept slightly moist for 4 weeks (initially with seawater and then with freshwater to account for evaporation). Subsequently, on July 14, 2006, plants were put into containers filled with dieback soil that had been subjected to these treatments (n=9 for each group).

Results: September 19, 2006: All plants survived and grew in both treatments and there were no obvious differences in plant height or number of leaves/shoots between groups (Figure 5).

Figure 5. Plants grown in dieback soils pre-treated with 1 mo. continuous flooding (left) vs. wet. But drained conditions (right).

Preliminary conclusions: For this sample of dieback soils collected from the field, pretreatment of dieback soils with prolonged flooding did not have any beneficial effect. In fact, no plant decline was observed whatsoever. However, any soil-based organism(s) responsible for dieback in the first place may well have been disappeared from this soil before it was used in this experiment. As such, it is difficult to interpret the results of this experiment. It does suggest, however, that there is no remnant chemical “toxicity” of any sort in dieback soils.

Question 3: can dead plant stems covered with fungus in dieback areas cause a decline in healthy plants when exposed?

Methods: On July 12, 2006, healthy cordgrass plants grown from West End marsh stock were put into containers and divided into three different groups. The first group (n=9) was subjected to flooding with full-strength sweater. Each plant had a ~ 5 cm segment of fungally-infected cordgrass stems, collected from a recent dieback area at the Wellfleet Wildlife Sanctuary (Audubon) attached to their shoots. Small incisions to the main stem of the healthy plants were made with a knife and the infected segments were pressed onto these incisions and fastened to the stems with cable ties in order to better facilitate infection (the diseased stem segments were collected from a dieback area at the Wildlife Sanctuary). The second group had no infected stem segment attached, but were similarly immersed in full-strength seawater. The third group was planted in dieback soil in which fungally-infected stem segments had been mixed in to facilitate root infection. Plants in this treatment were watered with full-strength sweater but kept drained to prevent death from anoxia.

Results: All plants in all treatments survived and grew during the period of the experiment. All plants flowered as well. No plants showed symptoms of infection or decline.

Preliminary conclusions: Fungi found on decaying plants from this particular dieback area do not cause direct mortality and do not easily pass from one plant to another. These fungi are probably opportunistically taking advantage of dying plants and may accelerate their demise but are not a direct cause. Alternatively, the fungi present on the stems of dead plants in the field may not be the same strain(s) as that which may cause dieback. They may be part of a community that is representative of the end stage of fungal succession after dieback has already occurred.

Question 4: Can chlorotic, wilted plants from around the edges of dieback areas be rehabilitated if removed from the field and grown in the greenhouse?

Methods: On July 17, 2006, wilted plants were harvested from around the edges of dieback areas of Lt. Island (Figure 6) and put into containers in greenhouse. One group (n=9) was immersed in full-strength seawater. A second group (n=9) was immersed in freshwater. The third group (n=9) was put into dieback soil saturated with full-strength seawater.

Figure 6. Wilted, stunted plants growing near the edges of a dieback area (Lt. Island, Wellfleet).

Results: In general, survival rate of these plants was marginal. Actual results are listed below:

Group 1 – flooded with salt water (no soil) – 5/8 survived
Group 2 – flooded with freshwater (no soil) – 4/7 survived
Group 3 – planted in dieback soil and flooded with saltwater – 2/8 survived

Preliminary conclusion: In this experiment, much of the observed mortality is believed to be due to stress induced by harvesting the plants from the ground. To do this, large rhizomes connecting clones had to be severed. Notwithstanding, a significant number of plants survived and grew, indicating that they had not contracted some disease with irreversible symptoms. Rather, their phenology was likely a result of some physiological stress under field conditions. In this regard, it is noteworthy that untouched wilted plants from the locations where experimental plants were harvested all survived and continued growing throughout the summer.

Question 5: Can necrotic plants from a brownmarsh area be rehabilitated?

Methods: On August 8, 2006, dying plants from brownmarsh area of Middle Meadow were harvested and put them in pots filled with potting soil (n=3, many plants). One group of plants was put into a pot filled with brownmarsh soil from the site. The plants were alternately watered with full-strength seawater and freshwater.

Results: As of September 19, 2006, the plants had exhibited relatively little decline and green portions of each plant survived (Figure 7). In addition, these plants showed a significant amount of new root and rhizome growth, suggesting that individuals were viable (Figure 8). By September 27, the plants had even produced new tillers.
These results are in stark contrast to plants in the field from the immediate vicinity of the harvested plugs, which all had no live foliage left by September 20, 2006.

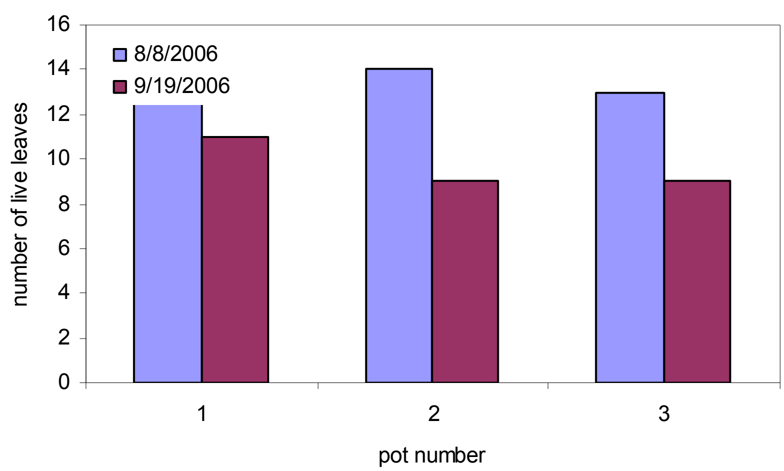


Figure 7. Photo of dying plants in drained pots of potting soil (above) and live leaf counts by date (below).

Figure 8. New root and rhizome growth on dying plants collected from brownmarsh sites. Photo taken after 1.5 months of growth in potting soil in the greenhouse.

Preliminary conclusions: The demise of plants from the brownmarsh area is highly influenced by some environmental factor(s) in the field since their decline was stopped once brought into the greenhouse. If a pathogen is the cause of decline, removal from the field and/or improvement in growing conditions allows plants to overcome the effect. As such, it appears that these plants did not contract some incurable disease that runs its course through to mortality once infection has occurred.

Question 6: Can changes in soil properties as a result of short-term extreme drought conditions induce mortality in cordgrass?

Methods: On August 16, 2006, healthy cordgrass plants (West End stock) (n=5) were planted into containers filled with dieback soil that had been left unwatered and drying for > 1 month outside (under a greenhouse cover). The plants were then re-watered with full-strength seawater and their survival subsequently monitored.

Results: All plants except 1 survived. In three plants the main shoot died but new tillers emerged, proving that the plants were still alive and viable (Figure 9). In addition, there was new root growth in these plants – a further indication of their viability (Figure 10).

Figure 9. Plants grown in dieback soil that had been dried for > 1 mo., then re-wetted.

Figure 10. healthy roots and new tillers (green arrows) on plants grown in previously dried/rewetted soil from a dieback area.

Note: Quite by accident, one container of cordgrass was left unwatered in a corner of the greenhouse for > 1 month. When it was discovered, the plants were green and healthy, even though the soil was a hardened, crumbling mass from being completely dried out (Figure 11).

Figure 11. Photo of plant that survived extreme desiccation during July – August 2006.

Preliminary conclusion: In a greenhouse setting, *S. alterniflora* is tolerant of severe, short-term drought conditions.

Transplant studies

Healthy *S. alterniflora* seedlings grown from tillers harvested from the West End marsh in Provincetown were transplanted into dieback areas in the Gut, Blackfish Creek, Loagy Bay and Mass Audubon (Wellfleet Bay) (Table 1). Many of the transplants appeared to be grazed (chewed at the base). However, some appeared to have been broken by wind or waves – presumably due to their isolation from the buffering effects of other vegetation. Some may also have died from "transplant shock". However, many survived quite well. Moreover, it is imperative to follow these plants through next spring to confirm whether they are alive or dead. For example, the original shoot can die with subsequent regrowth of tillers from the viable rhizomes (Figure 12). As such, the following results are preliminary and should not be interpreted until data from the spring of 2007 have been collected.

Table 1. Preliminary results of transplants trhough a single growing season. Plants will be re-evaluated in Spring 2007.

Site name	No original plants	Date transplanted	No. surviving (Aug 14, 2006)	Notes
the Gut(south)	10	7/5/2006	0	most broken off at stem base with rest of plant gone, some evidence of chewing
theGut(north)	10	7/5/2006	1	broken stems, grazing
Lt. Island-Loagy Bay	10	7/5/2006	0	most broken off at stem base
BFCreek	10	7/5/2006	7	doing quite well
Indian Neck	10	7/5/2006	0	all dead and gone
Audubon-site1	10	7/11/2006	3	dead ones completely gone
Audubon-site2	10	7/11/2006	0	
Audubon-site3	10	7/11/2006	2	dead ones completely gone
Audubon-site4	10	7/11/2006	6	one has primary shoot dead, new tiller alive

Figure 12. Photo showing new tiller growth from a plant on which the original stem died.

Brownmarsh transplants

On August 11, 2006, bundles of 10 cordgrass plants, grown from healthy tillers collected from the West End marsh, were transplanted into 6 different sites within the brownmarsh area of Middle Meadow (Figure 13,). The sites were marked with a PVC stake. On September 20, 2006 the transplants were examined for survival. The figure below illustrates the extremely poor survival percentage of the original shoots (Figure 14).

Figure 13. Brownmarsh area of Middle Meadow (left) vs. healthy area (Aug 2006).

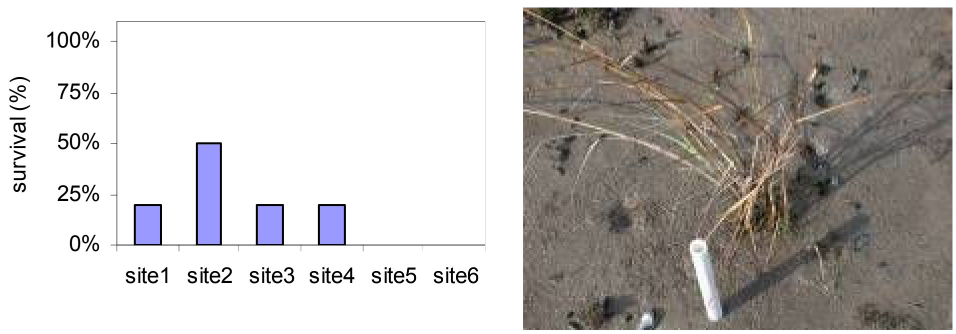


Figure 14. Transplant survival during the first 1.5 mo. after planting.

Although the transplants were preconditioned to 33 ppt salinity, transplant shock may be one reason for their poor survival. There was no evidence of grazing or stem breakage as has been observed with transplants to other dieback marshes and there was little visible fungus on the foliage. Regardless, all plants will be monitored through the spring of 2007 to assess whether total plant death has actually occurred.

Vegetation monitoring in dieback areas

In the summer of 2003-2004, a network of permanent $1m^2$ vegetation plots was established and surveyed to provide baseline data for long-term monitoring of salt marsh ecosystems throughout CACO. A subset of these plots were located in two marshes known as the Gut (n= 23) and Middle Meadow (n=34), where dieback has occurred since that time (Figure 15). In 2006, these plots were re-surveyed to gauge losses from dieback. Table 2 below summarizes how the area cover of bare ground has changed over time. Cover was assessed visually according to the Braun-Blanquet scale where 0=0, >0-1%=1, >1-5%=2, 6-10%=3, 11-25%=4, 26-50%=5, 51-75%=6, 76-100%=7. Only plots where cover class had changed by at least 2 categories were considered to have undergone significant change. Notwithstanding, the results show that both dieback and recovery are happening concurrently. In Middle Meadow, 7 sites have deteriorated since 2003 while 2 plots exhibited some recovery. In the Gut, deterioration and recovery occurred in 3 plots each. Most of the other plots showed no significant change.

Table 2. Cover class (CC) of bare ground (unvegetated) in Middle Meadow and the Gut plots (2003 vs. 2006) (NC=no change, DET=deterioration, REC=recovery).

Middle Meadow

Plot	CC 03	CC 06	Diff	Trend
MM1-000	2	1	-1	NC
MM1-060	6	4	-2	REC
MM1-120	0	0	0	NC
MM2-000	0	0	0	NC
MM2-060	2	1	-1	NC
MM2-120	7	7	0	NC
MM2-180	6	5	-1	NC
MM2-240	6	5	-1	NC
MM3-000	5	7	2	DET
MM3-060	0	0	0	NC
MM3-120	1	1	0	NC
MM3-180	7	7	0	NC
MM3-240	2	3	1	NC
MM3-300	1	4	3	DET
MM4-000	0	1	1	NC
MM4-060	0	0	0	NC
MM4-120	7	5	-2	REC
MM4-180	0	4	4	DET
MM4-240	1	1	0	NC
MM4-300	1	5	4	DET
MM4-360	2	4	2	DET
MM4-420	1	4	3	DET
MM5-000	0	0	0	NC
MM5-060	0	0	0	NC
MM5-120	2	1	-1	NC
MM5-180	3	2	-1	NC
MM5-240	1	1	0	NC
MM5-300	3	4	1	NC
MM5-360	2	4	2	DET
MM5-420	7	7	0	NC
MM6-000	0	1	1	NC
MM6-060	0	0	0	NC
MM6-120	4	5	1	NC
MM6-180	0	0	0	NC
		Totals	NC	25
			DET	7
			REC	2

the Gut

Plot	CC 04	CC 06	Diff	Trend
HR1-000	1	2	1	NC
HR1-010	4	4	0	NC
HR1-020	3	4	1	NC
HR1-040	1	5	4	DET
HR1-060	3	1	-2	REC
HR1-080	4	7	3	DET
HR1-100	0	0	0	NC
HR1-120	3	4	1	NC
HR2-000	5	3	-2	REC
HR2-010	1	1	0	NC
HR2-020	3	3	0	NC
HR2-040	1	2	1	NC
HR2-060	7	7	0	NC
HR2-080	6	7	1	NC
HR2-100	7	7	0	NC
HR2-120	4	5	1	NC
HR2-140	0	2	2	DET
HR3-000	3	3	0	NC
HR3-010	6	4	-2	REC
HR3-020	1	0	-1	NC
HR3-040	0	1	1	NC
HR3-060	2	2	0	NC
HR3-080	5	1	-4	(wrack disturbed)
		Totals	NC	16
			DET	3
			REC	3

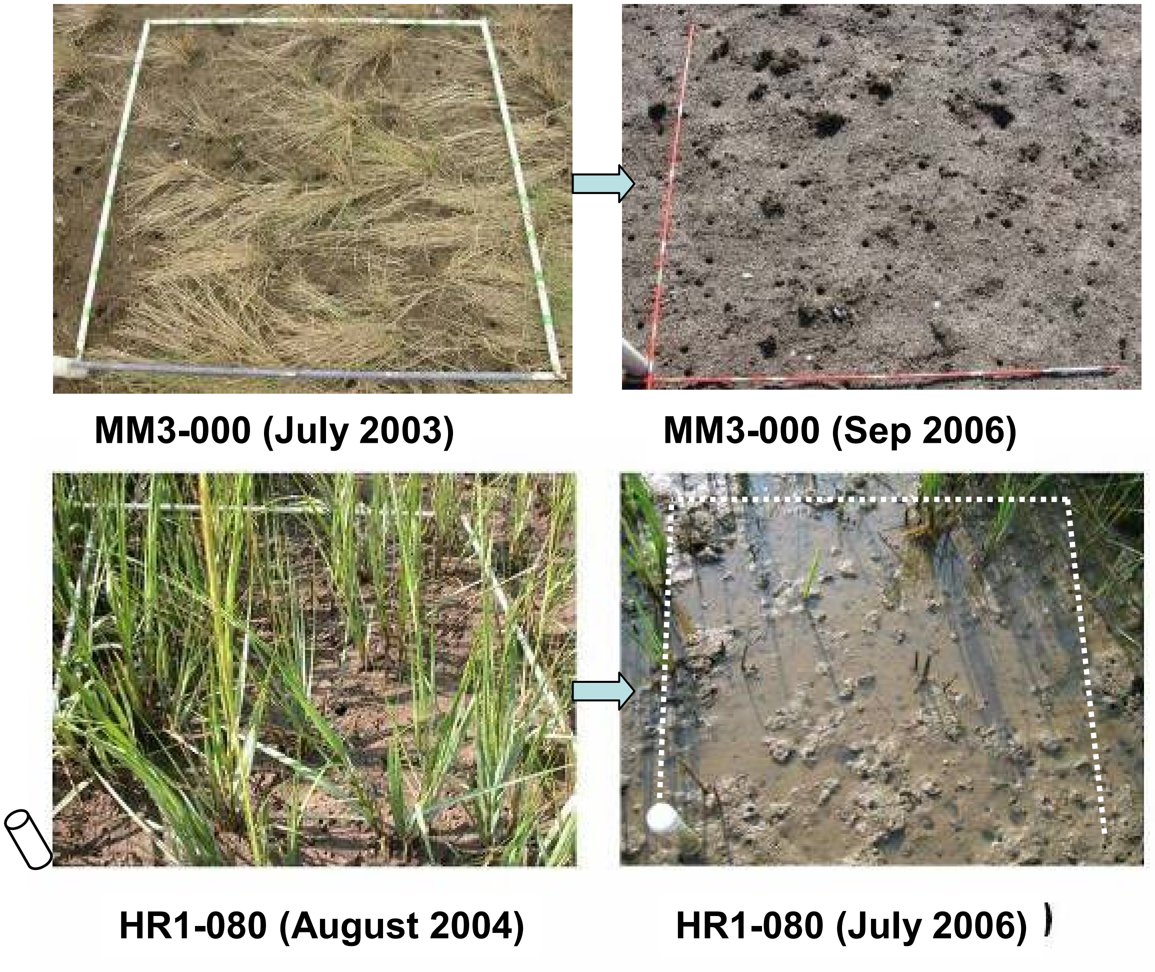


Figure 15. High and low marsh dieback captured in permanent vegetation monitoring plots in Middle Meadow (above pair) and the Gut (below pair).

Ten permanent plots (1m^2) were established in brownmarsh areas of Middle Meadow on August 18, 2006 (Figure 16). Individual tillers of *Spartina alterniflora* were counted and area cover of *Spartina alterniflora* and *Spartina patens* was estimated as well. These plots will be reassessed next growing season to determine whether plants actually died during the 2006 growing season or whether they underwent some kind of premature senescence.

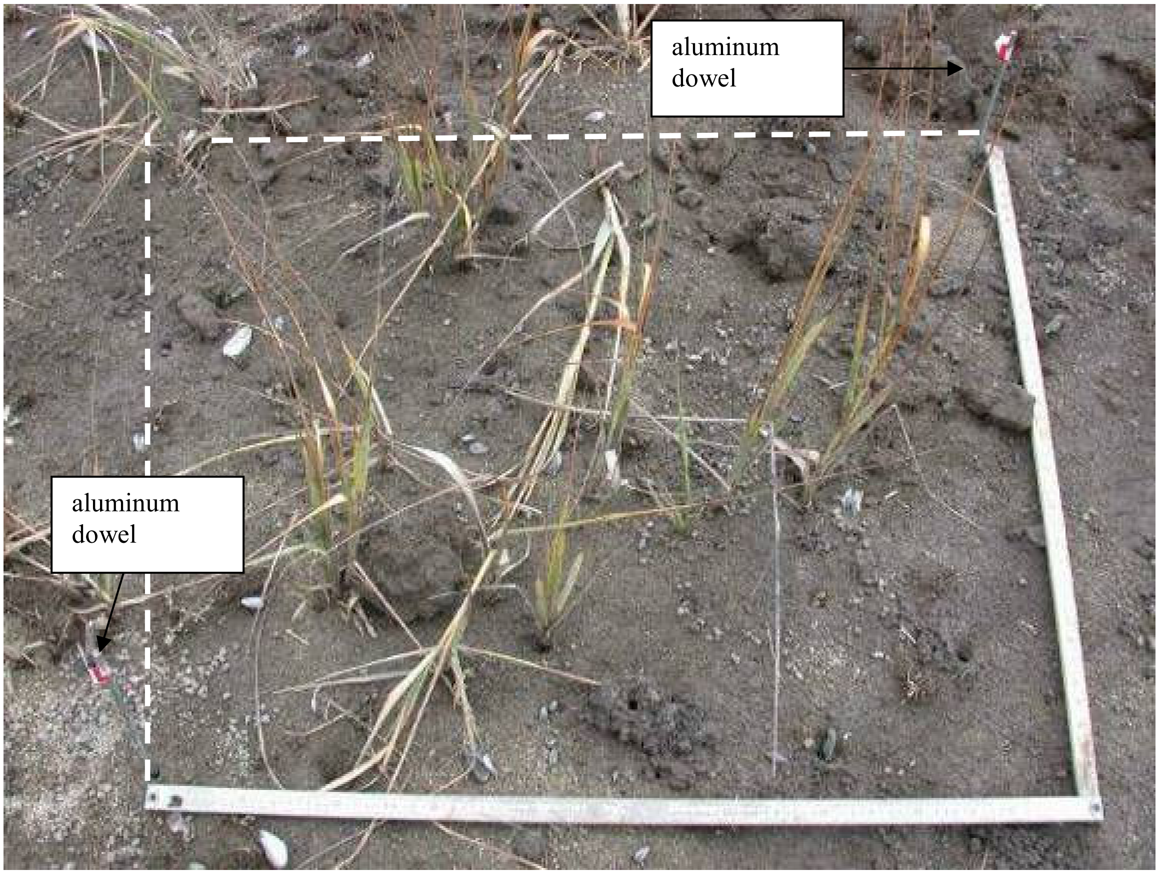


Figure 16. Photo of a square meter plot for tracking the fate of dying plants.

Elevation monitoring

Regardless of the cause(s) of dieback, it is clear that large amounts of sediment are being eroded away in areas with vegetation loss. The consequences of erosion are numerous. The lowering of ground surface elevations has enormous implications for recovery, since hydroperiod increases with decreasing elevation. Sediment loss from the marsh and transport to coastal waters can impact nearshore, and potential offshore, communities. Benthic organisms, in particular, may be affected by increased sedimentation rates.

To better understand how much erosion is taking place in dieback areas and when it occurs, 48 monitoring devices were developed and installed in three different marshes (Figure 17) within Wellfleet Bay. The monitoring devices consisted of thick-walled (schedule 80), 5 ft sections of PVC pipe hammered into the inorganic substrate underlying the marsh peat. The tops of each pipe were slotted so that a horizontal cross bar could be fit into it in two different positions 90 degrees from each other. A hole in the end of the crossbar allows a thin metal rod to be passed through. This way, the distance from the ground surface to the cross bar can be determined at 4 different points surrounding the pipe (18cm from the pipe itself). Each pipe was surveyed in relation to a benchmarks established in the adjacent upland. These will be resurveyed in the spring to assess whether the pipes are stable through winter ice, etc. The pipes were placed in low and high marsh areas where both unvegetated (dieback) and vegetated sites were present. In addition, vegetation cover was assessed visually in 1m^2 plots centered on the erosion pipes and crab burrows counted.

Figure 17. Map of elevation monitoring locations around Wellfleet Bay.

On August 8 (baseline) and Oct 30, 2006, elevation data were collected. The results, shown in Figure 18, revealed that during this time considerable erosion had occurred in all of the dieback areas. With the exception of one plot in Middle Meadow, elevations increased in the adjacent vegetated areas – as they normal do in healthy salt marsh systems.

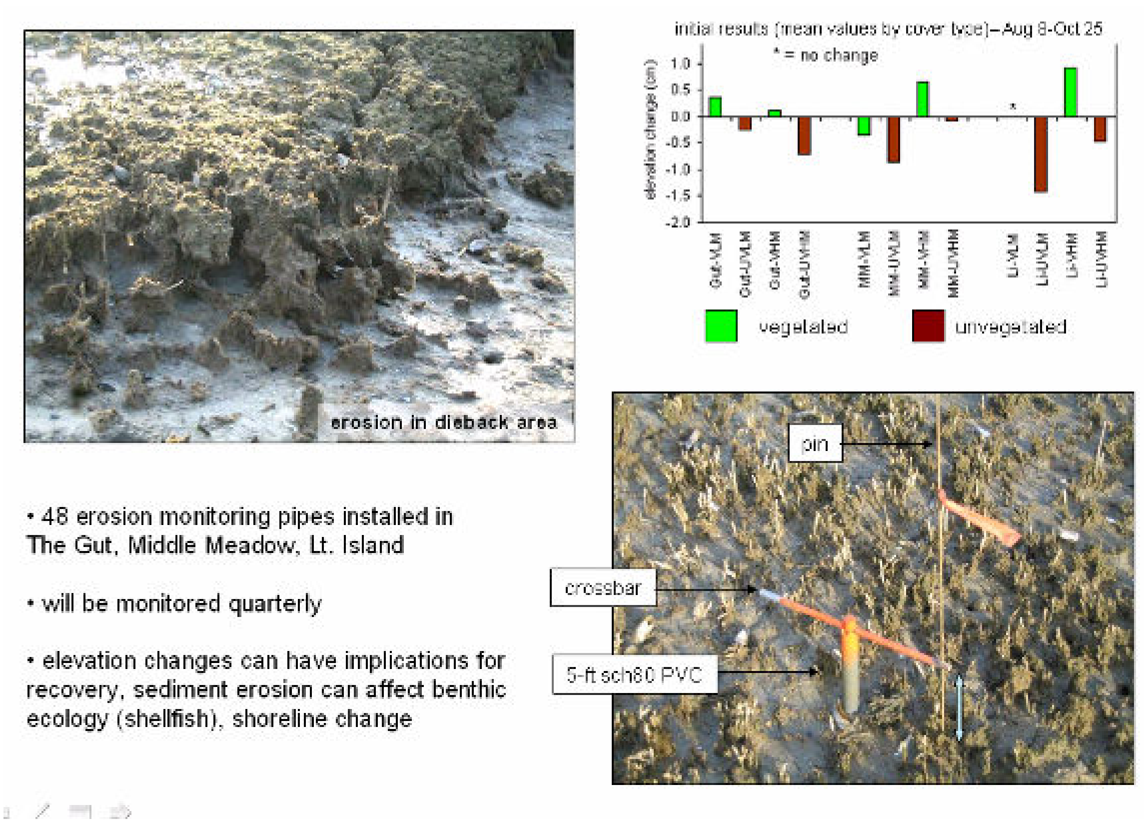


Figure 18. Monitoring erosion in vegetated vs. unvegetated areas of Middle Meadow, the Gut, and Lieutenant Island (Wellfleet).

Analysis of photopoint images

The establishment of 25 photo-point sites has allowed for qualitative determinations of trends in dieback areas. Since 2004, digital images have been taken from specific locations adjacent to dieback sites. Seven of the sites have been dropped as it is difficult to detect trends from the location/angle of the photo or the view is redundant with another location. Of the remaining 21, only 3 have deteriorated, 8 have shown recovery, and 10 have undergone no appreciable change (Figure 19-44). A key point is that almost all the sites showing "recovery" document *S. alterniflora* advancing into old *S. patens* dieback areas. In this sense, the recovery does not represent reclamation by the same species that died back in the first place. Rather, it is a landward shift in the low marsh zone.

Figure 19

Figure 20

Site 3 no appreciable change Figure 21

Site 4 no appreciable change Figure 22

Site 5 no appreciable change Figure 23

Site 6 no appreciable change Figure 24

Site 7 recovery Figure 25

Site 8 no appreciable change Figure 26

Site 9 no appreciable change Figure 27

Site 10 recovery Figure 28

Site 11 wrack disturbance Figure 29

Site 12 wrack disturbance Figure 30

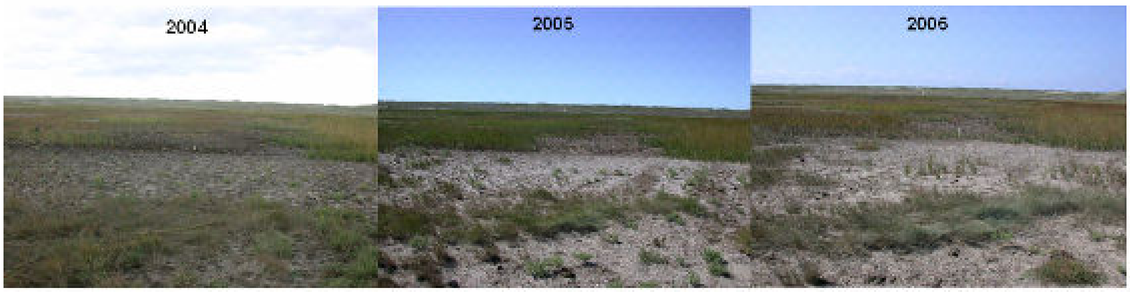
Figure 31

Site 13 no appreciable change

Figure 32

Site 14 redundant with Site 15

Site 15 deterioration Figure 33



Site 16 slight recovery Figure 34

Site 17 recovery Figure 35

Site 18 recovery Figure 36

Site 19 recovery Figure 37

Site 20 no appreciable change Figure 38

Site 21 inconclusive Figure 39

Site 22 inconclusive Figure 40

Site 23 recovery Figure 41

Figure 42

Site 24 deteriorating

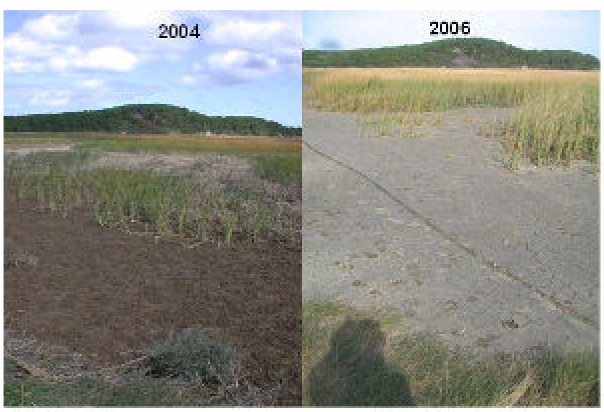


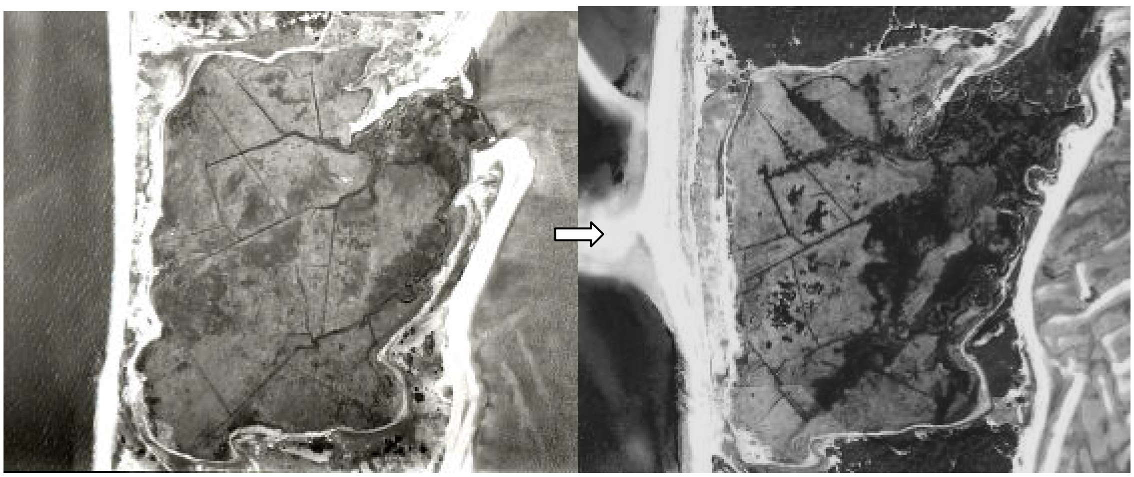
Figure 43

Site 25 deteriorating

Site 26 slight recovery Figure 44

Analysis of aerial photography

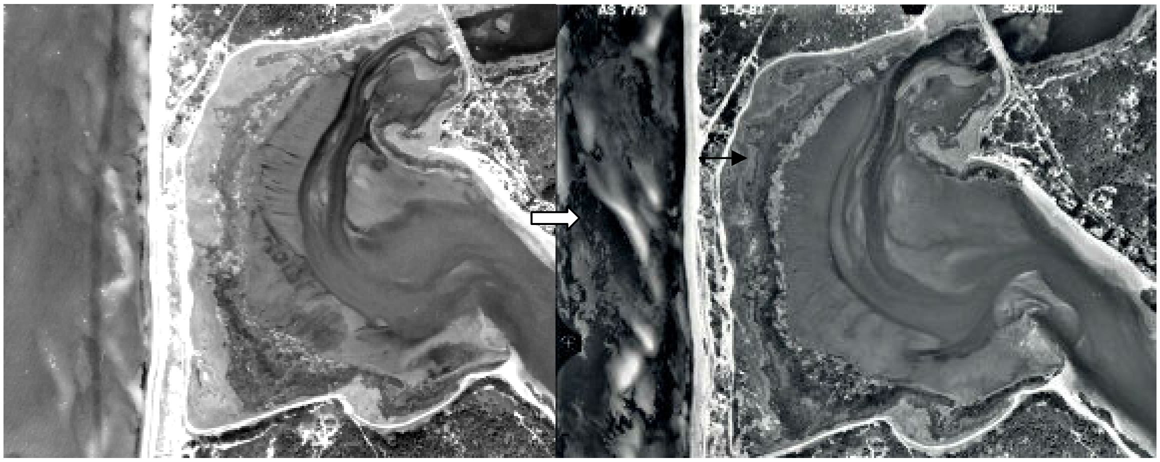
Middle Meadow - The salt marsh plant communities of Middle Meadow have changed noticeably over the past 70 years. The 1947 photo shows large areas of high marsh throughout most of the system. By 2000, however, there are large areas of dieback evident in many parts of the marsh, including around the high marsh mosquito ditches (Figure 45). Additionally, *S. alterniflora* has replaced *S. patens* over a large portion of the marsh.



Aug 1947 Oct 2000

Figure 45. Marshes around Lieutenant Island (Wellfleet) have undergone similar change, namely there has been extensive widening of tidal creeks and disintegration of islands of vegetation.

In the Gut marshes there is evidence of a large dieback event that happened sometime between 1977 and 1987 (Figure 46). In September 1987, aerial photos show that *S. alterniflora* more or less abuts *S. patens*/*Distichlis spicata* zone with little discontinuity in this border. By 1987, however, a large gap of bare sediment has opened up between the two species. This unvegetated zone persists today.



Sept 1977 Nov 1987

Sept 2006

Figure 46. Vertical aerial photos of the Gut in 1977 (top left), 1987 (top right) and an oblique angle photo in 2006 (bottom).

There have been astonishing losses of salt marsh habitat around Lieutenant Island (Wellfleet) over the last 30+ years (Figure 47). Many small tidal creeks have shown considerable widening and there are obvious losses of vegetation throughout the system.

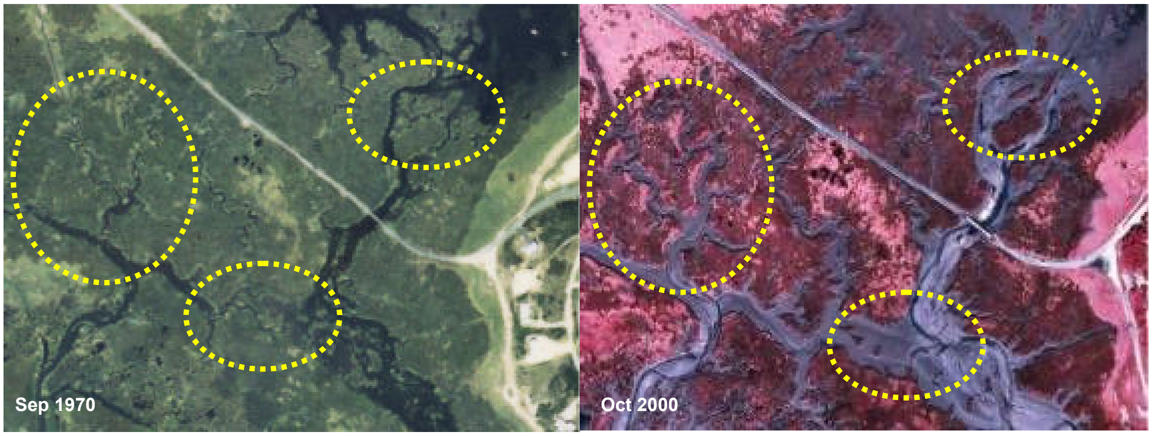
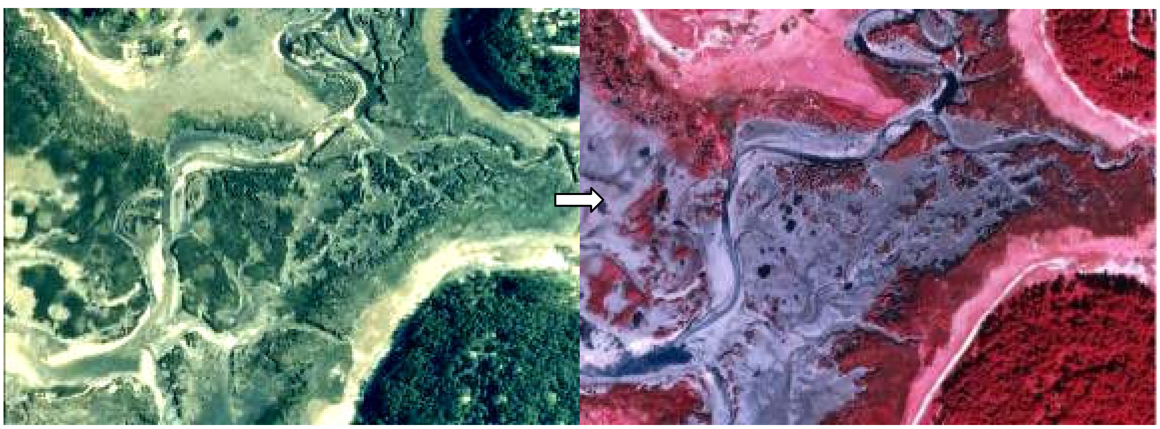


Figure 47. Lieutenant island salt marsh losses from Sept 1970 to Oct 2000.

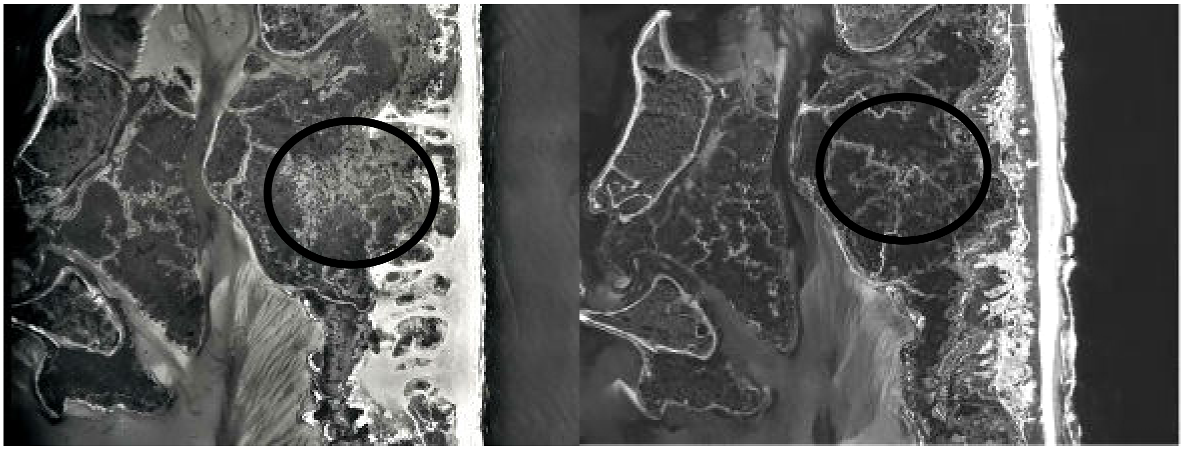
Some losses have occurred at an extremely rapid pace as depicted in the photos below (Figure 48).



Aug 1995 Oct 2000

Figure 48. An example of significant vegetation loss around Lt. Island (Wellfleet) during a recent 5 year period.

In marshes where dieback has not been found (e.g., Nauset marsh and Pleasant bay; Figure 49), major shifts in species composition have occurred (primarily the loss of *S. patens* to S. *alterniflora*) but the creation of unvegetated mudflats cannot detected.



Aug 1947 Oct 2000

Figure 49. Photo showing transition from high to low marsh vegetation (e.g., within circled area) without any noticeable loss in overall plant cover.

Evidence linking high marsh dieback with sea level rise on Cape Cod, Massachusetts

Many sudden wetland dieback sites on Cape Cod have been "misdiagnosed"

During field work conducted in October-December 2006, close examination of peat deposits within dieback zones revealed that a large proportion of what was thought to be low marsh dieback is actually high marsh dieback. The reasons for misdiagnosing these sites vary. However, in many areas one gets the distinct impression that *Spartina alterniflora* (the dominant low marsh species) died back simply because it surrounds and/or is scattered around the existing openings. In other settings, the disappearance of high marsh species from the tops of creekbanks has resulted in significant erosion and a major change in slope of the banks. What used to be steep vertical banks with elevations high enough at the edges of the banks to support high marsh species are now much lower and quite sloped. The resulting topography resembles habitat more suited to *S. alterniflora*. Thus, the absence of vegetation along these banks was assumed to be a consequence of *S. alterniflora* dieback. Finally, in some areas, high marsh dieback patterns are complicated by the topography of the marsh – especially where there is a mosaic of high and low elevations within the marsh rather than an obvious directional slope.

The figure below (Figure 50) illustrates the complexity of reconstructing history at these sites. In the top right photo, for example, it is easy to assume that this is an area of *S. alterniflora* dieback since this species currently exists on both sides of the unvegetated gap. However, close examination of the exposed peat reveals that most of it is *Spartina patens*. Further confirmation that *S. patens* once dominated here can be found in aerial photography. Thus, it appears that *S. patens* dieback was followed by *S. alterniflora* migration upslope. Since it is difficult for *S. alterniflora* to become established in dense, tight peat of *S. patens*, its distribution is very patchy and rather sparse through this zone. Nevertheless, its peripheral presence gives it the appearance of *S. alterniflora* dieback.

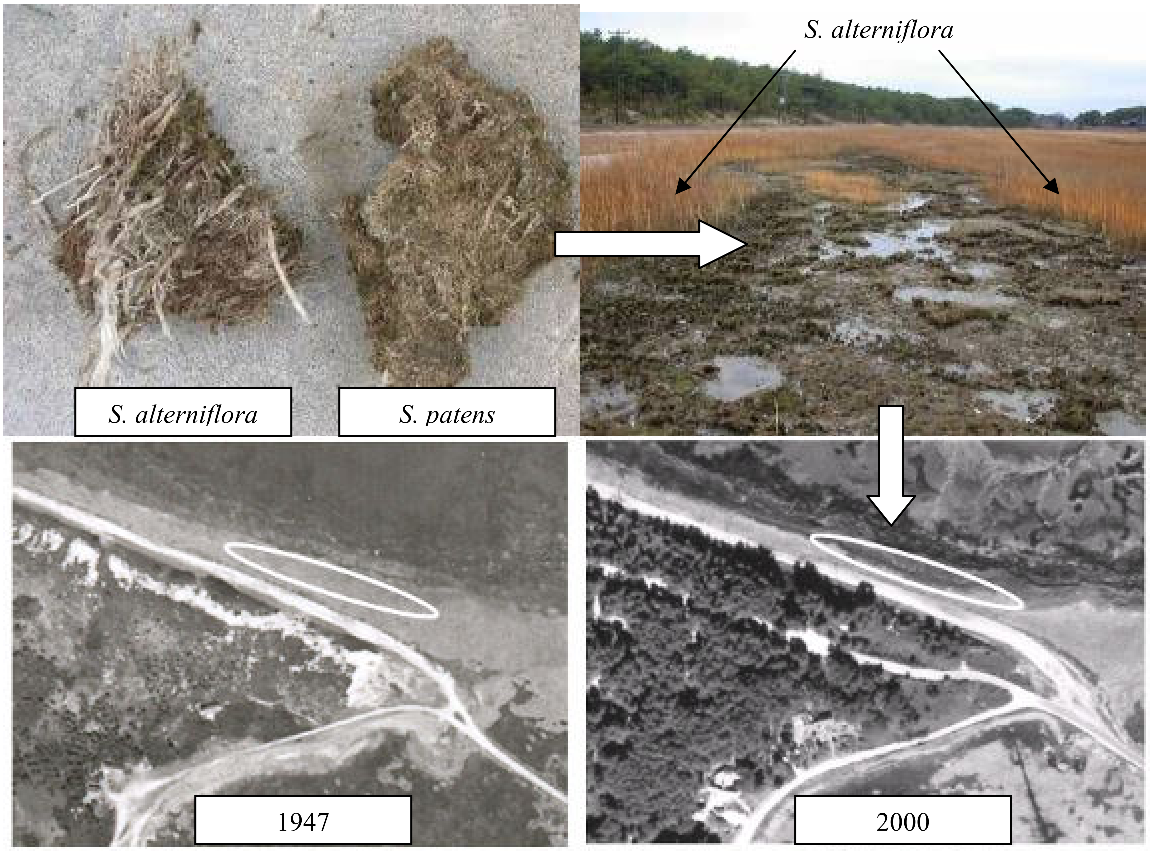


Figure 50. The above photo (top right) shows what appears to be *S. alterniflora* dieback but is really old peat of *S. patens* that died sometime before 2000. The bottom left side photo confirms that this area (circled) was originally *S. patens* (which has a light signature compared to *S. alterniflora*) and is now *S. alterniflora*.

The next figure (Herring River in Harwich) (Figure 51) shows a similar situation, where dieback in close proximity to the main tidal channel was mistaken to be *S. alterniflora* demise. Once again, however, the remnant peat indicates that this area was originally dominated by *D. spicata* and that the existing *S. alterniflora* represents that portion of the population that has been able to successfully migrate into the dieback zone. It does not represent "surviving" plants of a low marsh dieback zone.

Figure 51. This photo from the Herring River (Harwich, MA) shows old *Distichlis* peat within a dieback area. The invading *S. alterniflora*, which has become established upslope of the area, can give the impression of *S. alterniflora* dieback.

<u>High marsh dieback appears to be related to elevation</u>

When dieback sites were revisited and re-evaluated based on this new information, a relationship between the disappearance of high marsh vegetation and elevation became evident. The vast majority of high marsh dieback is occurring at lower elevations, particularly where *S. patens* and/or *Distichlis spicata* transitions into *S. alterniflora*. These high marsh species have much less aerenchyma (air space) in the rhizome system than *S. alterniflora* and are therefore less tolerant of prolonged inundation. In general, these species occupy a zone that spans elevations between mean high tide and maximum high tide.

Sea level rise will theoretically result in a shifting of the low/high marsh boundary to higher elevations. However, it is possible that changes in vegetation from sea level rise may not proceed in a steady, continuous manner. Instead, it may go through a series of "stutter steps" involving high marsh dieback followed by, or concurrent with, variable amounts of recolonization by *S. alterniflora*. Possible reasons for the inability of *S. alterniflora* to keep pace with high marsh retreat in some areas include: 1) difficulties in becoming established in remnant *S. patens* or *Distichlis* peat, which form very dense turfs, 2) *S. alterniflora* attempting to migrate landward is at the upper range of its elevation niche and may be stressed by conditions in this zone, and 3) biological factors such has herbivory may limit its advance.

The status of *S. patens* in permanent vegetation plots in Middle Meadow (Wellfleet) was assessed in 2006. Ground elevations of these plots were already known from an optical leveling survey done in 2004, although some changes may have occurred since that time. Notwithstanding, analysis of this data showed that healthy vegetation occurred in plots averaging 1.71 m (relative to MSL) in elevation, whereas dying and dead *S. patens* (sometimes replaced by *S. alterniflora* or annual forbs) averaged 1.54 m (Figure 52). Variability within these groups may be due to differences in soil drainage/water retention (properties that are independent of elevation) and/or changes in ground elevations (erosion or accretion) since 2004.

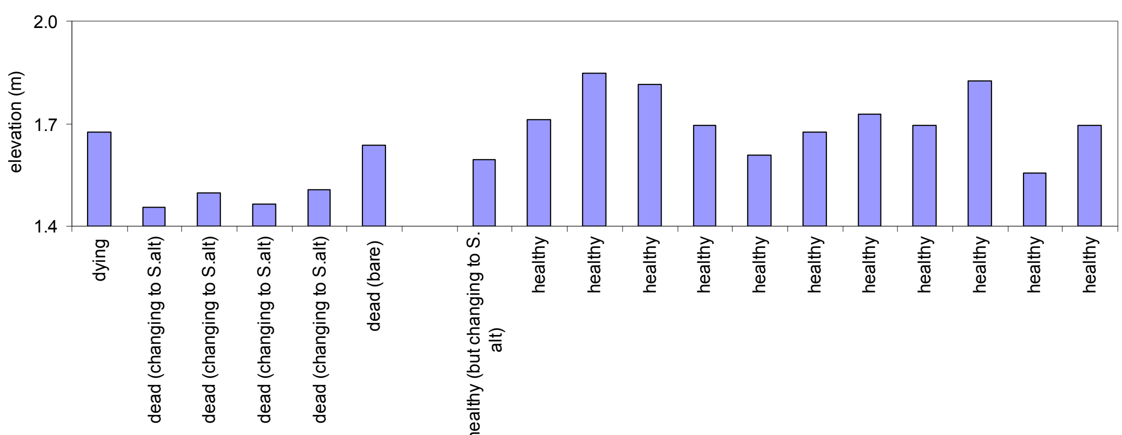


Figure 52. Status of *S. patens* and corresponding elevations (m-MSL) in permanent vegetation plots in Middle Meadow (2006).

To further investigate this apparent link between high marsh dieback and elevation, 135 points in Middle Meadow, the Gut, and Lieutenant Island (Wellfleet) were surveyed using optical leveling to determine elevations relative to a stable upland benchmark. Locations were randomly selected within *S. patens* zones that fell into 3 general categories of plant vigor: dead (virtually no vegetation left), dying (patchy vegetation), and healthy (nearly 100% cover). At all locations (Figure 53), the stadia rod was placed directly on top of the plant culms so that the data for the "dying" sites wouldn't be confounded by any erosion that may have occurred subsequent to dieback. This could even be done at the "dead" sites since there was still remnant shoot stubble present. The results of this survey (summarized in Table 3) show that for all three marshes, dying high marsh vegetation is significantly lower in elevation than where it remains healthy. As mentioned previously, variability within each group is likely a consequence of spatial heterogeneity in soil drainage.

Table 3. Relative elevations of dead, dying, and healthy high marsh areas around Wellfleet Bay.

Middle Meadow

	mean elevation relative to upland benchmark (m)	standard error
dead	-1.16	0.02
dying	-1.12	0.01
healthy	-1.09	0.02

The Gut

	mean elevation relative to upland benchmark (m)	standard error
dead	-1.41	0.03
dying	-1.26	0.02
healthy	-1.11	0.03

Lieutenant Island

	mean elevation relative to upland benchmark (m)	standard error
dead	-1.24	0.02
dying	-1.18	0.03
healthy	-0.95	0.05

The Gut sites Middle Meadow sites Lt. Island sites

Figure 53. Locations of elevation survey points.

In the absence of data for actual hydroperiod at these elevations, the photos below of high marsh dieback in the Gut and Lt. Island are informative. The first photo (Figure 54) was taken at the Gut on Sep 20, 2006 - exactly 30 min before a high tide level of 9.6 ft (relative to MLLW) (NOAA tide prediction model). It shows that the dieback area is starting to flood - and will be even more flooded 30 min later. The predicted mean high tide level for this area is 10.3 ft (max is 12.5 ft). Thus, the water level at this time would be ~ 28 cm higher than what is shown below. Moreover, the *S. patens*/*Distichlis* dieback area actually extends downslope past the *S. alterniflora* which has since invaded the area. Add more water on top of that to account for recent short term (i.e., seasonal and decadal) sea level peaks and it appears that both species at the seaward edge may be under considerable flooding stress.

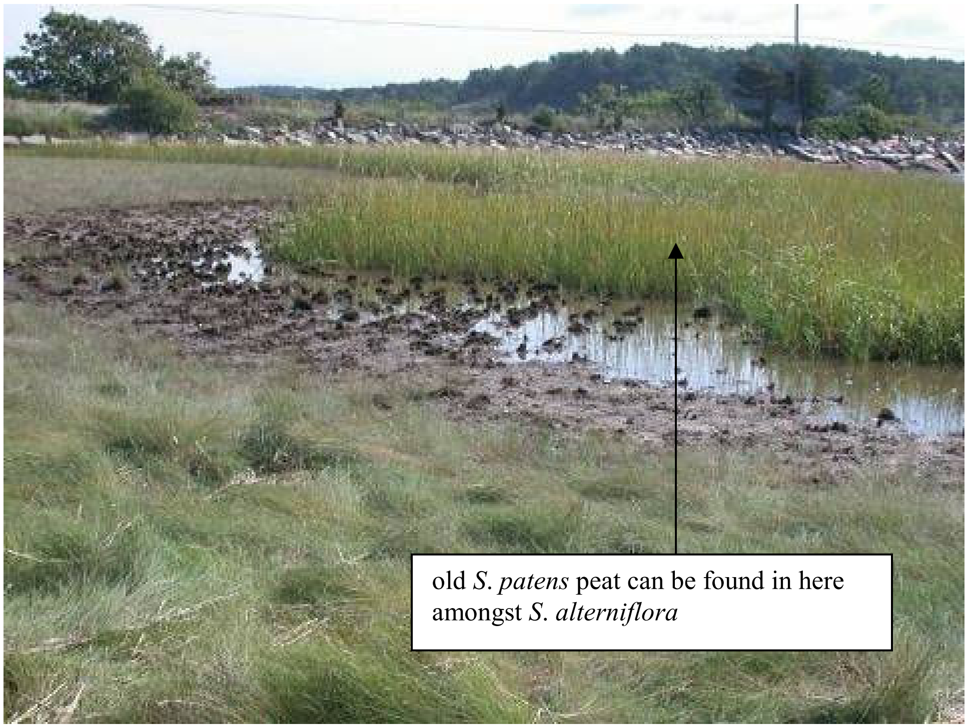


Figure 54. Bare mudflat area flooding 30min before a high tide of 9.6 ft relative to MLLW. Mean high tide is 10.3 ft.

The second and third photos were taken (Figure 55) around Lieutenant Island (Wellfleet) exactly 66 and 41 minutes before a high tide of 10.6 ft relative to MLLW (mean is 10.3 ft for the area). Most noteworthy is the fact that the dieback edge was already inundated well before high tide. In fact, water levels were ~ 13-15 cm above the ground surface in the photo taken 41 minutes before high tide. Thus, the dying edge of this high marsh area is considerably downslope of the mean high tide line (mean high tide is generally considered the seaward boundary for *S. patens*).

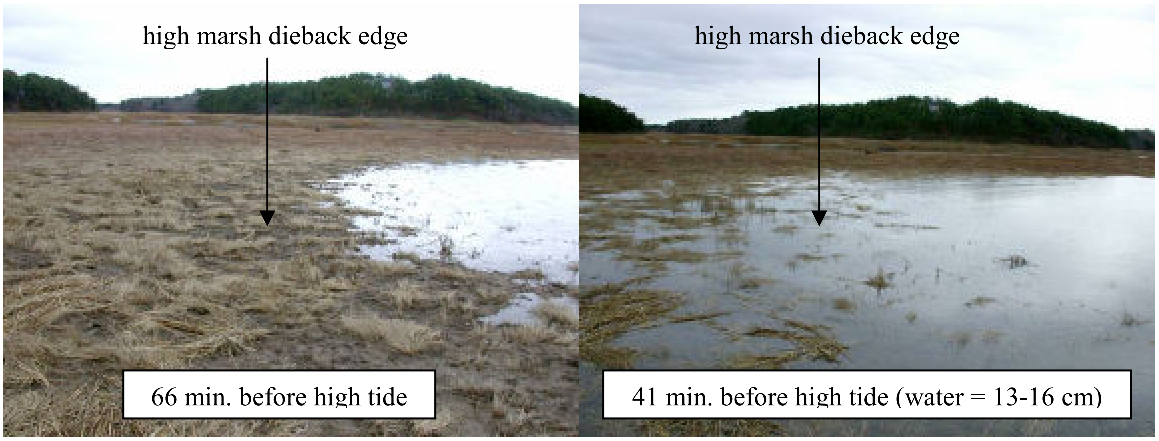


Figure 55. Photos showing water levels in relation to a high marsh dieback edge in the Lieutenant Island area. The photo on the left was taken 66 min. before a predicted high tide of 10.6 ft (mean high tide is 10.3 ft). The photo on the right was taken 41 minutes before a high tide that is close to the mean high tide for this area.

<u>Photographic evidence of the association between elevation and high marsh dieback</u>

The following photographs (Figures 56-62) provide qualitative evidence that high marsh dieback is linked to elevation.

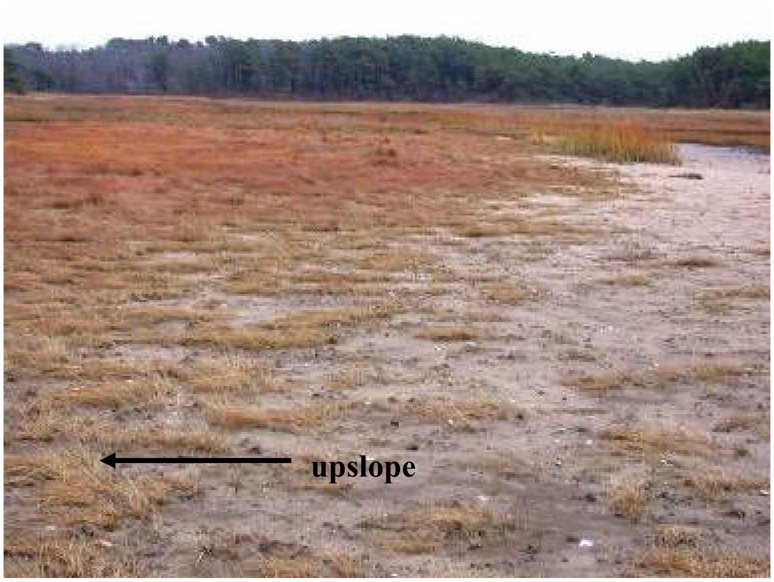


Figure 56. Retreat of *S. patens* from its seaward edge (Lieutenant Island, Wellfleet).

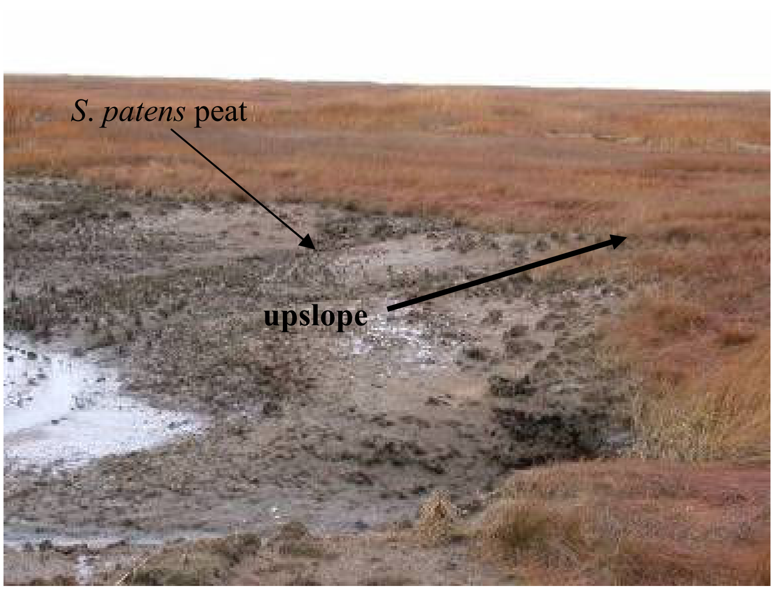


Figure 57. Retreat of *S. patens* from its seaward edge (Loagy Bay, Wellfleet).

Figure 58. Retreat of *S. patens* from its seaward edge (Loagy Bay, Wellfleet).

Figure 59. Retreat of *S. patens* from its seaward edge (the Gut, Wellfleet).

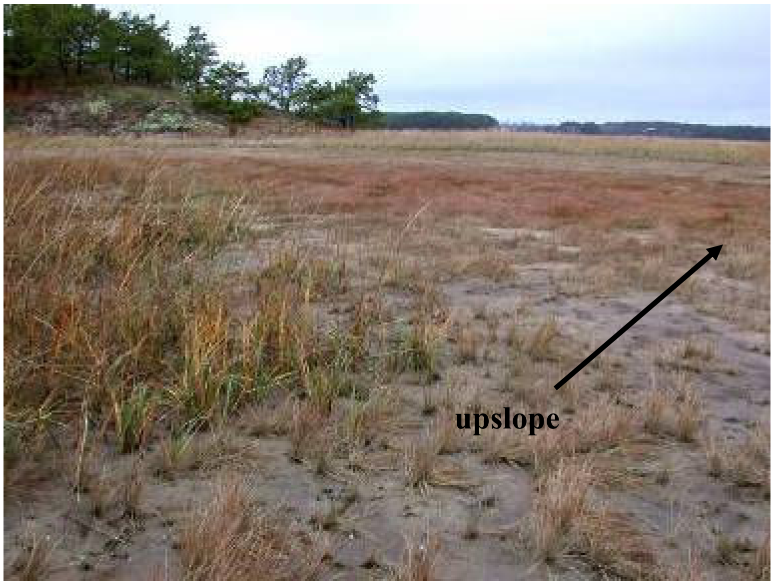


Figure 60. Retreat of *S. patens* from its seaward edge (Indian Neck, Wellfleet).

Figure 61. Retreat of *Distichlis spicata* from its seaward edge (Lieutenant Island, Wellfleet).

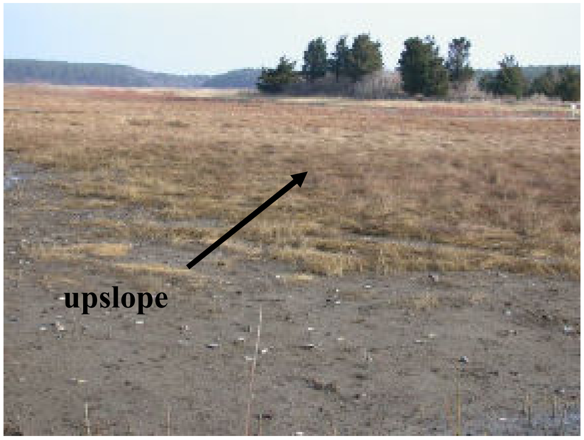


Figure 62. Retreat of *S. patens* from its seaward edge (Wellfleet Wildlife Sanctuary, Wellfleet).

<u>Salt marsh dieback on Cape Cod has been going on for decades</u>

A striking example of past high marsh dieback has been found for the Gut marsh (Wellfleet). Between 1977 and 1987 a long, continuous gap appeared between the high and low marsh vegetation (Figure 46 above). Based on the width of these vegetation zones prior to1977, it is clear that the newly created opening was the result of seaward edge losses of high marsh plants (today, *S. patens* and *D. spicata* remain healthy only at higher elevations while the seaward edge continues to disappear).

Examination of sea level data from NOAA's website, reveals that there have been two distinct peaks in the last 40 years, above and beyond the more gradual, long term rise (Figure 63). One occurred in the late 70s, which is intriguing since aerial photography shows that the Gut dieback event occurred between 1977 and 1987. By 1991, a massive area of barren mudflat had developed (Figure 64) that has since remained open (Figure 65).

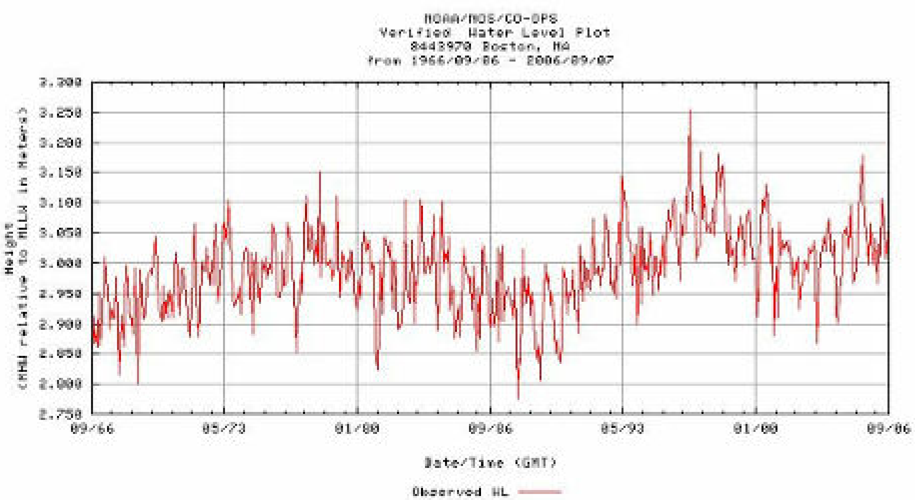


Figure 63. Height of mean high water relative to mean low water (m) in Boston Harbor between Sept 1966 and Sept 2006.

Figure 64. The Gut in Sept 1991. Note the long swath of unvegetated mudflat between the high and low marsh.

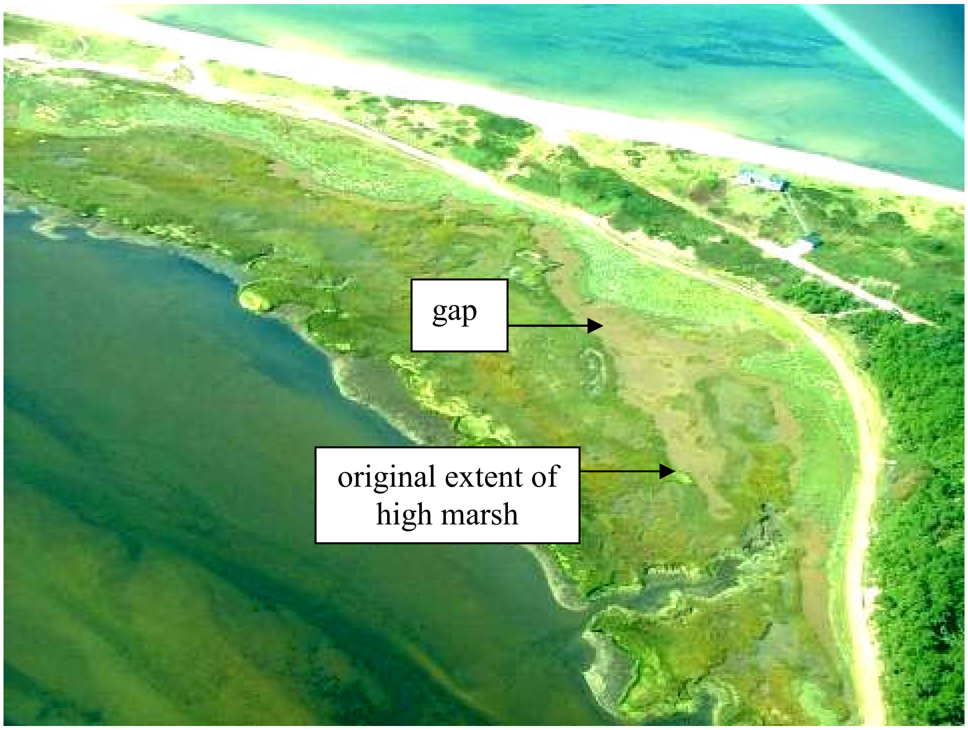


Figure 65. Seaward edge retreat of high marsh in the Gut began sometime between 1977 and 1987 and is still progressing today. Why the low marsh hasn't advanced forward to fill this gap is unknown.

In Middle Meadow, high marsh dieback is not the recent phenomenon it was originally thought to be. In fact, dieback is conspicuous in 1991 color aerial photography (Figure 66). By 2000, color IR photos show that while more high marsh dieback has occurred, some of the 1991 areas had been re-vegetated with *S. alterniflora* (Figure 67). Another sea level peak occurred in the late 1990s, which is significant because that's when high marsh dieback underwent a significant expansion based on comparisons of 2000 vs. 1995 photography (not shown).

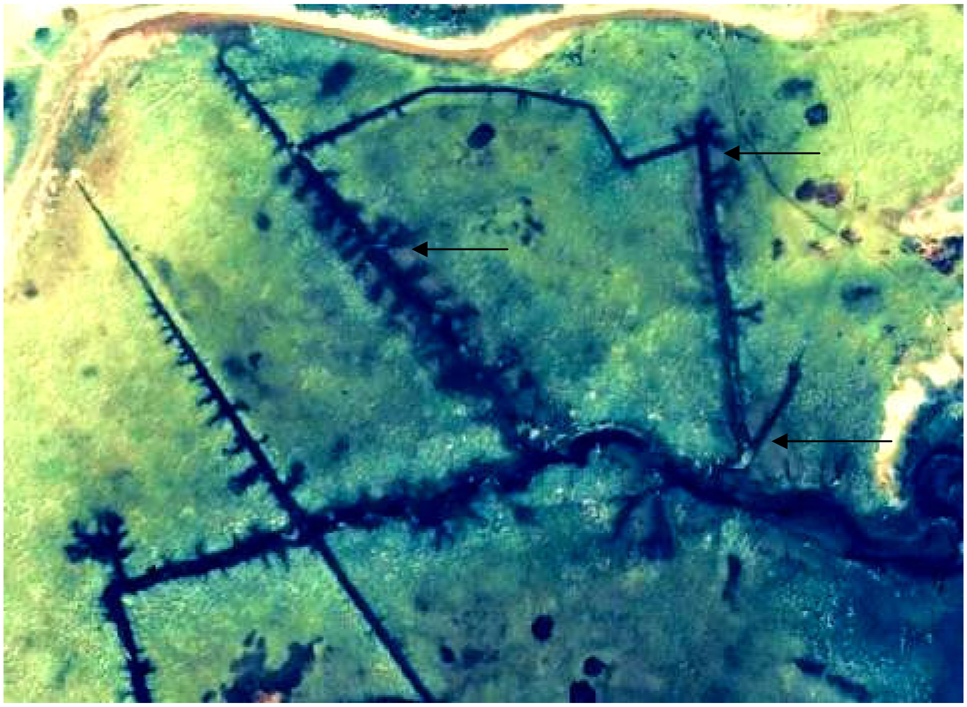


Figure 66. High marsh dieback (grey signature, arrows) alongside mosquito ditches is evident in this 1991 aerial photo of Middle Meadow (Wellfleet).

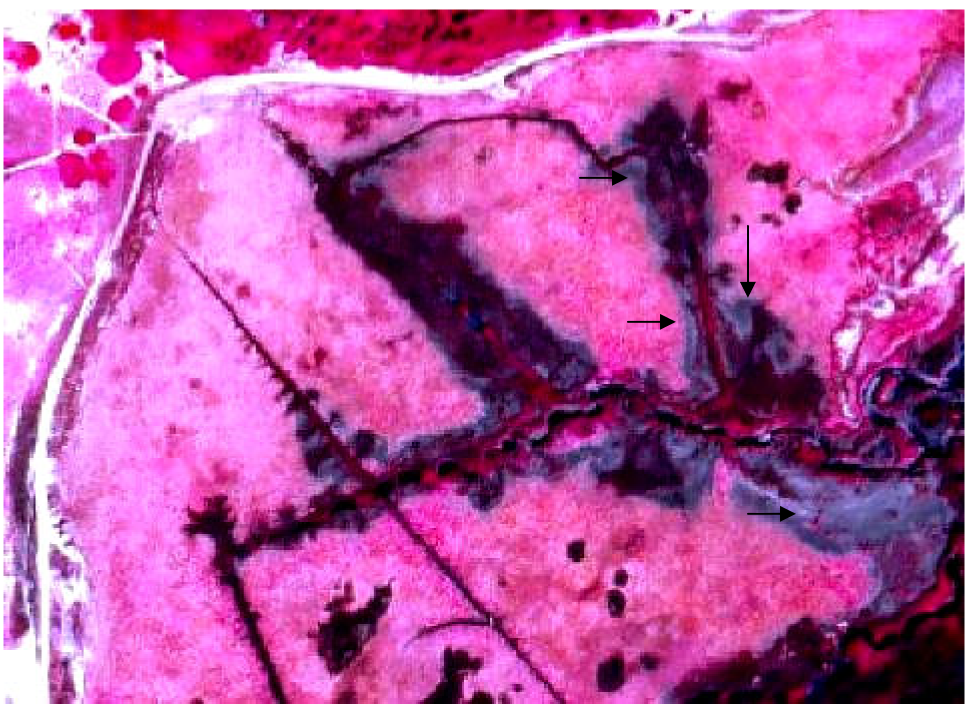


Figure 67. High marsh dieback areas are recolonized to some extent with *S. alterniflora* (bright red) by 2000. Also, new dieback areas (grey signature, arrows) in the high marsh have become noticeable (healthy vegetation = pink).

<u>Photographic evidence that dieback areas are created in the wake of high marsh retreat</u>

The following series of georectified aerial images (Figures 68-72) focuses on the vegetation history of known dieback sites. In each, the high marsh border, which even among photos with different color schemes has a distinct signature compared to *S. alterniflora* and salt marsh forbs, has been delineated. The landward (i.e., upslope) advance of this border over time has resulted in the development of sparsely vegetated (where *S. alterniflora* or various forbs can become established) or unvegetated (dieback) zones as shown in the inset oblique-angle photos.

Figure 68. High marsh seaward edge at an Indian Neck dieback site in 1994 (blue), 2000 (yellow), and 2005 (red) (present day character of dieback site is shown in inset photo).

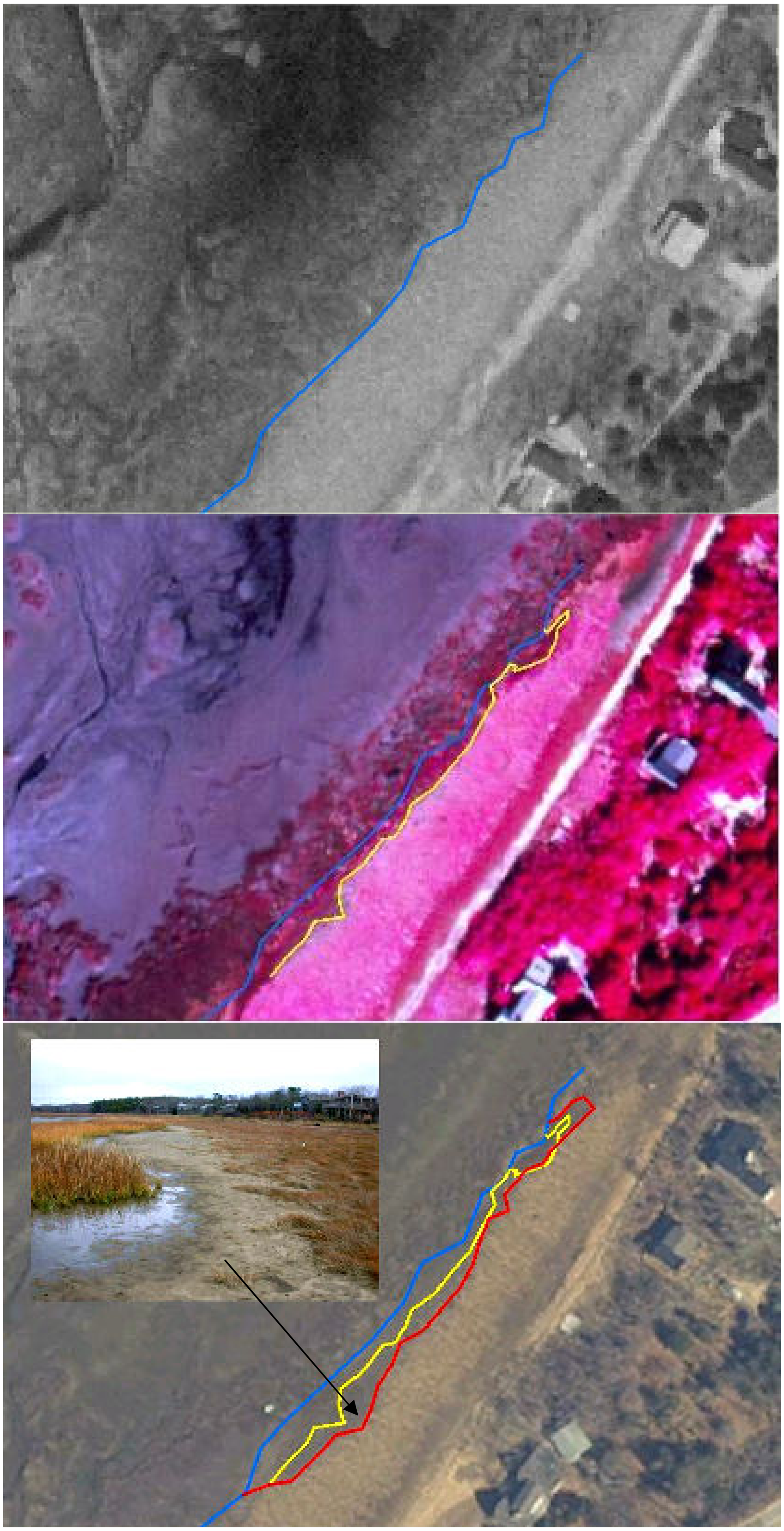


Figure 69. High marsh seaward edge at a Lt. Island dieback site in 1994 (blue), 2000 (yellow), and 2005 (red) (present day character of dieback site is shown in inset photo).

Figure 70. High marsh seaward edge at a Gut dieback site in 1994 (blue), 2000 (yellow), and 2005 (red) (present day character of dieback site is shown in inset photo).

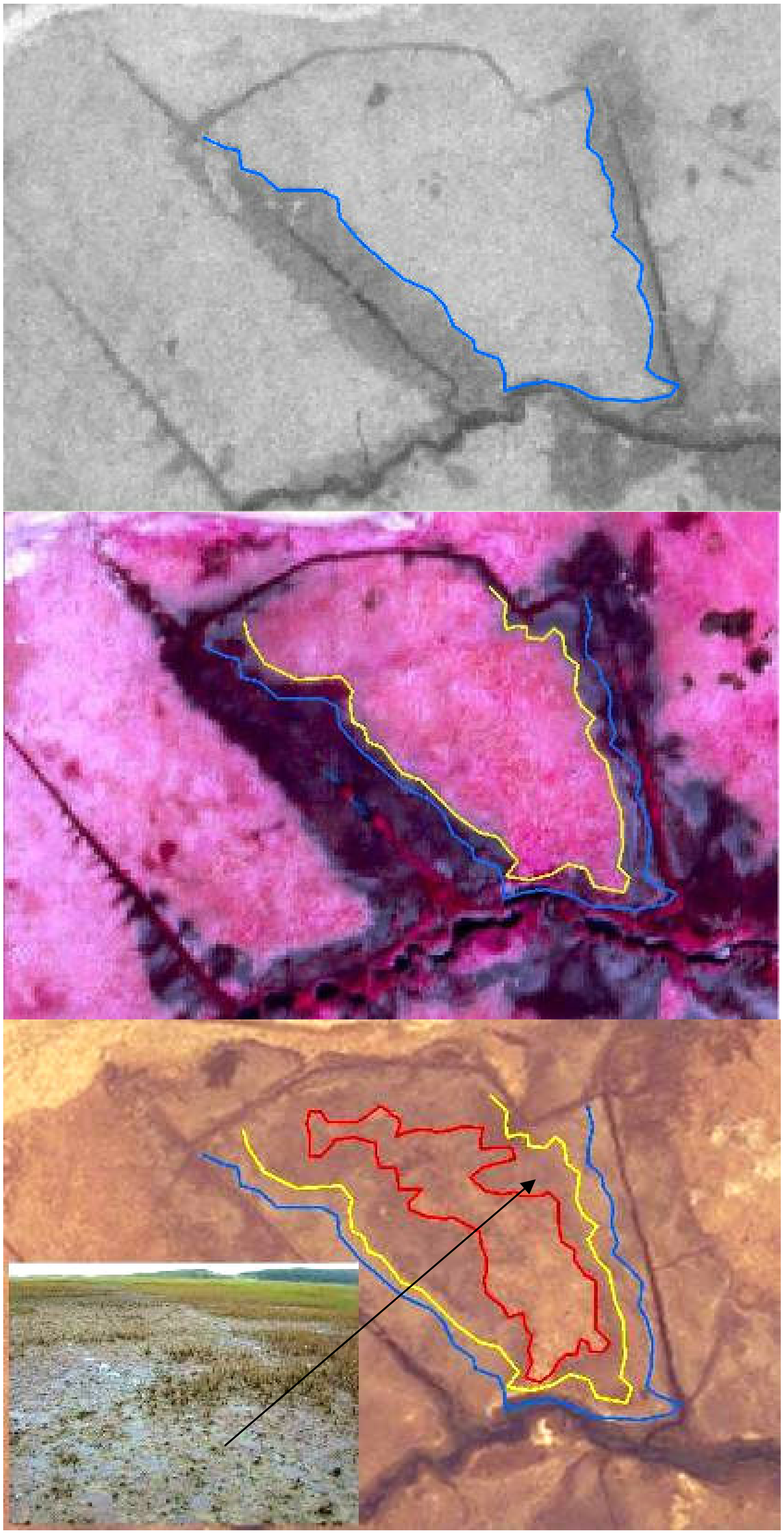


Figure 71.High marsh seaward edge at a Middle Meadow dieback site in 1994 (blue), 2000 (yellow), and 2005 (red).

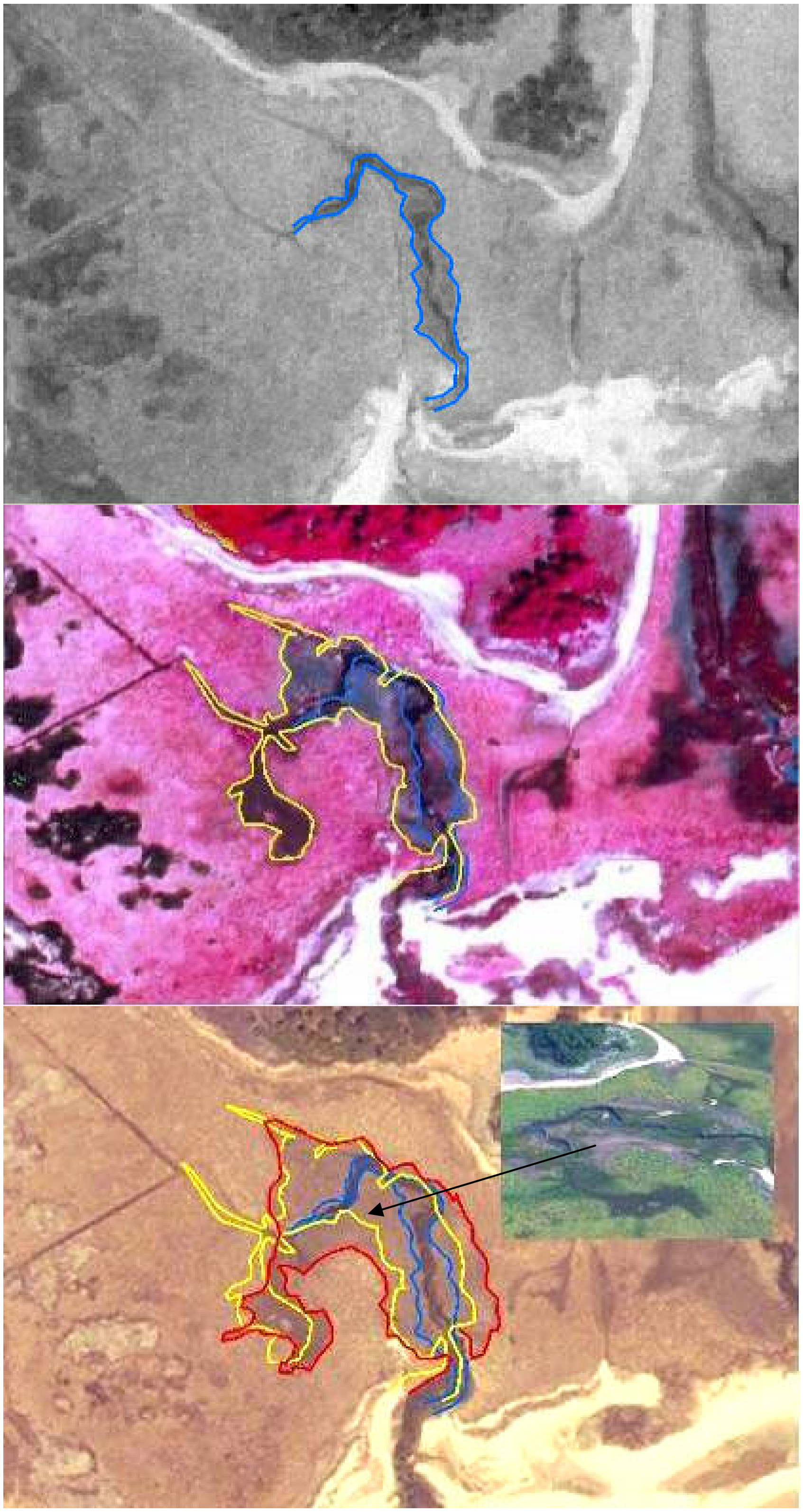


Figure 72 .High marsh seaward edge at Great Beach Hill marsh dieback site in 1994 (blue), 2000 (yellow), and 2005 (red). Note the expansion of subsequent *S. alterniflora* into the high marsh dieback zone.

Have we unwittingly facilitated high marsh dieback by ditching marshes?

By digging mosquito ditches through marshes, we may have unwittingly set up some of these marshes to "fail". In many cases, mosquito ditches, by facilitating drainage, converted low marsh to high marsh (Figure 72b). Thus, high marsh species became established at elevations that would, under natural conditions, be unsuitable. As these ditches have degraded and as sea level has risen substantially since the time of ditching, these areas are once again becoming unsuitable for growth due to prolonged inundation.

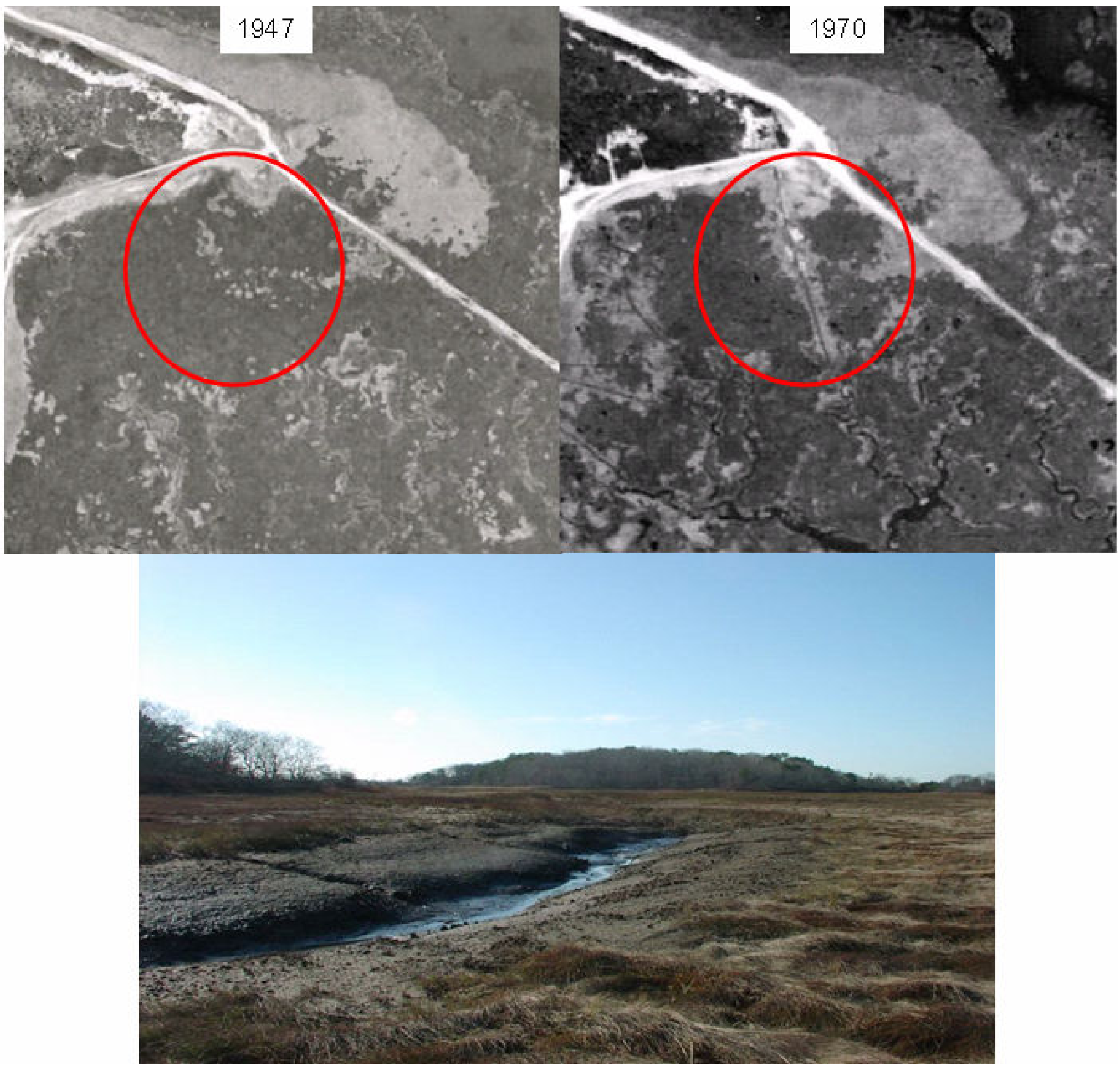


Figure 72b. Conversion of low marsh to high marsh by the construction of a mosquito ditch (top photos) and an example of subsequent high marsh dieback along one of these ditches (bottom photo).

<u>Preliminary conceptual model of high marsh dieback on Cape Cod</u>

- High marsh species (*Spartina patens*, *Distichlis spicata*) have retreated, and continue to retreat, from the lowest elevations of their current zones (i.e., seaward edges). There is some variability in this relationship that is probably due to heterogeneity in soil properties. For example, healthy *S. patens* can be found in a few isolated low spots where the substrate is almost pure sand.

- Rates of dieback may be highly variable over time, depending upon short term fluctuations in sea level along with interannual variability in climatic conditions such as drought, temperature, etc. (which may also permit some recovery in certain years)

- In some places, the boundary between *Spartina alterniflora* and high marsh vegetation simply shifts landward, more or less continuously, with no break in vegetation (i.e., no dieback).

- In some places, *Spartina alterniflora* cannot migrate upslope fast enough to keep pace with high marsh retreat. This may be due to a number of factors such as: 1) the rate of high marsh retreat simply exceeds the rate at which *S. alterniflora* can grow into the gap, 3) herbivory limits the landward edge advance of *S. alterniflora*, 3) environmental/edaphic conditions limit the landward advance of *S. alterniflora* since this is the extreme end of its preferred elevation niche.

- In some places, *Spartina alterniflora* is able to migrate into scattered pockets within high marsh dieback zones and/or is able to move beyond it so that it more or less surrounds the dieback area. This occurs where *S. alterniflora* has difficulty growing into dense, turf-like peat left behind by high marsh species.

Evidence linking low marsh dieback with sea level rise on Cape Cod, Massachusetts

S. alterniflora has clearly suffered major mortality in many locations. Creekbank dieoff seems to be particularly prevalent for this species but the patchy nature of loss has been somewhat puzzling. However, it may be that sea level is adversely impacting plants growing in the low marsh as well. The spatial pattern of dieback in this zone may be more complicated since the low marsh is subject to more pronounced physical forces related to water movement. Besides increased inundation from sea level rise, there are other physical factors that may influence survival in the low marsh - especially increased wave energy and subsequent erosion. Along creekbanks, where water velocities are highest, these forces are particularly strong. This may explain why most low marsh dieback occurs along creekbanks and why most creekbank dieback sites have shown no recovery over the past several years that they have been monitored (Figure 73).

Figure 73. Creekbank dieback along the main tidal channel of Blackfish creek (Wellfleet). No appreciable recovery has been observed over the course of 3 growing seasons.

<u>Salt marshes from other areas that are believed to be impacted by sea level rise have many of the same characteristics as dieback sites on Cape Cod.</u>

Instead of a gradual physiological decline (manifested as decreasing plant heights) and slow loss of cover at the lowest elevations, increasing hydroperiod/wave energy/erosion may act on the low marsh in a heterogeneous fashion. Moreover, there may be short term recovery - the spatial patterns of which are confounded by the difficulty of becoming established in old peat and/or changes in the ground surface topography that have resulted from erosion. Finally, the low marsh can be significantly impacted by severe storms and ice rafting. All these factors may produce a pattern of dieback and survival that is complex and doesn't, to the eye, appear to correlate with elevation.

Despite the complexities of diagnosing salt marsh dieback, there are numerous examples of marsh decline in other places that appear almost identical to many dieback sites on Cape Cod. The Keyhaven marshes around Lymington in southern England, for example, have exhibited significant deterioration. There, dieback and subsequent erosion have been attributed to sea level rise (Boorman 2003). Five mile River (Connecticut) and Jamaica Bay marshes (New York) have also degraded. The leading explanation for decline in these systems is submergence (Ron Rozsa, personal communication, Hartig 2001). However, the dieback in these places is patchy and not uniformly confined to the lowest elevations, which is similar to Wellfleet Bay sites on Cape Cod (Figure 74-76). Islands of relatively robust vegetation can exist within large areas of mortality. In fact, Hartig et al. (2002) reported that productivity (standing crop biomass) in many areas of Jamaica Bay, "was typical of healthy marshes in this region, in spite of other indicators of marsh degradation".

Figure 74. Patterns of low marsh loss attributed to submergence (left side photos) compared with low marsh losses on Cape Cod (right side photos). Note the patchy nature of dieback and survival in all cases (Big Egg photo from Gordon et al. 2001)

Figure 75. Photos of marsh edge dieback and erosion in Keyhaven marsh (England; phtot courtesy of Isle of Wight Centre for the Coastal Environment, 2004) (left) and Payne's Creek marsh (Brewster) (right). Keyhaven diebacks have been attributed to sea level rise and increased wave energy/erosion.

Figure 76. Photos of marsh edge dieback and erosion in Jamaica Bay (NY) (left; photo from Gordon et al. 2001) and Namskaket marsh (Brewster).

On Cape Cod the disappearance of low elevation marsh islands also leaves behind a complex mosaic of mudflat and surviving vegetation that makes present-day interpretation of events, and the underlying cause, somewhat difficult. Conceivably, the redistribution of sediments and accretion in certain locations may further complicate patterns by allowing new marsh to form or by allowing temporary recovery of degraded sites. Notwithstanding, the general pattern of shrinkage of the lower elevation islands and many ground-level symptoms (particularly severe erosion around marsh edges and channels) suggest that sea level may be the principal cause of decline in these areas (Figure 77, 78).

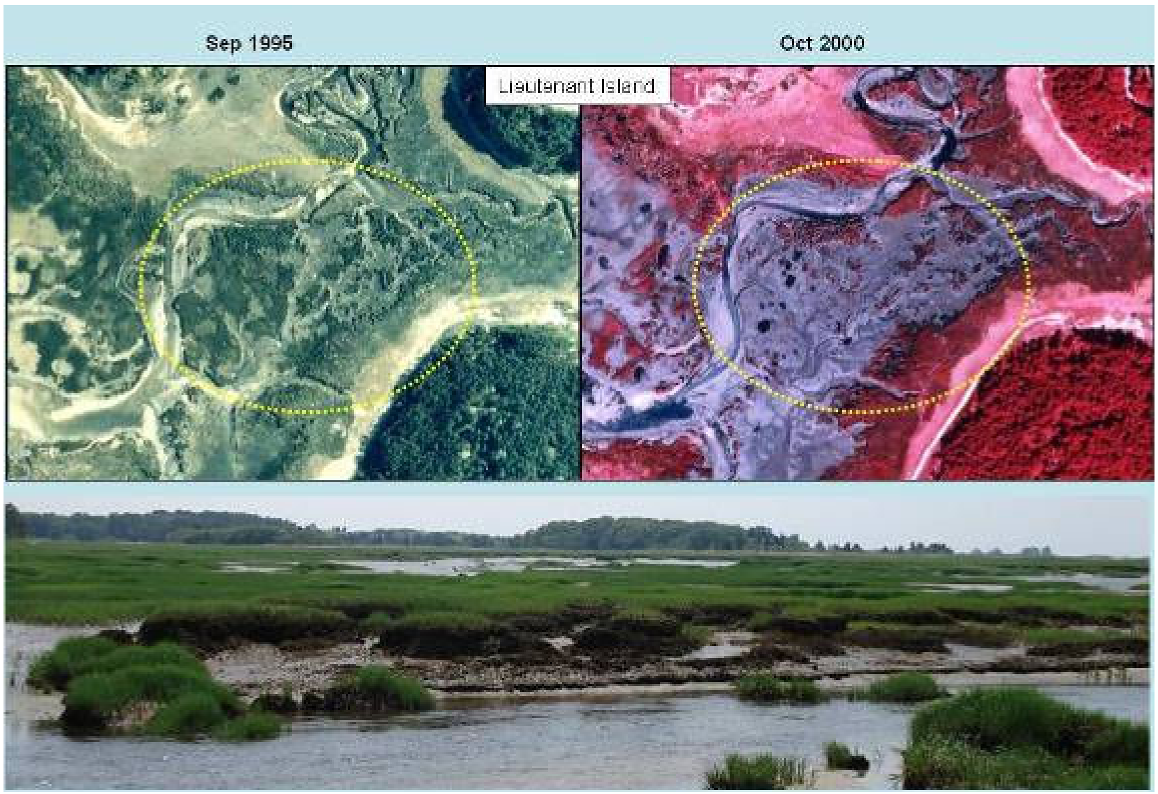


Figure 77. Vegetation loss from low elevation marsh islands (top photos) over the course of five years (1995-2000) (Wellfleet). The bottom photo shows a ground-level view of the spatially heterogeneous character of dieback and survival.

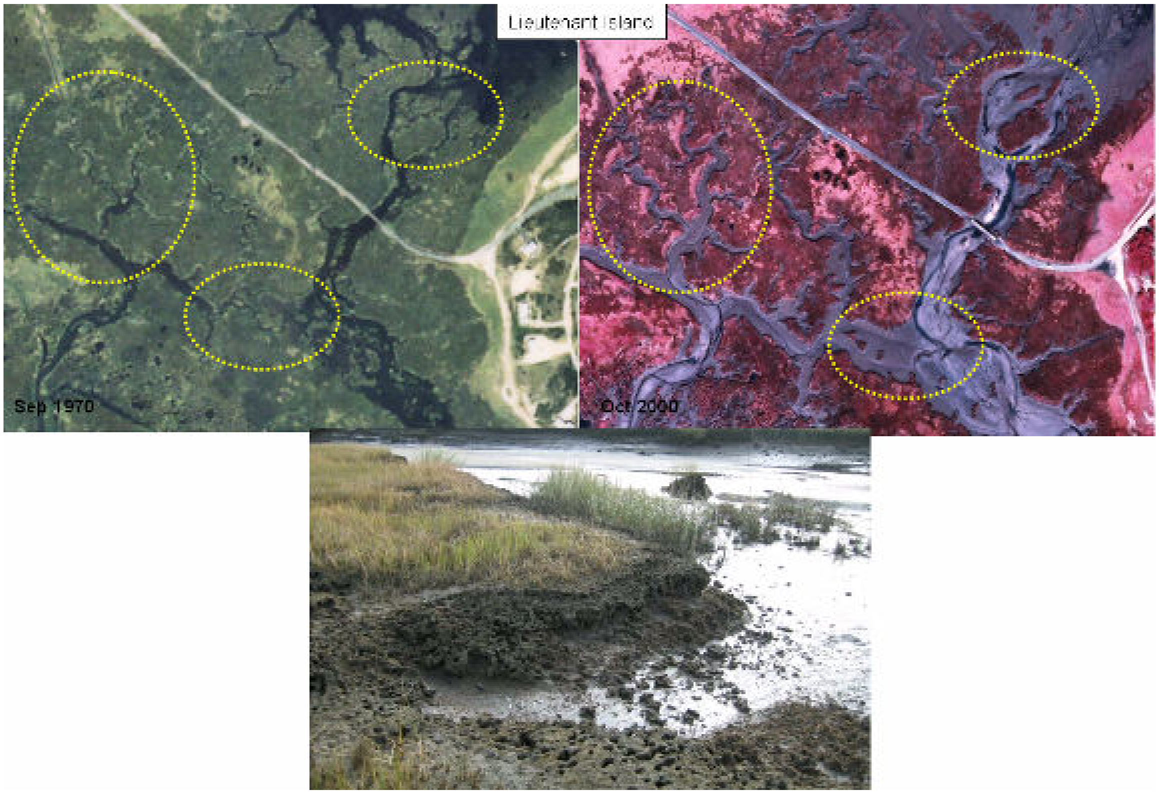


Figure 78. Extensive widening of tidal creeks over the course of 30 years around Lieutenant Island (Wellfleet) and corresponding ground-level view of creekbank losses.

The Saquatucket Harbor sea level rise "experiment"

Just before 1970, Saquatucket Harbor was dredged to provide access for large boats to a newly constructed marina. What was once a narrow, meandering tidal creek was widened into a large straight channel (Figure 79). This would have dramatically altered the tidal prism by allowing much more water into the system. As such, an artificial experiment in sea level rise was initiated. The marsh vegetation of Saquatucket Harbor has since undergone dramatic change, including massive dieback – the most severe among dieback sites along the south shore of Cape Cod (Figure 80). The dieback is essentially limited to the lower elevation edges of the marsh and its creeks throughout the entire system. This kind of dieoff, while more uniform in character and elevation range, is quite similar to other kinds of creekbank dieoff around Cape Cod that have likely happened over longer time scales. Notwithstanding, the Saquatucket "experiment" provides an indication of what may happen to marshes with sea level rise.

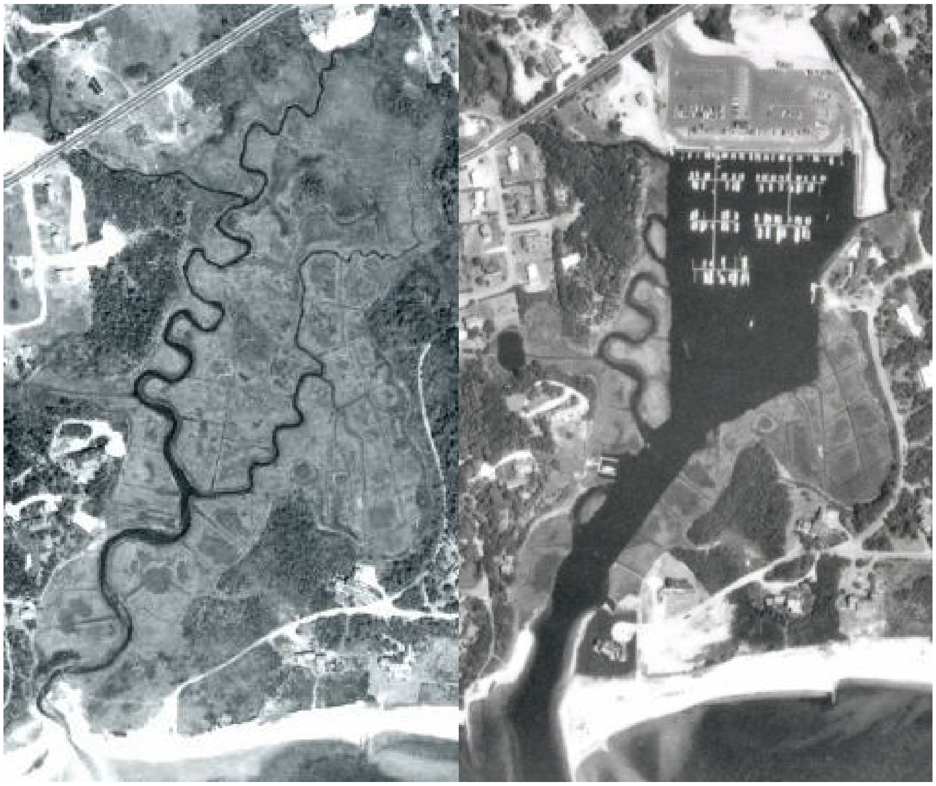


Figure 79. Saquatucket Harbor in 1952 vs. 1971, after channelization of the main tidal creek (photos provided by Donald Liptak, NRCS).

Figure 80. Severe creek bank dieoff at Saquatucket Harbor (April 2006). Note: creekbank deterioration can be detected in aerial photos taken by a private company in 1993 (permission to publish the 1993 image in this document was denied), suggesting that this site is not a case of "sudden wetland dieback".

Other examples of low elevation creekbank dieback and erosion that is very similar to submerging marshes in Long Island sound and the U.K. can be found all over Cape Cod (Figure 81-83).

Figure 81. Marsh edge dieback and erosion at Herring River in Eastham (left) and the Herring River in Harwich (right).

Figure 82. Marsh edge dieback and erosion at Indian Neck (Wellfleet) (left) and photo (by Karin Rosenthal) from Lt. Island (Wellfleet) (right) in 1995 showing that creek bank dieback and erosion has being happening for some time.

Figure 83. Marsh edge dieback and erosion at Boat Meadow (Eastham; top left), Nauset Marsh (Orleans; top right), Payne's Creek (Brewster; bottom left), and Pleasant Bay (Orleans, bottom right).

Mechanism

The mechanism by which sea level rise could result in low marsh dieback could be multifaceted. Increased hydroperiod would exert a physiological stress on plants. However, there may be physical factors that are equally or more important. In this regard, sediment erosion is likely a key process. On Cape Cod, we have witnessed significant erosion from around the root zones of healthy plants, which eventually results in the death of these plants. The photo below shows an area of healthy *S. alterniflora* at the end of a tidal channel in a Wellfleet marsh (Figure 84). All the sediments from around the roots are being washed away, even though the plants are tall, green, and show no foliar symptoms of disease. Eventually, the plants fall into the channel. Erosion, in addition to reducing sediment stability, also exposes plant roots to air and water, which may result in direct physical damage to the tissues. As such, it is possible that physical forces are contributing to plant demise (Figure 85). Loss of the buffering vegetation may then exacerbate these physical effects, resulting in radically altered marsh topography (Figure 86).

Secondarily, fiddler crabs may exacerbate erosion through their excavating activities. Bioturbation by fiddler crabs at most dieback sites on outer Cape Cod are intense. Fiddler crabs increase ground surface roughness, thereby increasing sediment suspension when water passed over it. As such, these animals could indirectly be accelerating marsh dieback.

Figure 84. *S. alterniflora* in the mid-elevation zone of the low marsh at the end of an eroded tidal creek at the Wellfleet Wildlife Sanctuary (Audubon). Healthy plants are falling into the tidal creek due to erosion of sediments from around the roots.

Figure 85. Extensive sediment loss from around healthy, robust plants (these photos were taken in Dec 06). Examples like these beg the question of whether sediment loss is a consequence of plant demise or the other way around.

Figure 86. Are features like these in fringing Cape Cod marshes evidence of increasing sea level causing increased sediment/materials transport?

Other marsh responses to sea level rise

In Virginia LTER, scientists have reported extensive "hummocking" of vegetation in response to sea level rise there (Christian et al. 2000, Buck 2001). Interesting, while hummocking of *S. patens* is also found along the seaward edges of high marsh zones on Cape Cod, low marsh hummocking is also present. Much of the *S. alterniflora* around Lieutenant Island, for example, exhibits this characteristic concurrent with dieback (Figure 88).

Figure 87. Hummock development in low marsh vegetation around Lt. Island (Wellfleet) coincident with dieback and around Morris Island (Chatham) with very little dieback.

On Cape Cod low marsh dieback is limited primarily to creekbanks in more sheltered marsh systems, whereas low marsh dieback occurs at both low and mid elevations in fringing marshes that are open to the prevailing winds across Cape Cod Bay

On Cape Cod, dieback of *Spartina alterniflora* in mid- to low marsh zones is largely confined to fringing marshes that are open to Cape Cod Bay (Figure 89, 90). Good examples of these kinds of sites exist around Lt. Island, where there is extensive dieback at mid elevations, particularly where there is a noticeable break in the elevation gradient (i.e., natural berms). This pattern of vegetation loss, with healthy plants at both lower and high elevations surrounding the dieback area, has also been observed in eroding marshes in Virginia (May 2002). These sites are exposed to prevailing winds virtually all year long – from the southwest in the summer and from the northwest in the winter. The winds, in addition to generating wave energy, also have a Seiche effect in Cape Cod Bay, and can significantly increase the height of high tides as water is piled up along the western shore of the peninsula. Thus, it makes sense that if physical forces were partly responsible for marsh dieback those that are more exposed to open water would exhibit losses over wider areas (i.e., at many different elevations).

Where marshes are more protected in bays and behind narrow tidal inlets, dieoff of *S. alterniflora* seems to be more prone to dieback along creekbanks, where the highest water velocities are.

Figure 89. Mid-elevation low marsh losses around Lt. Island (fringing) (left) vs. creekbank loss in Middle Meadow (sheltered).

From a Cape-wide perspective, Wellfleet Harbor is the epicenter of salt marsh dieback. In other words, the most extensive and severe dieback occurs in this area, particularly the fringing marshes of Lt. Island and the Wellfleet Wildlife Sanctuary. Perhaps it is no coincidence that the worst salt marsh dieback occurs in the area has 1) the largest tidal range of anywhere on the peninsula (which translates to higher water velocities across the marsh and through tidal creeks) and 2) the greatest exposure to prevailing NW and SW winds. In addition, the gradual submergence of Billingsgate, a large island that existed south of the Great Island peninsula on the western side of Wellfleet Harbor, is a loss of a significant buffer. Thus, a considerable portion of wave energy that was once dissipated by the island can now move unimpeded into the Harbor.

Figure 90. Marsh areas showing primarily creekbank (squares) vs. multi-elevation (circles) dieback of *S. alterniflora*.

Dieback at the landward edge (upper elevations) of the low marsh

S. alterniflora may be stressed at the other end of its elevation niche (i.e., the landward margin) as well. In Middle Meadow (2006), *S. alterniflora* plants that had successfully invaded high marsh dieback sites began to die themselves by mid-summer. The dying plants had grown to a height of approximately 50-80 cm before their decline - indicating that some physiological tipping point was reached during the growing season (Note" these plants must be monitored through the spring of 2007 to assess whether mortality has actually occurred or whether some form of early senescence was observed). This threshold may be related to hydroperiod given that the only plants to survive in this area were those growing in lower elevation, old mosquito ditches (Figure 91). As such, this area of the marsh, which formerly supported high marsh vegetation, may be currently teetering on the edge of suitability for *S. alterniflora*. Presumably, as sea level continues to rise, the suitability of higher elevation sites will increase and *S. alterniflora* will successfully expand its range. Fortunately, this is something that can be tracked on the ground with existing permanent plots and with aerial photography.

Figure 91. Dieback of *S. alterniflora* in Middle Meadow (Wellfleet). The only plants that have been able to survive dieback are those in the lower elevation mosquito ditches (left). Dying plants were confined to areas formerly occupied by *S. patens* (right).

The fact that dieback and recovery can occur simultaneously fits well with the idea that sea level is affecting both the low marsh and high marsh at both ends of their elevation niches (Figure 92). The seaward edge of the low marsh in Middle Meadow (Wellfleet) has exhibited extensive dieback, particularly along the major tidal creeks. The landward advance of the low marsh seems to be proceeding in a punctuated fashion. In other words, it appears that there may be sequences of advance, followed by dieback, and then advance again. Meanwhile the seaward edge of the high marsh is disappearing at a rate that has exceeded the ability of the low marsh to keep pace with it in many places. Herbivory in this zone may be one factor that limits the landward advance of *S.*

alterniflora is some places. This hypothesis is currently being investigated by Dr. Mark Bertness of Brown University.

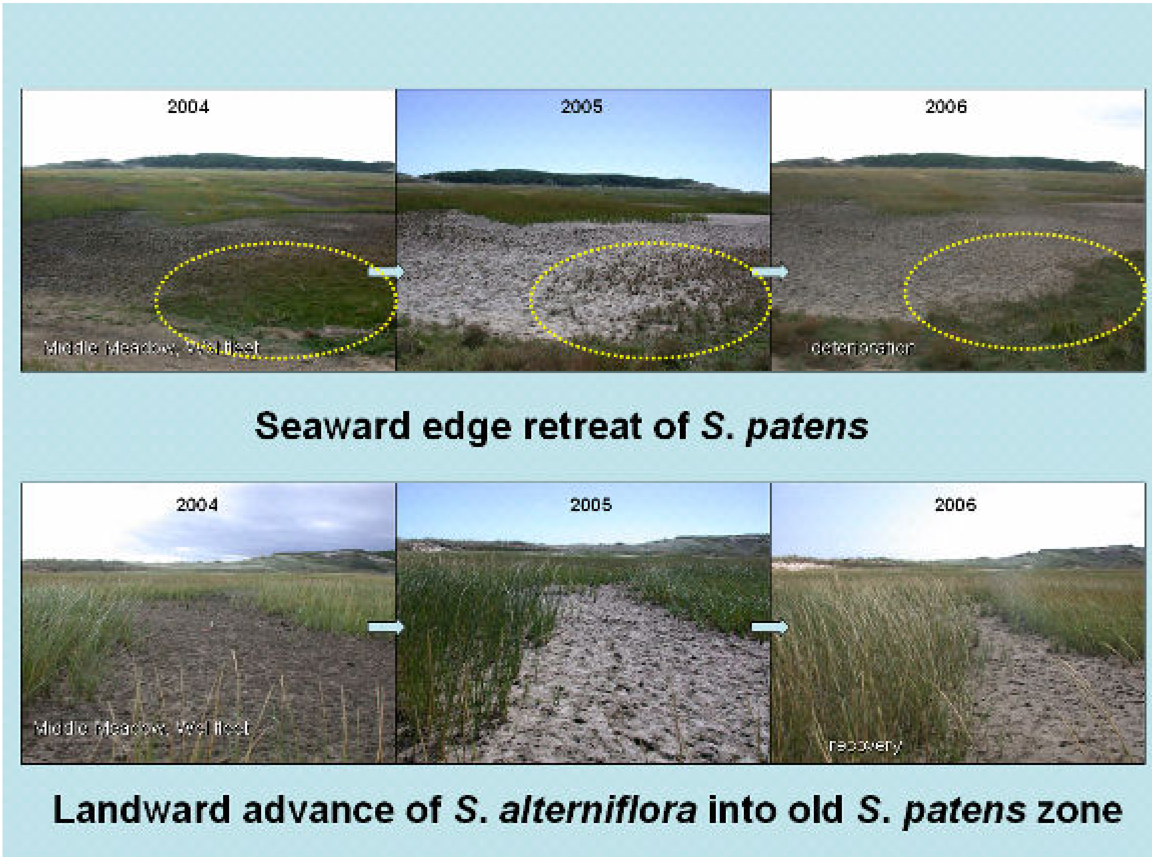


Figure 92. Photos showing simultaneous retreat of high marsh vegetation (top series) and advance of low marsh vegetation into an area formerly occupied by high marsh species (bottom series).

<u>Conclusion</u>

Both low and high marsh dieback may be proceeding in a way that differs from conventional wisdom about salt marsh responses to sea level rise. Rather than a smooth, gradual process of decreasing biomass at the seaward edge and species composition shifts at the landward edge, salt marsh dieback may be occurring in a spatially and temporally heterogeneous fashion. Patch dynamics in these marshes are becoming more and more significant. Present-day characteristics of degrading marshes may further complicated by survival and recovery processes, herbivory, peat rafting by storms or ice, and inter-annual climatic conditions that periodically set back or exacerbate dieback.

<u>Preliminary conceptual model of low marsh dieback on Cape Cod</u>

- Dieback of *Spartina alterniflora* at marsh edges, tidal creekbanks, and mid-elevation berms is the result of increased erosive forces due to sea level rise. Some dieback of this species at low elevations may be the result of increased inundation.

- The inability of *Spartina alterniflora* to migrate upslope fast enough to keep pace with high marsh retreat may be due to: 1) the physiological stress of growing into a zone that is on the periphery of its ecological niche, 2) the rate of high marsh retreat simply exceeds the rate at which *S. alterniflora* can grow into the gap, 3) herbivory limiting the landward edge advance of *S. alterniflora*.

- In some places, *Spartina alterniflora* is able to migrate into scattered pockets within high marsh dieback zones and/or is able to move beyond it so that it more or less surrounds the dieback area. This occurs where *S. alterniflora* has difficulty growing into dense, turf-like peat left behind by high marsh species.

Future work

- Comprehensive survey of salt marshes for elevation data, hydrology, tide creek water velocities, erosion, plant species composition, plant health, and soil properties.
- Compare sites where *S. alterniflora* has appeared to successfully recolonize old *S. patens* sites to sites where *S. alterniflora* has not be able to advance into these areas.
- Conduct field experiments where plugs of *S. patens*/*Distichlis* and *S. alterniflora* are artificially elevated and lowered along their seaward and landward edges.
- Conduct field experiments that artificially dampen wave energy in plots within fringing marshes experiencing erosion.
- Continue to collect, digitized, georeferenced, and analyze aerial photography in an attempt to reconstruct landscape history.

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