

FINAL REPORT

EPA Long Island Sound Study Grant

Understanding the Role of Nutrient Enrichment in Marsh Loss in Long Island Sound

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Shimon Anisfeld

Yale University School of Forestry and Environmental Studies

shimon.anisfeld@yale.edu



Drowning Marsh at Sherwood Island (photo: Anisfeld)

TABLE OF CONTENTS

Abstract (Public Summary)	3
1. Introduction (Project Description).....	5
1.1 Background.....	5
1.1.1 Marsh drowning.....	5
1.1.2 Effects of nutrients on marsh processes	7
1.1.3. Marsh restoration.....	9
1.2 Hypotheses	9
2. Methods (Activities and Accomplishments)	10
2.1 Study Sites	10
2.2 Plot Layout	13
2.3 Fertilization.....	16
2.4 Porewater Sampling and Analysis.....	16
2.5 Aboveground Productivity	17
2.6 Belowground Biomass and Productivity	17
2.6.1 Coring.....	17
2.6.2 Ingrowth Measurements	18
2.7 Aboveground and Belowground Nutrient and Metal Content	18
2.8 Decomposition and Respiration	19
2.8.1 Decomposition Experiments	19
2.8.2 Soil Respiration	20
2.9 Accretion and Elevation Change (Feldspar and SET Measurements)	20
2.9.1 SET Measurement	20
2.9.2 Feldspar Plots	21
2.10 Hydrology.....	21
2.11 Statistics.....	22
3. Results (Summary of Findings).....	23
3.1 Porewater.....	23
3.2 Aboveground Productivity	25
3.3 Belowground Biomass and Productivity	28
3.4 Aboveground and Belowground Nutrient and Metal Content	32
3.5 Decomposition and Respiration	37
3.6 Accretion and Elevation Change (Feldspar and SET Measurements)	39
3.7 Hydrology.....	46
3.7.1 Hoadley.....	46
3.7.2 Jarvis.....	51
3.7.3 Sherwood.....	55
3.7.4 Comparing the three marshes	59
4. Conclusions	63
4.1 Nutrient Effects	63
4.2 Inter-marsh Comparison.....	64
4.3 Thoughts on Marsh Drowning at Sherwood Island.....	66
4.4 Evaluating Our Hypotheses.....	67
5. References	68
6. Acknowledgments	71
Presentations/Publications/Outreach	72
APPENDIX I: Methodological Adjustments for Measuring CO ₂ Flux	73

ABSTRACT (PUBLIC SUMMARY)

Long Island Sound's tidal marshes are key components of the coastal landscape, providing valuable habitat and serving important functions. Several sites in Long Island Sound have been experiencing marsh drowning, in which the marsh becomes too wet to support vegetation and is converted to open mudflats. The causes of this phenomenon are unclear. While sea level rise is occurring in Long Island Sound, the rate of this rise is relatively low ($\sim 2.3 \text{ mm yr}^{-1}$) and has apparently not changed since the mid-19th century. In the absence of other stressors, one would expect marshes to be able to adjust to this rate of sea level rise by accumulating inorganic sediment and organic material in order to maintain their relative elevation.

This project was designed to test the hypothesis that excessive loading of nutrients (nitrogen (N) or phosphorus (P)) plays a role in causing marsh loss, either through a decrease in belowground production or through an increase in belowground decomposition. In addition, we examined the similarities and differences between the phenomenon of marsh drowning described above and the phenomenon of marsh restoration, in which the return of tidal flow to a marsh leads to a wetter system – but one that is on a trajectory of restoration rather than drowning.

The project involved both observational and experimental components. In the former, we compared 3 Connecticut marshes in different hydrologic settings: a stable marsh (Hoadley Creek, Guilford), a restoring marsh (Jarvis Creek, Branford), and a drowning marsh (Sherwood Island, Westport). In the latter, we established fertilization plots at Hoadley (24 plots treated for 3 years with N, P, both, or neither) in order to determine the effects of added nutrients on marsh processes. In both the inter-marsh comparison and the fertilization experiments, we examined a variety of marsh parameters and processes: porewater concentrations of nutrients, salinity, and sulfide; aboveground and belowground biomass and productivity; aboveground and belowground nutrient and metal content; decomposition and respiration; accretion and elevation change; and tidal hydrology.

We found that nutrient addition to marsh plots had significant effects on some aspects of marsh structure and function. N and P treatments led to increased nutrient concentrations (N and P, respectively) in porewater and aboveground vegetation. N fertilization led to higher aboveground productivity. P treatments led to higher P concentrations bound to mud.

Perhaps more interesting, however, are the effects that we did *not* observe. N and P fertilization generally did not appear to substantially affect belowground processes, including productivity, decomposition, and soil respiration. Likewise, there was no indication that N and P fertilization affected sediment accretion or net elevation change. As a result, we now consider it *unlikely* that excess nutrient loading is a major contributor to marsh drowning. Also supporting this conclusion is the fact that the drowning marsh (Sherwood) had lower nutrient concentrations than the reference marsh (Hoadley).

In our inter-marsh comparison, we found several important differences between the sites:

- Jarvis is much wetter than Hoadley and Jarvis, with a longer high water period.

- Jarvis has high rates of both accretion and elevation change, while Sherwood has moderate rates of both. Hoadley has moderate rates of accretion but low (even negative) elevation change, reflecting substantial subsidence (belowground loss of elevation e.g., through compaction or decomposition).
- Jarvis has lower belowground biomass and more mud than Hoadley and Sherwood, perhaps because of its higher rates of trapping of inorganic sediment.

We believe that the high rates of accretion and elevation change at **Jarvis** (the “restoring” marsh) are related to the favorable hydrology of this site. The marsh surface at Jarvis is flooded on ~80% of high tides, and is under water about 1/3 of the time. This provides ample opportunity for sediment deposition on the marsh surface. In addition, the change in the slope of the Jarvis hydrograph at roughly the elevation of the marsh surface (not seen at the other marshes) may reflect the slowing of the tidal waters as they overtop the channel and spread across the marsh surface. In sum, Jarvis is a successful restoration site. Although current conditions are certainly on the wetter end of the acceptable range for *S. alterniflora*, the marsh is not drowning. The site appears to be on a trajectory of increasing elevation relative to water level.

The substantial subsidence that we observed at **Hoadley** (the “stable” marsh) is an extremely important phenomenon, but one that we have no explanation for. The subsidence appears to be unrelated to nutrient treatment.

Despite the mudflat that has developed nearby, our plots at **Sherwood** (the “drowning” marsh) are not yet drowning. Flooding frequencies and durations are low to moderate – no wetter than Hoadley and certainly drier than Jarvis. In fact, the marsh would have to lose about **40 cm** of elevation relative to water level to be faced with the same flooding duration as Jarvis. Productivity at Sherwood is reasonably high both aboveground and belowground, and generally quite comparable to Jarvis. At the same time, the low accretion rates that we measured, especially in one of our plots, may indicate an absence of sediment delivery to this marsh.

We speculate that the nature of drowning at Sherwood Island is closely linked to its hydrology. Due to the relatively small size of this marsh system, the nature of the tidal regime, and perhaps changes to the surrounding hydrology (i.e., the Millpond), there appears to be a large volume of water moving relatively rapidly through this system. The parts of the marsh (like our plots) that are relatively high are only flooded on ~15% of high tides, and when the flooding tides do come, they may be moving too rapidly to deposit sediment. On the other hand, the parts of the marsh that are a bit lower (e.g., the mudflat), are no doubt flooded frequently, but the water seems to be moving too rapidly to deposit sediment, and instead is likely to erode existing sediment.

Thus, we believe that the causes of marsh drowning at this site are likely to be found in inorganic sediment delivery (and erosion) processes rather than productivity and decomposition processes. This is consistent with our conclusion that nutrients (which are more likely to affect productivity and decomposition) do not play a major role in marsh loss at Sherwood Island.

1. INTRODUCTION (PROJECT DESCRIPTION)

1.1 Background

1.1.1 Marsh drowning

Tidal marshes are key components of the coastal landscape, and play a variety of valuable roles, including: habitat for wading birds, juvenile fish, and invertebrates; sites of high organic matter production and nutrient processing; buffers for removal of land-derived pollutants; and flood protection for coastal habitats and dwellings (Teal and Howes 2000). While direct impacts (e.g., filling) to coastal marshes in Long Island Sound (LIS) have largely been eliminated by protective legislation, recent evidence suggests that these ecosystems are threatened by indirect impacts, specifically “drowning,” a phenomenon characterized by a loss in elevation of the marsh surface relative to water level, accompanied by a loss of vegetation and conversion into mudflat.

In order to survive, marshes must gain elevation by accumulating sediment (both tidally-derived material, primarily inorganic; and in-situ produced organic material) at a rate roughly equal to the rate of local relative sea level rise (RSLR). There has been growing concern that over the next several decades, an acceleration in the rate of sea level rise (caused by global climate change) may lead to the inundation and erosion of large areas of tidal wetlands.

Loss of tidal marshes has already been occurring for several decades in the Mississippi Delta, Chesapeake Bay, and other areas, though the causes and mechanisms are still under debate (e.g., Turner 1997; Day et al. 2000; Kearney et al. 2002). Recently, vegetation change (to wetter species) and tidal marsh loss have been observed in the Northeast as well, despite the lower rates of RSLR that are characteristic of this region ($\sim 0.2 \text{ cm yr}^{-1}$, compared to $\sim 0.4 \text{ cm yr}^{-1}$ in Chesapeake Bay and $\sim 1 \text{ cm yr}^{-1}$ in the Mississippi Delta).

Shifts in tidal marsh vegetation towards “wetter” species (particularly shifts from high marsh vegetation to *Spartina alterniflora*) have been observed at several locations in New England, including Sherwood Island, CT (Civco et al. 1986), Hammonasset, CT (Civco et al. 1986), Barn Island, CT (Civco et al. 1986; Warren and Niering 1993), Succotash, RI (Donnelly et al. 1999), Rumstick Cove, RI (Donnelly and Bertness 2001), Nag Creek, RI (Donnelly and Bertness 2001), and Waquoit Bay, MA (Orson and Howes 1992). Recent studies suggest that some of the observed changes in vegetation dominance may reflect not changes in hydroperiod, but rather changes in inter-species competition due to higher nutrient loads (Bertness et al. 2002).

Actual marsh loss (as opposed to vegetation change) has not been widely studied in New England, but recent work has begun to identify areas where this is occurring. At Jamaica Bay, NY, rates of salt marsh loss of 12 ha yr^{-1} (1.5% per year) were observed over the period 1974-1999, a period in which the marshes were protected from dredge and fill activities (Hartig et al. 2002). Possible contributing factors include reduced sediment supply, indirect impacts of dredging activity, erosion from boat wakes, and RSLR. In the brackish marshes of the Quinnipiac River, CT, we have observed vegetation loss (of *Phragmites australis* and *Typha glauca*) in 45% of our 53-ha study site over the period 1974-2000, despite apparent surface

accretion rates that are higher than RSLR at New London (Anisfeld, unpublished data). Inspection of historic and current aerial photographs shows a large number of sites in southwestern Connecticut where significant vegetation loss may have occurred since the 1970s (Figure 1; Ron Rozsa, CT DEP, personal communication). Similar observations have been made on the north shore of Long Island (Fred Mushacke, NY DEC, personal communication). A systematic analysis of aerial photographs for 6 estuaries in southwestern CT (Figure 2) found 27-54% loss in low marsh over the period 1974-2004, with corresponding increase in area of tidal mudflat (Tiner et al. 2006).

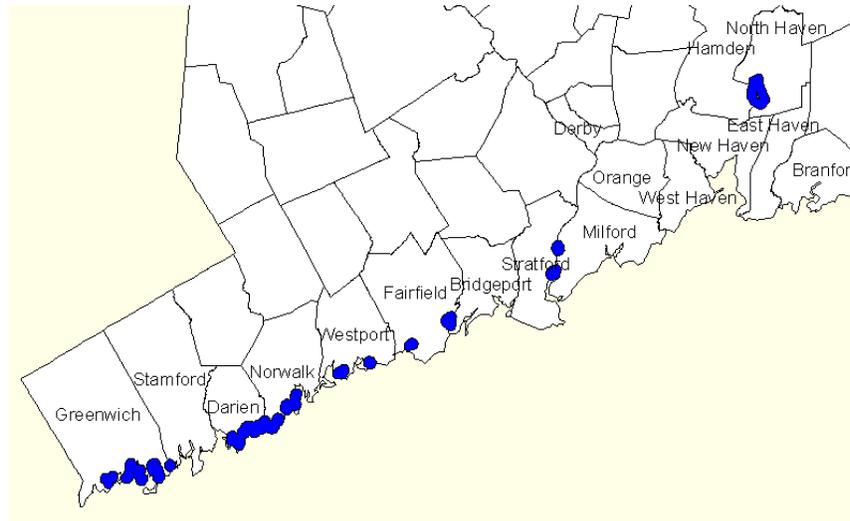


Figure 1. Distribution of subsiding tidal wetlands in CT based on aerial photography (source: R. Rozsa).

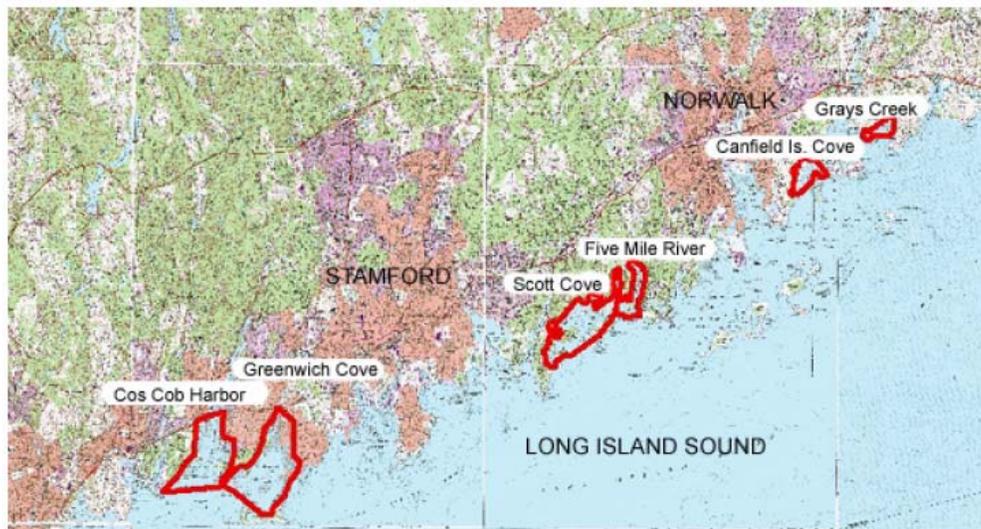


Figure 2. Estuaries in southwestern CT where Tiner et al. estimated marsh loss rates by analysis of aerial photography (source: Tiner et al. 2006).

In addition, cases of “sudden marsh dieback” have been observed recently throughout New England. While many scientists consider this a different phenomenon than the long-term (decades-long) drowning discussed in this report, Smith (2006) has argued that marsh dieback on Cape Cod may in fact be due to drowning as a result of sea level rise.

The causes of marsh drowning are still not clear. LIS tide gauge data (e.g., from New London, CT, Figure 3) show little evidence for an acceleration in RSLR over the last 70 years. On the other hand, the mid-19th century acceleration in RSLR is well-documented, and some have argued that marsh systems are still responding to that change (Donnelly and Bertness 2001, R. Rozsa, pers. comm.). Still, current RSLR of $\sim 2.3 \text{ mm yr}^{-1}$ are not very high and it is hard to imagine that this rate of RSLR on its own would lead to extensive marsh drowning.

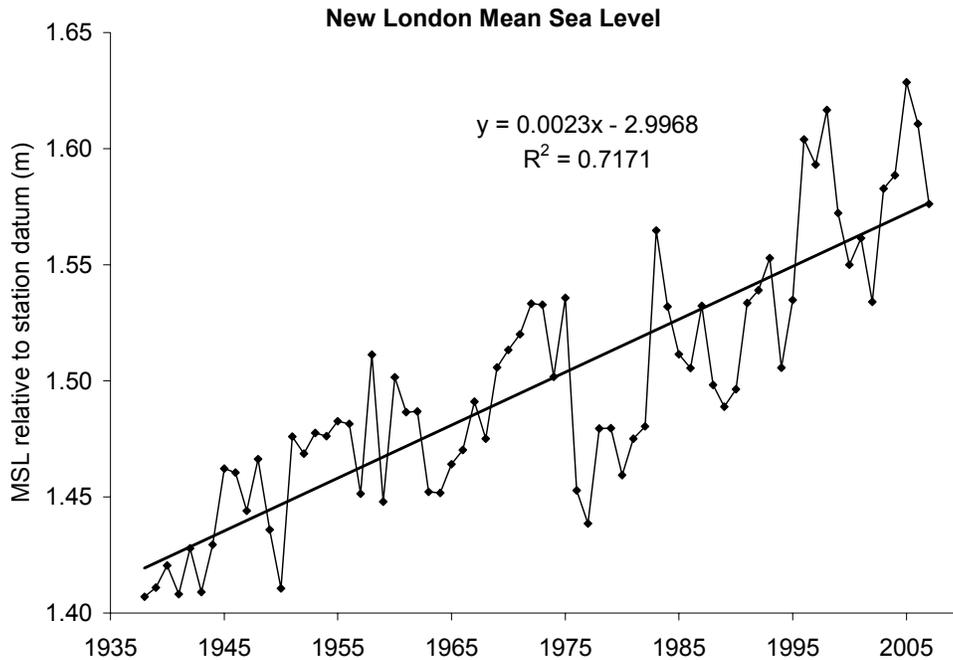


Figure 3. Mean sea level, 1938-2007, New London, CT, with linear fit. Data source: NOAA.

Analysis of the geographic distribution of marsh loss sites has revealed that many of these sites are “mid-sub-estuary,” which may reflect a greater susceptibility of these marshes to drowning, since they are often lower in the tidal range to start with and may also be sediment-deprived. Of perhaps greater significance is the fact that wetland loss has been observed in western, but not eastern, LIS (Figure 1). This is puzzling, since western LIS has a higher tidal range and would thus be expected to be less susceptible to drowning (due to the smaller change in hydroperiod for the same accretion deficit). RSLR rates do not appear to differ significantly between western and eastern LIS (e.g., Bridgeport tide gauge RSLR (1965-2007) = 2.4 mm yr^{-1} ; New London tide gauge RSLR over the same tide period = 2.8 mm yr^{-1}).

One possible stressor which probably does – at least in gross terms – co-vary with the observed patterns of wetland loss is nutrient loading, which is generally higher in western LIS.

The overall objective of this project is to assess the possible role of nutrient enrichment as a contributing force to marsh drowning in LIS.

1.1.2 Effects of nutrients on marsh processes

Several links between nutrient over-enrichment and wetland elevation loss can be hypothesized, though evidence to support them is scant. First, nitrogen (N) enrichment may

lead to a **decrease in belowground production**, with consequently lower accretion rates. Salt marsh macrophytes are N limited (except when they are limited by biochemical stressors like sulfide or salinity), so that N enrichment generally leads to an increase in aboveground primary production (e.g., Valiela and Teal 1974; Mendelsohn 1979), which could increase accretion rates (through higher litter inputs and greater trapping of tidal sediment). There is some evidence, however, that belowground primary production does not follow this same trend, and may indeed decrease, as plants shift energy away from root growth towards aboveground structures (Valiela et al. 1976). However, other fertilization studies suggest an increase in belowground primary production under high nutrient conditions (Morris and Bradley 1999).

Second, N or P enrichment may lead to **an increase in belowground decomposition**, leading to subsidence and wetland drowning. Given the well-known high N requirements of bacterial decomposers (Valiela et al. 1985; Benner et al. 1991), it would seem logical that increasing N availability would increase decomposition rates, either by increasing organic matter N concentrations (internal enrichment) and thus making the OM more palatable, or by increasing soil DIN concentrations (external enrichment) and thus providing adequate N for microbial growth. Indeed, several studies have shown higher decomposition rates for salt marsh grasses upon addition of N (Haines and Hanson 1979; Marinucci et al. 1983) or N and P (Valiela et al. 1985). Recent studies (Sundareshwar et al. 2003) have shown that the bacterial community in *Spartina alterniflora* salt marshes is actually P-limited, and others (Foote and Reynolds 1997) have suggested that higher P levels may be responsible for faster decomposition of *Spartina patens* shoots and leaves in litter bags. Results for other vegetation types (e.g., freshwater marshes) are mixed (e.g., Rybczyk et al. 1996; Qualls and Richardson 2000; Villar et al. 2001; Newman et al. 2001).

An additional effect of N load on decomposition rates may be relevant when the N is supplied in the form of NO_3^- , namely, a possible increase in OM loss through denitrification. In salt marshes, NO_3^- reduction is generally much less important than SO_4^{2-} reduction as a pathway for oxidation of OM (Howarth and Teal 1979; Kaplan et al. 1979). Still, quick calculations show that an additional annual increment of $30 \text{ mole NO}_3^- \text{ m}^{-2} \text{ yr}^{-1}$ could oxidize $450 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Stumm and Morgan 1981), a significant fraction of net primary production in most marshes.

To summarize, then, arguments could be made that the net effect of nutrient enrichment on sediment elevation is a positive one (through higher primary production) or a negative one (through faster decomposition and lower belowground primary production). In Louisiana, nutrient addition has been suggested as a way to combat marsh loss by increasing plant density in salt marsh dieback areas (Wilsey et al. 1992). Studies in subsiding forested wetlands in Louisiana have found that sites receiving nutrient-rich wastewater effluent had higher surface accretion rates (Rybczyk et al. 1998; Rybczyk et al. 2002). In South Carolina, a set of combined N/P fertilization experiments found that nutrient addition resulted in a net carbon loss from the sediment through an increase in decomposition that was greater than the apparent increase in belowground primary production (Morris and Bradley 1999). At the same time, however, fertilized sites showed a higher, not lower, rate of elevation gain, presumably because of greater aboveground primary production and consequent sediment trapping (Morris et al. 2002). These results from other systems are not directly applicable to LIS, where rates of primary production/decomposition and organic:inorganic ratios are different from more southern marshes.

1.1.3. Marsh restoration

Many marshes in LIS have experienced some form of tidal restriction, with negative effects on substrate, vegetation, and fauna. Recently, efforts have been made to restore tidal flow to many of these marshes, which often has resulted in successful restoration of vegetation and other aspects of ecosystem structure and function (Warren et al. 2002). However, when too much tidal flow is allowed back into the marsh, “restoration” can result in conversion to open water systems.

It is important to note that both drowning and restoration result in systems with high flooding frequencies and durations. In the face of the marsh drowning phenomenon, it is worthwhile to ask:

- Is there an increased risk of causing marsh drowning as a result of tidal flow restoration; or are restoring and drowning marshes fundamentally different in their trajectories, despite their similar hydroperiods?
- If drowning and restoring marshes are both wetter than typical marshes but are different in their trajectories, can we identify the differences between the systems that cause these different trajectories?

Although addressing these questions was not one of the objectives of our original proposal, we did add an aspect to our research that began to examine these issues.

1.2 Hypotheses

This report summarizes the research we carried out with funding from the EPA (Long Island Sound Study) to examine the following overall hypotheses:

- 1. Adding nutrients can result in marsh drowning as a result of increased decomposition and/or decreased belowground production.**
- 2. Drowning and restoring marshes are both wet systems, but are on different trajectories.**

More specifically, we tested the following hypotheses:

1. Adding N or P singly or in combination to salt marsh plots will lead to the following effects:
 - a. an increase in net aboveground primary production (NAPP)
 - b. a decrease in belowground primary production
 - c. an increase in sediment respiration
 - d. a decrease in belowground dead macro-organic matter and total belowground organic matter (due to the combination of b and c)
 - e. a decrease in accretion rate and net elevation change and a corresponding increase in hydroperiod.
2. Compared to a stable marsh, a drowning marsh will have:
 - a. greater flooding frequency and duration
 - b. lower rates of belowground primary production
 - c. higher rates of sediment respiration
 - d. lower rates of accretion and net elevation change
3. Compared to a stable marsh, a restoring marsh will have:
 - a. greater flooding frequency and duration
 - b. similar or higher rates of accretion and net elevation change

2. METHODS (ACTIVITIES AND ACCOMPLISHMENTS)

2.1 Study Sites

We carried out this research at 3 sites on the Connecticut coast in central and western Long Island Sound (Figure 4):

- Hoadley Creek: a stable marsh
- Jarvis Creek: a restoring marsh
- Sherwood Island: a drowning marsh.

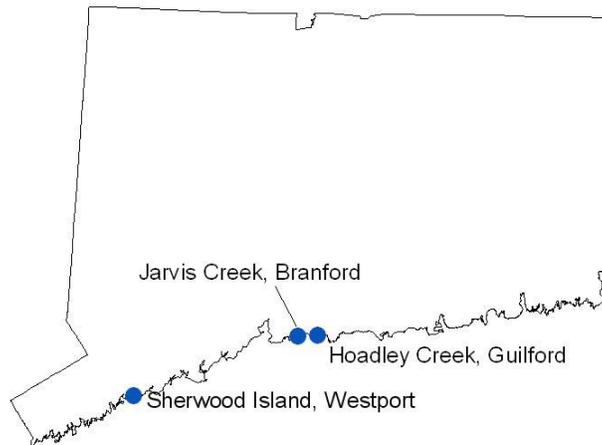


Figure 4. Location map for the three study sites.

Hoadley Creek (Figure 5) is a small, meandering marsh surrounded by upland. Despite mosquito ditching and a historic rock wall/dike, it is relatively undisturbed and has apparently undergone little change in the last 50 years or so. Our study area was seaward of the dike and close to the main tidal channel, so that flows were generally natural. Vegetation in this area consists of short *Spartina alterniflora* with some *S. patens* mixed in, and tall *S. alterniflora* along the tidal channel.

Until 1979, the upper part of **Jarvis Creek** (Figure 6) had significant flow restriction caused by a tide gate in the downstream railroad bridge; due to this restriction, the vegetation was dominated by *Phragmites australis*. In approximately 1979, the tide gate was removed (apparently accidentally in a storm) and fuller tidal flows were restored to this system. The *Phragmites* began to die back and by 2004 had been completely replaced by tall form *S. alterniflora*. The system still gives the impression of being fairly wet (see results for more details).

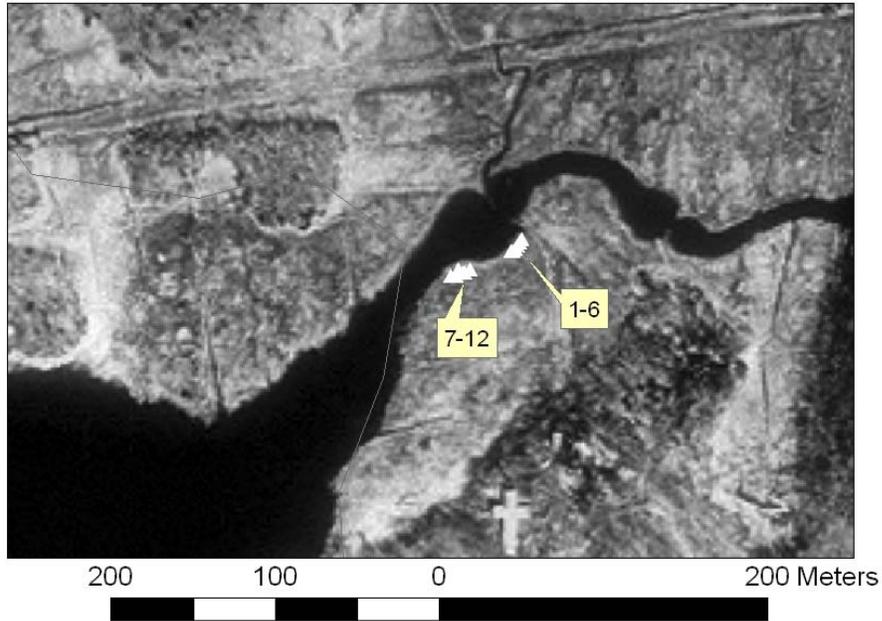


Figure 5. Hoadley Creek, showing plots and surroundings. Location: 41.262°N, 72.734°W. Image: 1990 orthophoto (USGS, 2000).

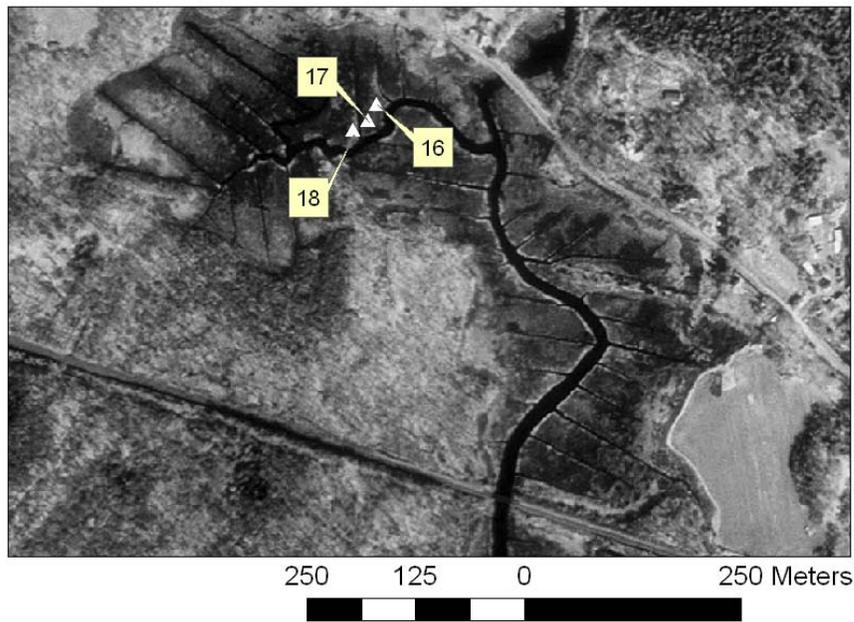


Figure 6. Jarvis Creek, showing plots and surroundings. Location: 41.271°N, 72.741°W. Image: 1990 orthophoto (USGS, 2000).

The **Sherwood Island** marshes, located at Sherwood Island State Park, exhibit classic symptoms of marsh drowning, with significant areas of marsh losing vegetation and being converted to mudflat (Figure 7). The vegetation in our study area is mostly *S. alterniflora*, with some *S. patens* mixed in. The marshes and the creek that feeds them (New Creek) have a complex hydrologic history, mostly related to the Sherwood Millpond at their western edge. Between 1800 and 1803, a stone dam was constructed at the seaward (eastern) end of New Creek, in order to channel more tidal flow through the sluice gates at the entrance of the Millpond. It is unknown when this dam was removed. Today the main tidal flow of New

Creek is through the eastern connection to LIS, though there is some flow under the Sherwood Island Connector to the Millpond. The Millpond sluice gates are now operated electronically, allowing the pond to drain only when low tide is at night.

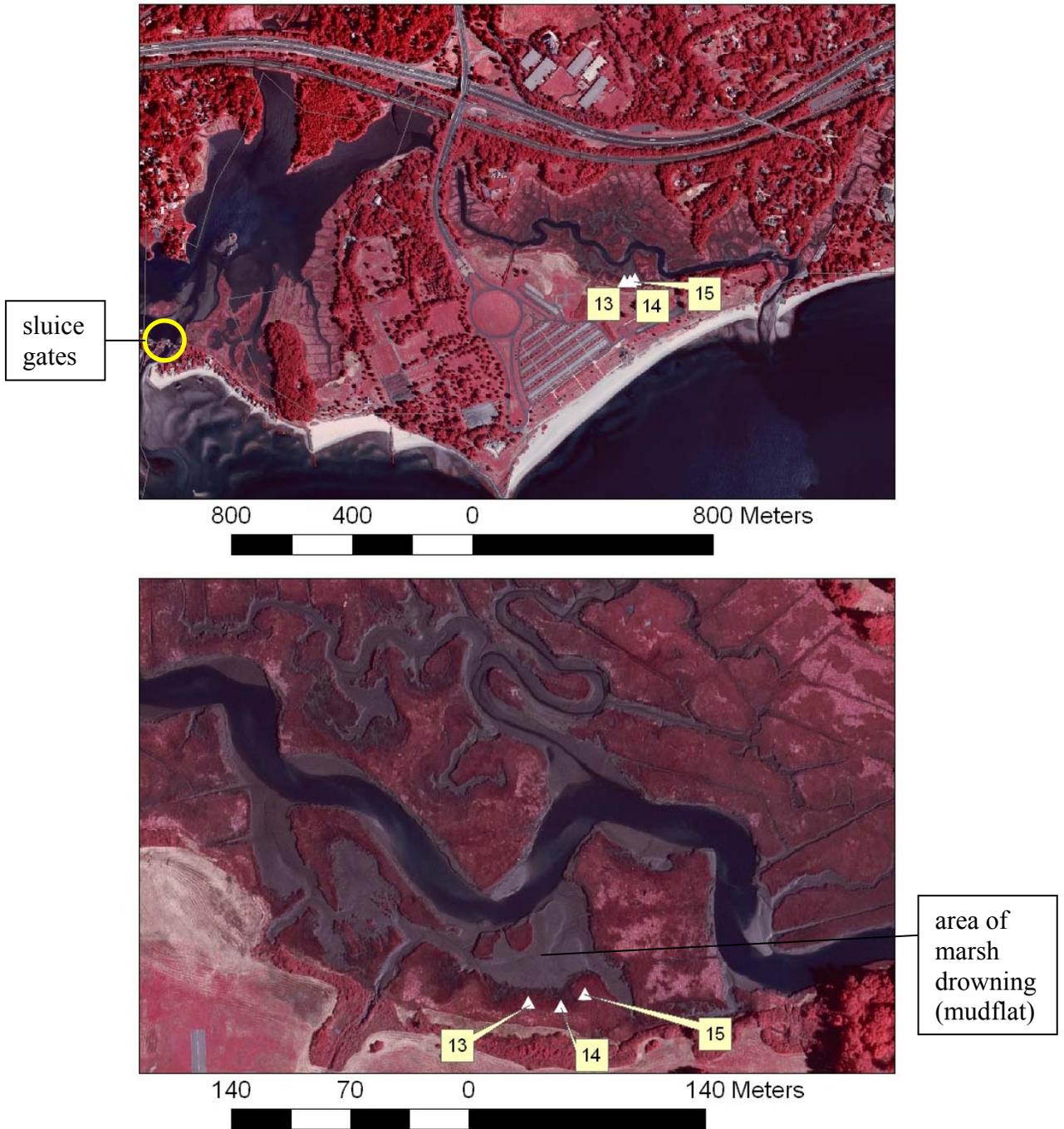


Figure 7. Sherwood Island, showing plots and surroundings, at two different scales. Location: 41.116°N, 73.325°W. Image: 2005 false color infrared photo (CT DEP).

2.2 Plot Layout

Our plot layout was designed to allow 2 types of comparisons:

- *inter-marsh comparison*: Comparing the control plots at Hoadley (stable marsh) with the plots at Sherwood (drowning) and Jarvis (restoring) allowed us to understand differences and similarities among these 3 marshes.
- *fertilization experiment*: Comparing the control plots at Hoadley with the fertilization plots allowed us to understand the role of nutrient addition in marsh processes.

Our sampling design involved 30 plots distributed over the 3 marshes discussed above. The plots at Hoadley are classified both by nutrient treatment (C, N, P, NP) and by hydrology (12 plots each in slightly higher and slightly lower parts of the marsh):

- Hoadley (reference marsh): 24 plots
 - high site: 12 plots (plots 1A-6B): 3 each of control (C), nitrogen addition (N), phosphorus addition (P), and nitrogen+phosphorus addition (NP)
 - low site: 12 plots (plots 7A-12B): 3 each of C, N, P, and NP
- Jarvis (restoring marsh): 3 plots (plots 16-18)
- Sherwood (drowning marsh): 3 plots (plots 13-15)

The locations of all plots are shown in Figures 5-7. At Hoadley, plots were arranged in a linear layout parallel to the main tidal channel; this meant that all plots were approximately the same distance from the channel edge (~2-3 meters) and that the direction of flow was perpendicular to the plot layout, so that exchange of water between plots was minimal. At Jarvis, the plots were distributed haphazardly through a representative section of marsh; all 3 plots were approximately the same distance from the tidal channel (~2 meters). At Sherwood, the plots were distributed haphazardly through a section of marsh bordering the developing mudflat; all 3 plots were approximately the same distance from the mudflat (~3 meters).

Sampling platforms were constructed at all sites to allow us to access the plots without stepping on the marsh surface. Sampling platforms were modeled on those described by USGS (<http://www.pwrc.usgs.gov/set/installation/Platforms.html>), and were installed shortly before installation of SET's (fall 2004 for Hoadley and Sherwood; spring 2005 for Jarvis). Each sampling platform consisted of 4 permanent teeth installed into the peat, along with 3 moveable light-weight aluminum planks (8 inches wide by 10 feet long) that were laid across the teeth to access all parts of the plot.

At Hoadley, an extensive boardwalk of permanent teeth and seasonally-permanent planks was constructed to run parallel to the tidal channel (landward of the plots), which allowed easy access to all plots without stepping on the marsh surface. The moveable planks were stored on the boardwalk and deployed onto the teeth for each plot only during sampling of that plot.

At Jarvis, access to the plots was by canoe. When plots were being sampled, the moveable planks (stored in New Haven) were brought to the marsh and deployed onto the teeth. Because of the need for transporting 3 large planks by canoe, sampling this site was more labor-intensive than the other sites. In addition, there was a narrow window of time to work in this

marsh, since at high tide, the plots were generally flooded (see below), while at low tide, extensive channel areas of exposed mud made accessing the plots extremely difficult.

At Sherwood, the plots were approached by walking through the marsh. When plots were being sampled, the moveable planks (stored in New Haven) were brought to the marsh and deployed onto the teeth.

Sediment elevation table (SET) benchmarks were installed for each plot, with the guidance and assistance of Jim Lynch of USGS. At Sherwood and Jarvis, each SET benchmark served one plot, for a total of 3 benchmarks at each marsh, while at Hoadley, each benchmark served 2 plots, for a total of 12 benchmarks. Information on benchmarks is shown in Table 1.

Table 1. Information on SET benchmarks.

Benchmark #	Plot numbers	Marsh	Date installed	Number of 4' survey rods used	Latitude (decimal degrees)	Longitude (decimal degrees)
1	1A, 1B	Hoadley	10/4/04	6.5	41.262517	-72.734333
2	2A, 2B	Hoadley	10/4/04	6.5	41.262500	-72.734350
3	3A, 3B	Hoadley	10/4/04	6.5	41.262483	-72.734367
4	4A, 4B	Hoadley	10/3/04	6.5	41.262467	-72.734383
5	5A, 5B	Hoadley	10/3/04	6.5	41.262450	-72.734400
6	6A, 6B	Hoadley	10/3/04	6.5	41.262450	-72.734417
7	7A, 7B	Hoadley	10/3/04	7.5	41.262350	-72.734717
8	8A, 8B	Hoadley	10/3/04	7.5	41.262333	-72.734750
9	9A, 9B	Hoadley	10/3/04	8	41.262333	-72.734767
10	10A, 10B	Hoadley	10/3/04	8	41.262350	-72.734800
11	11A, 11B	Hoadley	10/3/04	8 + 6" section	41.262317	-72.734817
12	12A, 12B	Hoadley	10/3/04	9	41.262317	-72.734850
13	13	Sherwood	10/4/04	6	41.116367	-73.325467
14	14	Sherwood	10/4/04	6	41.116350	-73.325233
15	15	Sherwood	10/4/04	6	41.116417	-73.325067
16	16	Jarvis	6/8/05	5	41.271483	-72.741400
17	17	Jarvis	6/8/05	6	41.271317	-72.741517
18	18	Jarvis	6/8/05	5	41.271217	-72.741717

At Jarvis and Sherwood, plots were approximately 2 meters by 2 meters centered on the SET benchmark (plot boundaries did not need to be defined precisely), while at Hoadley, each plot was 2 meters long by 0.85 meters wide, with the benchmark along one edge of the plot (see Figure 8). "A" and "B" plots at Hoadley (e.g., plots 1A and 1B) shared a boundary line, which was centered on the SET benchmark. Each pair of plots at Hoadley was separated from the adjacent pair (e.g., 1B was separated from 2A) by the space for the teeth/plank setup, or approximately 0.5m. After the field season of 2005, we became concerned over possible "leakage" of nutrients between plots sharing a boundary line, and we installed separators along these boundary lines in May 2006. These separators (0.062" thick plexiglass) were inserted into the peat to a depth of ~5-7 cm, leaving ~15cm emerging above the peat surface.

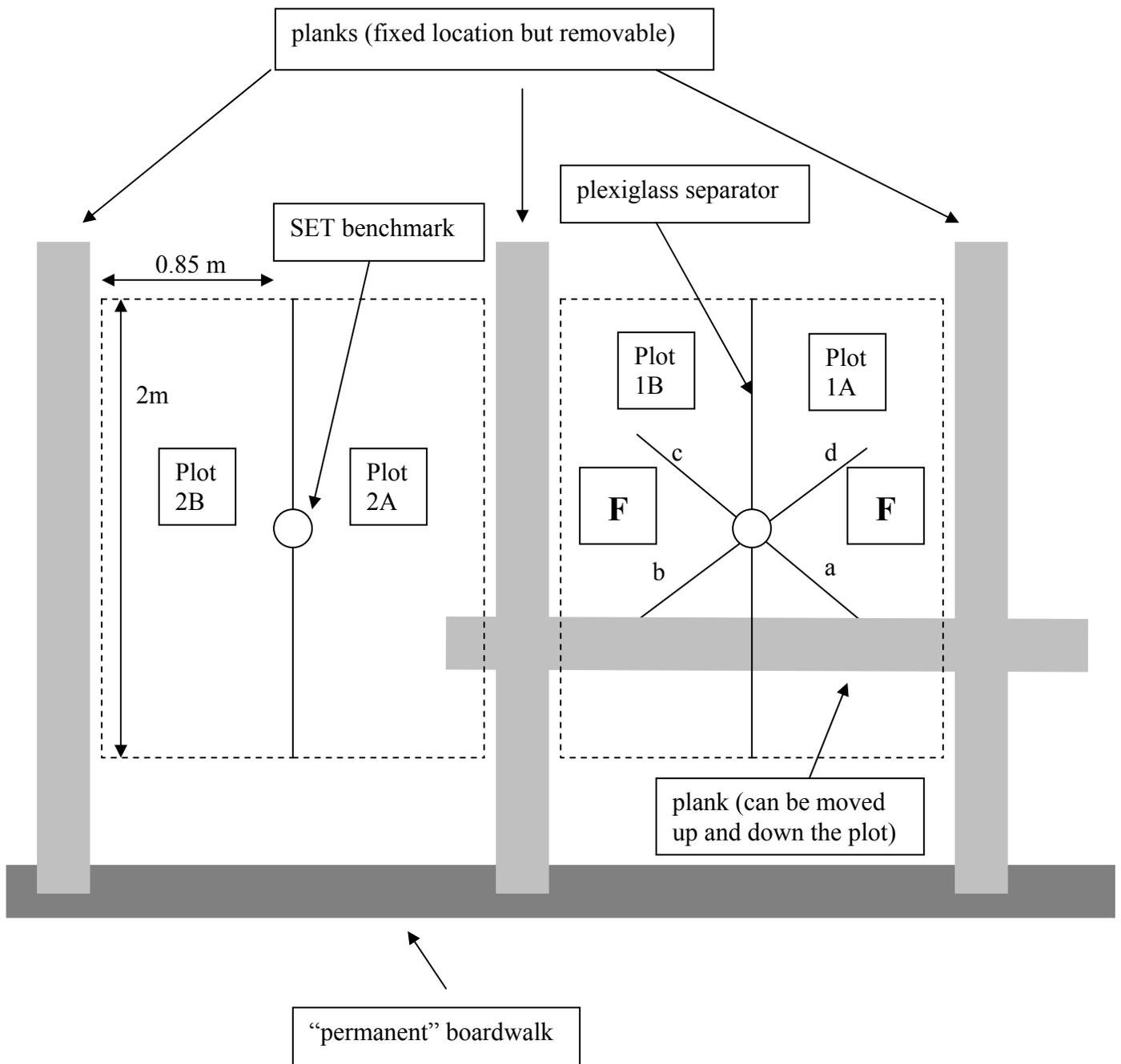


Figure 8. Layout of a representative section of the plots at Hoadley. The main tidal channel is parallel to the boardwalk, ~2m off the top of the picture. Letters (a) through (d) represent the 4 directions where SET readings were carried out. Boxes designated "F" indicate the location of the feldspar plots.

2.3 Fertilization

Within each of the 2 hydrologic regimes at Hoadley (“low” and “high”), the 12 plots were assigned randomly to the 4 treatments. The resulting plot arrangement is shown in Figure 9. Fertilizer amounts applied were as follows:

- C: control, no fertilizer application
- N:
 - 2005: ammonium nitrate applied at a rate of 30 mole N m⁻² yr⁻¹ (420 g N m⁻² yr⁻¹)
 - 2006 and 2007: ammonium nitrate applied at a rate of 15 mole N m⁻² yr⁻¹ (210 g N m⁻² yr⁻¹)
- P:
 - 2005: super triple phosphate¹ applied at a rate of 15 mole P m⁻² yr⁻¹ (465 g P m⁻² yr⁻¹)
 - 2006 and 2007: super triple phosphate applied at a rate of 3 mole P m⁻² yr⁻¹ (93 g P m⁻² yr⁻¹)
- NP: both N and P applied at the rates specified above.

In all 3 years of fertilization, the annual fertilizer amount was divided into 12 applications, done approximately semi-monthly from mid-April to mid-October. Fertilizer application was done on the falling tide after a neap tide, in an attempt to give the fertilizer as much time as possible to be absorbed before the next tide that would flood the marsh surface. To apply fertilizer to a plot, a portable PVC frame was placed over the plot to define more clearly the plot borders², and a pre-weighed bag of fertilizer was hand broadcast over the plot, taking care to distribute the fertilizer evenly.

12	12	11	11	10	10	9	9	8	8	7	7	gap of	6	6	5	5	4	4	3	3	2	2	1	1
B	A	B	A	B	A	B	A	B	A	B	A	~20m	B	A	B	A	B	A	B	A	B	A	B	A
C	NP	NP	N	N	P	N	P	C	NP	C	P		N	P	N	C	NP	P	NP	C	N	C	NP	P

Figure 9. Plot layout at Hoadley.

2.4 Porewater Sampling and Analysis

Porewater was collected from each plot 6-8 times during the summer and fall of 2005, and analyzed for salinity, sulfide, NH₄, NO₃, and PO₄. Samples were collected from simple PVC wells (1.5 inch diameter, 25 cm deep) installed at the beginning of the summer. Wells were pumped dry and allowed to refill before sample collection.

Samples for sulfide were filtered in the field (0.45 μm syringe filters) and preserved as ZnS precipitates by addition of Zn(OAc)₂ and NaOH. Upon return to the lab, samples were analyzed using the methylene blue method, using a freshly prepared calibration curve.

¹ 46g P₂O₅ per 100g fertilizer

² The PVC frame was not used in 2005.

Samples for salinity and nutrients were returned on ice to the lab, where they were measured for conductivity/salinity using an Oakton conductivity probe, filtered (0.45 µm filters) and frozen for later nutrient analysis. Nutrients were analyzed using an Astoria 2 flow analyzer. Due to problems with running samples of varying salinities on this instrument, precision of these measurements was not very good, with average coefficients of variation (CV's) of 18%, 31%, and 14%, respectively, for NH₄, NO₃, and PO₄ measurements.

2.5 Aboveground Productivity

Net aboveground primary production (NAPP) was measured for each plot using the peak standing crop method. Small quadrats were placed on the plot and all vegetation within the quadrat was clipped at the sediment surface, returned to the lab, rinsed with tap water followed by DI water, dried at 60-70 °C, and weighed. This was done as follows:

- 2005: 10 x 10 cm (0.01 m²) plots were clipped on 8/10/05 and 8/11/05 (Hoadley), 8/12/05 (Sherwood), and 8/17/05 (Jarvis)³
- 2006: 30 x 30 cm (0.09 m²) plots were clipped on 8/15/06 (Sherwood), 8/16/06 (Hoadley), and 8/17/06 (Jarvis).
- 2007: 20 x 20 cm (0.04 m²) plots were clipped on 8/14/07 (Jarvis and some of the Hoadley plots), 8/15/07 (Sherwood), and 8/23/07 (the remainder of the Hoadley plots). The number of stems and the height of the tallest 3 stems in each plot were recorded.

The majority of vegetation in each plot was live *Spartina alterniflora*. Occasionally, there were significant amounts of dead material or of *Spartina patens*; these were collected and weighed separately.

2.6 Belowground Biomass and Productivity

In order to understand the contributions of belowground material to marsh elevation, we carried out several types of measurements.

2.6.1 Coring

Cores (0-25cm) were collected with a Russian peat corer, as follows:

- 2005: Cores were collected in each vegetation clip plot on the same dates as aboveground harvesting (see above).
- 2006: Cores were collected in 18 plots (all plots except for Hoadley plots 7A-12B) on 6/1/06 (Hoadley), 6/13/06 (Jarvis), and 6/20/06 (Sherwood). These cores were used for decomposition experiments, as described below.

Cores were returned whole to the lab, weighed, and wet-sieved through a 1 mm sieve. The sieve-retained material (macro-organic matter, MOM) was dried at 60 °C and weighed, while the sieve-passing material (mud, along with all the water used to perform the sieving) was dried at 80 °C and weighed.⁴

³ At Jarvis, because of the obvious patchiness of the vegetation, larger (0.08 m²) clip plots were used in addition to the smaller plots.

⁴ Since the 2006 samples were subsequently to be used for decomposition experiments, MOM was actually dried at 40 °C, with a subsample dried to 60°C, and mud was dried only to a smooth consistency, with a subsample dried to 80°C. All weights are reported as corrected to dry weight at 60°C (MOM) and 80°C (mud).

2.6.2 Ingrowth Measurements

Due to the difficulty of distinguishing live and dead belowground material, we decided to measure belowground productivity using ingrowth chambers. Our first attempt involved ingrowth bags placed into the marsh peat in August of 2005. The bags were constructed from onion bag netting (3 mm nylon mesh) sewn into tubes using fishing line. On the day of core extraction at each plot (see above), ingrowth bags were partially filled with sieved mud (<1mm), placed into the holes created by core extraction, and then completely filled with sieved mud. These bags were collected in August of 2006 (on the dates of NAPP measurements), weighed, and sieved. The MOM was dried and weighed. However, this method suffered from difficulties associated with the lack of rigidity and poorly-defined sampling volume of the bags: when the bags were extracted, it was clear that there was great variability in the amount of sediment that each bag retained. We consider the ingrowth rates sampled by these bags to be unreliable and do not present these data, although we do present C and N content of this belowground material.

Our second, more successful attempt to measure ingrowth utilized rigid chambers constructed of ~5cm diameter PVC piping. Most of the PVC material was cut out from the piping and replaced with nylon mesh. This permitted the chamber to retain its rigidity, but still allowed for unimpeded ingrowth. Chambers were filled with sieved peat and deployed from April to October of 2007. Chambers were extracted by cutting around each with a saw and pulling out of the sediment. Chamber contents were sieved and MOM was dried at 60 °C.⁵ Four plots received duplicate chambers. The CV's of these duplicate measurements of belowground production ranged from 0.4% to 33% (average = 11%), with 3 of the 4 duplicates having CV's less than 10%.

2.7 Aboveground and Belowground Nutrient and Metal Content

Aboveground and belowground material retrieved from the marsh plots was generally dried, ground, and analyzed for carbon and nitrogen content using a LECO CNS analyzer. Lab replicates were analyzed at a frequency of ~10%, and almost always had a coefficient of variation (CV) of <5%.

Aboveground and belowground material from 2005 was also sent to SGS Inc. for analysis of phosphorus and metals by aqua regia digestion followed by ICP. This is a partial digestion, and is not expected to release silicate-bound elements. The elements analyzed are shown in Table 2, along with the percent recovery for each element (based on an estuarine sediment standard). Lab replicates were analyzed at a frequency of 11 out of 54 (20%), with an average CV over all analytes of 4.2%.

⁵ Because this material was subsequently to be used for decomposition experiments, MOM was actually dried at 40 °C, with a subsample dried to 60°C; all weights are reported as corrected to dry weight at 60°C.

Table 2. Elements analyzed and recoveries for an estuarine sediment standard. Aqua regia digestion is expected to be a partial digestion.

Ag	Al	As	Ba	Be	Bi	Ca	Cd	Co	Cr	Cu
NA	23%	75%	7%	NA	NA	62%	NA	67%	49%	97%
Fe	K	La	Li	Mg	Mn	Mo	Na	Ni	P	Pb
73%	23%	57%	59%	71%	47%	56%	65%	84%	111%	63%
Sb	Sc	Sn	Sr	Ti	V	W	Y	Zn	Zr	
NA	30%	NA	27%	4%	39%	NA	NA	67%	NA	

2.8 Decomposition and Respiration

2.8.1 Decomposition Experiments

Two types of decomposition experiments were carried out: *litterbag* experiments to determine rates of MOM decomposition; and *mud tube* experiments to determine rates of micro-organic matter decomposition. All decomposition experiments were carried out on 18 of the plots (all plots except 7A-12B at Hoadley).

Litterbags (5 x 7 cm) were constructed from fiberglass mesh window screen (~1 mm x 1.5 mm), sewed closed with nylon thread. For each plot, 8 litterbags were prepared, each using ~1/9th of the MOM material collected from that plot in June 2006. The 9th portion was reserved for correction of wet to dry weights, and for measurement of initial C and N content. The dry mass in each litterbag ranged from 0.17g to 0.76g.

Mud tubes were constructed from a short length (2.5 cm) of LDPE tubing (5/8" diameter) with SpectraMesh polyester screening (21 µm) on one end. Tubes were filled with mud (dried to a moist consistency) and sealed with SpectraMesh screening. For each plot, 8 tubes were prepared, each containing dry weight equivalent of 1.1 to 2.5g. Additional material was reserved for correction of wet to dry weights, and for measurement of initial C and N content.

Litterbags and mud tubes were deployed July 8-11, 2006⁶, by placing them into the holes created during core extraction. Holes were partially filled with mud, followed by tubes (approximate depth 15-20cm), followed by litterbags (approximate depth 10-15 cm), followed by additional mud.

Litterbags and tubes were retrieved after ~1 month (8/15/06 – 8/17/06⁷), ~3 months (10/14/06-10/16/06⁸), and ~1 year (7/17/07-7/24/07⁹). After retrieval, litterbags were returned to the lab, washed gently, dried at 60 °C, and weighed to determine loss of material through decomposition. CN analysis was also carried out on this material. During the third retrieval period, we found extensive ingrowth of roots and rhizomes into the bags; this was confirmed in the lab by surprisingly high weights. We consider these data to be unreliable, and only report data from the first two retrieval periods.

⁶ Hoadley: July 8; Sherwood: July 10; Jarvis: July 11

⁷ Sherwood: Aug. 15; Hoadley: Aug. 16; Jarvis: Aug. 17

⁸ Hoadley and Jarvis: Oct. 14; Sherwood: Oct. 16

⁹ Hoadley and Jarvis: July 17; Sherwood: July 24

After retrieval, mud tubes were opened, and the mud was washed into a beaker, dried at 80 °C, and weighed. CN analysis was carried out to determine loss of micro-organic matter through decomposition.

2.8.2 Soil Respiration

Soil respiration was measured using a Li-COR 6200, a closed-dynamic-chamber system with an automated CO₂ analyzer (described by Norman et al. 1997). Data were collected from each plot in June, September, and October 2007.¹⁰ June data were collected using a Li-COR soil collar (10 cm diameter), which by necessity included several *Spartina alterniflora* culms. Because the plants were too large to fit into the respiration chamber, culms were cut and sealed with silicone sealant immediately prior to taking measurements. We believe these measurements correctly represent CO₂ fluxes as that point in time. However, measurements at the same sites in the following weeks made it clear that culm-cutting had perturbed the system and stimulated emission of labile organic matter belowground, which, after several days, artificially enhanced rates of CO₂ flux. We spent much of July and August devising ways to avoid this problem (see appendix for details). Ultimately, for the September and October readings, we used a 15 cm tall chamber composed of 3.75 cm diameter PVC, similar to a larger-scale community chamber described by Neubauer et al. (2000). The unit encompassed 6.28 cm² of sediment surface area, and this small size allowed deployment between culms, minimizing perturbation. Unfortunately, due to the difficulties we encountered in solving the chamber-size problem, we did not obtain respiration measurements for July and August.

In order to calculate annual CO₂ fluxes, we assumed that the June measurements were representative of fluxes for June, July, and August, while the September and October measurements represented fluxes for April, May, September and October. We assumed no CO₂ flux during November – March.

2.9 Accretion and Elevation Change (Feldspar and SET Measurements)

2.9.1 SET Measurement

For each benchmark, 4 of the 8 possible directions were chosen for reading, and were designated (a) through (d). At Hoadley, 2 of the 4 chosen directions were located in each of the 2 plots served by a given benchmark, with directions (a) and (d) located in plot A, while directions (b) and (c) were in plot B (see Figure 8).

The first (baseline) reading for each benchmark took place several weeks after installation. Subsequent readings took place one to two times per year. For the first one or two reading sessions, readings were done by students as well as by Shimon Anisfeld (the PI), but beginning in November 2005, only Anisfeld carried out readings, in order to ensure consistency in pin placement and reading.

Precision of SET readings was assessed through occasional replication of the entire process of arm-leveling, pin-setting, and reading. Of a total of 3056 individual pin readings carried out for this project, 414 of them were replicated (14%), with an average standard deviation (SD) of 1.4

¹⁰ Hoadley: June 6, Sep. 12-13, Oct. 6-7; Jarvis: June 7, Sep. 16, Oct. 2; Sherwood: June 3, Sep. 18, Oct. 4

mm. This compares favorably with the goal outlined in our QAPP of 5% replication with a SD of 3 mm.

2.9.2 Feldspar Plots

At the time of baseline SET reading, 2 marker horizon plots were established for each benchmark to allow for future assessment of surface sediment accretion rates. This was done by sprinkling feldspar by hand over the marsh surface in defined “feldspar plots” designated with corner stakes. Feldspar plots were 30 cm x 30 cm, and were generally located: between SET directions (a) and (d); and between SET directions (b) and (c), as shown for Hoadley in Figure 8. Note that for Jarvis and Sherwood, there were 2 feldspar plots per larger plot, while for Hoadley, there was only 1 feldspar plot per larger plot.

Feldspar plot sampling was generally done the same day as SET readings. Cryogenic sampling was done as described by USGS (<http://www.pwrc.usgs.gov/set/readmarkers.html>), and the height of sediment above the feldspar layer was recorded to the nearest mm. Multiple readings were taken on the same cryo-core, along different faces. When the first cryo-core did not yield a clean, readable face, a second cryo-core was taken. During some of the early SET readings, the feldspar plots still had visible feldspar at the surface on at least part of the plot, so feldspar sampling was not done.¹¹

2.10 Hydrology

In order to understand the tidal hydrology at each site, tide gauges were deployed in the main tidal channel at each marsh. Tide gauges were Global Water WL-15 or WL-16 water level loggers, and were set to record water level every 5 minutes. Due to variable deployment periods and instrument malfunction, the time period of good data from each marsh varies, as follows:

- Hoadley: 4/7/05-7/27/05; 8/12/05-11/9/06; 11/16/06-3/13/07
- Jarvis: 10/22/04-3/8/05; 9/14/05-10/7/05; 12/19/05-5/17/06; 6/20/06-3/13/07
- Sherwood: 5/12/05-3/8/06; 5/17/06-10/13/06

In order to relate these data to a longer time period, we downloaded tidal data from NOAA (http://www.tidesandcurrents.noaa.gov/olddata/data_retrieve.shtml?input_code=100111111vwl) for 2 sites: New Haven Harbor (ID 8465705) and Bridgeport (ID 8467150).

In addition, tide sticks (PVC stakes painted with a mixture of red food coloring and water-soluble glue) were deployed in each plot several times, which allowed us to calculate flooding frequencies and durations for each plot.

¹¹ Specifically, feldspar sampling was not done: during the second SET reading at Jarvis (10/7/05), the second SET reading at Hoadley (4/16/05), and the second and third SET readings at Sherwood (5/12/05 and 10/10/05). During the third SET reading at Hoadley (November 2005), feldspar sampling was done with a sharp knife (rather than cryogenically) and was carried out on Nov. 16, which was 2 weeks after the SET reading for plots 1-4 and on the same date as the SET reading for plots 5-8.

2.11 Statistics

All statistical tests were carried out using Minitab 15 and used a significance level of 0.05. For the inter-marsh comparison, we compared Hoadley control plots, Jarvis plots, and Sherwood plots, using a one-way ANOVA, with a Tukey's test used to evaluate pairwise differences. For the fertilization comparison, we compared P, N, NP, and C (control) plots at Hoadley using a one-way ANOVA, with a Dunnett's test used to determine whether fertilized plots were different from the control plots. There were no indications of differences between the "high" and "low" site at Hoadley, so data were combined across these 2 sites, except for the accretion, elevation change, and hydrology data shown in Sections 3.6 and 3.7.

For porewater data, we calculated means for each plot over the different dates sampled and compared those means using ANOVA as described above. For NH_4 , NO_3 , and PO_4 , a log transformation was first done on each value before taking the mean over time and carrying out an ANOVA.

3. RESULTS (SUMMARY OF FINDINGS)

3.1 Porewater

Porewater DIN was dominated by NH_4 , rather than NO_3 , for all plots (Figure 10). Plots receiving N fertilizer had very high concentrations of NH_4 , concentrations that were significantly higher than in control plots. Sherwood and Jarvis had lower NH_4 concentrations than Hoadley.

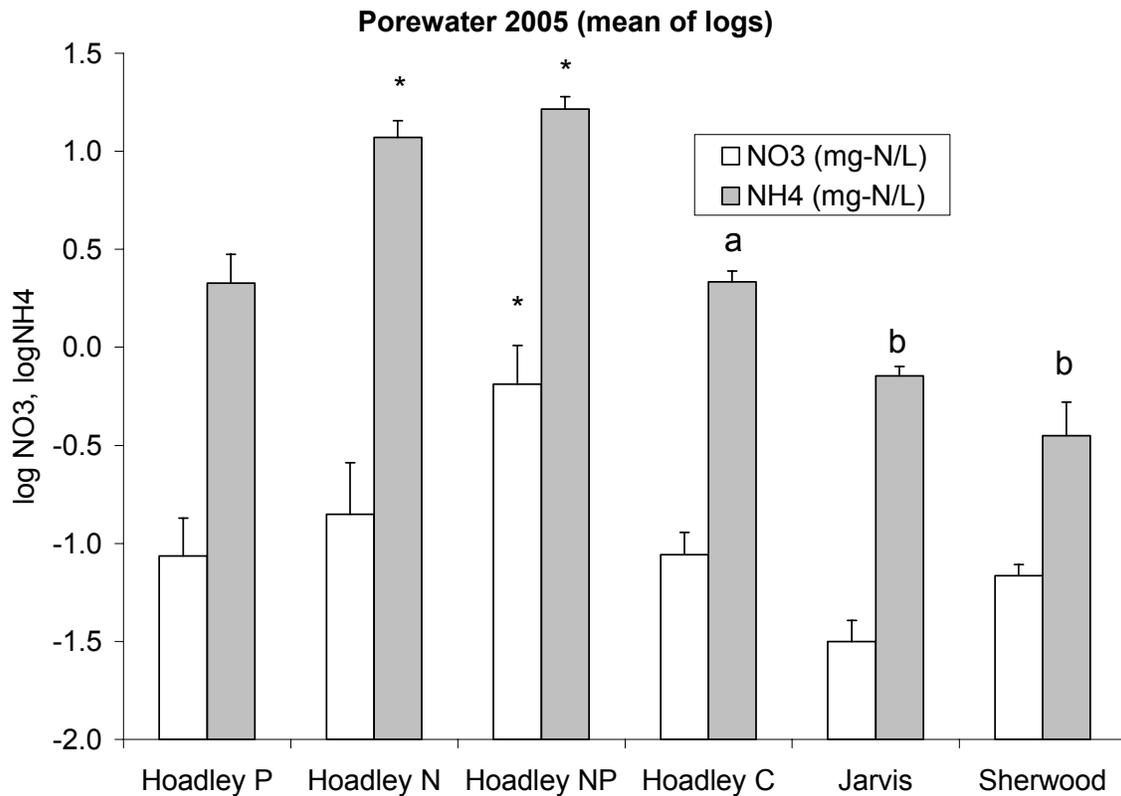


Figure 10. Log NO_3 and NH_4 concentrations for the three marshes and for the 4 nutrient treatments at Hoadley (P, N, NP, and control). Data for each plot type represent the mean (and standard error) of 3-6 plots; the data point for each plot is the mean of the log-transformed N concentration from 6-8 sampling dates over the summer and early fall of 2005. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

Similar patterns were found for PO_4 (Figure 11). Plots receiving P fertilizer had significantly higher concentrations of PO_4 than controls, and Sherwood and Jarvis had lower PO_4 concentrations than Hoadley.

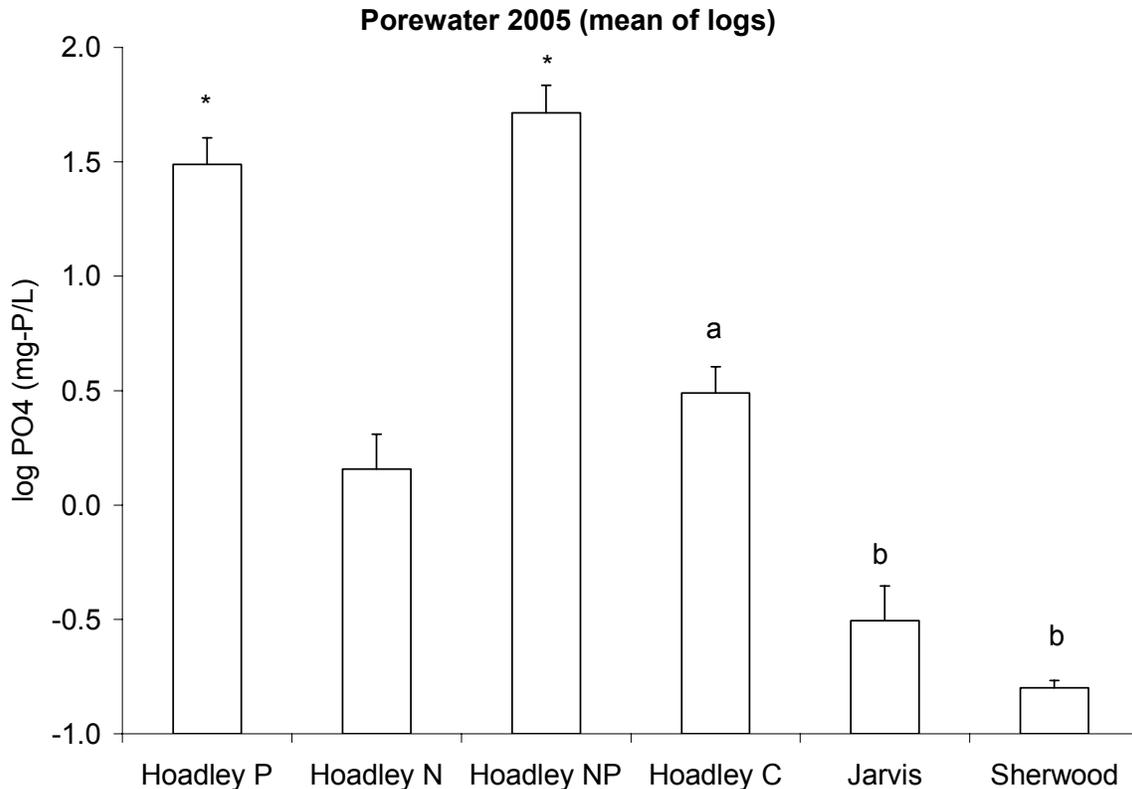


Figure 11. Log PO₄ concentrations for the three marshes and for the 4 nutrient treatments at Hoadley (P, N, NP, and control). Data for each plot type represent the mean (and standard error) of 3-6 plots; the data point for each plot is the mean of the log-transformed PO₄ concentration from 6-8 sampling dates over the summer and early fall of 2005. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

We believe that the nutrient concentrations measured in the control plots at Hoadley may reflect slight or occasional contamination with nutrients from adjacent plots. In other words, while the nutrient concentrations measured in the control plots are much lower than in the fertilized plots, we believe that they may not represent the conditions that would exist at this site in the absence of any fertilization activity. This may be due in part to the manner in which we collected pore water samples. By drawing the wells dry and then letting them refill, we were changing the hydraulic gradients and potentially drawing water across plot boundaries. For this reason, 2 changes were made beginning in 2006: porewater was no longer sampled; and barriers were put in place between plots, as described above.

The effectiveness of these measures in reducing cross-plot contamination is unknown. In any case, it is clear that even if the control plots were not entirely pristine, our fertilization treatments were effective in producing very different levels of N and P availability, as evidenced both by the porewater data shown here and by the data shown in sections 3.2 and 3.4.

Salinity did not differ among treatments at Hoadley, but was significantly lower at Sherwood and Jarvis compared to Hoadley (Figure 12). Sulfide levels were slightly reduced in the N fertilized plots and significantly reduced in the NP fertilized plots.

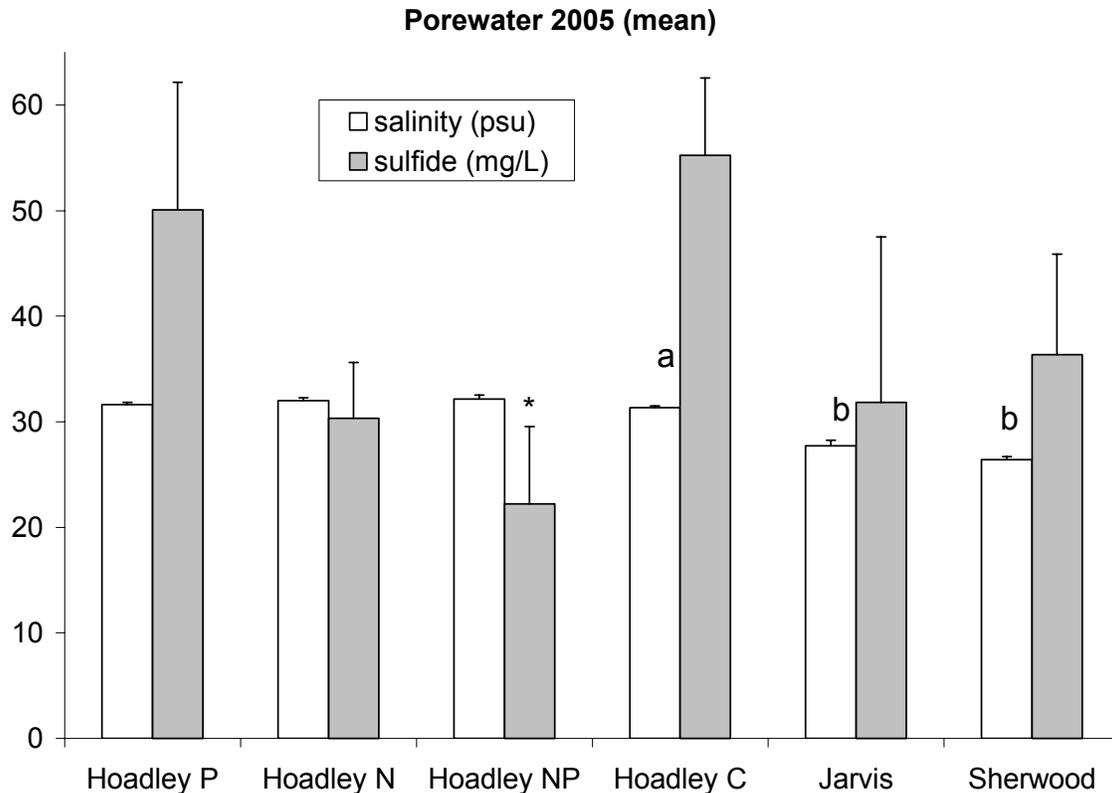


Figure 12. Salinity and sulfide concentrations for the three marshes and for the 4 nutrient treatments at Hoadley (P, N, NP, and control). Data for each plot type represent the mean (and standard error) of 3-6 plots; the data point for each plot is the mean of the salinity (or sulfide) from 6-8 sampling dates over the summer and early fall of 2005. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

3.2 Aboveground Productivity

NAPP measurements are shown in Figure 13. As expected, in the first year of fertilization (2005), productivity was significantly higher than the control in plots receiving N addition (with or without P), while P fertilization had no effect on productivity. This effect was also clear visually in the field, where the N-receiving plots could be identified by the visibly higher level of plant biomass.

The same visual effect of fertilization was found in 2006 and 2007 (Figures 14 and 15). In 2007, productivity measurements corroborated these differences, although the plots receiving only N were not statistically different from the controls, due to high variability. The 2006 data stand out as both being considerably lower overall than the other years, and showing no increase at all in productivity as a result of fertilization. In part, this may be an artifact of the small clip plots that we were using.¹² However, we also observed that parts of certain fertilized plots were unproductive in 2006 because of the high mass of dead material covering the

¹² Small clip plots (<0.1m²) were used because we did not want to interfere with the inputs of organic matter to any significant fraction of our plots, which have a total area of only 1.7 m².

sediment surface from the highly productive 2005 season. This led to patchy coverage of plants, with plants growing productively in the N-fertilized plots only where they were not smothered by dead material.

Jarvis and Sherwood were consistently more productive than the control plots at Hoadley, with the difference being statistically significant for Jarvis in 2005 and 2006 and for Sherwood in 2006.

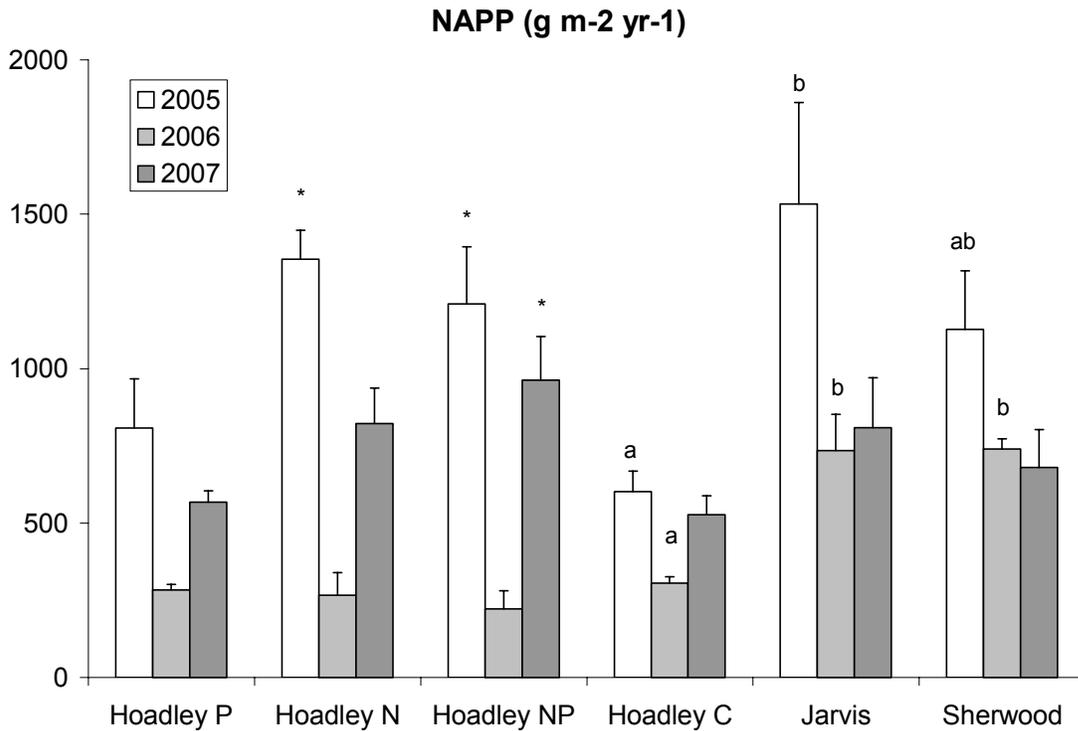


Figure 13. Net aboveground primary production for the three marshes and the 4 nutrient treatments at Hoadley (P, N, NP, and control). Data for each plot type represent the mean (and standard error) of 3-6 plots. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

Culm height and density data from 2007 (Figure 16) illustrate the mechanism by which N fertilization leads to higher productivity, namely by causing individual culms to grow significantly taller than culms in control plots. There is also a suggestion (though not statistically significant) of fewer culms in N-fertilized plots (consistent with the observations of patchiness mentioned above). Note also that the patterns of productivity at Jarvis and Sherwood are quite different, despite their similar overall NAPP: Jarvis has many fewer, but taller, culms than Sherwood.



Figure 14. View of a stretch of plots at Hoadley in summer 2007. This stretch (1B through 6B) consists of alternating N-fertilized (N and NP) and non-N fertilized (C and P) plots (see Figure 9), and the visual difference between the two types is striking (photo: Anisfeld).



Figure 15. Close-up of a N-fertilized plot (left) and a non-N-fertilized plot (right) in summer 2007. Line indicates the approximate boundary between the 2 plots (photo: Anisfeld).

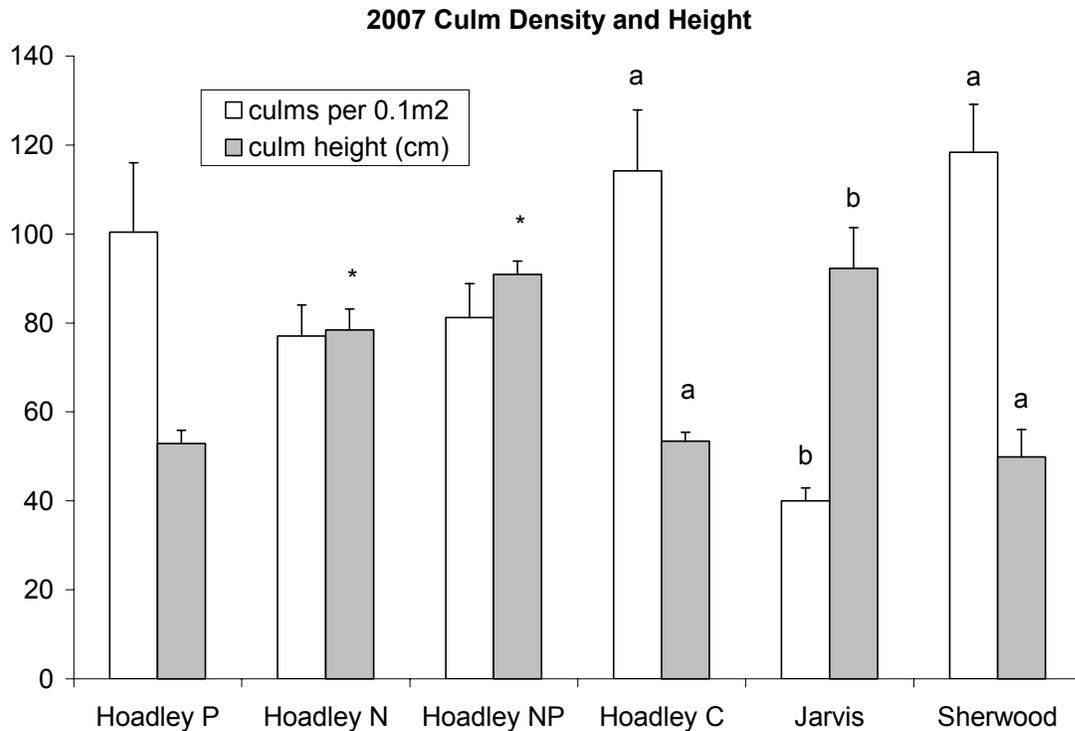


Figure 16. Density and height of culms in 2007 clip plots (mean and standard error). Height is average of tallest 3 culms; density includes all culms above 10 cm in height. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

3.3 Belowground Biomass and Productivity

Sieving of cores in 2005 and 2006 allowed us to separate below-ground material into 3 components: water; macro-organic matter (MOM; roots and rhizomes larger than 1 mm); and “mud” (sieved peat containing no MOM). These data (Figure 17) showed that the MOM content of the plots did not differ between control and fertilized plots, or between Hoadley and Sherwood. However, Jarvis had significantly lower MOM than the other sites (on the order of 4% of dry weight compared to ~12% of dry weight). This meant, of course, that Jarvis had significantly more mud than the other sites.

We converted MOM content from a percent-of-dry-weight basis to a mass-per-unit-area basis. To do this, we calculated the area sampled by each core, using the following assumptions¹³:

- the core area is equal to the core volume divided by 25 cm (the core height)
- the core volume is the sum of the volume of water, MOM, and mud
- the densities of water, MOM, and mud are, respectively, 1, 1.1, and 2.5 g cm⁻³.

By this measure, too, Jarvis was significantly lower in MOM inventory than the other sites (Figure 18).

¹³ We did not use the nominal sampling area of the Russian corer (11 cm²) for this calculation, since in practice, the corer does not cut a clean half-cylinder of consistent size.

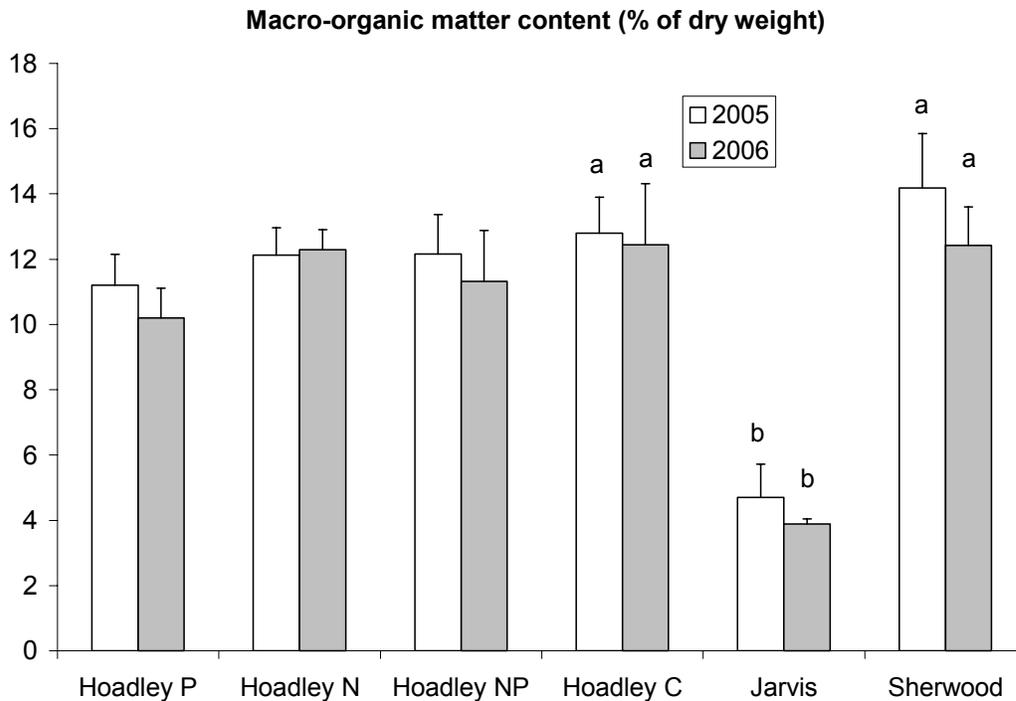


Figure 17. MOM content (mean and standard error) expressed as % of dry weight of all material (MOM+mud). N for 2005 is 30; n for 2006 is 18. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

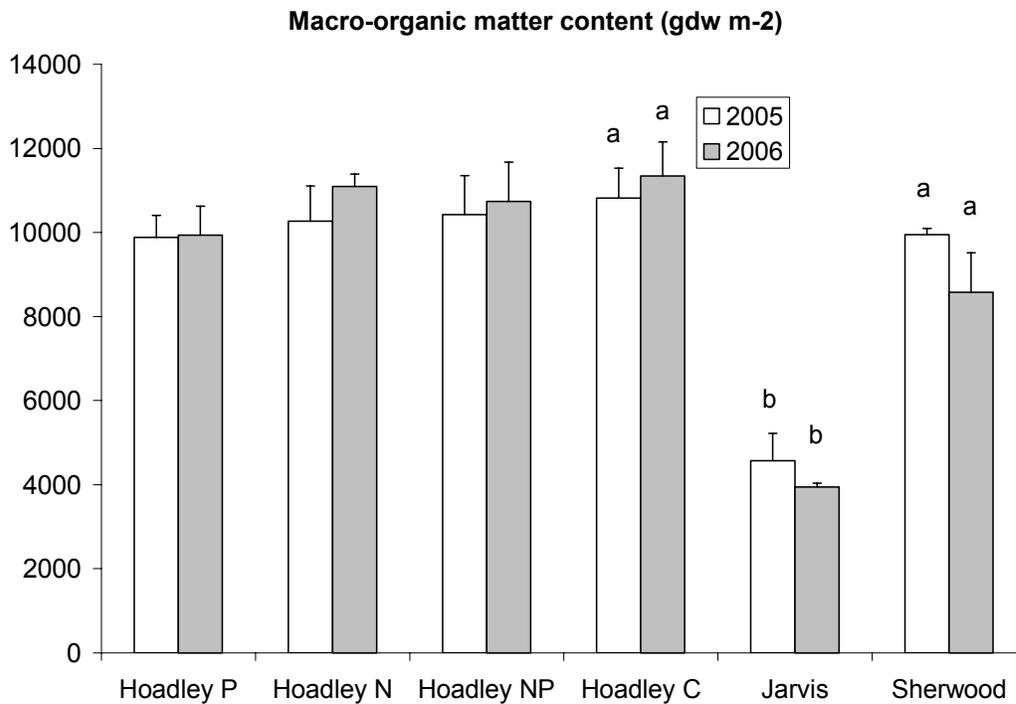


Figure 18. MOM content (mean and standard error) expressed as mass per unit area of marsh. N for 2005 is 30; n for 2006 is 18. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

Carbon content of the mud (MOM-free component) varied by site, but not by fertilization treatment (Figure 19). Sherwood was significantly higher in %C than Jarvis; values at Hoadley were generally intermediate between the other 2 sites.

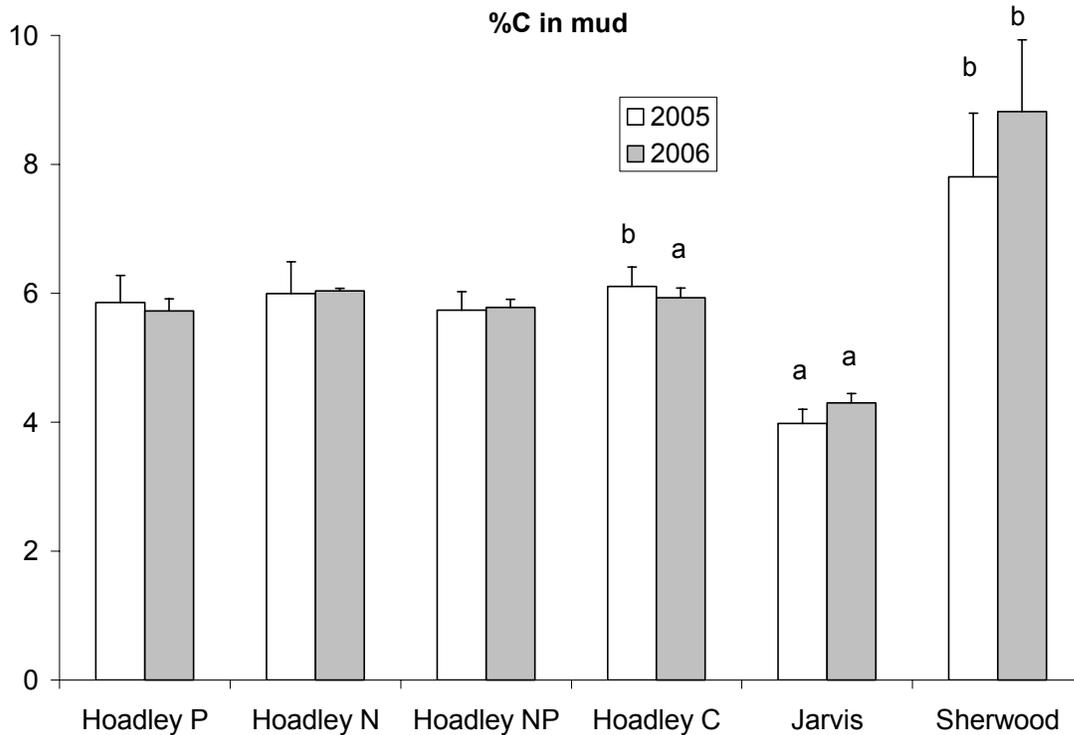


Figure 19. Percent carbon in mud (mean and standard error). N for 2005 is 30; n for 2006 is 18. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

We calculated total belowground organic matter by adding together the carbon content of the MOM and the carbon content of the mud and then converting from carbon to organic matter using a factor of 2 (Figure 20). Not surprisingly, given Jarvis' lower MOM content and lower carbon-in-mud percentage, Jarvis had significantly lower total organic matter in the top 25 cm than the other 2 marshes.

Data from our ingrowth chamber (Figure 21) showed that belowground productivity was higher than aboveground productivity at all sites in 2007. Belowground production was significantly higher at Hoadley than at Sherwood and Jarvis. There were no significant effects of fertilization on belowground production, although the fertilized plots showed a hint of a decrease in belowground production (average productivities at P and N (but not NP) plots were ~75% of controls).

We calculated turnover times for belowground MOM from the 2007 productivity data and the 2005/06 belowground biomass data. The average for all plots was 3.2 ± 0.3 years (mean \pm SE). There were no significant differences among sites, though Sherwood appeared to have a slightly longer turnover time than Jarvis and Hoadley.

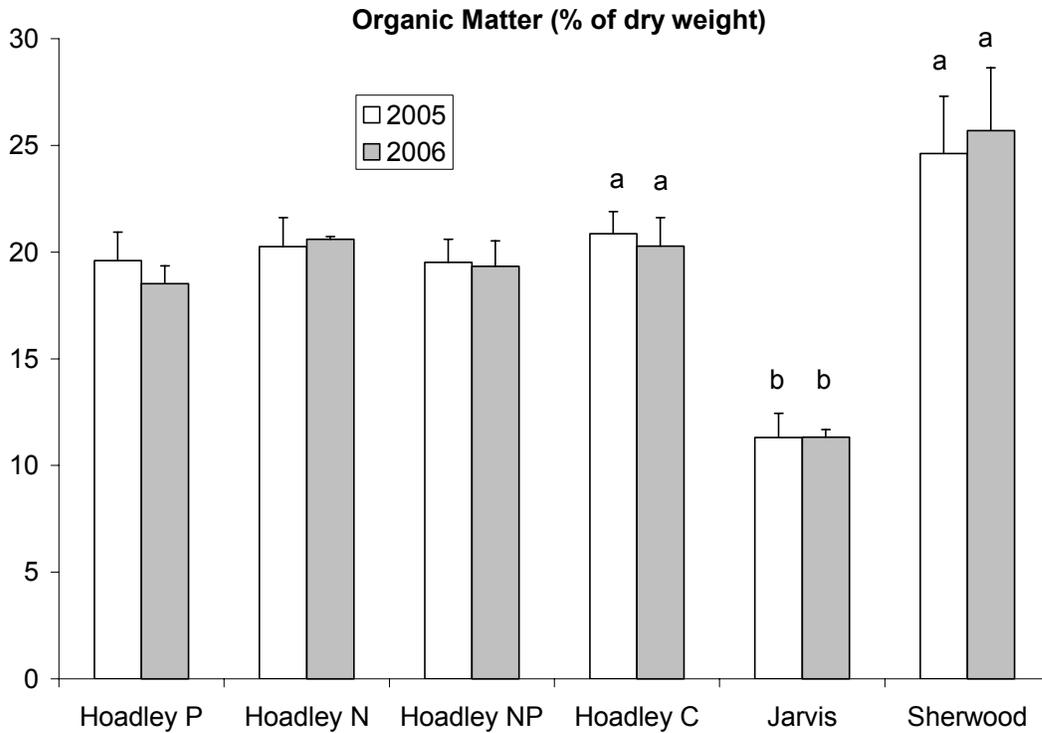


Figure 20. Total belowground organic matter content (mean and standard error). N for 2005 is 30; n for 2006 is 18. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

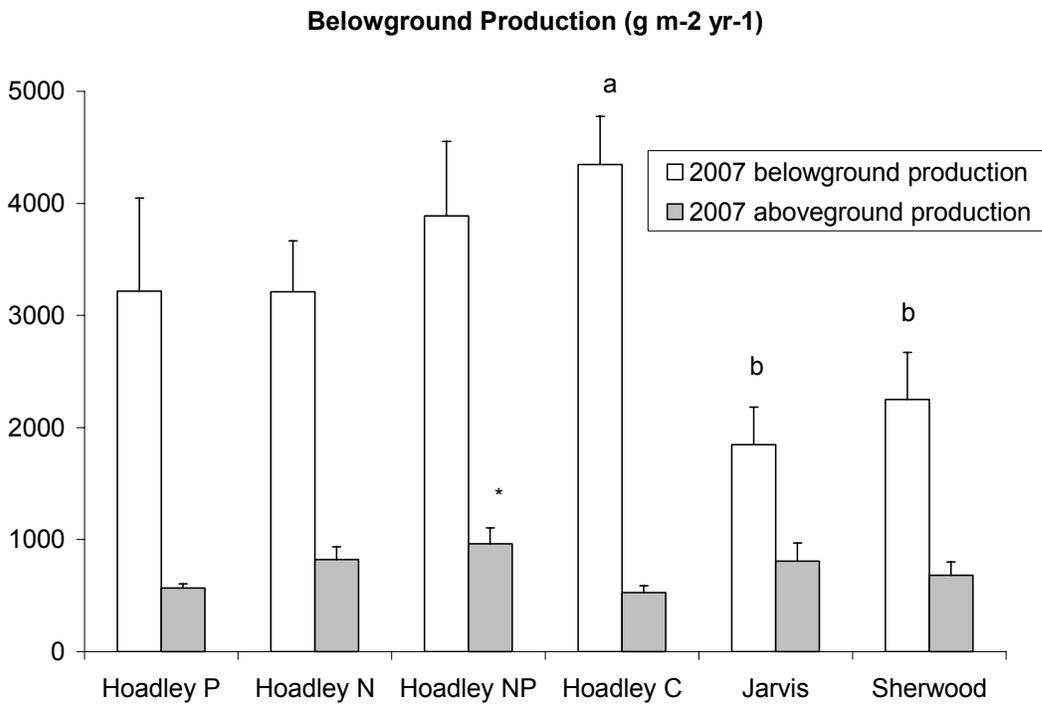


Figure 21. Belowground production (PVC ingrowth chamber method, mean and standard error) for 2007 (n=18). Also shown, for comparison, is aboveground production for 2007 (from Figure 13). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

3.4 Aboveground and Belowground Nutrient and Metal Content

Nitrogen concentrations in aboveground plant material were substantially higher in the N-fertilized plots compared to the controls (Figure 22). N concentrations were slightly higher at Hoadley (control plots) compared to Jarvis and Sherwood.

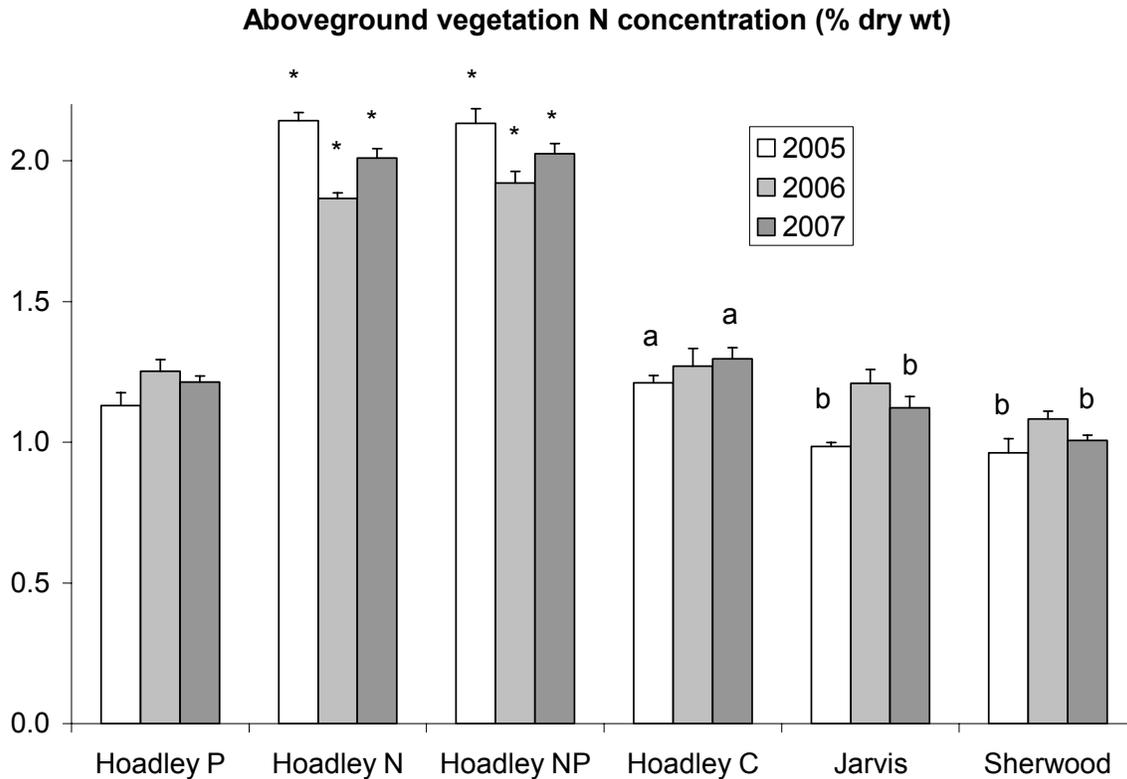


Figure 22. Nitrogen concentrations (% dry weight) in aboveground vegetation (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

Belowground N concentrations in MOM (Figure 23) were generally around 1% for all plots, but N-fertilized plots seemed to be slightly higher than controls (significant difference only for 2005, only for N (but not NP) plots), and Jarvis seemed to be slightly higher than Hoadley. N concentrations in mud were generally around 0.5%, with no patterns associated with fertilization, and with Sherwood showing slightly higher values than the other 2 marshes.

The belowground N concentration data shown in Figure 23 represents material that had accumulated over multiple years. In order to examine N levels in freshly produced material, we conducted CN analysis on freshly produced MOM from our ingrowth chambers in 2006 and 2007. These data are presented as C:N ratios (Figure 24), in order to avoid artifacts associated with different amounts of inorganic sediment still present on the washed MOM. Surprisingly, there were no significant differences in C:N ratio between N-fertilized and unfertilized plots, although N and NP plots were slightly lower in C:N ratio than P and C plots.

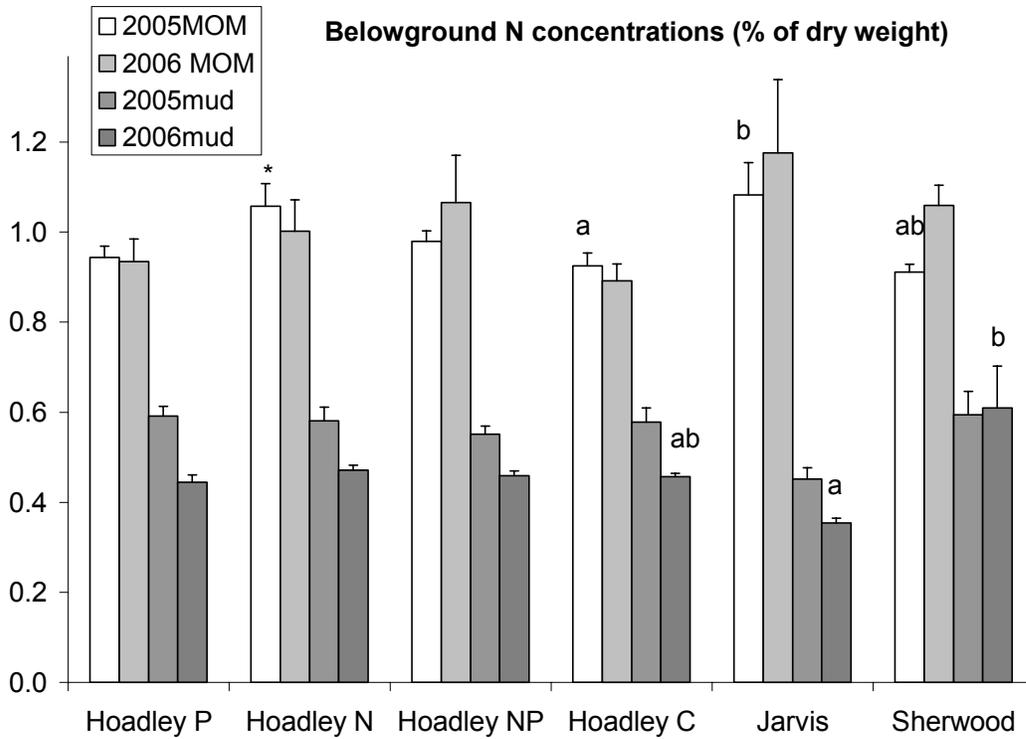


Figure 23. Nitrogen concentrations (% dry weight) in belowground macro-organic matter and mud (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

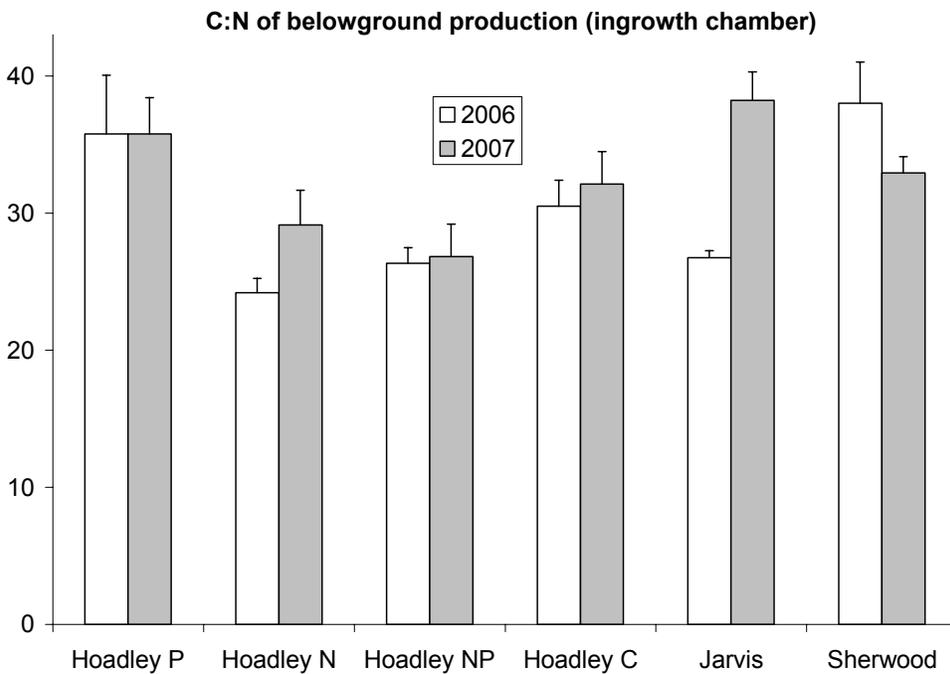


Figure 24. C:N ratios in belowground macro-organic matter growing into our ingrowth chambers (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

We combined our N concentration data with our aboveground and belowground biomass measurements to calculate the amount of N stored in different aboveground and belowground compartments (Figure 25). The N-fertilized plots, with their higher aboveground productivity and their higher aboveground N concentrations, had about 3 times the aboveground N content of control plots. However, the vast majority of N in all plots was belowground (mostly in the mud) and N-fertilized plots were no different from controls in total N stored.

For aboveground material, the N content shown in Figure 25 can also be interpreted as an annual N uptake rate (assuming one crop per year). For 2005, the difference in live biomass N uptake between control plots and plots receiving N fertilization was $\sim 17 \text{ g N m}^{-2} \text{ yr}^{-1}$, or $\sim 4\%$ of the N applied as fertilizer.

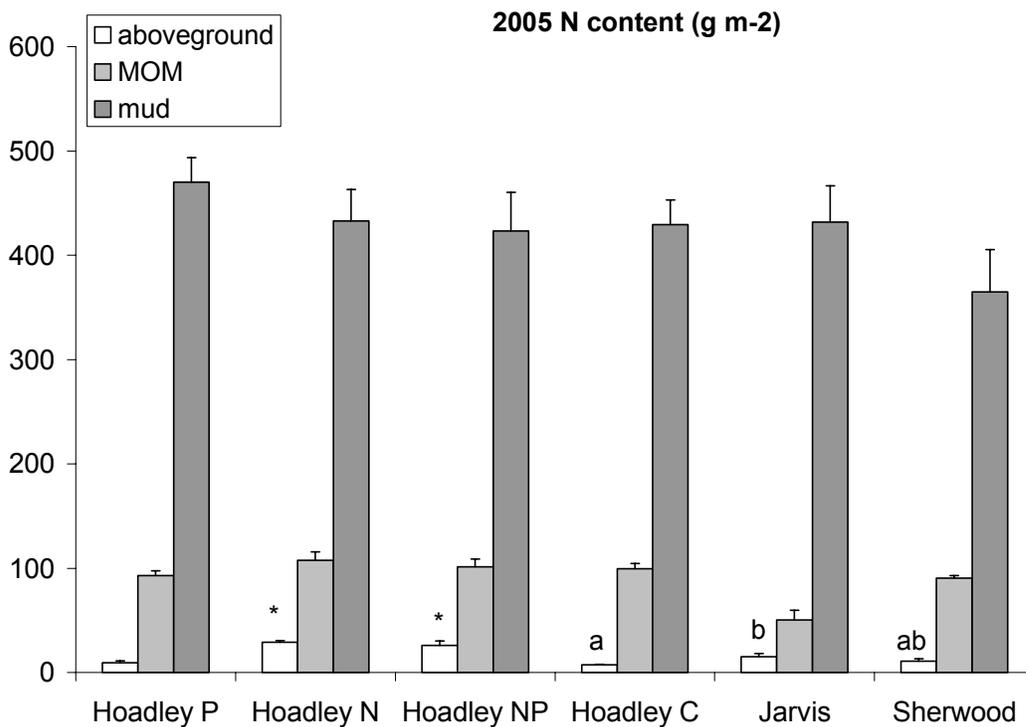


Figure 25. Nitrogen content (g m^{-2}) in aboveground vegetation, belowground vegetation, and mud in 2005 (mean and standard error). Data are similar for 2006 and 2007 (not shown). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control.

P concentration data are available only for the material collected in 2005 (Figure 26). Generally, P-fertilized plots seemed to have higher P concentrations than controls in aboveground vegetation, MOM, and mud, although the difference was only significant for: aboveground vegetation for NP plots; and mud for both P and NP fertilized plots. When P levels are expressed as mass per unit area (Figure 27), it becomes clear that the vast majority of the P is in the mud component, and that the P-fertilized plots contain roughly 3 times as much P as the controls. The difference in total belowground P content between fertilized and control plots is $\sim 160 \text{ g m}^{-2}$, or $\sim 35\%$ of the P applied as fertilizer.¹⁴

¹⁴ Since 2005 was the first year of fertilization, the entire difference in belowground P content can be attributed to that year's fertilization.

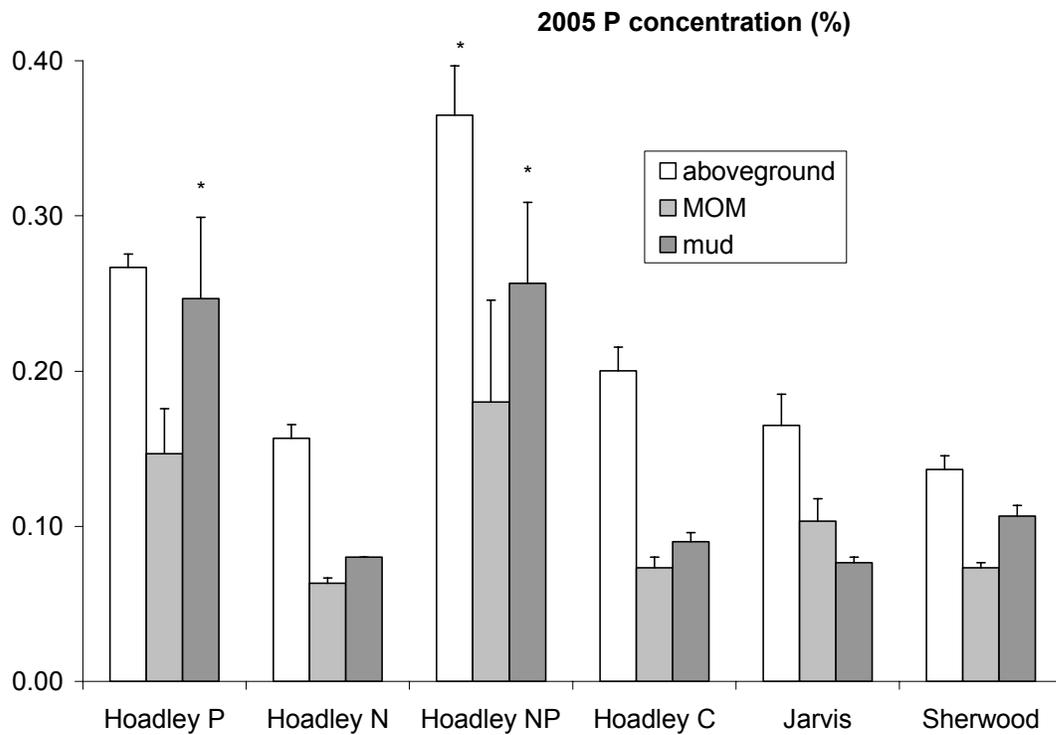


Figure 26. Phosphorus concentrations (% of dry weight) in aboveground vegetation, belowground vegetation, and mud in 2005 (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

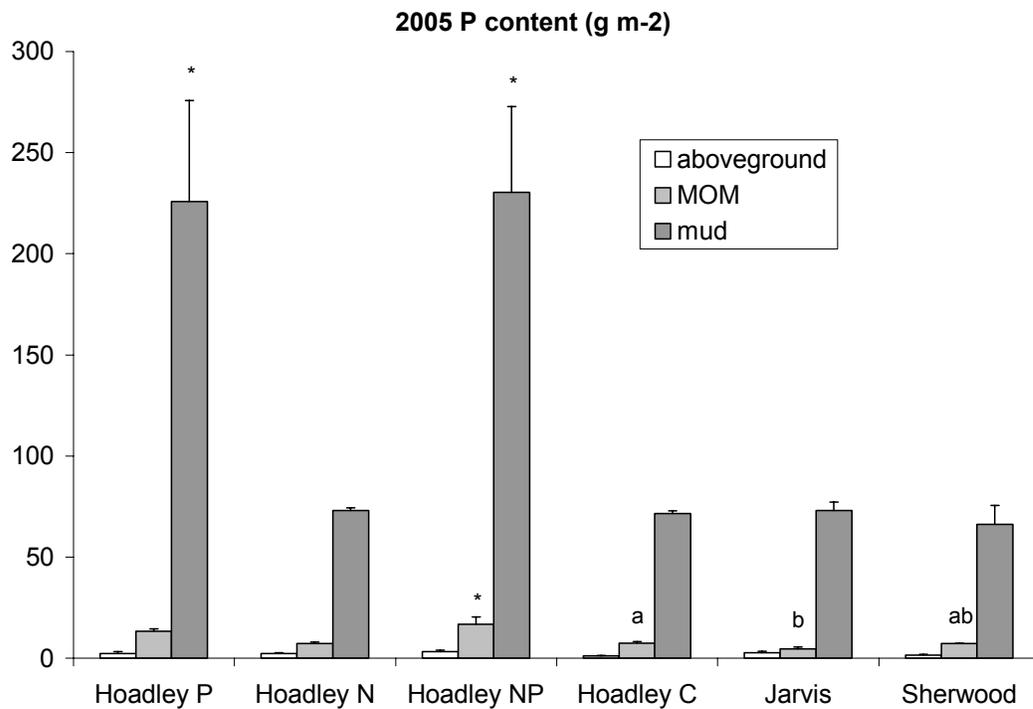


Figure 27. Phosphorus content (g m⁻²) in aboveground vegetation, belowground vegetation, and mud in 2005 (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

Data for lead and zinc in aboveground and belowground material are shown in Figures 28 and 29. Fertilization did not affect Pb and Zn concentrations or plant uptake, but there were some interesting differences among the sites. Most dramatically, Jarvis had much lower Pb concentrations in MOM despite concentrations in mud that were similar to the other sites. Aboveground plant material had very low Pb concentrations at all sites. Zinc, on the other hand, was found at relatively higher concentrations in aboveground material.

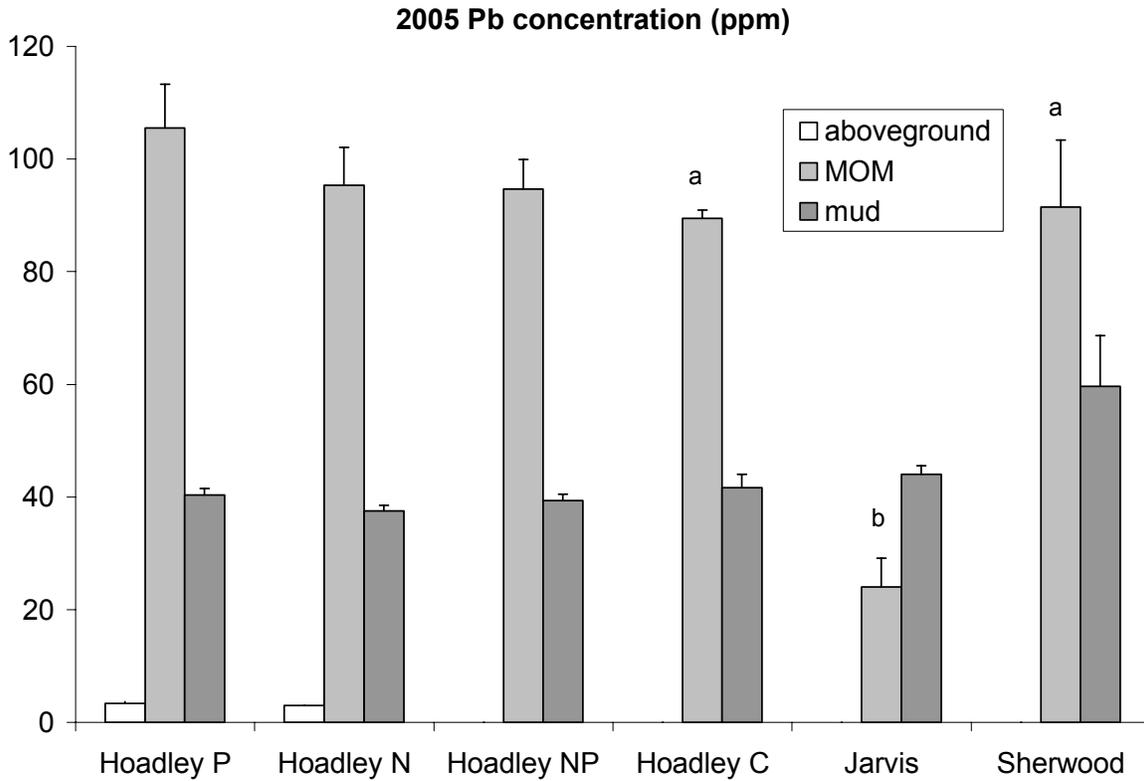


Figure 28. Lead concentrations (ppm dry weight) in aboveground vegetation, belowground vegetation, and mud in 2005 (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

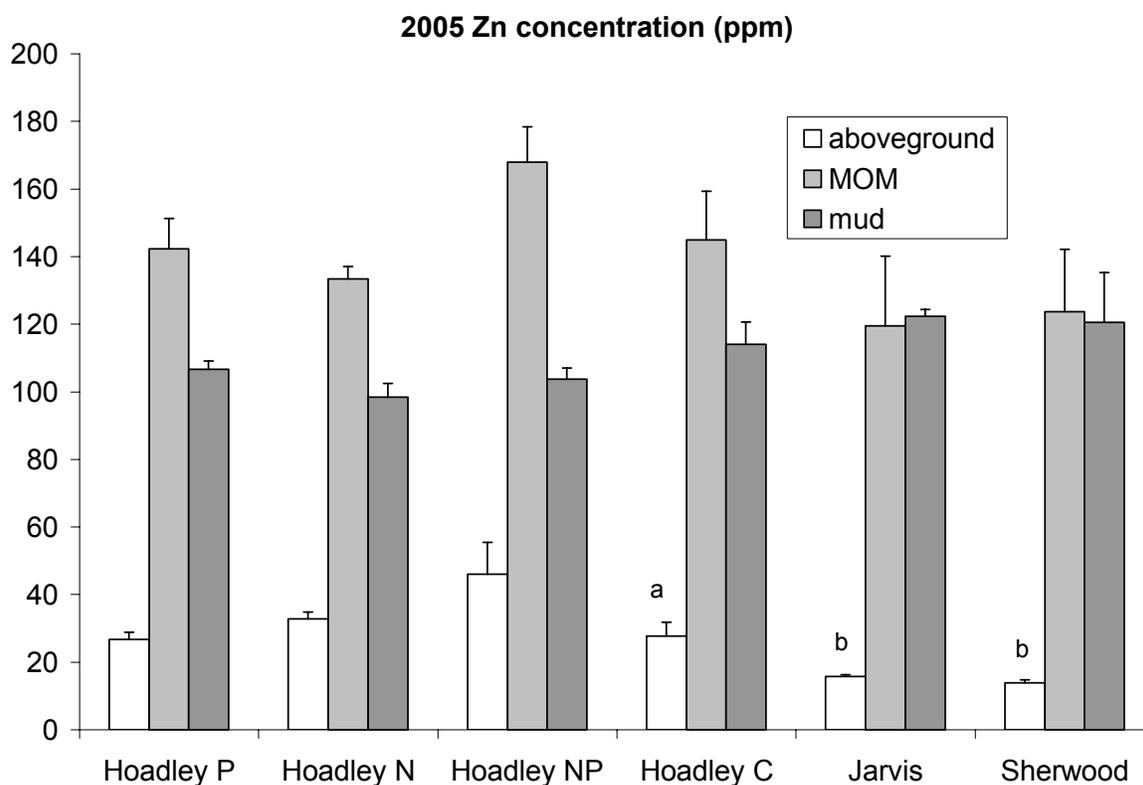


Figure 29. Zinc concentrations (ppm dry weight) in aboveground vegetation, belowground vegetation, and mud in 2005 (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

3.5 Decomposition and Respiration

Even after one year, mud tubes showed no decrease in %C or %N beyond the analytical uncertainty of the measurement, with all tubes from all time points showing a C and N content which was between 90 and 110% of the original value for that plot (data not shown). We conclude that there was no measurable decomposition of micro-organic matter over the span of one year.

Litter bags containing MOM did show measurable decomposition over the first 3 months of burial. Unfortunately, we do not have good data from beyond the first 3 months, since our 1-year data point was contaminated with ingrowth of root and rhizome material into the litter bags.¹⁵ The 3-month data (Figure 30) showed no significant effect of fertilization on decomposition rates. Decomposition rates at Hoadley seemed to be slightly lower than at Jarvis and Sherwood. Another interesting observation was that loss of nitrogen was consistently more rapid than bulk mass loss rates or carbon loss rates, as expected in early stages of decomposition.

¹⁵ This occurred despite the relatively fine mesh of the litter bags used (~1 mm). We attempted to remove recently grown material from the litter bags before weighing, but this proved impossible to do in a consistent manner.

Litter bag decomposition after 3 months

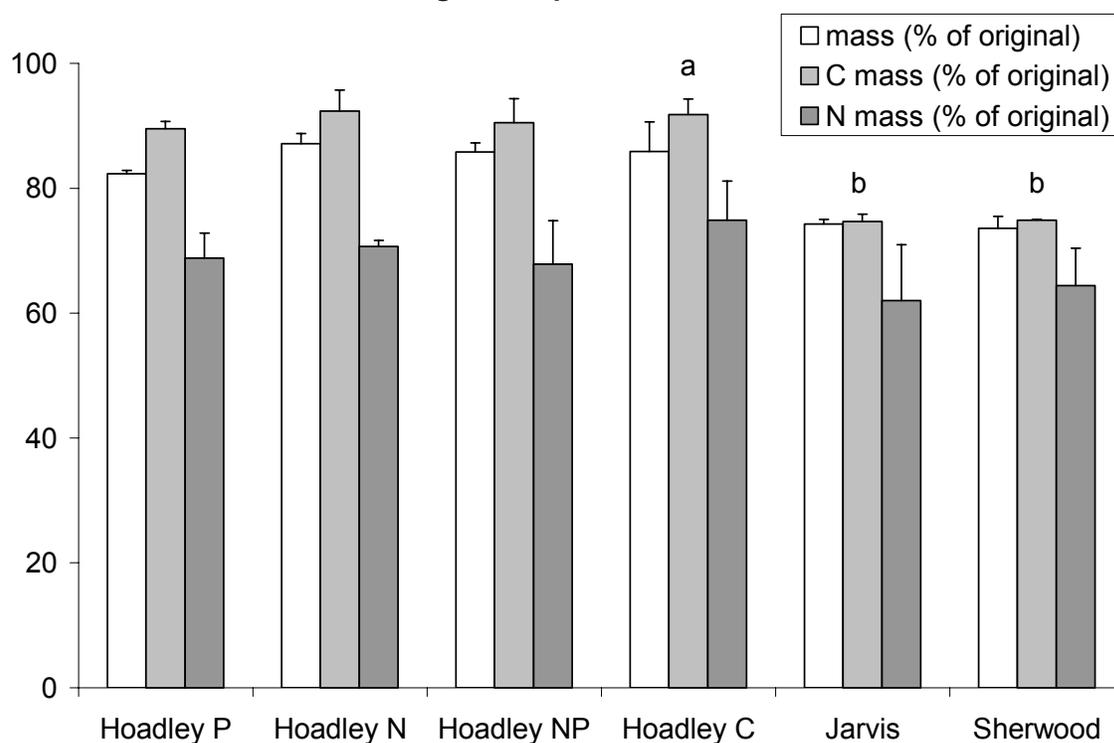


Figure 30. Decomposition of litter buried for 3 months, expressed as % of original mass remaining (mean and standard error). For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

Soil respiration rates were relatively high in June and much lower in September and October (Figure 31).¹⁶ Estimated annual CO₂ fluxes were approximately 400-600 g C m⁻² yr⁻¹. Because of the high variability in this measurement, there were no significant differences in annual CO₂ fluxes based on fertilization status or marsh site, although there is a hint that the NP fertilized plots may have higher fluxes than controls.

¹⁶ We did not measure respiration in July or August (see Section 2.8.2).

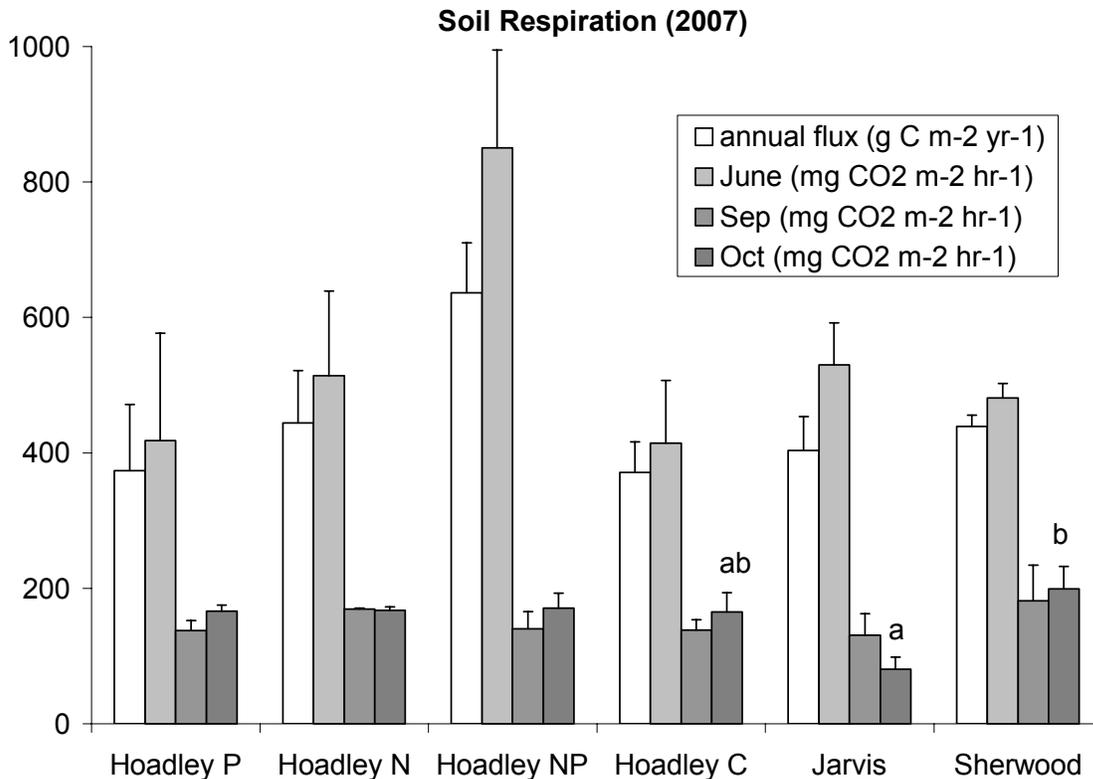


Figure 31. Soil respiration rates (mean and standard error). Annual CO₂ fluxes are calculated by applying June rates to June-August and Sep/Oct rates to April, May, Sep, and Oct, as described in Section 2.8.2. For intermarsh comparisons, bars with the same letter are not significantly different. For fertilization comparison at Hoadley, asterisks indicate significant differences from the control

3.6 Accretion and Elevation Change (Feldspar and SET Measurements)

Figures 32-41 present graphs of accretion (based on feldspar plots) and elevation change (based on SET measurements) over time at each plot, organized by plot type (Sherwood, Jarvis, different elevations and fertilization treatments at Hoadley). In addition, we show the net accretion and elevation change over the project period, by plot (Figure 42) and averaged by plot type (Figure 43). Several observations can be made:

- Most of the plots do not show simple linear increases over time; rather there are complex patterns of rises and falls over time, perhaps having to do with real seasonal changes in the marsh system. As a result, we have not attempted to fit lines to these data to calculate average accretion and elevation change rates.
- The vast majority of the plots at Hoadley show a pattern in which elevation increased from October 2004 to October 2005 and subsequently decreased to July 2007, with many plots showing a net elevation change over the project period of close to, or less than, zero. During the period of elevation decrease, accretion rates continued to be positive, indicating the onset of significant subsidence.
- The subsidence at Hoadley did not appear to be related to fertilization treatment. There did seem to be a spatial pattern to the subsidence, with the only plots not showing significant net subsidence being found in 2 clusters (1A-1B, 9A-10B). The high site generally had lower elevation change than the low site.

- In general, plots at Sherwood and Jarvis showed more of a continuous increase in both accretion and elevation than plots at Hoadley. At both Jarvis and Sherwood, elevation change was approximately equal to accretion (indicating no subsidence), with the exception of one plot (14 at Sherwood), where elevation change was substantially more positive than accretion.
- Jarvis had the highest rate of accretion and elevation change. Sherwood (the “drowning” marsh) also had a positive, but relatively low, rate of accretion and elevation change.

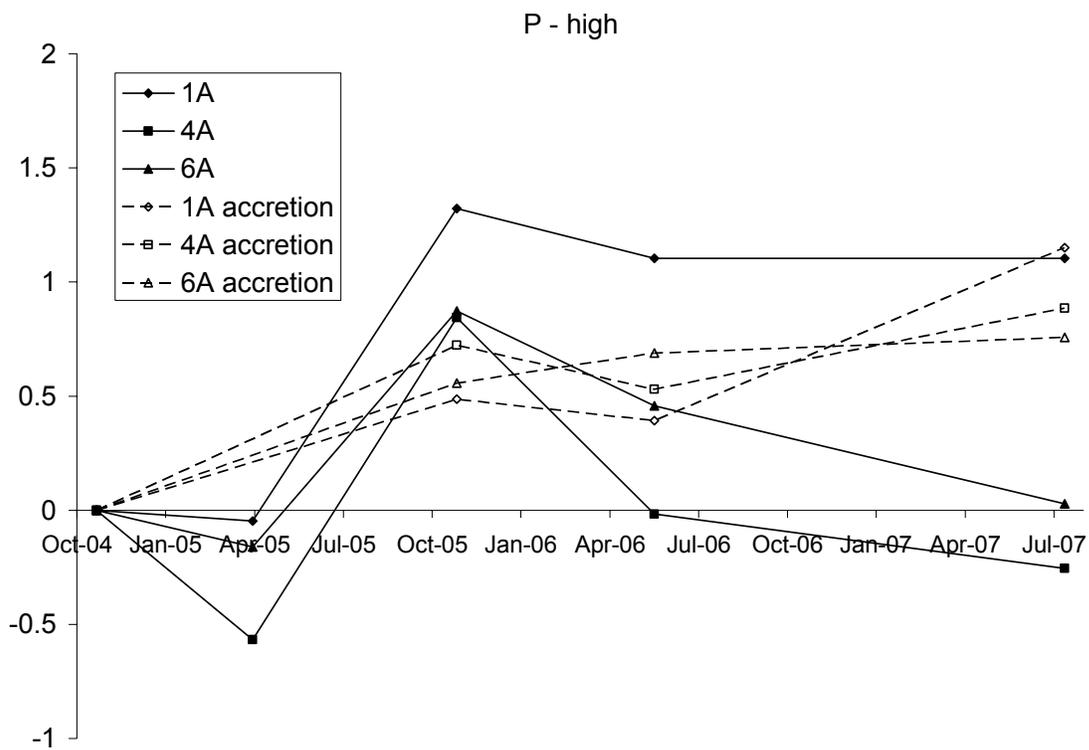


Figure 32. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 P-fertilized plots in the high site at Hoadley.

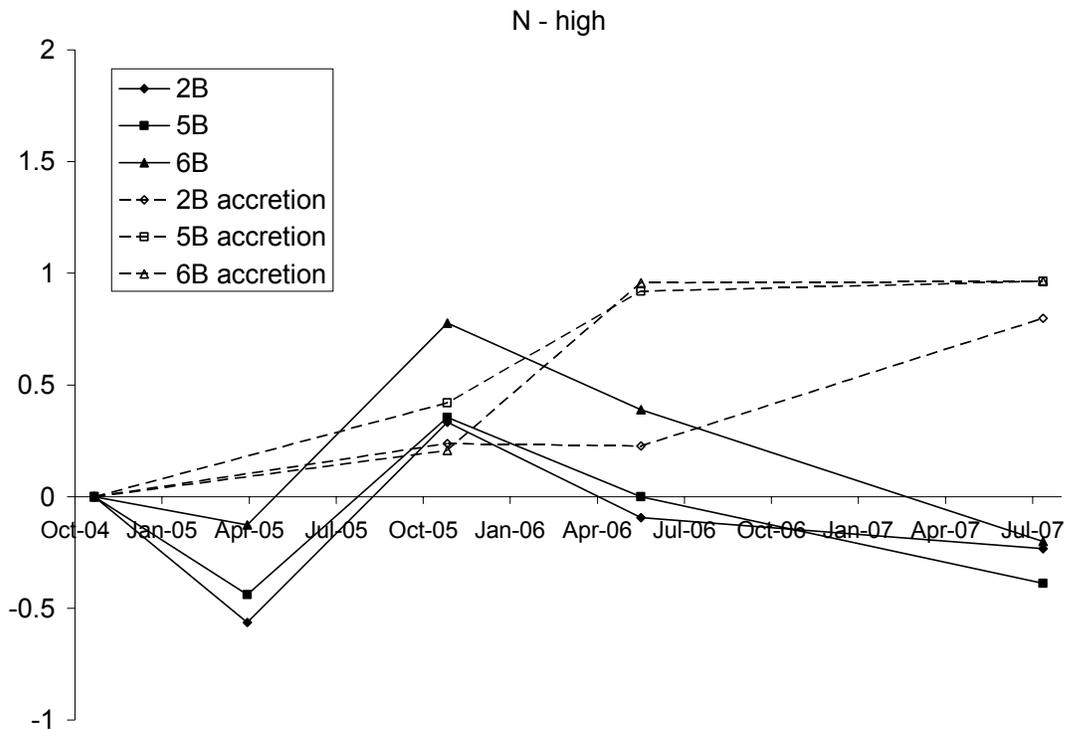


Figure 33. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 N-fertilized plots in the high site at Hoadley.

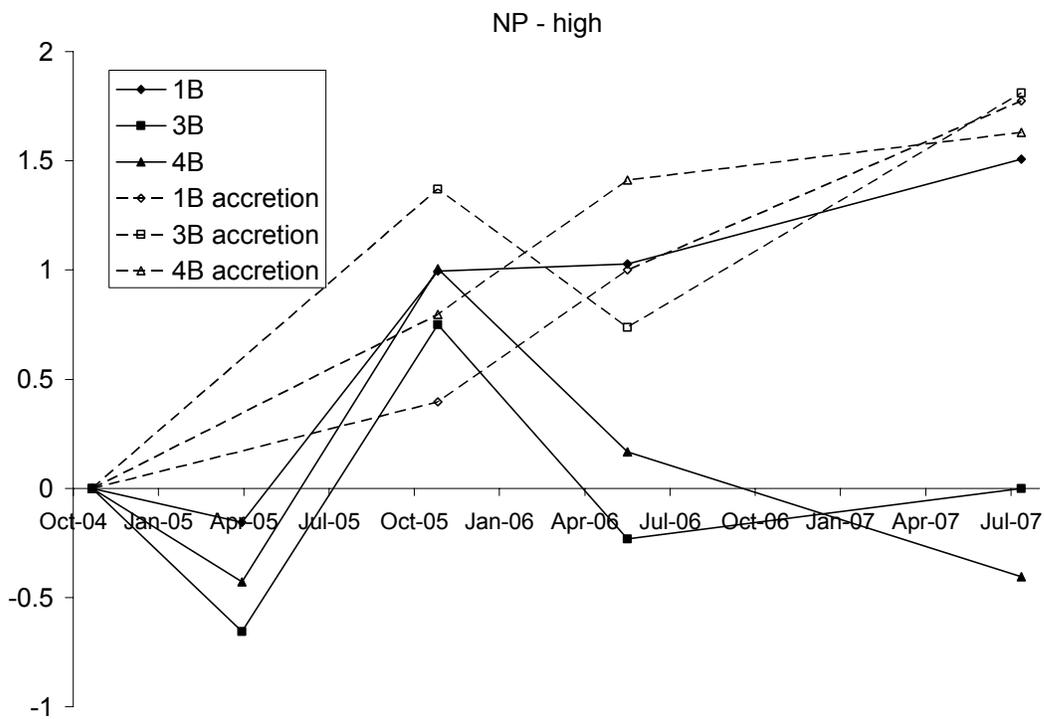


Figure 34. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 NP-fertilized plots in the high site at Hoadley

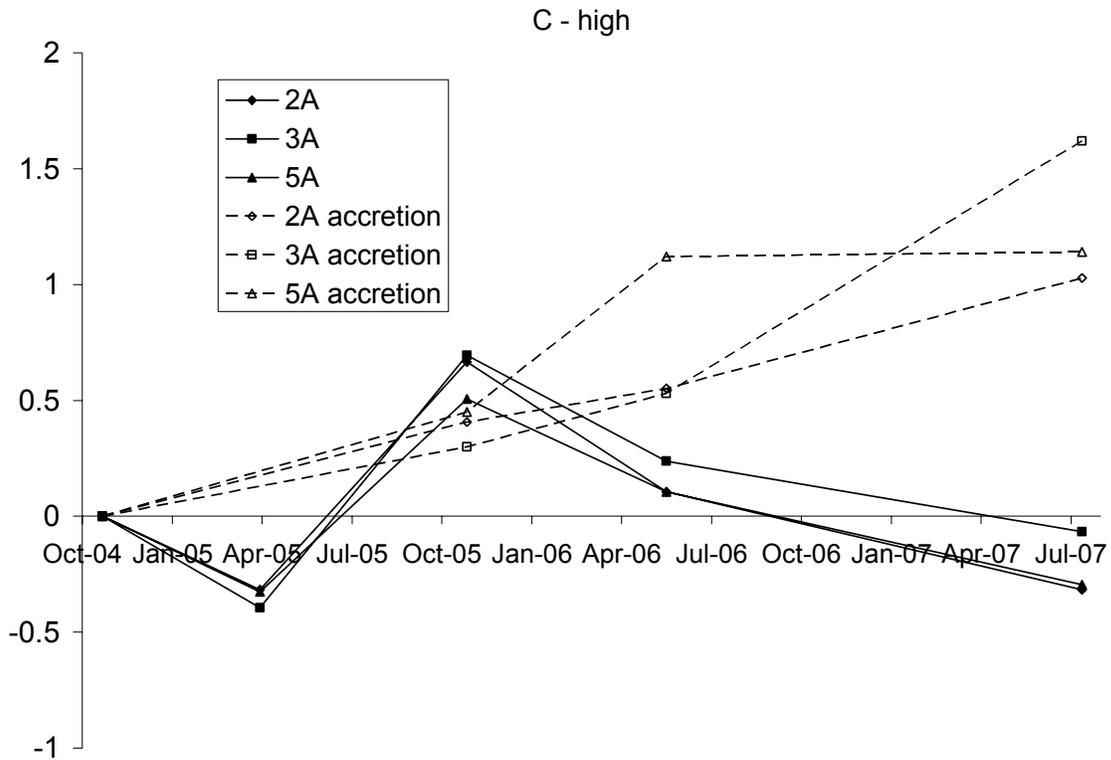


Figure 35. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 control plots in the high site at Hoadley

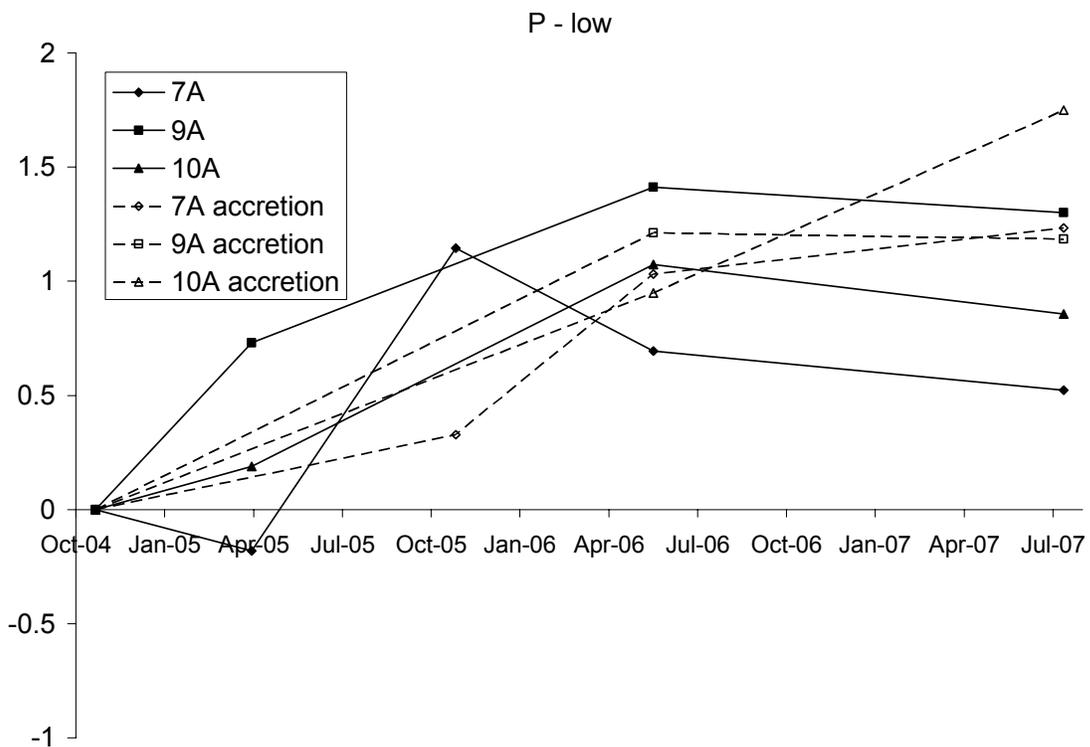


Figure 36. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 P-fertilized plots in the low site at Hoadley

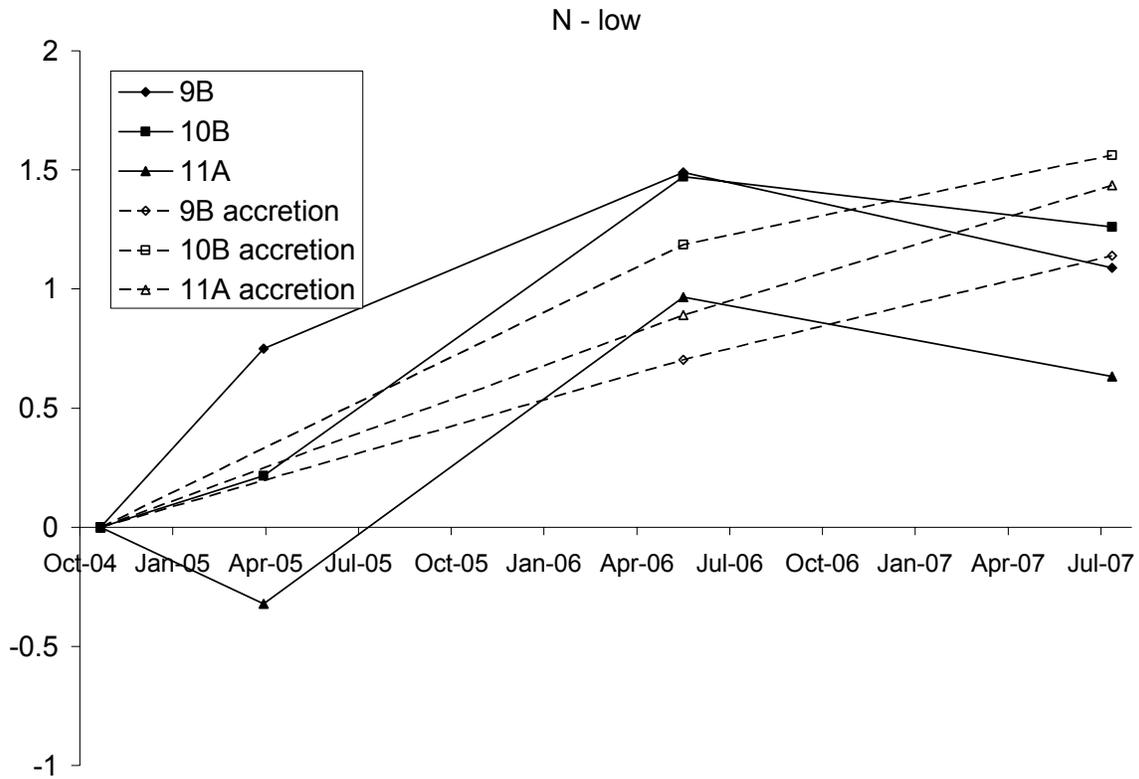


Figure 37. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 N-fertilized plots in the low site at Hoadley.

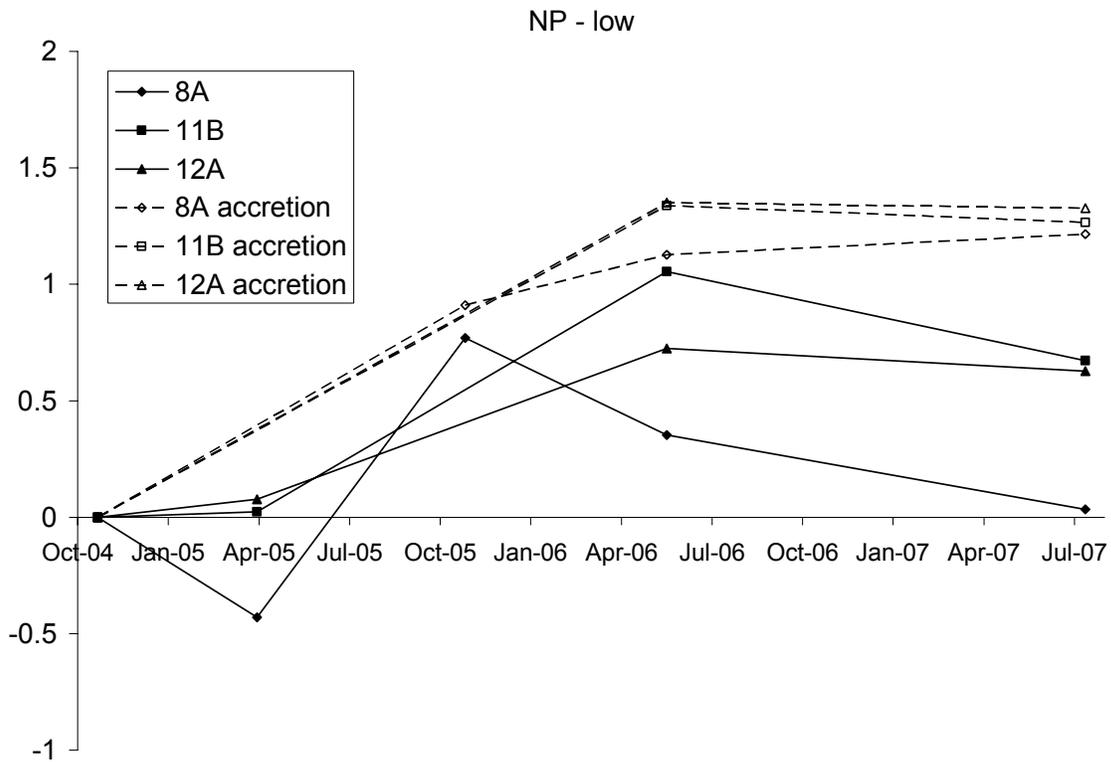


Figure 38. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 NP-fertilized plots in the low site at Hoadley.

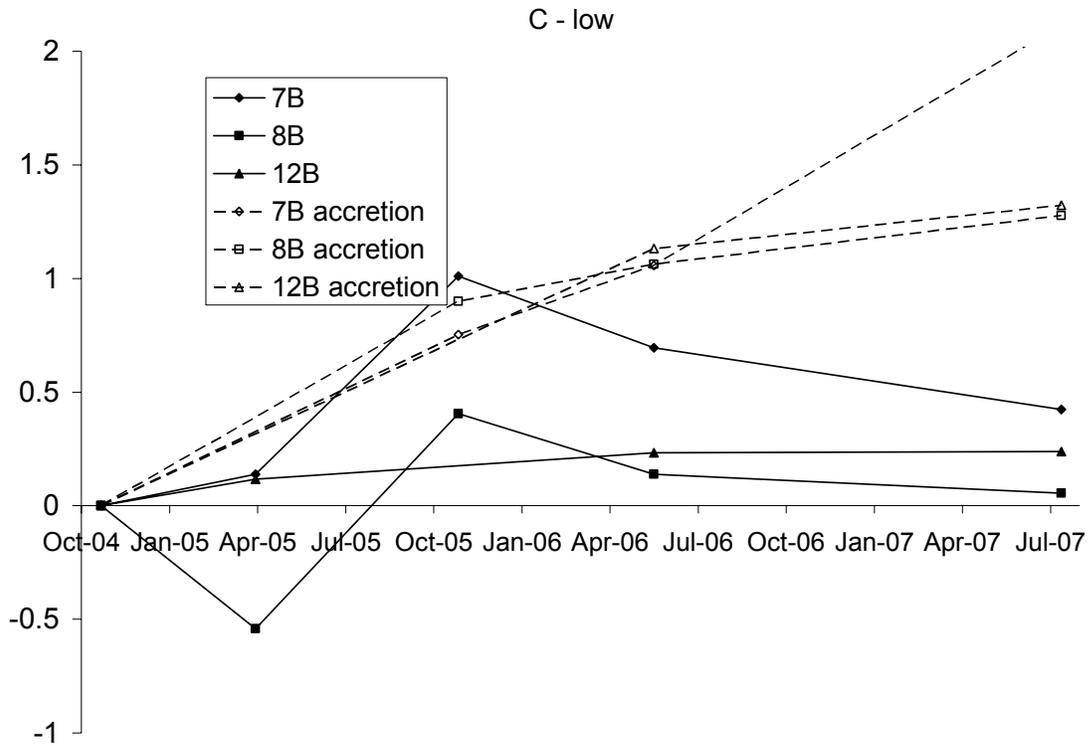


Figure 39. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 control plots in the low site at Hoadley.

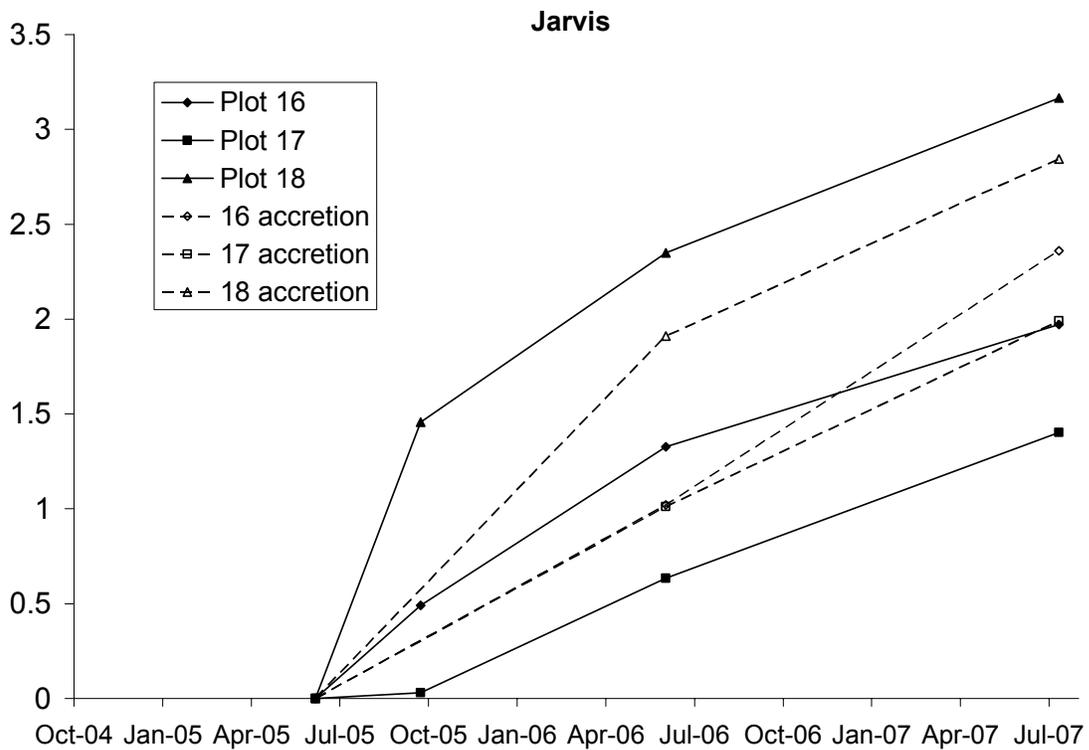


Figure 40. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 Jarvis plots.

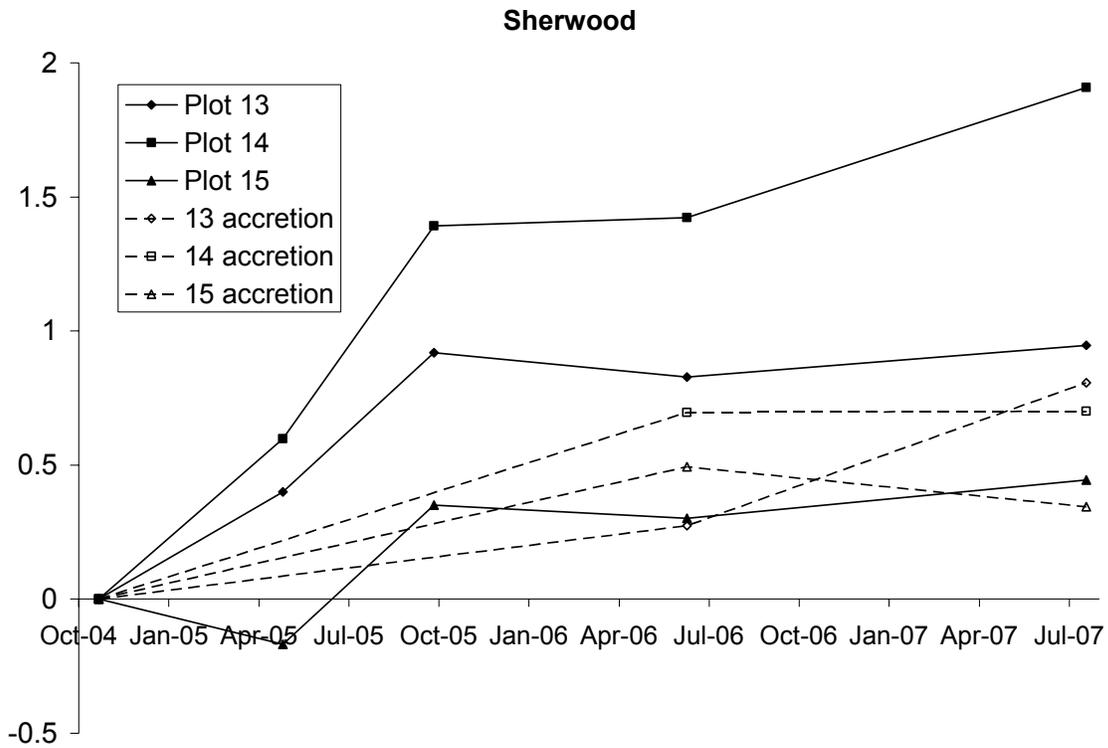


Figure 41. Elevation change (SET, solid lines) and accretion (feldspar, dashed lines), in cm, for the 3 Sherwood plots.

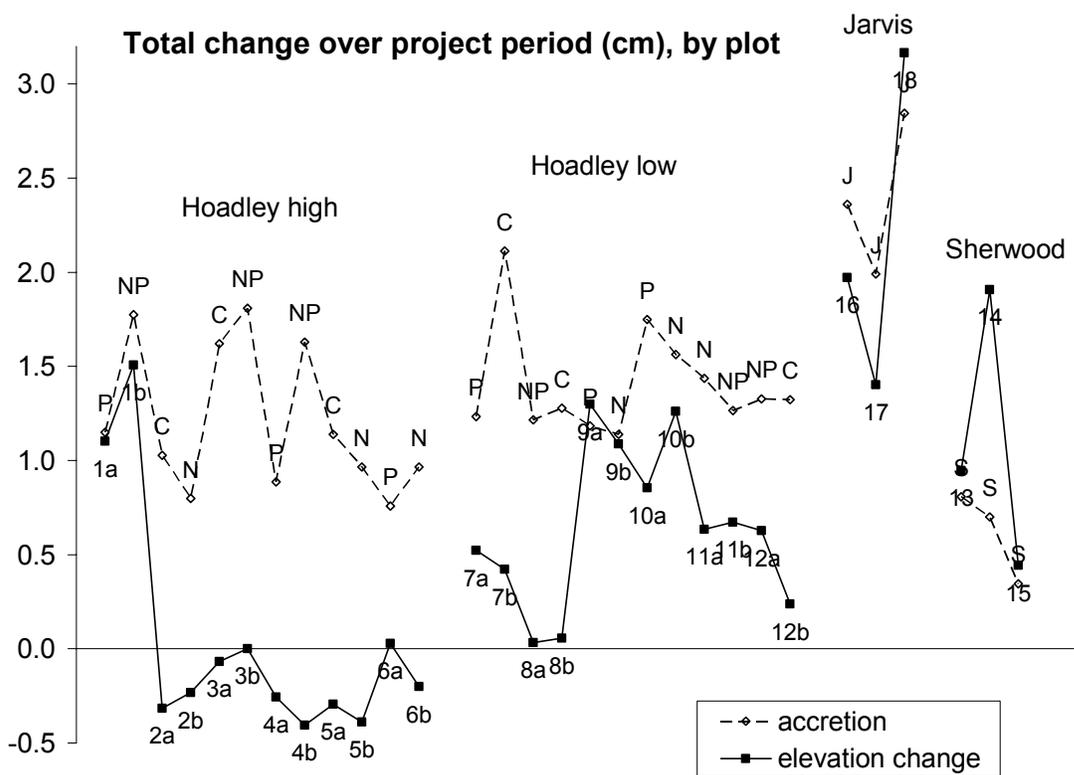


Figure 42. Net elevation change (SET, solid lines) and net accretion (feldspar, dashed lines) over the project period, in cm, for all plots, shown with plot number and treatment.

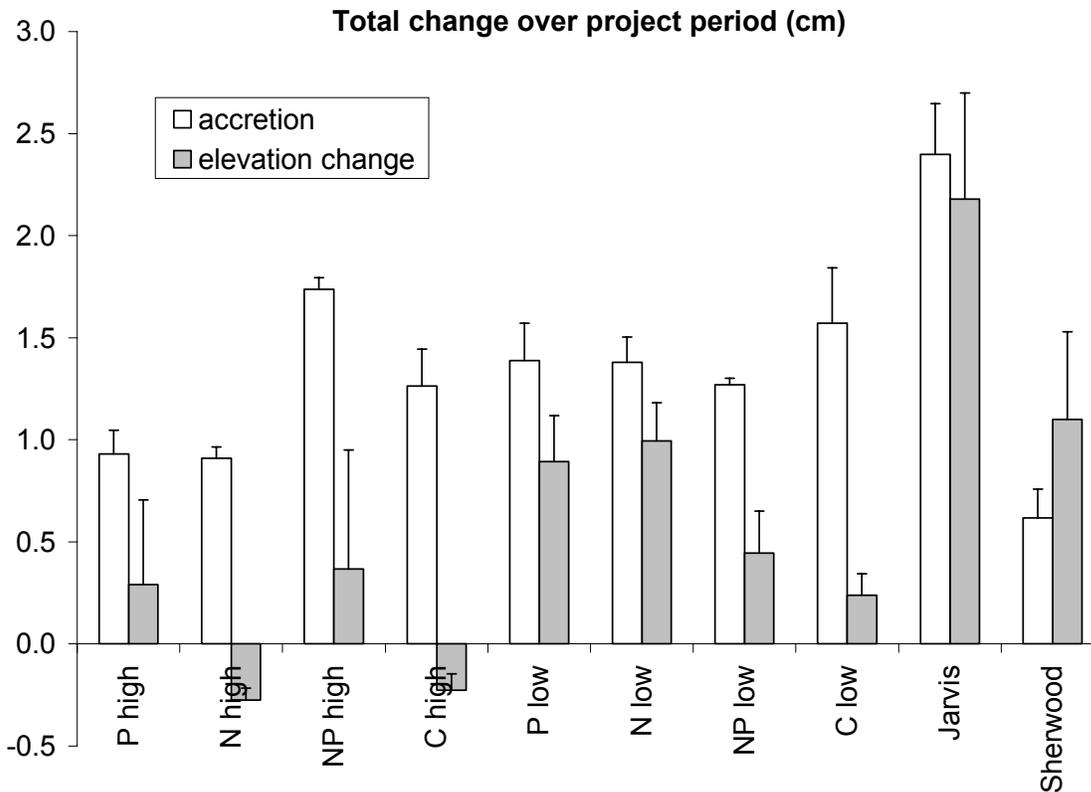


Figure 43. Net elevation change (SET) and net accretion (feldspar) over the project period, in cm, for all plots, shown as mean and standard error by site/treatment.

3.7 Hydrology

3.7.1 Hoadley

All of the 5-minute hydrology data from Hoadley are presented in Figure 44. In order to deal with gaps in the record and extend the time coverage of our hydrology data, we related our data to NOAA data from New Haven Harbor (NHH, station 8465705) by plotting the height of each high tide in Hoadley against the height of the corresponding high tide in New Haven Harbor (Figure 45). As can be seen, there is quite a good relationship, although it seems to have shifted abruptly by about 22 cm around 2/15/07. The February 2007 data from New Haven Harbor, Hoadley, and Bridgeport are all plotted in Figure 46. The storm that came through the area around 2/15 is apparent in the unusually high tides recorded at Hoadley and at Bridgeport and in the missing data from NHH, apparently a result of instrument malfunction.

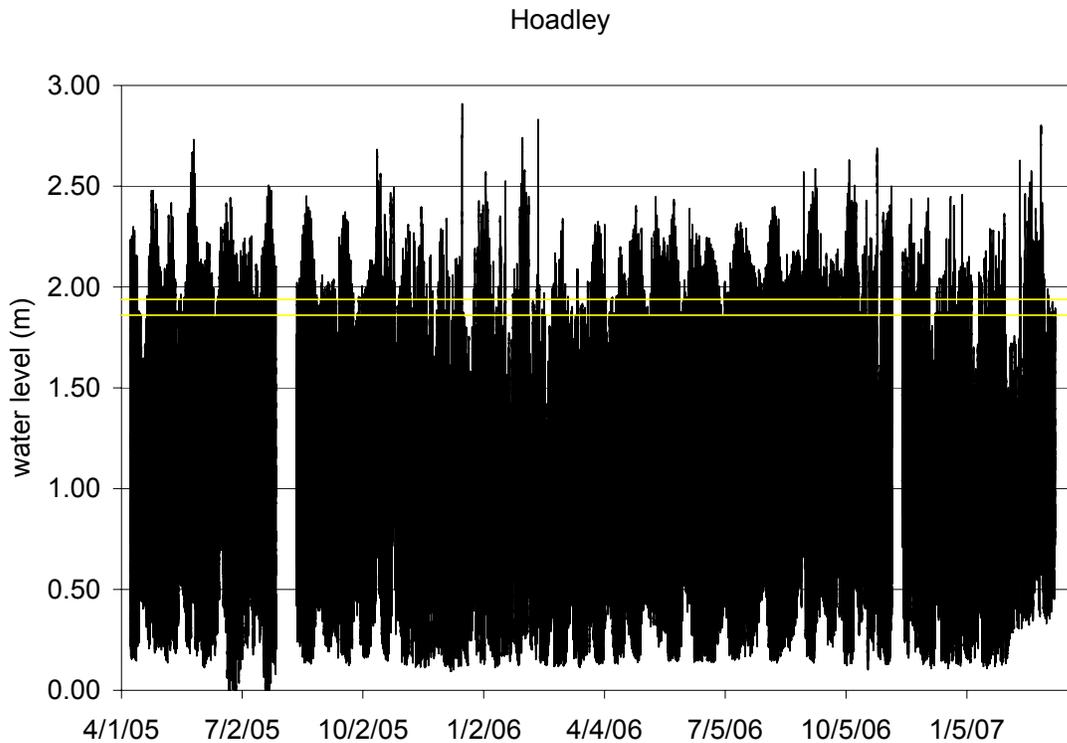


Figure 44. Hydrologic data collected at Hoadley over the entire project period (5 minute time interval), relative to the local (arbitrary) datum. Elevations of the lowest and highest plots at Hoadley (relative to the same datum) are shown as horizontal lines. Note that data after 2/15/07 are offset from this datum by about +22 cm (see text and Figure 45).

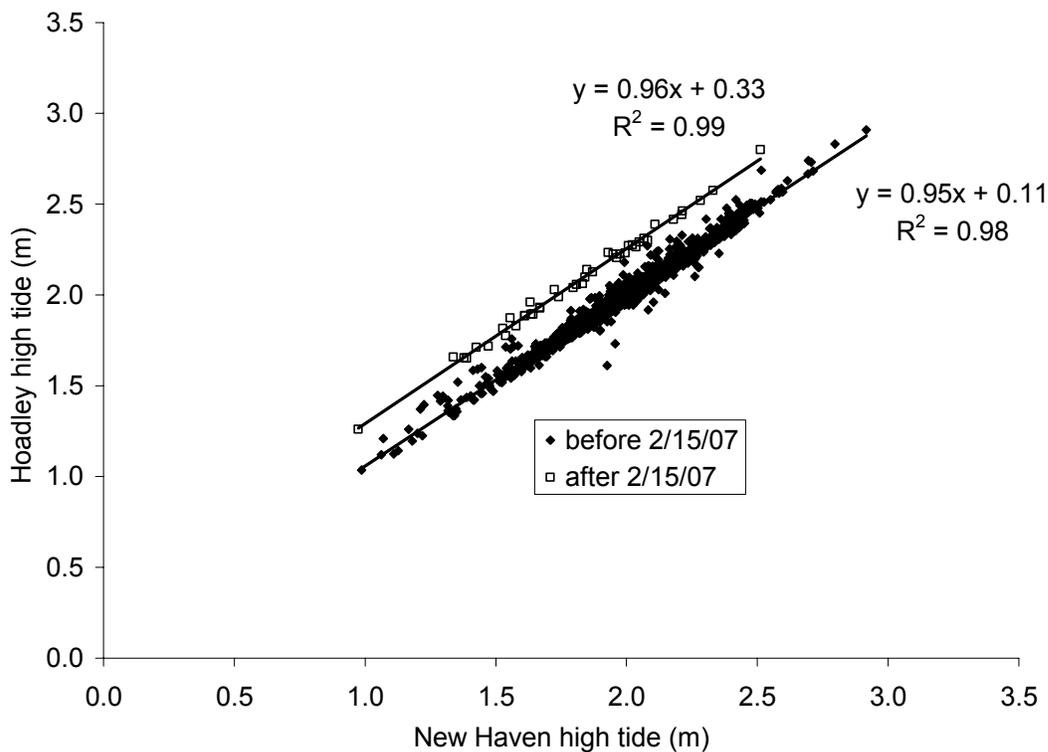


Figure 45. Relationship between high tide at Hoadley (as recorded by our water level logger) and high tide at New Haven Harbor (data from NOAA).

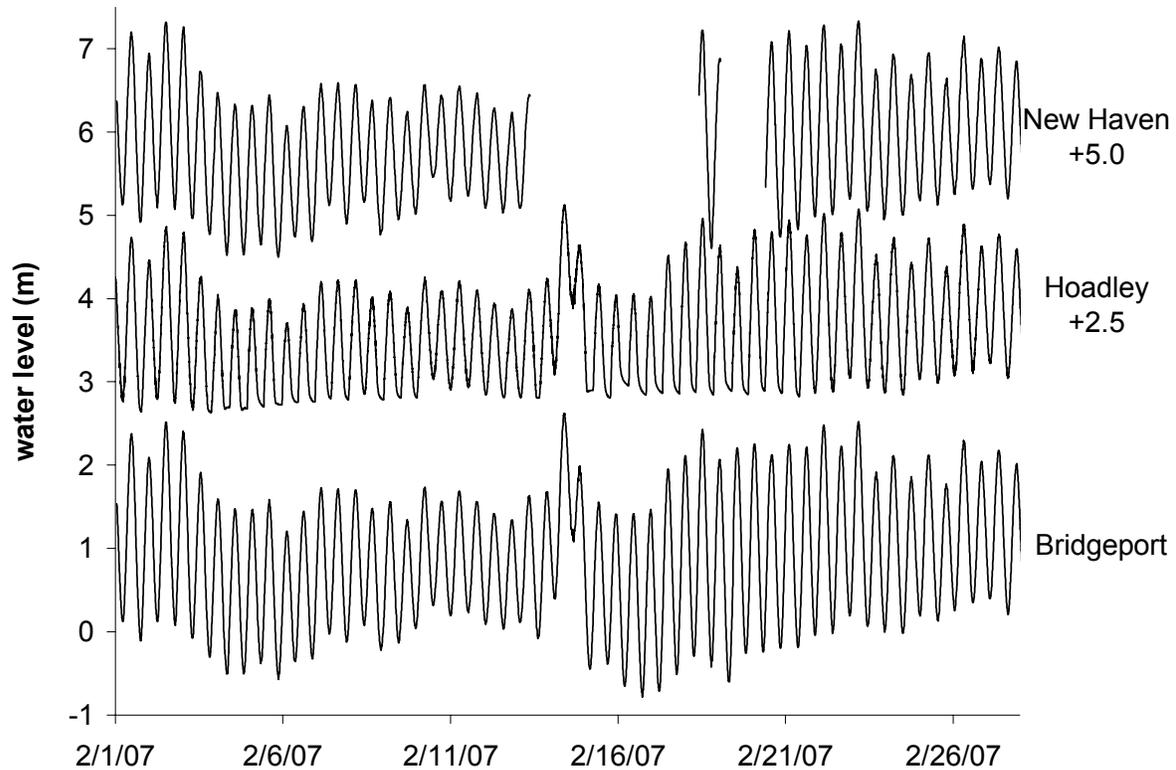


Figure 46. Hydrologic data from Hoadley and 2 NOAA stations over the month of February 2007. Hoadley and NHH data have a constant offset added for visibility. Note the storm event of Feb. 15, 2007.

There are two possible explanations for the shift in the relationship between Hoadley and NHH coinciding with the 2/15/07 storm: an actual change in the hydrology at one or the other of these 2 sites; or an artifact due to some change to our instrument at Hoadley (e.g., shifting of its position). We believe that the latter explanation is more likely, given that: there is no shift in the relationship between NHH and Bridgeport (data not shown); and there is no change in the relationship between Hoadley and NHH as revealed by the tide stick data (Figure 47, below).

In any case, it is clear that we can relate high tides at Hoadley to high tides at NHH using a factor of 0.95 (slope of both lines in Figure 45). We can thus create a synthetic dataset of Hoadley high tides over whatever time period is desired, by multiplying NHH high tides by 0.95. Over the time period when we have actual measurements of high tide (Figure 44), the synthetic dataset has the same variability as our measurements, but a different datum: we are essentially using 0.95 times NHH MLLW as our datum. We refer to this as the Hoadley-NHH datum, as opposed to the local datum, which is the actual bottom of our water level logger (an arbitrary level). Note that the synthetic dataset consists only of high tides and thus cannot be used to calculate flooding duration, for example.

Over the summers of 2005-2007, we collected 8 tide stick measurements for each SET benchmark at Hoadley; these measurements were obtained under a range of tidal heights (NHH HT = 1.99 to 2.23 meters). Each measurement is a record of water level at high tide relative to the top of the cap of the SET benchmark. Subtraction of these measurements from the corresponding Hoadley high tide (from the synthetic dataset) allows calculation of the height of

each benchmark cap relative to the Hoadley-NHH datum.¹⁷ As can be seen in Figure 47, these offsets were, as expected, stable over time, and could be measured with good precision (~2-4 mm).

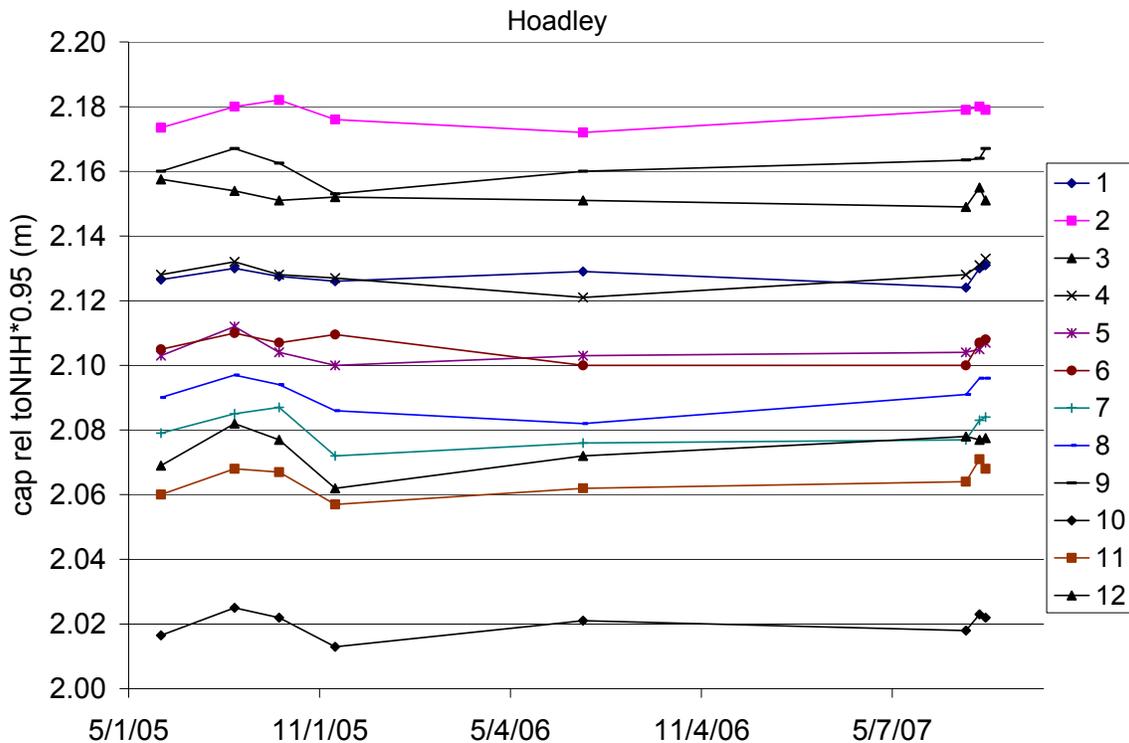


Figure 47. Calculated height of each SET benchmark cap relative to the Hoadley-NHH datum, as determined from tide stick data.

We combined the tide stick data with the SET data to calculate the elevation of each plot relative to the Hoadley-NHH datum¹⁸ (see Table 3, below). We then used the synthetic high tide dataset for 2005-2007 to calculate flooding frequency for this 3 year period (i.e., percent of high tides flooding the surface) as a function of surface elevation (Figure 48). The range of sediment surface elevations for our plots is also shown, and indicates that our plots are flooded on 54-68% of high tides (see also Table 3).

To calculate flooding duration (% of the time that each plot is submerged), we used our hydrology data from the summer of 2006 (6/20/06-10/13/06)¹⁹, together with our estimated elevation of each plot relative to the local datum. Results (Figure 49 and Table 3) indicate that our plots are flooded 14-18% of the time.

¹⁷ height of cap relative to Hoadley-NHH datum = NHH high tide *0.95 – high tide relative to cap (as recorded by tide stick)

¹⁸ sediment surface relative to Hoadley-NHH datum = cap relative to Hoadley-NHH datum (from Table 3) – (39.5cm – average SET pin reading in cm)/100, where 39.5cm takes into account the total height of the pins and the height from the cap to the SET arm; note that the elevation of the sediment surface is defined as the average of the sediment surface elevation at the 18 SET pin locations. A similar procedure was used to calculate plot sediment surface relative to the Hoadley water level logger datum itself; the range of resulting surface elevations is plotted in Figure 44.

¹⁹ This time period was used because we have good data from all 3 sites.

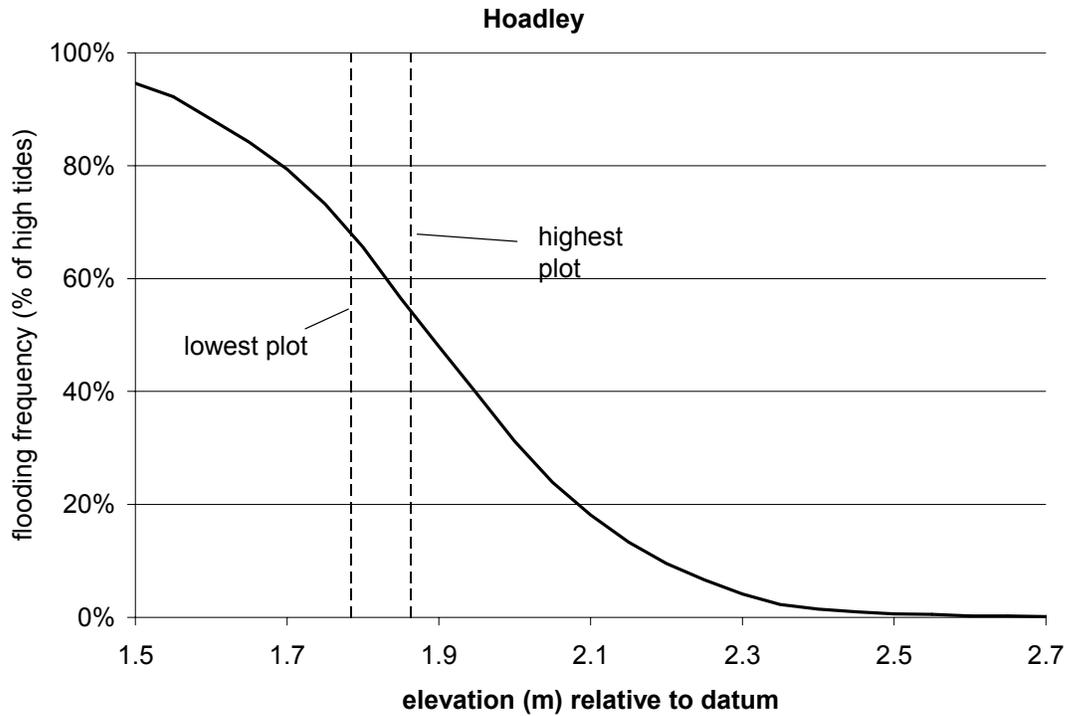


Figure 48. Elevation-frequency curve for Hoadley, showing elevations (and flooding frequencies) of lowest and highest plots. Datum = Hoadley-NHH datum.

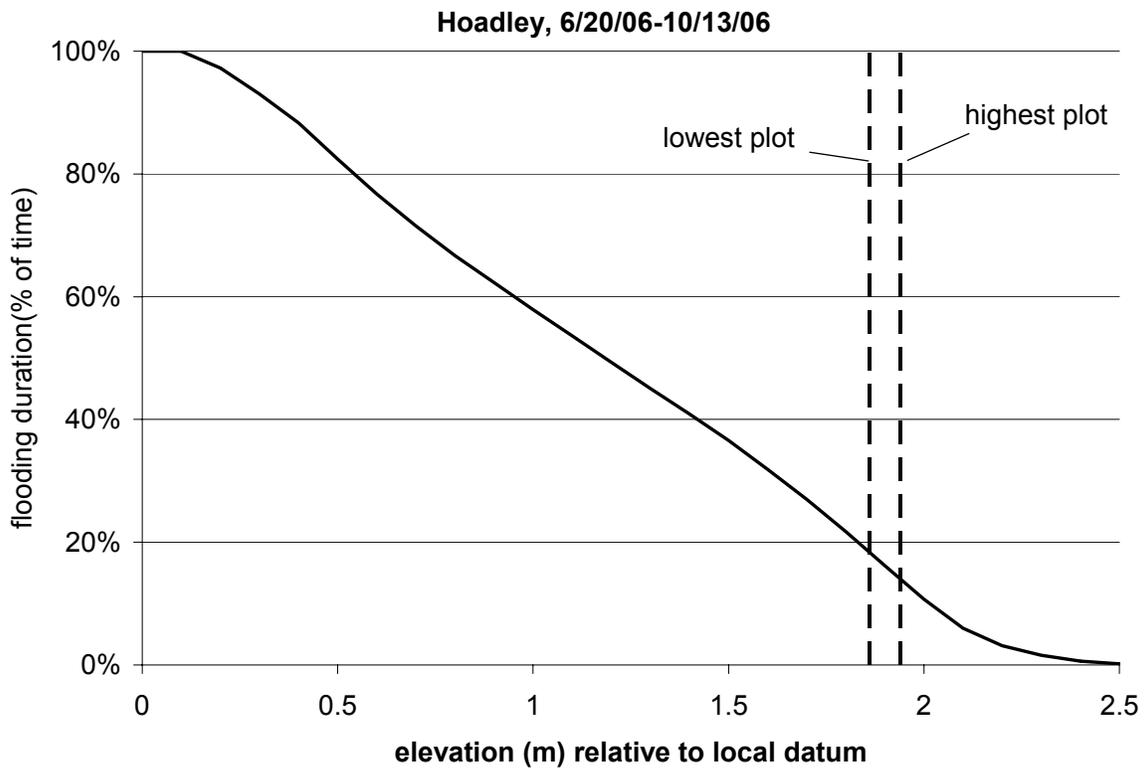


Figure 49. Elevation-duration curve for Hoadley, showing elevations (and flooding durations) of lowest and highest plots. Datum = local datum.

Fi

3.7.2 Jarvis

All of the 5-minute hydrology data from Jarvis are presented in Figure 50. In order to deal with gaps in the record and extend the time coverage of our hydrology data, we related our data to NOAA data from New Haven Harbor (station 8465705) by plotting the height of each high tide in Jarvis against the height of the corresponding high tide in New Haven Harbor (Figure 51). As can be seen, there is quite a good relationship, although it seems to have shifted abruptly twice, first around 1/21/05 and then again around 2/18/07. As above, we suspect that storms led to changes in the relative position (or calibration offset) of our instrument.

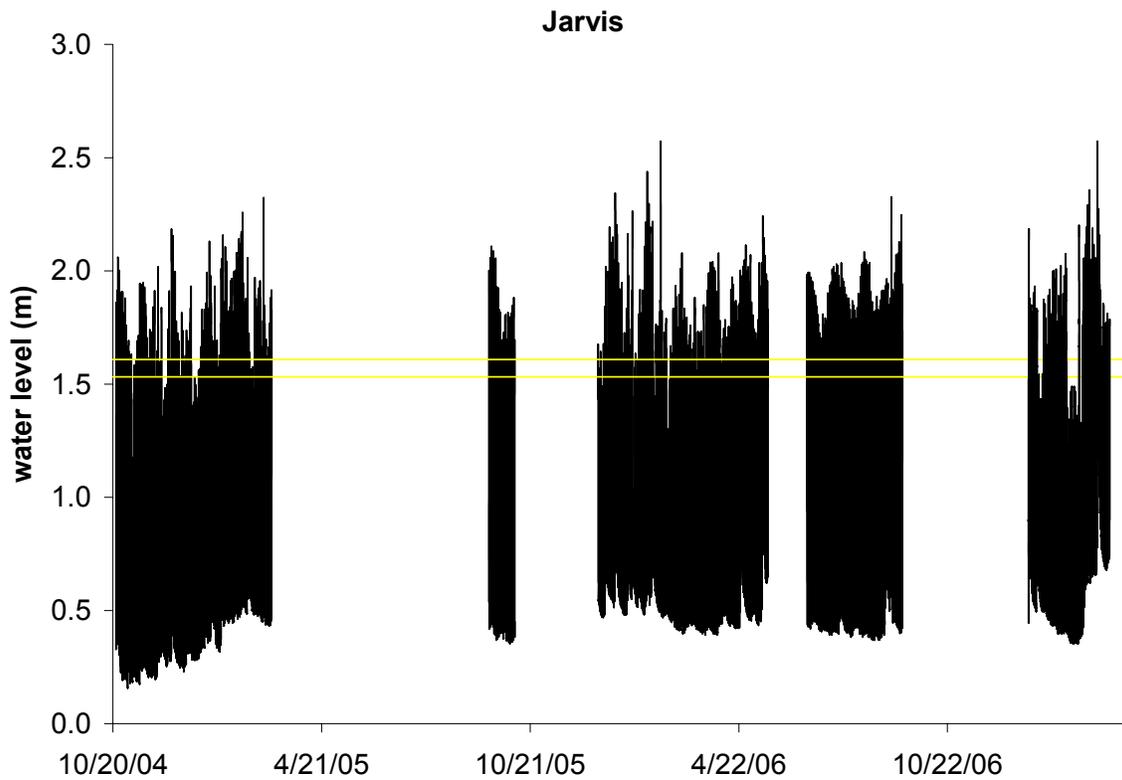


Figure 50. Hydrologic data collected at Jarvis over the entire project period (5 minute time interval), relative to the local (arbitrary) datum. Elevations of the lowest and highest plots at Jarvis (relative to the same datum) are shown as horizontal lines. Note that data before 1/21/05 are offset from this datum by about -15cm and data from after 2/19/07 are offset from this datum by about +27 cm (see text and Figure 51).

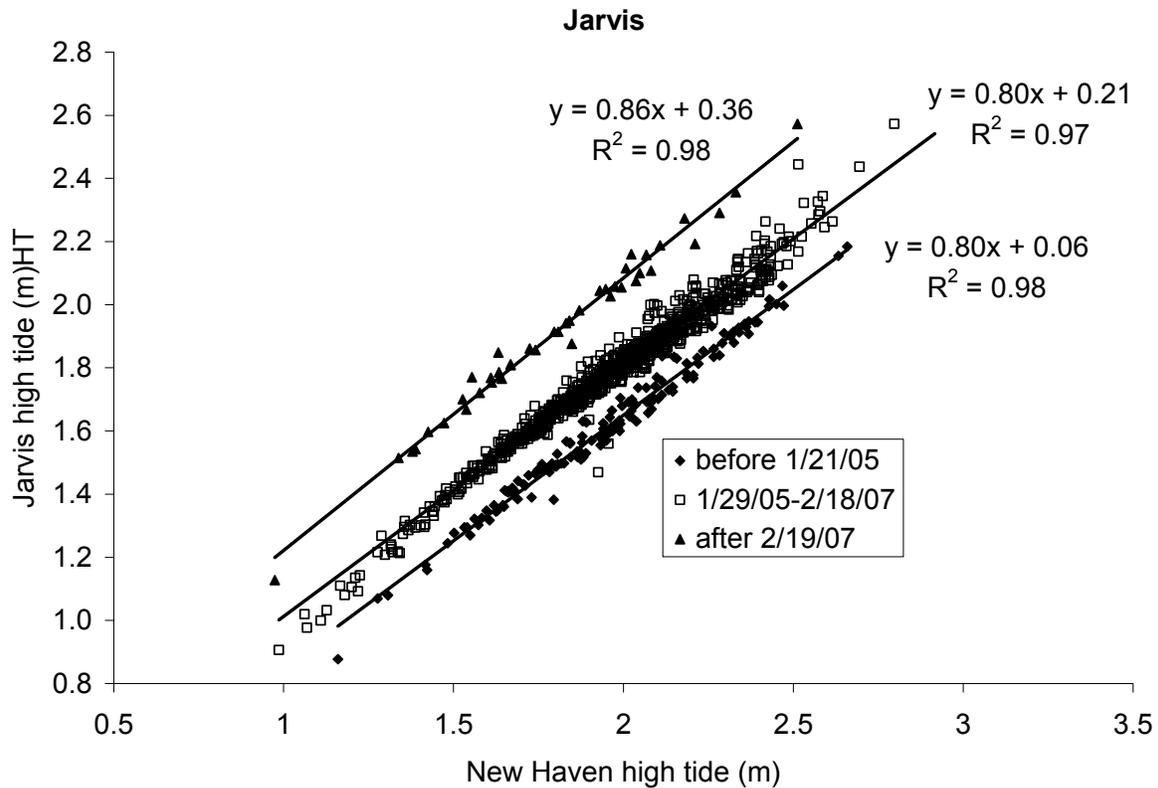


Figure 51. Relationship between high tide at Jarvis (as recorded by our water level logger) and high tide at New Haven Harbor (data from NOAA).

In any case, it is clear that we can relate high tides at Jarvis to high tides at NHH using a factor of 0.80 (slope of both lines in Figure 51; the third line has a slope of 0.86, but it has relatively few data points). We can thus create a synthetic dataset of Jarvis high tides by multiplying NHH high tides by 0.80. This synthetic dataset has $0.80 \times \text{NHH MLLW}$ as its datum (“Jarvis-NHH datum”).

Over the summers of 2005-2007, we collected 6 tide stick measurements for each SET benchmark at Jarvis; these measurements were collected under a range of tidal heights (NHH HT = 2.02 to 2.25 meters). Each measurement is a record of high tide water level relative to the top of the cap of the SET benchmark. Subtraction of these measurements from the corresponding Jarvis high tide (from the synthetic dataset) allows calculation of the height of each benchmark cap relative to the Jarvis-NHH datum.²⁰ As can be seen in Figure 52, these offsets were, as expected, stable over time, and could be measured with reasonably good precision (~5 mm).

²⁰ height of cap relative to Jarvis-NHH datum = NHH high tide * 0.8 – high tide relative to cap (as recorded by tide stick)

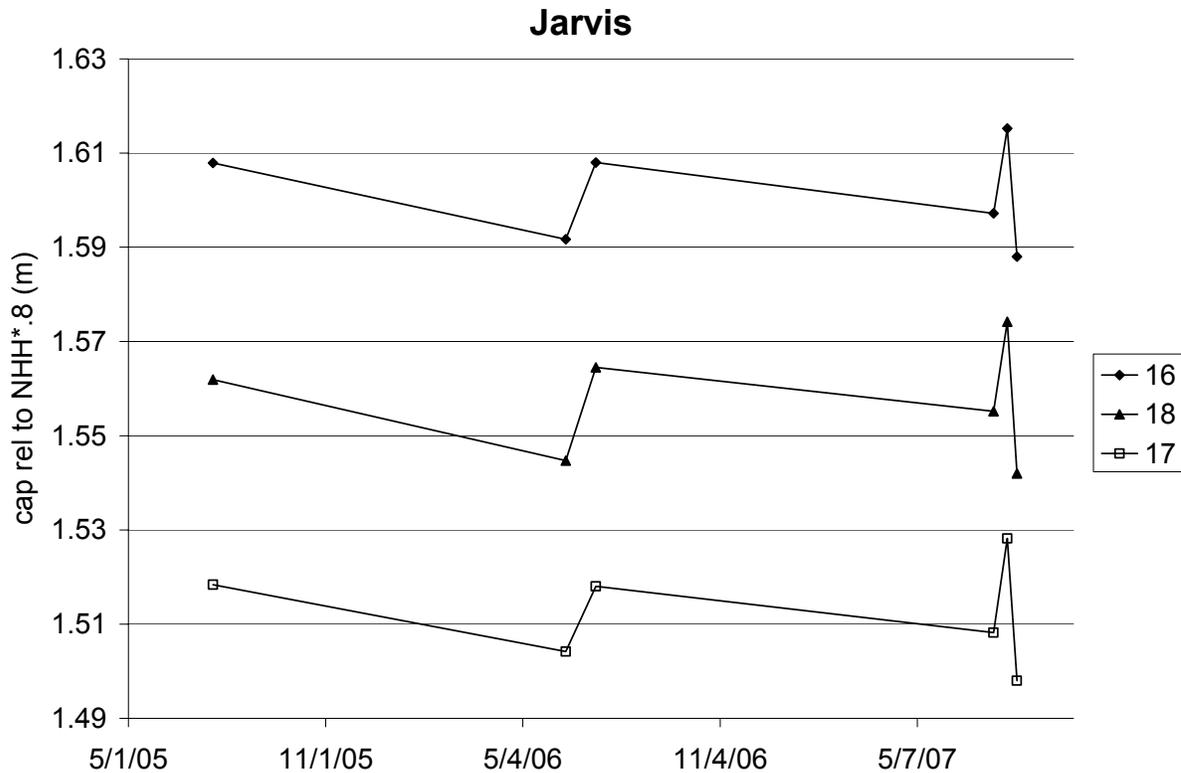


Figure 52. Calculated height of each SET benchmark cap relative to the Jarvis-NHH datum, as determined from tide stick data.

We combined the tide stick data with the SET data to calculate elevations of each plot relative to the Jarvis-NHH datum²¹ (see Table 3 below). We then used the synthetic high tide dataset for 2005-2007 to calculate flooding frequency for this 3 year period (i.e., percent of high tides flooding the surface) as a function of surface elevation (Figure 53). The range of sediment surface elevations for our plots is also shown, and indicates that our plots are flooded on 79-87% of high tides (see also Table 3).

To calculate flooding duration (% of the time that each plot is submerged), we used our hydrology data from the summer of 2006 (6/20/06-10/13/06)²², together with our estimated elevation of each plot relative to the local datum. Results (Figure 54 and Table 3) indicate that our plots are flooded 31-35% of the time.

²¹ sediment surface relative to Jarvis-NHH datum = cap relative to Jarvis-NHH datum (from Table 3) – (39.5cm – average SET pin reading in cm)/100, where 39.5cm takes into account the total height of the pins and the height from the cap to the SET arm; note that the elevation of the sediment surface is defined as the average of the sediment surface elevation at the 36 SET pin locations. A similar procedure was used to calculate plot sediment surface relative to the Jarvis water level logger datum itself; the range of resulting surface elevations is plotted in Figure 48.

²² This time period was used because we have good data from all 3 sites.

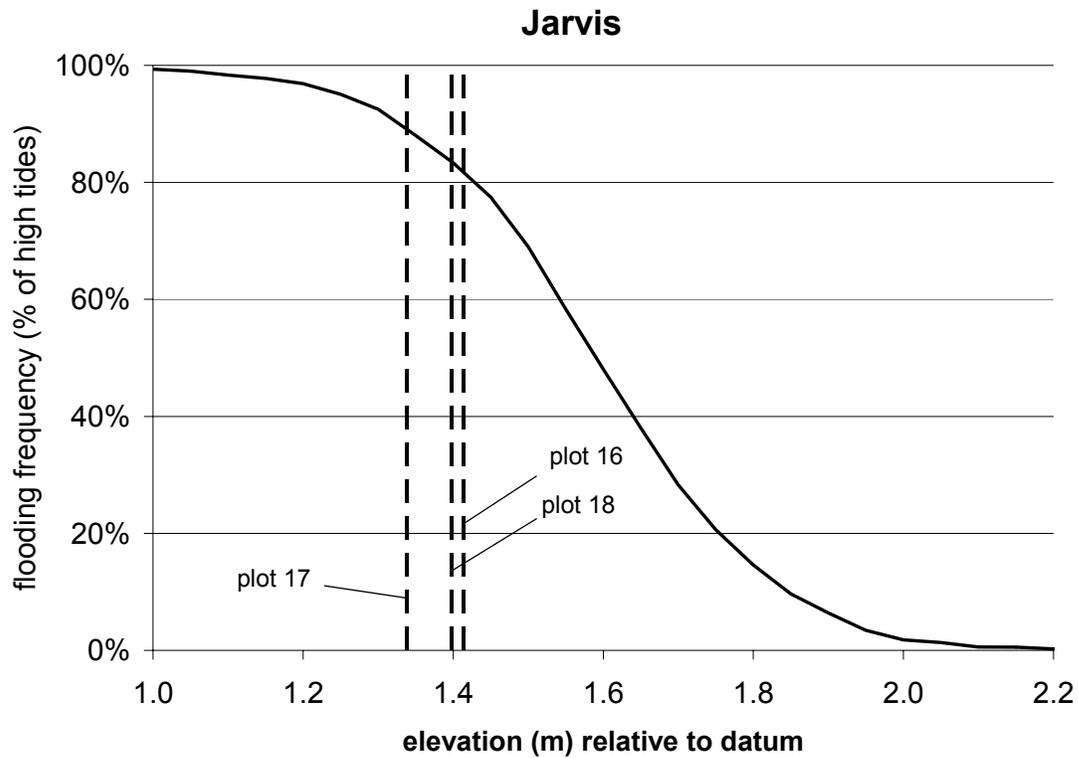


Figure 53. Elevation-frequency curve for Jarvis, showing elevations (and flooding frequencies) of the plots. Datum = Jarvis-NHH datum.

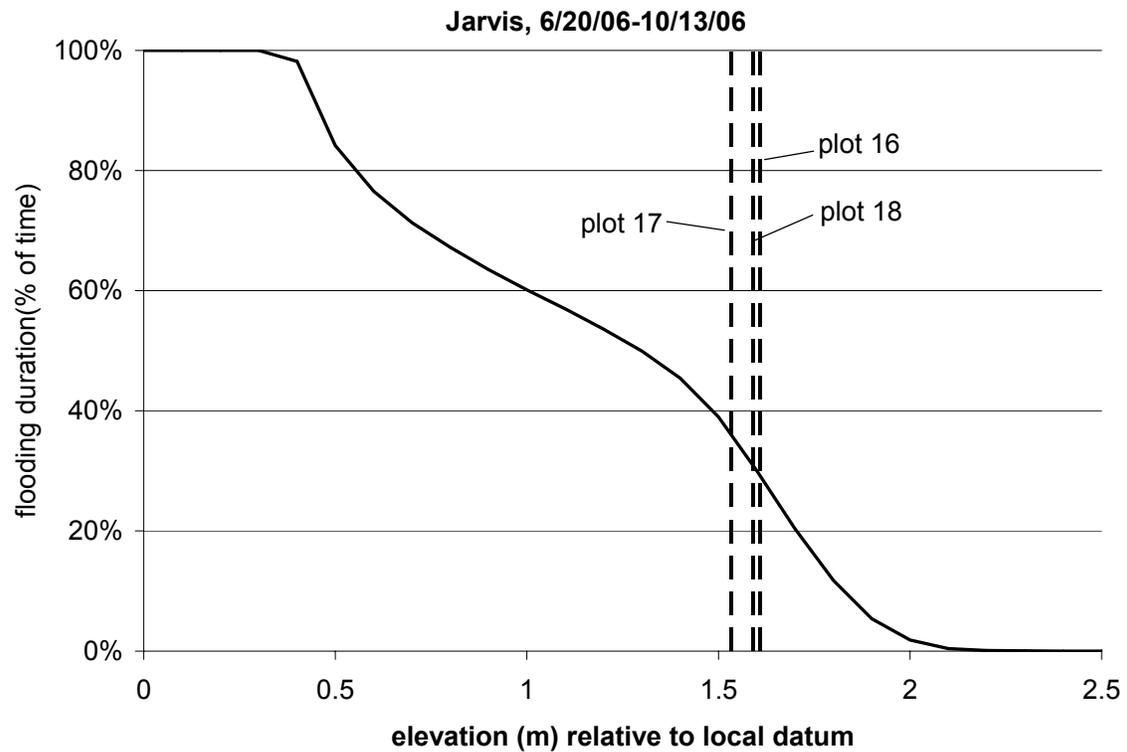


Figure 54. Elevation-duration curve for Jarvis, showing elevations (and flooding durations) of lowest and highest plots. Datum = local datum.

3.7.3 Sherwood

All of the 5-minute hydrology data from Sherwood are presented in Figure 55. In order to deal with gaps in the record and extend the time coverage of our hydrology data, we related our data to NOAA data from Bridgeport (station 8467150) by plotting the height of each high tide in Sherwood against the height of the corresponding high tide in Bridgeport (Figure 56). As can be seen, there is quite a good relationship between the two.

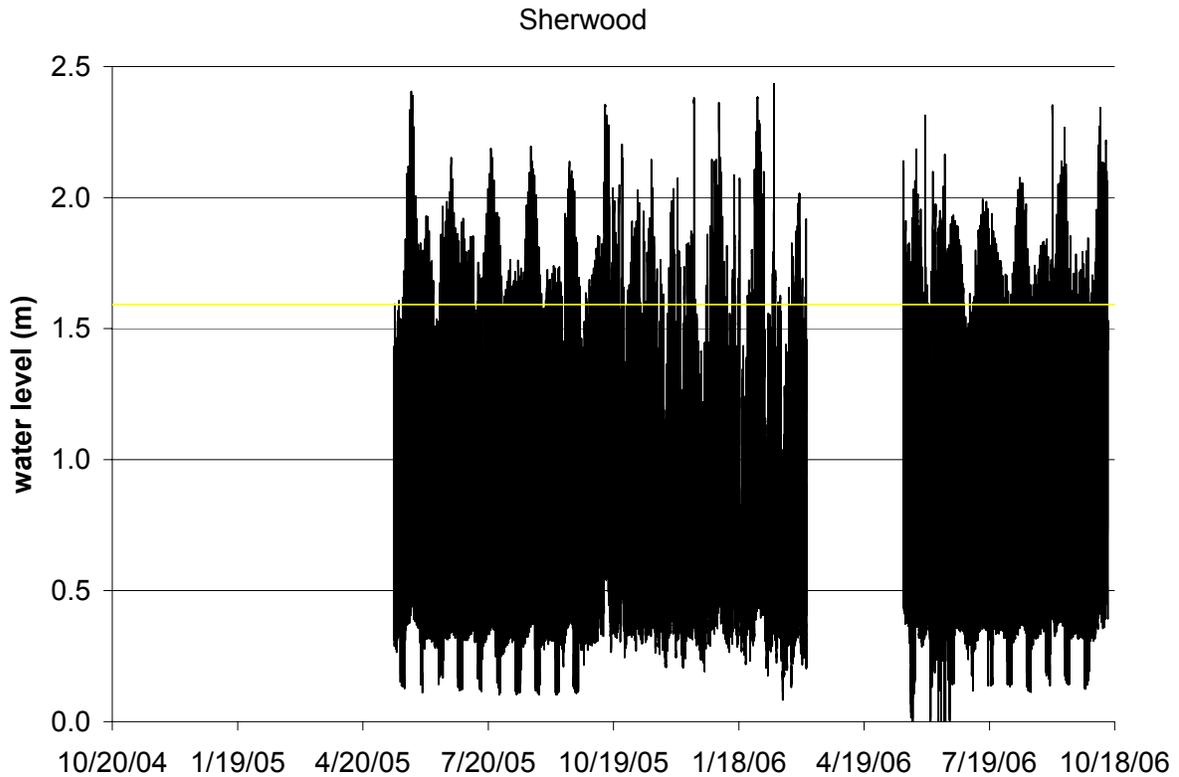


Figure 55. Hydrologic data collected at Sherwood over the entire project period (5 minute time interval), relative to the local (arbitrary) datum. Elevations of the plots at Sherwood (relative to the same datum) are shown as horizontal lines (they are not distinguishable at this scale).

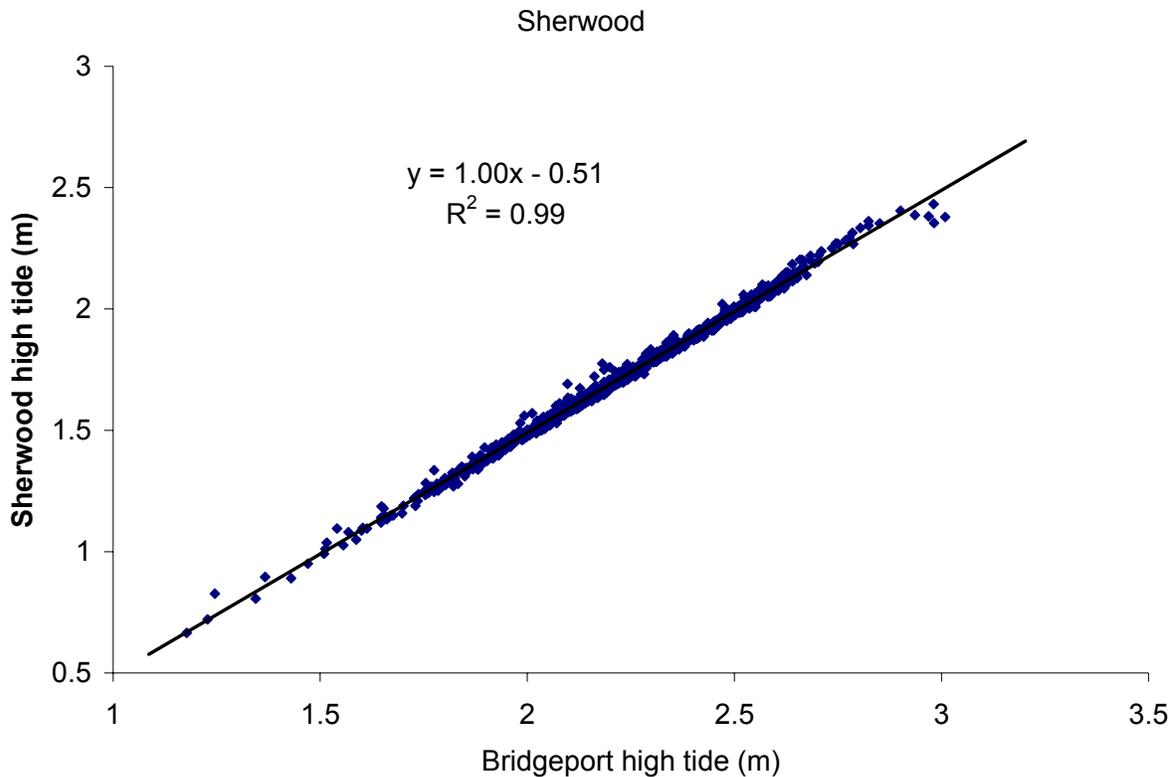


Figure 56. Relationship between high tide at Sherwood (as recorded by our water level logger) and high tide at Bridgeport (data from NOAA).

It is clear that we can relate high tides at Sherwood to high tides at Bridgeport using a factor of 1.00 (slope of the line in Figure 56). We can thus create a synthetic dataset of Sherwood high tides by using Bridgeport high tides. This synthetic dataset has Bridgeport MLLW as its datum (Sherwood-Bridgeport datum).

Over the summers of 2005-2007, we collected 5-7 tide stick measurements for each SET benchmark at Sherwood; these measurements were collected under a range of tidal heights (Bridgeport HT = 2.27 to 2.65 meters). Each measurement is a record of high tide water level relative to the top of the cap of the SET benchmark. Subtraction of these measurements from the corresponding Sherwood high tide (from the synthetic dataset) allows calculation of the height of each benchmark cap relative to the Sherwood-Bridgeport datum.²³ As can be seen in Figure 57, these offsets were, as expected, stable over time, and could be measured with reasonably good precision (~4 mm).

²³ height of cap relative to Bridgeport = Bridgeport high tide – high tide relative to cap (as recorded by tide stick)

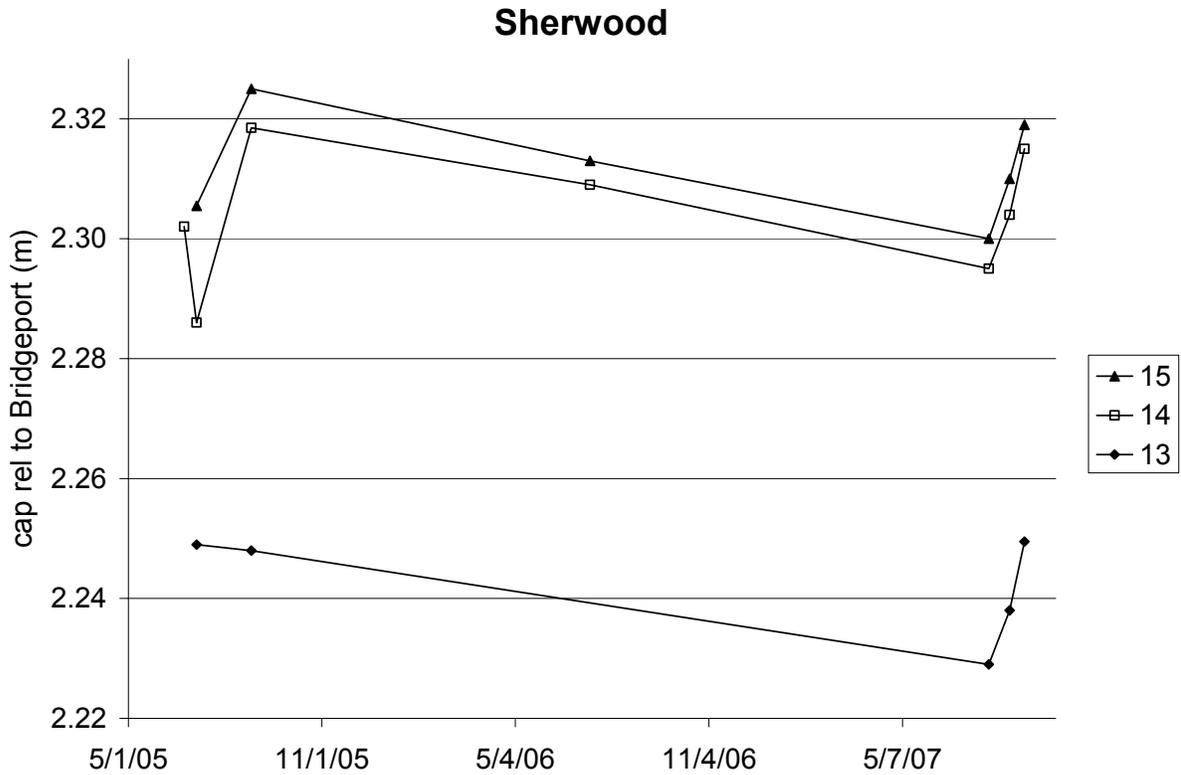


Figure 57. Calculated height of each SET benchmark cap relative to the Sherwood-Bridgeport datum, as determined from tide stick data.

We combined the tide stick data with the SET data to calculate elevations of each plot relative to the Sherwood-Bridgeport datum²⁴ (see Table 3, below). We then used the synthetic high tide dataset for 2005-2007 to calculate flooding frequency for this 3 year period (i.e., percent of high tides flooding the surface) as a function of surface elevation (Figure 58). The range of sediment surface elevations for our plots is also shown, and indicates that our plots are flooded on 58% of high tides (see also Table 3).

To calculate flooding duration (% of the time that each plot is submerged), we used our hydrology data from the summer of 2006 (6/20/06-10/13/06)²⁵, together with our estimated elevation of each plot relative to the local datum. Results (Figure 59 and Table 3) indicate that our plots are flooded 15% of the time.

²⁴ sediment surface relative to Sherwood-Bridgeport datum = cap relative to Sherwood-Bridgeport datum (from Table 3) – (39.5cm – average SET pin reading in cm)/100, where 39.5cm takes into account the total height of the pins and the height from the cap to the SET arm; note that the elevation of the sediment surface is defined as the average of the sediment surface elevation at the 36 SET pin locations. A similar procedure was used to calculate plot sediment surface relative to the Sherwood water level logger datum itself; the range of resulting surface elevations is plotted in Figure 53.

²⁵ This time period was used because we have good data from all 3 sites.

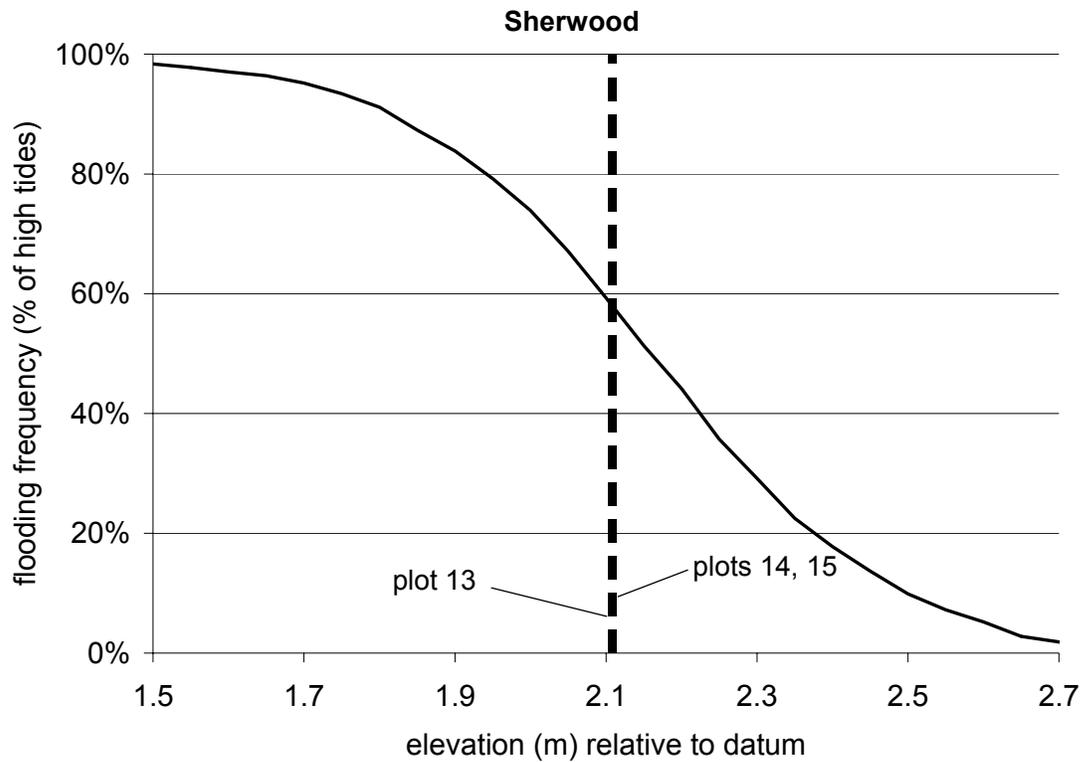


Figure 58. Elevation-frequency curve for Sherwood, showing elevations (and flooding frequencies) of plots. Datum = Sherwood-Bridgeport datum.

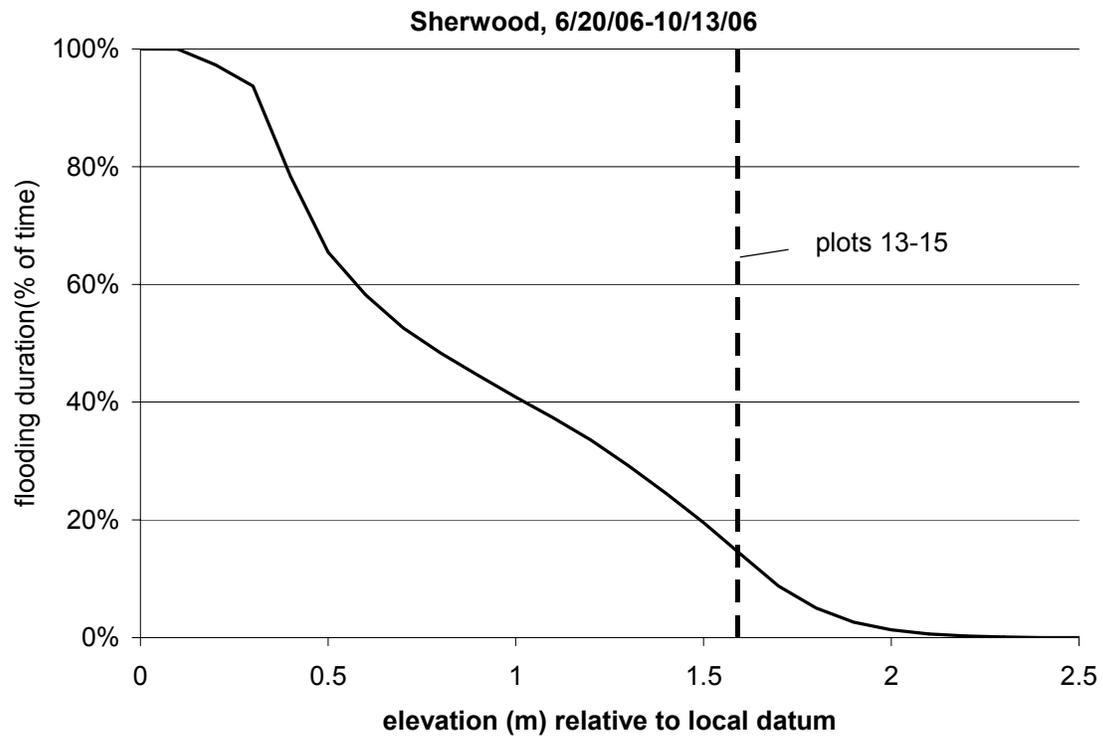


Figure 59. Elevation-duration curve for Sherwood, showing elevations (and flooding durations) of plots. Datum = local datum.

3.7.4 Comparing the three marshes

The elevation and hydrologic data presented above are summarized for all 3 marshes in Table 3. Table 4 presents additional data for each marsh: the mean tidal range (derived from our hydrologic data for the period of record at each marsh); the maximum differences in elevation and flooding frequency between plots at each site (summarized from Table 3), and the average elevation differences within a plot (from our SET data).

For direct comparison of the tidal regime at each marsh, we also present a representative 2-day portion of the hydrology data for each marsh, in Figures 60-62.

Several observations can be made:

- There are no differences by nutrient treatment in elevation or hydrology. Given the relatively short time period of fertilization and the lack of effect on accretion rates, this is not surprising
- Sherwood (the drowning marsh) is not particularly wet – it is roughly comparable to the drier section of Hoadley in both flooding frequency and duration.
- Jarvis (the restoring marsh) is considerably wetter than Hoadley and Sherwood in both flooding frequency and (especially) duration.
- Jarvis has a distinctly different tidal regime than the other 2 marshes (Figures 60-62), with a change in slope at roughly the elevation of the marsh surface. This results in a long period of flooding.
- The difference in elevation between plots at Hoadley and Jarvis are about the same (~8 cm), although this translates into more of a difference in flooding frequency at Hoadley than at Jarvis. The plots at Sherwood are all at a remarkably consistent elevation. This may be due in part to the way in which we positioned the plots, or it may reflect a larger feature of this marsh system.
- The micro-relief within plots (expressed as the average of the standard deviations of 18 pin measurements) is on the order of 1 cm at all marshes, though it may be slightly greater at Jarvis.

Table 3. Elevation and hydroperiod data for each plot. Highest and lowest plots at Hoadley are identified with bold italics.

Site	Plot	Elevation of benchmark cap (m), mean \pm standard error		Elevation of mean sediment surface (m)		Flooding frequency (% of high tides, 2005-2007)	Flooding duration (% of time, 6/20/06-10/13/06)
		relative to non-local datum	relative to local datum	relative to non-local datum	relative to local datum		
Hoadley high	1A	2.020 \pm	2.096 \pm	1.851	1.927	56.4	14.7
	1B	0.002	0.007	1.863	1.938	54.4	14.1
	2A	2.069 \pm	2.144 \pm	1.864	1.939	54.2	14.0
	2B	0.002	0.005	1.861	1.936	54.7	14.2
	3A	2.045 \pm	2.121 \pm	1.852	1.928	56.3	14.6
	3B	0.002	0.007	1.859	1.935	55.1	14.2
	4A	2.021 \pm	2.095 \pm	1.850	1.924	56.5	14.9
	4B	0.002	0.006	1.842	1.916	57.9	15.3
	5A	1.998 \pm	2.071 \pm	1.836	1.910	58.9	15.7
	5B	0.003	0.007	1.832	1.905	59.7	15.9
	6A	1.998 \pm	2.074 \pm	1.824	1.899	61.0	16.2
	6B	0.002	0.005	1.819	1.895	61.8	16.5
Hoadley low	7A	1.972 \pm	2.047 \pm	1.788	1.864	67.0	18.2
	7B	0.003	0.006	1.786	1.861	67.4	18.3
	8A	1.984 \pm	2.057 \pm	1.816	1.889	62.3	16.8
	8B	0.003	0.005	1.817	1.890	62.1	16.7
	9A	2.055 \pm	2.127 \pm	1.821	1.894	61.5	16.5
	9B	0.003	0.007	1.814	1.887	62.6	16.9
	10A	1.912 \pm	1.987 \pm	1.787	1.861	67.3	18.3
	10B	0.003	0.007	1.785	1.859	67.6	18.4
	11A	1.957 \pm	2.030 \pm	1.788	1.861	67.1	18.3
	11B	0.003	0.007	1.789	1.862	67.0	18.3
	12A	1.967 \pm	2.039 \pm	1.791	1.862	66.6	18.2
	12B	0.004	0.007	1.789	1.861	66.9	18.3
Jarvis	16	1.602 \pm 0.004	1.775 \pm 0.003	1.435	1.608	79.4	31.4
	17	1.513 \pm 0.005	1.686 \pm 0.003	1.359	1.532	86.9	35.0
	18	1.557 \pm 0.005	1.729 \pm 0.002	1.418	1.591	81.0	32.3
Sherwood	13	2.243 \pm 0.004	1.729 \pm 0.005	2.105	1.591	58.4	14.6
	14	2.304 \pm 0.004	1.784 \pm 0.007	2.111	1.591	57.5	14.6
	15	2.312 \pm 0.004	1.794 \pm 0.003	2.109	1.591	57.8	14.6

Table 4. Summary of hydrology and elevation data at the three marshes.

Marsh	Mean Tidal Range (m)	Maximum Inter-plot Difference in Elevation (cm)	Maximum Inter-plot Difference in Flooding Frequency (percentage points)	Average Intra-plot Difference in Elevation (cm)
Hoadley	1.71	7.9	13.4	0.8
Jarvis	1.31	7.6	7.5	1.4
Sherwood	1.38	0.1	0.9	1.0

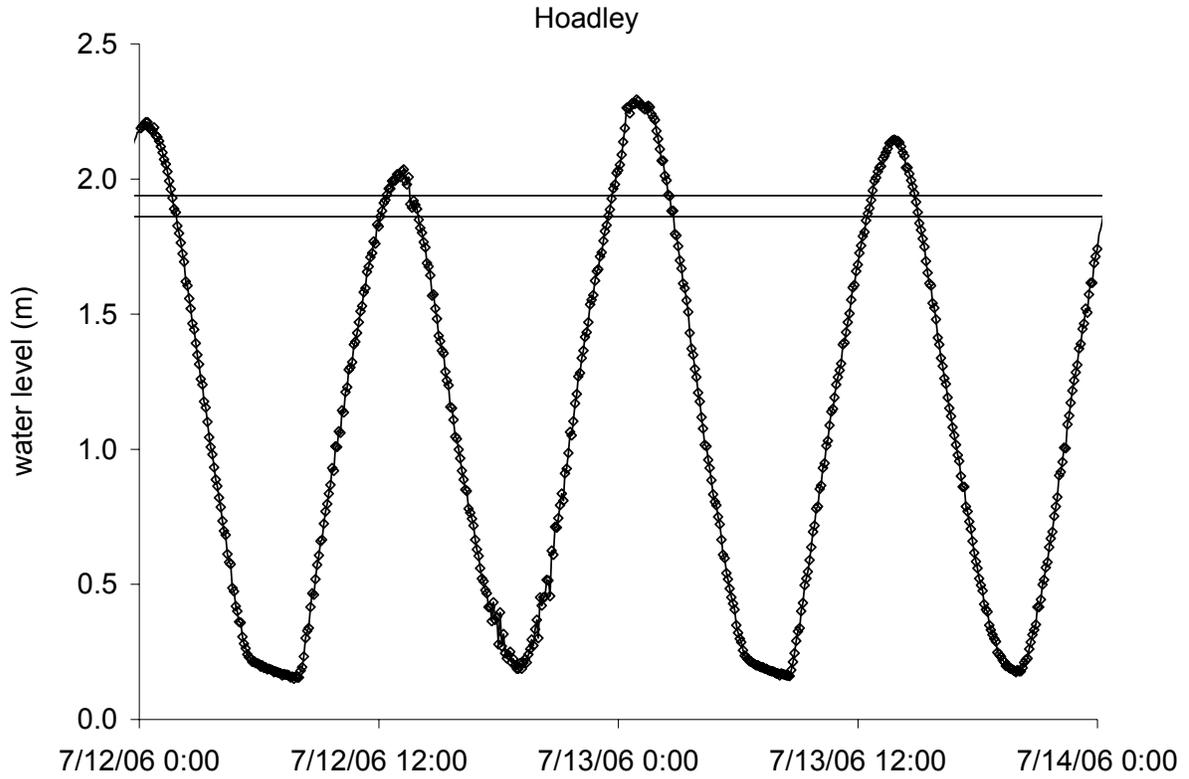


Figure 60. Two days of tidal flows at Hoadley. Elevation of highest and lowest plots is shown.

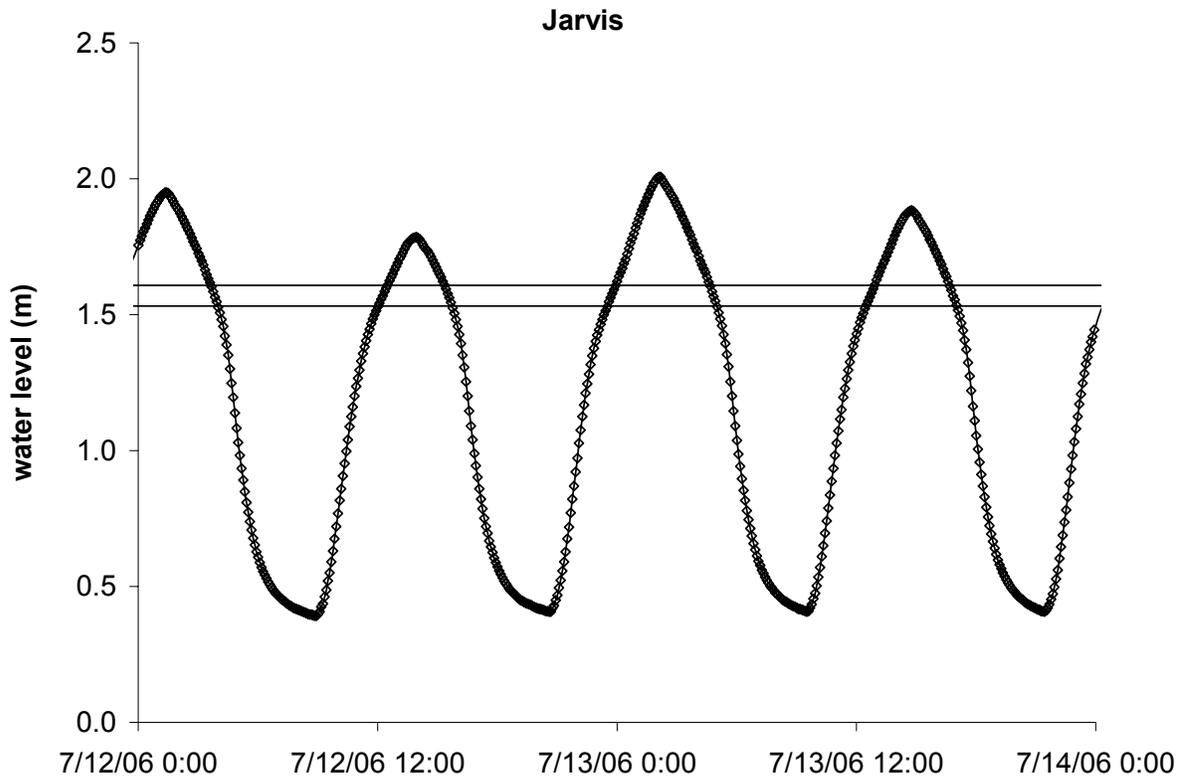


Figure 61. Two days of tidal flows at Jarvis. Elevation of highest and lowest plots is shown.

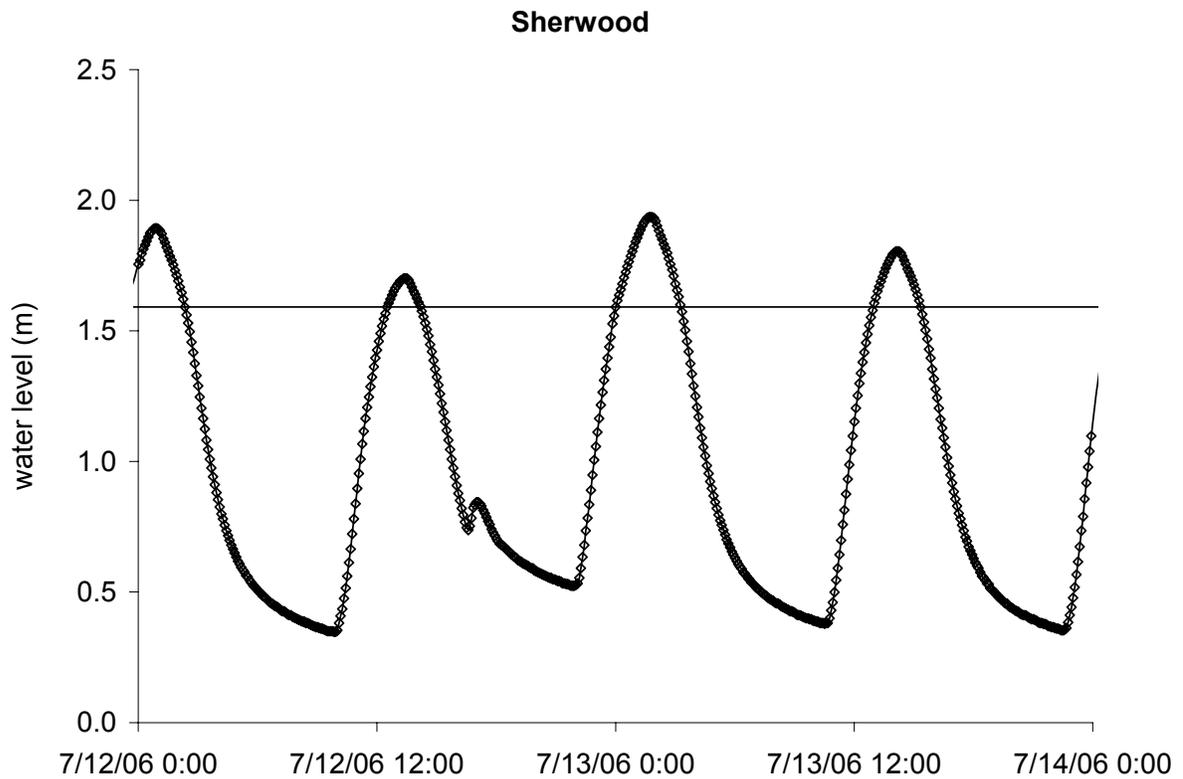


Figure 62. Two days of tidal flows at Sherwood. Elevation of plots is shown.

4. CONCLUSIONS

4.1 Nutrient Effects

A summary of the results of our fertilization experiments is shown in Table 5.

Table 5. Summary of the results of fertilization experiments at Hoadley.

Parameter/process	Nutrient Effect?	Fig. #	Comment
porewater N and P concentrations	yes	10,11	N higher in N plots; P higher in P plots
aboveground veg. N and P concentrations	yes	22,26	N higher in N plots; P higher in P plots
belowground N	mostly not	23-25	marginal (but sig.) increase in MOM N concentration in 2005 data; no other differences in N concentration or belowground N storage
belowground P	yes	26,27	much higher P in mud in P plots
porewater sulfide	?	12	lower sulfide in N plots?
aboveground productivity	yes	13	generally higher in N plots
belowground productivity	?	21	no significant differences, possibly slightly lower in N plots
belowground macro- and micro-organic matter content	no	17-19	no differences in MOM or %C in mud
decomposition	no	30	3 month litter bag experiment; only ~15% decomposition; could there be differences with longer decomposition periods?
respiration	?	31	summer CO ₂ flux was higher in NP plots, but high inter-plot variability make this not statistically sig., and the fact that we have only 1 summer data point makes it hard to draw conclusions
accretion and elevation change	no	42,43	no systematic differences in accretion (feldspar) or elevation change (SET) measurements
hydrology	no	Table 3	

As can be seen in Table 5, our nutrient treatments clearly had significant effects on some aspects of marsh structure and function. N and P treatments led to increased nutrient concentrations (N and P, respectively) in porewater and aboveground vegetation. N fertilization led to higher aboveground productivity. P treatments led to higher P concentrations bound to mud.

Perhaps more interesting, however, are the effects that we did *not* observe. N and P fertilization generally did not appear to substantially affect belowground processes, including

productivity, decomposition, and soil respiration. Likewise, there was no indication that N and P fertilization affected sediment accretion or net elevation change. To some extent, our ability to observe these differences may have been confounded by the naturally high variability between plots, but we can safely conclude that these differences, if they exist, are subtle and unlikely to be of major importance. As a result, we consider it *unlikely* that excess nutrient loading is a major contributor to marsh drowning. Also supporting this conclusion is the fact that the drowning marsh (Sherwood) had lower DIN and DIP concentrations than the reference marsh (Hoadley).

An interesting side note concerns the difference in behavior between added N and added P. We were surprised to find that, unlike aboveground biomass, belowground MOM in N-fertilized plots did not take up substantial additional N, even when the MOM was freshly-grown (ingrowth chambers). Likewise (but less surprisingly), mud in N-fertilized plots did not retain N, presumably because of loss of the highly soluble DIN to washout and denitrification. In 2005, N plots retained only ~4% of the N applied as fertilizer, and this was in the form of aboveground vegetation. In contrast, P-fertilized plots had P concentrations in both MOM and mud that were about twice the concentrations in control plots, and retained ~35% of the added P, all belowground.²⁶

4.2 *Inter-marsh Comparison*

A summary of the results of our inter-marsh comparison is shown in Table 6. The most important differences between the marshes are as follows:

- Hoadley appears to have higher porewater salinity than Jarvis and Sherwood.
- Hoadley appears to have lower aboveground productivity, but higher belowground productivity, than Jarvis and Sherwood, perhaps related to its higher salinity.
- Jarvis has taller culms but lower culm densities than Hoadley and Sherwood.
- Jarvis is much wetter than Hoadley and Jarvis, with a longer high water period.
- Jarvis has high rates of both accretion and elevation change, while Sherwood has moderate rates of both and Hoadley has moderate rates of accretion but low elevation change, reflecting substantial subsidence.
- Jarvis has lower MOM content and more mud than Hoadley and Sherwood, perhaps because of its higher rates of trapping of inorganic sediment.
- Topographic relief within the marsh appears to be lower at Sherwood (at least in our study plots) than in the other 2 marshes.

²⁶ The difference in MOM P concentrations is not statistically significant, due to high variability and low sample numbers.

Table 6. Summary of the results of the inter-marsh comparison (Hoadley, Jarvis, Sherwood).

Parameter/process	Inter-marsh differences?	Fig. #	Comment
porewater N and P concentrations	yes	10,11	N and P both higher at Hoadley; is this a “leakage” effect from the fertilization?
aboveground veg. N and P concentrations	yes	22,26	N slightly higher at Hoadley; no differences in P
belowground N	no	23-25	no consistent or clear differences; Jarvis slightly higher in MOM N; Sherwood slightly higher in mud N
belowground P	no	26,27	
porewater salinity	yes	12	Hoadley has higher salinity
aboveground productivity	yes	13	Hoadley often less productive; Jarvis has fewer, taller culms than Sherwood and Hoadley
belowground productivity	yes	21	Hoadley more productive
belowground macro- and micro-organic matter content	no	17-19	Jarvis much lower in MOM and %C in mud
decomposition	no	30	3 month litter bag experiment; only ~15% decomposition; could there be differences with longer decomposition periods?
respiration	no	31	no difference in annual CO ₂ flux
accretion and elevation change	yes	42,43	Jarvis has highest rates of accretion and elevation change; Hoadley has substantial subsidence, resulting in low net elevation change; Sherwood has intermediate elevation change and low accretion
hydrology	yes	Table 3	Hoadley has a higher tidal range; Jarvis has a higher flooding frequency and duration than Hoadley and Sherwood, and has a different flooding regime, with a longer high water period

We believe that the high rates of accretion and elevation change at Jarvis are related to the favorable hydrology of this site. The marsh surface at Jarvis is flooded on ~80% of high tides, and is under water about 1/3 of the time. This provides ample opportunity for sediment deposition on the marsh surface. In addition, the change in the slope of the Jarvis hydrograph at roughly the elevation of the marsh surface (not seen at the other marshes) may reflect the slowing of the tidal waters as they overtop the channel and spread across the marsh surface. Another factor in these differences may be that, compared to the other marshes, Jarvis is less directly connected to LIS. This may affect the hydrograph and may result in slower water movement and more opportunities for sediment deposition.

We believe that the patterns of productivity at Jarvis also reflect this difference in hydrology and sediment dynamics. The lower belowground MOM content seen at Jarvis probably does

not reflect lower belowground productivity (which we did not observe in our ingrowth chambers), but rather the higher inputs of inorganic sediment from tidal deposition. The low culm density may also be related to high sediment deposition rates and conforms to the general pattern of lower-elevation tall-form *Spartina alterniflora*.

In sum, Jarvis is a successful restoration site. Although current conditions are certainly on the wetter end of the acceptable range for *S. alterniflora*, the marsh is not drowning. This site appears to be on a trajectory of increasing elevation relative to water level. Despite the patchiness of the vegetation, overall productivity is high and the marsh is likely to continue to thrive.

The substantial subsidence that we observed at Hoadley is an extremely important phenomenon, but one that we have no explanation for. The subsidence appears to be unrelated to nutrient treatment; if anything, the plots with the least subsidence are fertilized ones, but there are plenty of fertilized plots that also show a great deal of subsidence. The subsidence is not apparent in the first year of monitoring, and appears to have begun sometime in winter 2005 to summer 2006. Seasonal or tidal variation in marsh level may be important in this marsh and may confound our interpretation of SET and feldspar data.

4.3 Thoughts on Marsh Drowning at Sherwood Island

Despite the mudflat that has developed ~2m away, our plots at Sherwood Island are not yet drowning. Flooding frequencies and durations are low to moderate – no wetter than Hoadley and certainly drier than Jarvis. In fact, the marsh would have to lose about **40 cm** of elevation relative to water level to be faced with the same flooding duration as Jarvis. Productivity at Sherwood is reasonably high both aboveground and belowground, and generally quite comparable to Jarvis.

At the same time, the accretion data give reason for concern. For plots 13-15, accretion over the project period was 3.0, 2.6, and 1.3 mm yr⁻¹, respectively, while elevation change was 3.5, 7.1, and 1.6 mm yr⁻¹.²⁷ It is not clear why plot 14 has so much larger an elevation change than its accretion rate (and than the other plots). In any case, the low accretion rates, especially in plot 15, may indicate an absence of sediment delivery to this marsh.

We speculate that the nature of drowning in this marsh system is closely linked to its hydrology. Due to the relatively small size of this marsh system, the nature of the tidal regime, and perhaps changes to the surrounding hydrology (i.e., the Millpond), there appears to be a large volume of water moving relatively rapidly through this system. The parts of the marsh (like our plots) that are relatively high are only flooded on ~15% of high tides, and when the flooding tides do come, they may be moving too rapidly to deposit sediment. On the other hand, the parts of the marsh that are a bit lower (e.g., the mudflat that is ~2m away from our plots), are no doubt flooded frequently but the water seems to be moving too rapidly to deposit sediment, and instead is likely to erode existing sediment.

²⁷ calculated as (final – initial)/(timeperiod)

Thus, we believe that the causes of marsh drowning at this site are likely to be found in inorganic sediment delivery (and erosion) processes rather than productivity and decomposition processes. This is consistent with our conclusion that nutrients (which are more likely to affect productivity and decomposition) do not play a major role in marsh loss at Sherwood Island.

4.4 Evaluating Our Hypotheses

To summarize, we revisit and evaluate our hypotheses:

1. Adding N or P singly or in combination to salt marsh plots will lead to the following effects:
 - a. an increase in net aboveground primary production (NAPP): **confirmed**
 - b. a decrease in belowground primary production: **rejected**
 - c. an increase in sediment respiration: **rejected**
 - d. a decrease in belowground dead macro-organic matter and total belowground organic matter (due to the combination of b and c): **rejected**
 - e. a decrease in accretion rate and net elevation change and a corresponding increase in hydroperiod: **rejected**

2. Compared to a stable marsh, a drowning marsh will have:
 - a. greater flooding frequency and duration: **rejected**
 - b. lower rates of belowground primary production: **confirmed (but mitigated by higher rates of aboveground production)**
 - c. higher rates of sediment respiration: **rejected**
 - d. lower rates of accretion and net elevation change: **confirmed in part (lower rates of accretion, higher rates of elevation change)**

3. Compared to a stable marsh, a restoring marsh will have
 - a. greater flooding frequency and duration: **confirmed**
 - b. similar or higher rates of accretion and net elevation change: **confirmed (higher)**

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PRESENTATIONS/PUBLICATIONS/OUTREACH

The following presentations on this project were made by Dr. Anisfeld:

- April 13, 2005: Southern Connecticut State University
- February 23, 2006: Connecticut Association of Wetland Scientists
- April 30, 2007: Massachusetts College of Liberal Arts

The following master's theses were written as part of this project:

- Jessica Darling, April 2006, "Controls on aboveground productivity in three salt marshes on Long Island Sound."
- Joanna Carey, December 2006, "Effects of nutrients on decomposition rates in New England salt marshes."
- Troy Hill, August 2007 (expected), "Carbon dynamics in Long Island Sound salt marshes: Impacts of nutrients and hydrology."

We expect to prepare several manuscripts for publication in the peer-reviewed literature based on this research.

APPENDIX I: METHODOLOGICAL ADJUSTMENTS FOR MEASURING CO₂ FLUX

BY TROY HILL

This Appendix details the various devices constructed and used to obtain measurements of carbon dioxide fluxes from the sediment surface over the course of the summer 2007 (Fig. A1.1). All measurements were taken with a LI-COR 6200 closed-dynamic chamber system with an automated CO₂ analyzer. Modifications regard the connection between the analyzer and the marsh surface.

Part 1: Culm Cutting

The first approach relied on the LI-COR respiration chamber, which was connected to a soil collar permanently implanted in the marsh surface. These traditional soil collars measured flux over 83.32 cm² of sediment, and were accompanied by a total system volume of 1252 cm³. The collars were 10 cm in diameter, so in our marshes they inevitably encompassed culms of *Spartina* and other flora. Because the plants were too large to fit into the respiration chamber, culms were cut and sealed with silicone sealant prior to taking measurements. The first round of data obtained in this way is reviewed in the attached report. To summarize, data generated in the first round, collected between June 3rd and June 7th, 2007, at sediment temperatures (measured at a depth of 10 cm) between 17.1 and 21.2°C, were on par with flux rates reported elsewhere (Howarth and Teal 1979; Howarth and Giblin 1983; Houghton and Woodwell 1980).

The second round of data using this method, during the last week of June, revealed drastically accelerated rates of flux (Fig. A1.2). Sediment temperatures at a depth of 10 cm were between 20.2 and 23.2°C during the second round. In most salt marshes, Q₁₀ values, or the multiplier that describes how flux rates change with a 10°C increase in temperatures, are approximately two (e.g., Morris and Whiting 1986). The second round of data gathered in this study using traditional soil collars saw CO₂ fluxes triple or quadruple over very minor increases in temperature. This is very discordant with the literature, and it was surmised that cutting culms stimulated releases of labile organic matter belowground, which then augmented CO₂ fluxes. The first round of data was taken immediately after culm cutting, and thus was not influenced by releases of labile organic matter. It therefore represents an accurate, if incomplete, portrayal of CO₂ fluxes. In order to understand monthly and seasonal trends in CO₂ fluxes, and to more effectively evaluate differences between treatments, it was necessary to obtain more than a single data point for each plot. It became apparent that a methodological shift was needed.



Figure A1.1: The methods used to obtain CO₂ flux data. From left to right, an original soil collar, a modified soil collar, the community chamber, and the mini-chamber (with its soil adapter). (Photo: Hill)

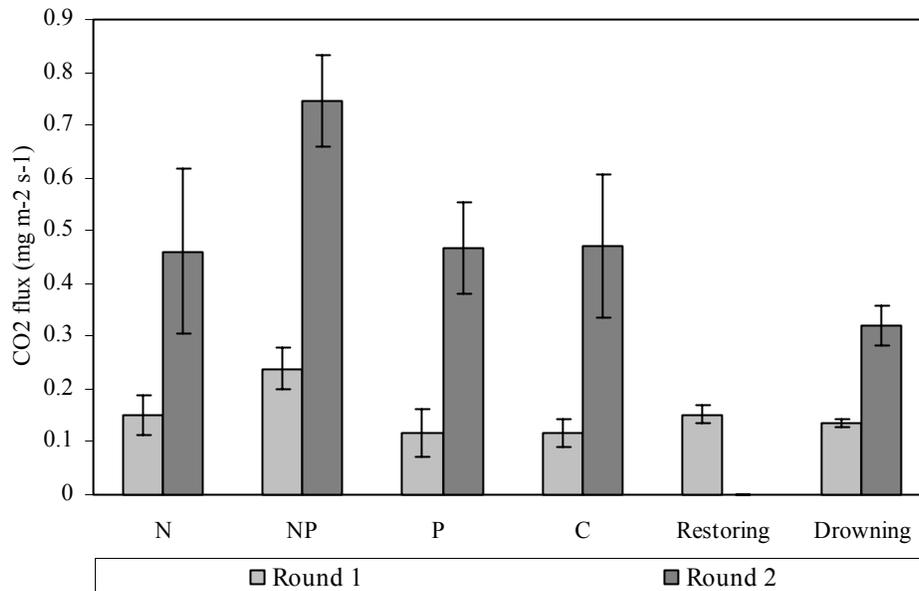


Figure A1.2: Comparison of two rounds of data collected using unmodified collars (mean \pm SE). Data were not gathered for the restoring marsh during the second round.

Part 2: Modified Soil Collars

To avoid artifacts created by cutting culms, modified PVC soil collars were created to fit in patches of sediment between the culms of vegetation (Fig. A1.1). The collars relied on a small piece of 3.75 cm diameter PVC that penetrated the sediment, connected to an adapter that expanded the collar up to the 10 cm required for connecting the LI-COR 6200 respiration chamber. The collars measured flux across an area of 6.28 cm² and the total system volume when using the modified collars was 1598 cm³. These collars produced data similar to that recorded in the initial round using unmodified soil collars (Fig. A1.3), a positive sign given their comparable field temperatures (17.1 – 21.2°C with original collars, and 18.2 – 25.2°C for the modified collars). Still, raw data from the LI-COR displayed a pattern of rapidly decreasing flux over small (3 ppm) intervals, indicating poor circulation inside the modified collars; the LI-COR seemed to only be sampling from the upper-most portion of the collar. In addition, the high chamber volume relative to its surface area meant that increases in CO₂ in the chamber were very slow.

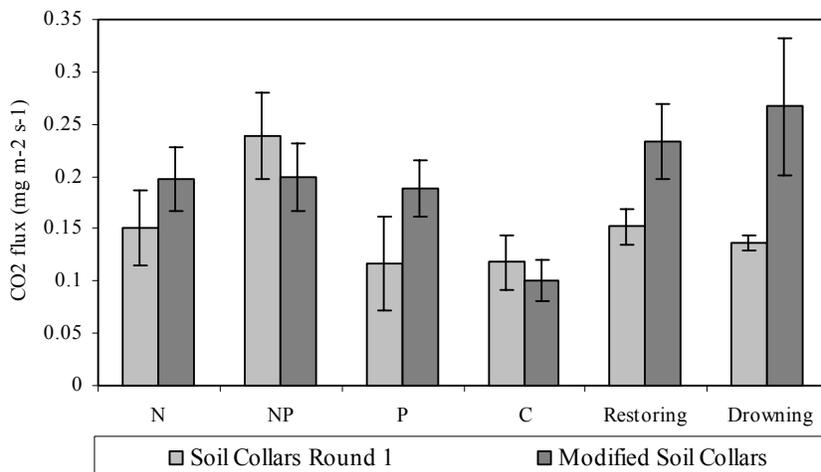


Figure A1.3: Comparison of data from original soil collars and modified soil collars (mean \pm SE).

Part 3: Community Chamber

To account for circulation issues, and attempt to increase the sediment surface area from which CO₂ flux was

measured, a community chamber was constructed of 10 cm diameter PVC (based on a design in Neubauer et al. 2000). Three 40 mm fans directing air upwards were located on one side of the chamber, and one fan on the top of the opposing side directed air downwards (Fig. A1.4). The chamber was 61 cm tall, and would enclose vegetation when deployed at a plot, while attempting to minimizing the total volume. Several layers of paint were applied to the chamber so as to stop enclosed plants from photosynthesizing during measurement, thus eliminating photosynthesis as a confounding factor. Soil collars implanted at the plots prior to connecting the community chamber mitigated disturbance to the sediment surface. The chamber worked effectively, but because of its cumbersome size and volume (6157 cm³ total volume), field use was judged to be less than ideal, particularly at the restoring marsh, which requires canoe access during a limited tidal window. The restoring marsh also has vegetation exceeding 1 meter in height – too large even for this chamber.



Figure A1.4: Left panel – fans inside the community chamber ensured air circulation. Right panel – a view of one of the ports that connect to the LI-COR. (Photos: Hill)

Part 4: Mini-Community Chamber

The mini-community chamber is essentially just that – a miniature version of the community chamber, measuring just 15 cm tall, and drawing on a 6.28 cm² sediment surface area (the unit was made of 3.75 cm diameter PVC). The small diameter allows deployment between culms, and two 17 mm fans circulate air in opposite directions within the chamber (Fig. A1.5). Adapters are deployed at plots before the mini-chamber is connected, in order to minimize disturbance to the sediment.

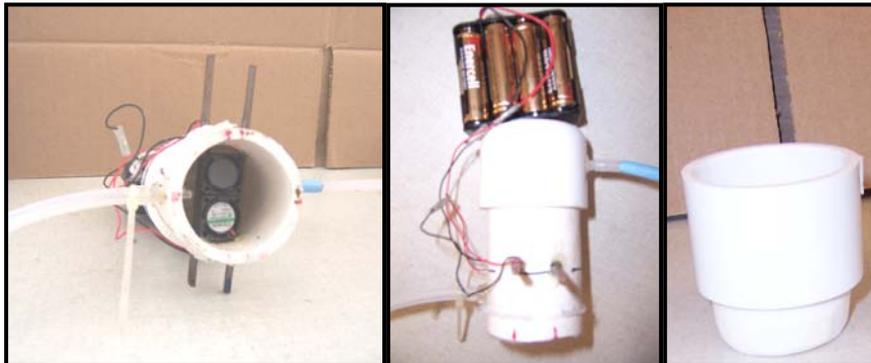


Figure A1.5: The mini-community chamber (left and center panels), along with its soil adapter (right panel). (Photos: Hill)

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