Estuaries and Coasts
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MANAGEMENT APPLICATIONS

# An Experimental Evaluation of Dock Shading Impacts on Salt Marsh Vegetation in a New England Estuary

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**Abstract** Docks constructed over salt marsh can reduce vegetation production and associated ecosystem services. In Massachusetts, there is a 1:1 height-to-width ratio (H:W) dock design guideline to reduce such impacts, but this guideline's efficacy is largely untested. To evaluate dock height effects on underlying marsh vegetation and light availability, we deployed 1.2-m-wide experimental docks set at three different heights (low (0.5:1 H:W), intermediate (1:1 H:W), and high (1.5:1 H:W)) in the high and low marsh zones in an estuary in Massachusetts, USA. We measured temperature, light, vegetation community composition, and stem characteristics under the docks and in unshaded control plots over three consecutive growing seasons. Temperature and light were lower under all docks compared with controls; both increased with dock height. Maximum stem height and nitrogen content decreased with available light. In the *Spartina patens*-dominated high marsh, stem density and biomass were significantly lower than controls under low and intermediate but not high docks. *Spartina alterniflora*, the dominant low marsh vegetation, expanded into the high marsh zone under docks. *S. alterniflora* aboveground biomass significantly differed among all treatments in the low marsh, while stem density was significantly reduced for low and intermediate docks relative to controls. Permit conditions and guidelines based on dock height can reduce dock impacts, but under the current guideline of 1:1 H:W, docks will still cause significant adverse impacts to vegetation. Such impacts may interfere with self-maintenance processes (by decreasing sediment capture) and make these marshes less resilient to other stressors (e.g., climate change).

**Keywords** Aboveground biomass · Ecosystem services · Height · Pier · *Spartina* · Stem density

## Introduction

Salt marshes are among the most productive ecosystems worldwide, providing a variety of ecosystem services (Barbier et al. 2011). Live salt marsh vegetation provides habitat while detritus fuels estuarine food webs supporting a variety of fish and invertebrate species (Boesch and Turner 1984; Deegan and Garritt 1997; Deegan et al. 2000; Baker et al. 2016). Salt marshes also provide carbon sequestration through burial of organic matter in marsh peat (Mcleod et al. 2011) and coastal resilience by buffering against erosion, waves, and storm surge (Barbier et al. 2011).

Docks and piers are common in estuaries worldwide (Gissy 1985; Kennish 2002; Kelty and Bliven 2003; Kennish 2016). Such structures provide property owners in coastal areas with direct access to bordering waterways for boating, swimming, fishing, and other forms of recreation. A continued desire for these amenities combined with increased coastal development has resulted in dock proliferation along the US east coast in recent decades (Chinnis and Stidham 2001; Kelty and Bliven 2003; Seabrook 2012).

This proliferation of docks and piers has led to concerns among coastal resource managers about cumulative environmental impacts (Buchsbaum 2001; Kelty and Bliven 2003). Piles supporting these structures directly displace marsh

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vegetation (Kennish 2001) while shading from the walkway and support structures reduce vegetation density (Kearney et al. 1983; Sanger et al. 2004; Alexander and Robinson 2006; Vasilas et al. 2011) and biomass (Alexander 2012). Shading from walkways over salt marsh can also alter underlying community composition (Vasilas et al. 2011) and stem height (Kearney et al. 1983; Colligan and Collins 1995; Sanger et al. 2004; Vasilas et al. 2011; Alexander 2012). These impacts to marsh production can reduce salt marsh ecosystem services since vegetation type and density directly influence the functioning of such services (Barbier et al. 2011).

Coastal towns and states along the US east coast have a variety of permitting conditions and best management practice guidelines designed to minimize dock impacts to salt marsh (e.g., Bliven and Pearlman 2003; Patterson 2003a; Patterson 2003b), but many of these conditions and guidelines lack scientific support. Recent studies have challenged the efficacy of dock design conditions in minimizing impacts to salt marsh (Vasilas et al. 2011; Alexander 2012). Alternative decking is currently required for docks built over salt marsh in Georgia that exceed 279 $m^2$ (The Savannah District US Army Corps of Engineers 2012), but recent experimental data show reductions in stem density and biomass under docks with grated decking and no increases in photosynthetically active radiation (PAR) relative to docks with traditional decking (Alexander 2012). In Maryland, docks constructed over salt marsh have maximum width and minimum height (91 cm for both) requirements to reduce shading impacts (COMAR 2016), but field data only support width-based restrictions (Vasilas et al. 2011).

In Massachusetts, the Department of Environmental Protection (DEP) recommends a variety of dock and pier design conditions to minimize shading impacts on salt marsh (Bliven and Pearlman 2003). These conditions include minimizing dock width, constructing docks in a north-south orientation, maintaining ≥1.9 cm spacing between decking boards, and maintaining a ≥1:1 height-to-width ratio (H:W). While all of these recommendations warrant experimental evaluation, dock widths in Massachusetts are mostly ≤1.2 m (Bliven and Pearlman 2003; Logan et al. 2015), orientation is constrained by the pathway available between the upland and adjacent waterway at a given property, and deck spacing for most docks is at the recommended 1.9 cm threshold (Logan et al., unpublished data). Dock height and H:W are more variable (Logan et al. 2015), and previous studies based on opportunistic sampling of private docks have shown differing influences of dock height on underlying marsh vegetation. Height was not significantly correlated with stem density for docks sampled in Maryland (Vasilas et al. 2011) or Georgia (Alexander and Robinson 2004), but docks sampled in the northeast USA showed reduced impacts for stem density (Kearney et al. 1983) and index of cover (Colligan and Collins 1995) with increasing dock height. In addition to Massachusetts, the 1:1 minimum H:W standard is also part of dock construction guidelines (Connecticut, New Hampshire) and federal permitting conditions (Maine, New Hampshire) for several New England states (New Hampshire Department of Environmental Services 2009; The New England District US Army Corps of Engineers 2012, 2015; Connecticut Department of Energy and Environmental Protection 2015).

To evaluate dock height and H:W impacts on underlying salt marsh vegetation, we conducted a controlled field study in which we deployed experimental docks set at three different heights and H:W (0.5:1, 1:1, and 1.5:1 H:W) over salt marsh in a Massachusetts estuary. Over three consecutive growing seasons, we evaluated abiotic conditions (temperature and light) and marsh vegetation characteristics (visual and clip plot sampling) under these docks and in unshaded control plots. We interpreted results in the context of current guidelines for docks and piers constructed over salt marsh in Massachusetts.

## Methods

### Study Site

We installed an experimental array of docks at the English Salt Marsh on the North and South River system in Marshfield, Massachusetts, USA (42.157054° N, −70.717731° W—see Google Earth v.6.1 imagery 24 August 2013, 27 September 2014, and 6 June 2015 for aerial views of the array). The English Salt Marsh Wildlife Management Area is a 288.5-acre parcel of salt marsh habitat managed by the Massachusetts Division of Fisheries and Wildlife (MacDonnell 2014). The marsh site is bisected by a dirt and gravel road that connects the mainland to a series of islands terminating at Trouant's Island. The islands are developed with small residential communities, but the marsh site has low nutrient loading (Mansfield and Grady 2015). The islands are bordered by higher elevation marsh dominated by *Spartina patens* with patches of *Distichlis spicata*. The site is exposed to the northeast, and the northern portion of the high marsh is hummocky (Smith and Carullo 2007; Mansfield and Grady 2015). The remaining area of the English Salt Marsh is low elevation marsh where *Spartina alterniflora* is the dominant species.

### Field and Laboratory

We installed 24 docks over the marsh platform in April 2013 (year 1) with half of the docks installed over the *S. patens*-dominated high marsh and the remaining half installed over the *S. alterniflora*-dominated low marsh (Fig. 1). We installed docks that were 1.2 m wide and 3.7 m long following a randomized complete block design (RCBD). All dock

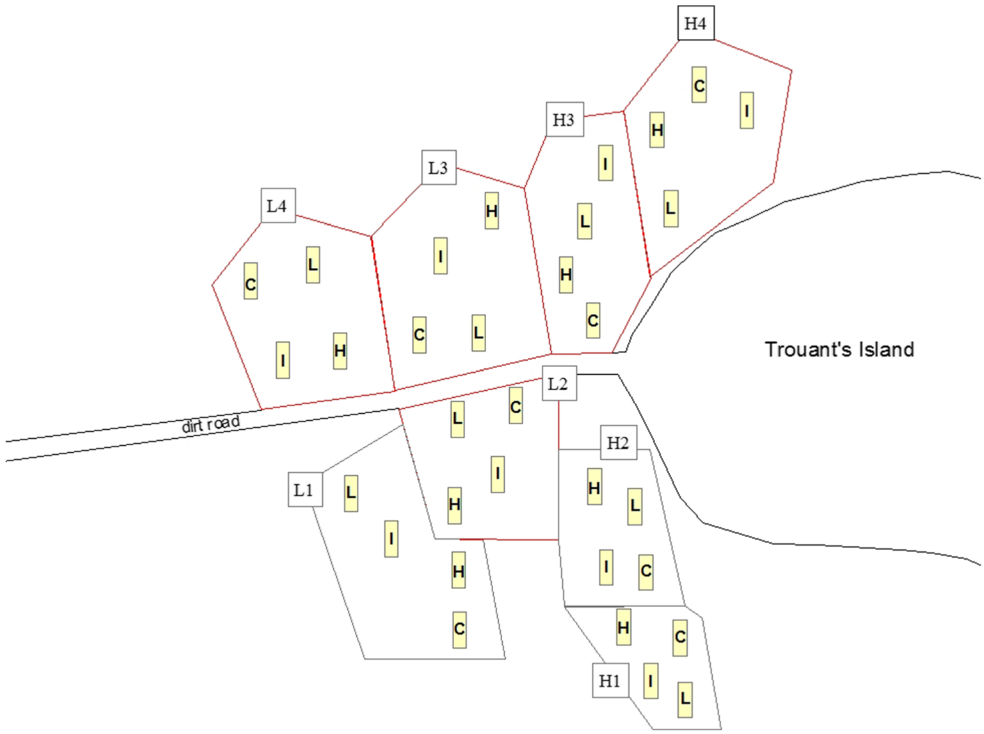


**Fig. 1** Experimental dock array organized following a randomized complete block design. Each block contains a low (0.5:1 height to width (*H:W*); *L*), intermediate (1:1 H:W; *I*), and high (1.5:1 H:W; *H*) dock as well as an unshaded control plot (*C*). Treatments within each block were separated by approximately 7.5 m. Four blocks were installed over the high marsh (*H1–H4*) and four blocks were installed over the low marsh (*L1–L4*). Half of the blocks were installed on each side of a dirt and gravel road that bisects the marsh and connects Trouant's Island to the mainland to the west of the project site

decking was 15.2-cm-wide 3.2-cm-thick cedar planking that was set with 1.9 cm spacing between planks. We included two 15.2-cm-wide cedar cross bracings at the two ends for additional support as well as a 3.2 × 15.2 cm cedar board (horizontal stringer) along the outer lengths of each side. For support structures, we set 10.2 × 10.2 cm pine supports at the four corners of the decking. For both high and low marsh locations, we installed two blocks of docks on each side of the dividing road (Figs. 1 and 2). The two northern high marsh blocks (H3 and H4) were in an area dominated by *S. patens* with a hummocky topography. Of the two southern high marsh blocks, H2 contained a co-dominant mixture of *S. patens* and *D. spicata* while H1 was *S. patens* dominated. *S. alterniflora* was the predominant species in all four of the low marsh blocks (L1–L4). Each block contained a single low (0.6 m; 0.5:1 H:W), intermediate (1.2 m; 1:1 H:W), and high (1.8 m; 1.5:1 H:W) dock as well as a control plot of the same dimensions that contained no dock (Fig. 2). For each block, we separated individual dock and control treatment plots by approximately 7.5 m. We included this buffer to minimize potential impacts of adjacent treatment plots (e.g., side shading), and set it at a slightly greater distance than the 5-m separation used for control site sampling in previous dock shading studies (Alexander and Robinson 2004; Sanger et al. 2004; Alexander 2012). We aligned all docks in a north-south orientation and secured each dock to the marsh platform with ropes and stakes extending from the four dock corners.

During the growing season (May–September), we installed 12 HOBO light and temperature loggers (model UA-002-64; Onset Computer Corporation). We set the loggers to record temperature (°C) and light (lumens m$^{-2}$) at 2-min intervals. HOBO logger total lux measurements are significantly correlated with photosynthetically active radiation (PAR) (Long et al. 2012; Medeiros et al. 2013), so relative light levels provide information relevant to primary production. We mounted loggers on wooden stakes set 0.3 m above the marsh platform and placed them under the centers of the dock and in the middle of the control footprints. We continuously monitored the H2 block throughout each growing season with four loggers, one under each dock treatment and one in the unshaded control plot. We rotated the remaining eight loggers weekly to

**Fig. 2** Image of a single block of the experimental dock array layout consisting of docks set at height-to-width ratios (H:W) of 0.5:1 (low), 1:1 (intermediate), and 1.5:1 (high) above the marsh platform as well as an unshaded control plot. Four replicate blocks were installed over the low marsh (*L1-L4*) and high marsh (*H1-H4*). Treatments within each block were separated by approximately 7.5 m

biweekly among the remaining seven blocks to allow for temperature and light-level comparisons among blocks. This rotation system generated a minimum of six and a maximum of 64 days of data per block per year (Online Resource 1). We plotted and visually examined temperature and light data, and only used data if accurate and complete results were available for all plots for a given block.

We removed the docks in October after each growing season to avoid loss or damage from winter storms and ice scouring. To ensure installation over the same footprint, we marked the corners of each dock and control area with wooden stakes during seasonal dock removal. We reinstalled all docks in March to April in 2014 (year 2) and 2015 (year 3).

At the end of the first growing season (year 1), we measured the relative elevation of all of the treatment plots using tide sticks (LeMay 2007). During a spring tide, we inserted peeled *Phragmites* stems coated with a mixture of water-soluble glue and red dye in the marsh platform at the center of each treatment plot during low tide. When the tide rose over the stems, the red coating dissolved up to the high water mark, leaving a clear indication of relative tidal elevation. After the tide had risen and fallen, we measured elevation at each site as the vertical distance from the marsh platform to the red line separating the dissolved and existing glue/dye sections of each stick.

We performed visual surveys at the end of the growing season (mid-September) of each sampling year. Visual surveys consisted of approximate estimates of percent cover of each vegetation type using the Braun-Blanquet cover-abundance scale (Roman et al. 2001). Following a visual survey of the entire area under each dock and control site, we assigned a percent cover estimate of <1–5%, 6–25%, 26–50%, 51–75%, or 76–100% to each species present.

We also collected end-of-season clip plot samples at all treatment plots. To determine the appropriate number of replicate samples per treatment plot, we first collected test clip plots from the high and low marsh zones adjacent to the experimental array. We collected sixteen 1/16 $m^2$ test plots from each zone and removed all aboveground biomass associated with stems originating within the quadrat area for each sample. We transferred samples to frozen storage, then later thawed, rinsed, and sorted samples in the laboratory by separating live and dead stems and further partitioning live stems by species. We counted the total number of live stems by species and measured total stem length for all *S. patens* (high marsh) and *S. alterniflora* (low marsh) samples using an electronic measuring board (± 0.1 cm). We placed all live stems in a drying oven for >48 h at 65 °C and weighed (± 0.01 g) each species individually. For each metric (stem density, median stem length, and stem dry weight), we randomly sampled (bootstrap set to 1000) increasing sample sizes ($n$ = 2 to $n$ = 16 quadrats) and generated mean and 95% confidence intervals. Based on a visual observation of these plots, we selected a sample size of eight quadrats since confidence intervals remained relatively constant across greater sample sizes (Fig. 3). We collected these eight clip plot samples from locations within each treatment plot that we previously selected based on a random number generator. To avoid edge effects, the potential sampling area for each dock was bounded by a 0.6 m buffer from each dock end and a 0.3 m buffer from each dock side edge. For blocks H3 and H4, we skipped any quadrats that landed in depressions as these areas lacked vegetation consistently across treatment plots and independently of light availability. We replaced such depression areas with samples taken from the nearest bordering quadrat area to the right of the depression. For experimental clip plot samples, we followed the same field and laboratory protocols applied to the test clip plots.

For each block, we pooled all live dry *S. patens* (high marsh) and *S. alterniflora* (low marsh) from a given dock or control site, homogenized the material using a food processor or glass blender, then stored an aliquot of each homogenate in glass scintillation vials. We weighed and packed approximately 4 to 5 mg of each homogenate into a tin capsule and analyzed each sample for % carbon (C) and % nitrogen (N) relative to aspartic acid using a CHN elemental analyzer at the Ecosystems Center of the Marine Biological Laboratory (MBL) in Woods Hole, Massachusetts, USA. The mean standard deviation of duplicate samples ($n$ = 10) for % C and N was 0.29% and 0.04%, respectively.

## Statistical Analysis

We assessed temperature and light data for each dock height treatment relative to control, unshaded plots. For all days from May through September in which we had temperature and light data for a complete block, we calculated the average temperature and total available light. We normalized dock temperature and light-level data relative to controls as $temperature_{control} - temperature_{dock}$ and $light_{control} - light_{dock}$. To assess how closely temperature and light conditions tracked across blocks, for each treatment, we calculated temperatures and light levels relative to the fixed H2 block (e.g., H2 low dock relative to H1 low dock).

We compared dock shading impacts on stem density and dry biomass using a mixed-model ANOVA in the “nlme” package in R (R Core Team 2016) separately for each marsh zone. Fixed effects were dock height treatment, year, and the interaction between dock height and year. We included plot nested within block as a random effect to account for pseudoreplication for each given treatment due to quadrat subsampling. We performed post hoc multiple comparisons of treatments for each sampling year using the “lsmeans”

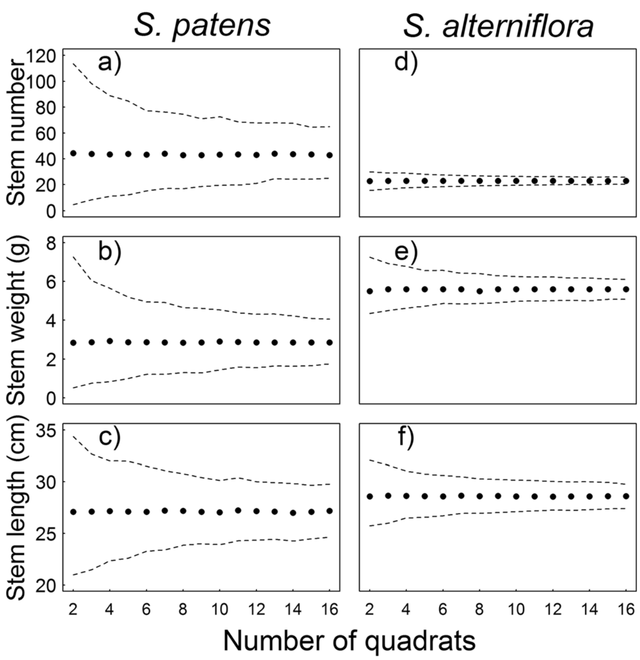


**Fig. 3** Stem number (**a**, **d**), weight (g; **b**, **e**), and median length (cm; **c**, **f**) for *Spartina patens* (**a**–**c**), and *Spartina alterniflora* (**d**–**f**) sampled at the English Marsh experimental dock array site. Mean (*solid circles*) and 95% confidence intervals (*dashed lines*) are based on 1000 bootstraps to increasing quadrat sample sizes from 2 to 16

package in R with a Holm adjustment (Holm 1979) for multiple comparisons. For the high marsh, we performed analyses based on combined data for *S. patens*, *D. spicata* (dominant and secondary species, respectively), and *S. alterniflora*. We included *S. alterniflora* in the high marsh analyses since visual surveys showed low but variable proportions of this species for dock and control treatments. For the low marsh, we performed analyses based only on *S. alterniflora* data.

We assessed live stem carbon (% C), nitrogen (% N), and carbon:nitrogen ratio (C:N) values for *S. patens* (high marsh) and *S. alterniflora* (low marsh) as a function of total seasonal light exposure for each dock height treatment. We summed the total amount of light (lumens $m^{-2}$) for each treatment from May through September and normalized values relative to the unshaded control plots (% control). We compared stem carbon and nitrogen values for each sampling year with the respective annual light (% of control) availability using ordinary least squares (OLS) regression. We evaluated relationships between elemental composition and light exposure based on slope 95% confidence intervals.

We used quantile and OLS regression to explore patterns in live stem length in relation to relative light availability for *S. patens* (high marsh) and *S. alterniflora* (low marsh). Using the same annual relative light availability applied to stem elemental composition analyses, we compared minimum (5th quantile), mean, and maximum (95th quantile) live stem lengths across treatments using the "stats" and "quantreg" packages in R.

## Results

### Site Characterization (Elevation)

While most plots within the respective high and low marsh zones had similar elevations, we observed two outliers in the low marsh zone. One low dock (L4) and one control plot (L2) were at lower and higher elevations, respectively, than remaining low marsh plots. We relocated these two plots for years 2 and 3 to areas with elevations that matched remaining low marsh sites based on another tide stick survey conducted in year 2. Final elevations, expressed as mean water height ± 1 SD (cm) above the marsh platform, during the year 1 spring high tide, were 33 ± 2 and 47 ± 3 cm for the high and low marsh blocks, respectively.

### Temperature and Light

Average temperature and total light under docks increased with dock height, and control plots had higher temperatures and light levels than all dock treatments (Online Resource 1; Fig. 4). High, intermediate, and low docks had average temperatures that were approximately 0.7, 1.2, and 2.1 °C lower than unshaded controls. The average daily light under low docks was approximately 20% of control light. For intermediate docks, underlying total light was more than double the low dock light levels and was approximately 50% of control light levels. Light under high docks was more than three times that of low docks and was approximately 65% of controls. Replicate treatments had similar temperatures and light levels across blocks (Online Resource 2). Relative to the H2

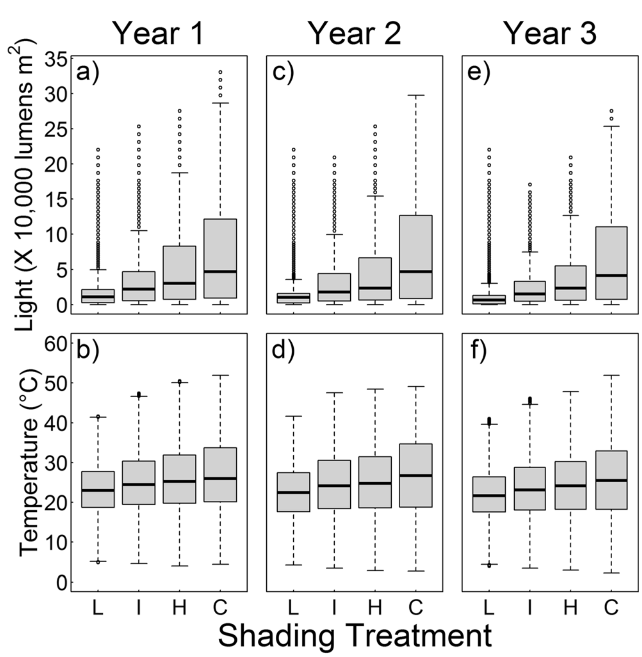


**Fig. 4** Box plots of light (**a**, **c**, **e**) and temperature (**b**, **d**, **f**) from the H2 block for each sampling year. *Each box* corresponds to an individual shading treatment consisting of low (*L*), intermediate (*I*), and high (*H*) docks as well as unshaded control plots (*C*)

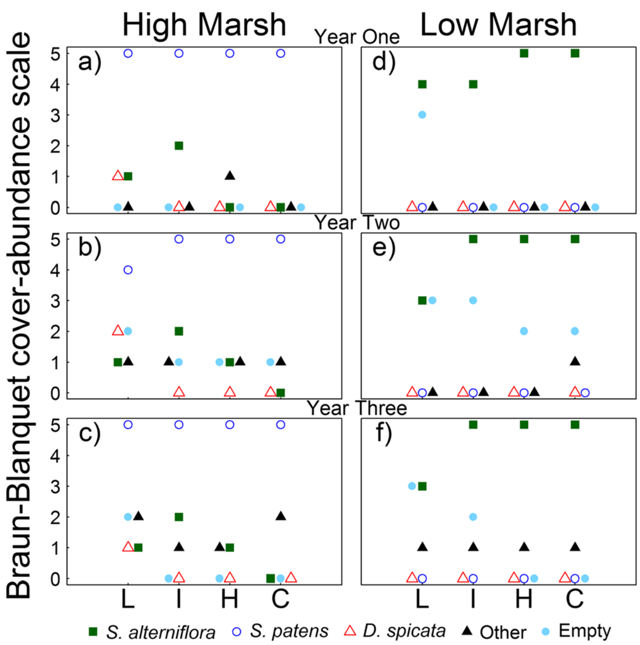


**Fig. 5** End-of-growing season Braun-Blanquet cover abundances of low (*L*), intermediate (*I*), and high (*H*) docks as well as unshaded control plots (*C*). *Symbols* represent median estimates among four replicates for *Spartina alterniflora* (*solid green rectangle*), *Spartina patens* (*open blue circle*), *Distichlis spicata* (*open red triangle*), all other species (solid black triangle), and bare, unvegetated marsh platform (*solid light blue circle*). The *y*-axis is ordinal number transformations that correspond to Braun-Blanquet abundance scale values where 1 is <1–5%, 2 is 6–25%, 3 is 26–50%, 4 is 51–75%, and 5 is 76–100%. Zero values represent species that are absent from a treatment

block, average temperatures and light levels ranged from 97.2 to 99.6% and 88.5 to 131.5%, respectively (Online Resource 2).

## Visual Surveys

Braun-Blanquet cover surveys showed a general stability in species composition for each treatment across sampling years for both high and low marsh habitats (Fig. 5). In the high marsh, *S. patens* was the dominant plant species in all treatments in all years. *D. spicata* was a secondary species in all treatments except absent in intermediate docks, and *S. alterniflora* was present in low densities in all dock treatments but not control, unshaded plots. In the low marsh, *S. alterniflora* was the dominant species across all treatments and years; the low docks also had a high proportion of unvegetated space in all 3 years (Fig. 5).

## Clip Plots

All of the main and interaction effects were significant for both marsh zones (Online Resource 3). Stem density and biomass values varied among dock treatments and sampling years (Figs. 6 and 7). For high marsh plots, relative stem density and dry biomass changed among treatments over the

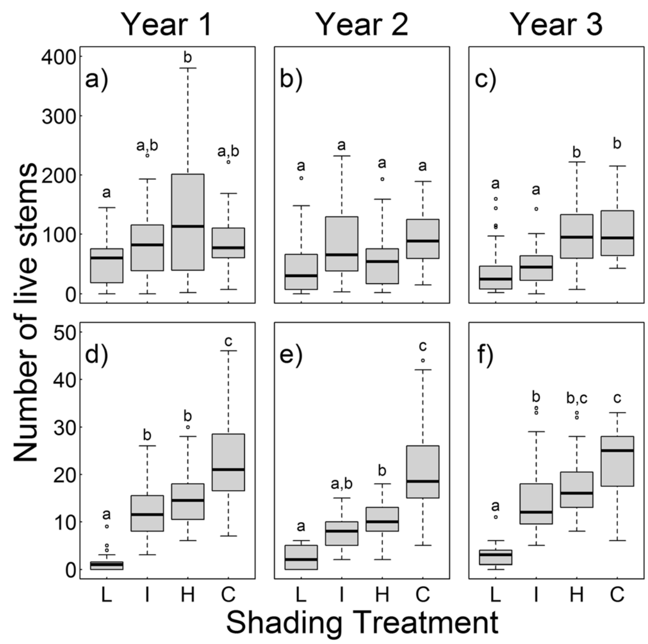


**Fig. 6** Box plots of live stem density (number of stems) per 1/16 m$^2$ plot from the high marsh (**a**–**c**) and low marsh (**d**–**f**) arrays for sampling years 1 (**a**, **d**), 2 (**b**, **e**), and 3 (**c**, **f**). *Each box* corresponds to an individual shading treatment consisting of low (*L*), intermediate (*I*), and high (*H*) docks as well as unshaded control plots (*C*). *All boxes for a given year* and *zone with different letter superscripts* significantly differed ($P < 0.05$)

3-year survey with a delayed response (Online Resources 3, 4, and 5; Table 1; Figs. 6 and 7). Relative to controls, dock plots did not show any significant reductions until the end of the

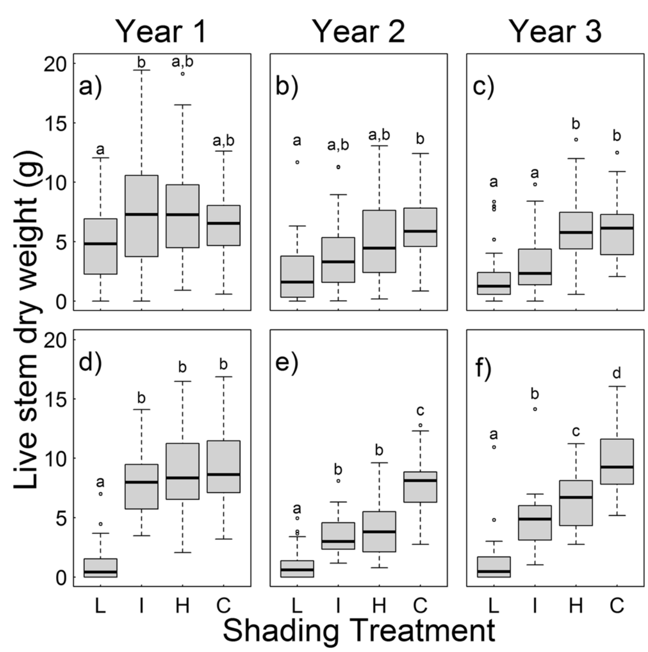


**Fig. 7** Box plots of live stem dry weight (g) per 1/16 m$^2$ plot from the high marsh (**a**–**c**) and low marsh (**d**–**f**) arrays for sampling years 1 (**a**, **d**), 2 (**b**, **e**), and 3 (**c**, **f**). *Each box* corresponds to an individual shading treatment consisting of low (*L*), intermediate (*I*), and high (*H*) docks as well as unshaded control plots (*C*). *All boxes for a given year* and *zone with different letter superscripts* significantly differed ($P < 0.05$)

**Table 1** Dock and control September stem density and biomass estimates

| Year | Treatment | Stem density (stems/0.5 $m^2$) | Stem biomass (g/0.5 $m^2$) | Stem density (% control) | Stem biomass (% control) |
|---|---|---|---|---|---|
| High marsh | | | | | |
| Year 1 | Control | 697 ± 167 | 52 ± 9 | | |
| | High | 1022 ± 683 | 62 ± 24 | 147 | 120 |
| | Intermediate | 682 ± 187 | 66 ± 22 | 98 | 126 |
| | Low | 453 ± 199 | 40 ± 16 | 65 | 77 |
| Year 2 | Control | 756 ± 93 | 48 ± 7 | | |
| | High | 669 ± 126 | 43 ± 19 | 88 | 88 |
| | Intermediate | 447 ± 167 | 31 ± 9 | 59 | 65 |
| | Low | 342 ± 78 | 19 ± 4 | 45 | 38 |
| Year 3 | Control | 888 ± 349 | 49 ± 7 | | |
| | High | 830 ± 314 | 49 ± 15 | 94 | 100 |
| | Intermediate | 386 ± 144 | 26 ± 3 | 43 | 52 |
| | Low | 357 ± 110 | 18 ± 5 | 40 | 36 |
| Low marsh | | | | | |
| Year 1 | Control | 186 ± 91 | 74 ± 25 | | |
| | High | 120 ± 37 | 71 ± 4 | 65 | 96 |
| | Intermediate | 96 ± 36 | 62 ± 7 | 52 | 84 |
| | Low | 10 ± 3 | 9 ± 6 | 6 | 12 |
| Year 2 | Control | 163 ± 61 | 62 ± 5 | | |
| | High | 80 ± 19 | 33 ± 10 | 49 | 53 |
| | Intermediate | 64 ± 12 | 28 ± 7 | 39 | 46 |
| | Low | 19 ± 12 | 8 ± 9 | 12 | 14 |
| Year 3 | Control | 178 ± 41 | 78 ± 17 | | |
| | High | 131 ± 32 | 52 ± 8 | 74 | 67 |
| | Intermediate | 110 ± 56 | 38 ± 12 | 62 | 49 |
| | Low | 20 ± 17 | 10 ± 11 | 11 | 13 |

Values are mean ± standard deviation estimates of four replicates per treatment per year and the average percent of the respective control

second growing season (low dock stem biomass), but by the end of the third growing season, both low and intermediate dock plots had significantly reduced stem density and biomass relative to tall docks and controls.

For low marsh plots, stem density and biomass responded more immediately to shading impacts (Online Resources 3, 4, and 5; Figs. 6 and 7). Low dock stem density and biomass were both significantly reduced relative to taller docks and controls after the first growing season, and both low dock stem density and biomass remained below 15% of control values throughout the study (Table 1). By the end of the third growing season, stem density for both low and intermediate docks was significantly lower than controls. Low marsh stem biomass significantly differed among all treatments at the end of the study with biomass scaling with light availability (Fig. 4).

Stem nitrogen content and C:N varied consistently with light level while carbon content did not (Online Resource 6; Fig. 8). Carbon content increased for both *Spartina* species in year 1, then decreased for *S. alterniflora* in year 2, and otherwise did not significantly vary as a function of light. Nitrogen content significantly decreased with increasing light in all three sampling years for both *S. alterniflora* and *S. patens*. Stem C:N increased with light level for years 1 and 2 (*S. alterniflora*) and for all 3 years (*S. patens*) mainly due to decreases in % N (Online Resource 6; Fig. 8).

Maximum live stem lengths significantly decreased with increasing light levels for both *S. patens* and *S. alterniflora* while relationships with minimum and mean lengths were inconsistent (Online Resource 7; Fig. 9). Mean lengths significantly decreased with increasing light for *S. patens* in all 3 years (Online Resource 7; Fig. 9).

## Discussion

Temperature, light, vegetation density, and vegetation biomass all increased with dock height, providing support for height-based design guidelines. For common 1.2-m-wide docks, these patterns also scale with H:W. Observed experimental results agree with previous surveys of private

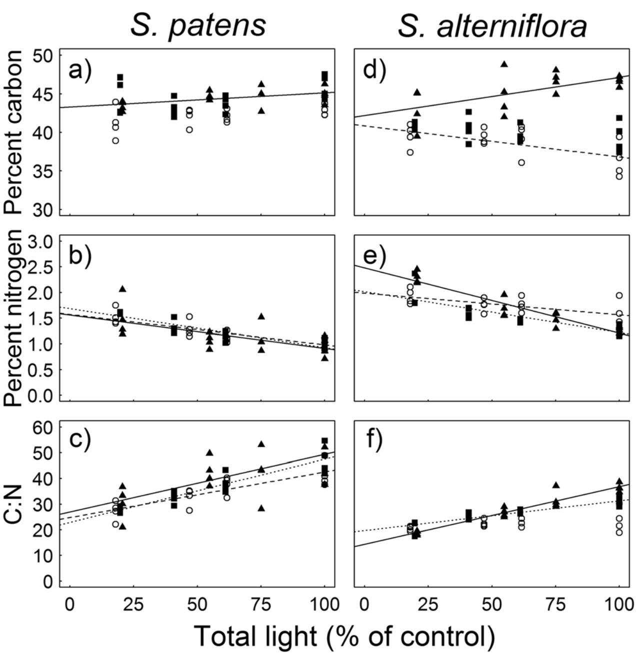


**Fig. 8** Plots of *Spartina patens* (**a**–**c**) and *Spartina alterniflora* (**d**–**f**) live stem percent carbon (**a**, **d**), percent nitrogen (**b**, **e**), and C:N ratios (**c**, **f**) relative to total available light normalized to total light for control, unshaded plots. Individual points represent elemental composition data for years 1 (*solid triangle*), 2 (*open circle*), and 3 (*solid square*). *Lines* are significant best fits based on ordinary least squares regression for years 1 (*solid*), 2 (*dashed*), and 3 (*dotted*)

docks and piers in New England showing reduced marsh impacts with increases in dock height (Kearney et al. 1983; Colligan and Collins 1995) and H:W (Colligan and Collins 1995). In a 12-week greenhouse incubation experiment, *S. alterniflora* grown with 50 and 75% shading of incident light had an average reduction in aboveground biomass of 37 and 98%, respectively (Medeiros et al. 2013). These shading treatments closely match the light reduction observed under our intermediate and low docks in the low marsh zone of 48 and 89%, respectively, and a reduction in biomass after 3 years of 51 and 87%. The near-complete loss of aboveground biomass after a single growing season was consistent between our study and the other for the increased shading condition. The minimum 1:1 H:W guideline provided a reduction of impact in the low marsh where docks set at 0.5:1 had lower stem density and biomass. Within the high marsh, stem density and biomass below low and intermediate docks were indistinguishable, and high docks supported greater stem density than intermediate docks. Based on our 3-year study, dock H:W guidelines would need to be increased from 1:1 to 1.5:1 to reduce significant impacts to marsh production.

Observed differences in shading impacts in the two marsh zones could reflect different responses among species or in relation to the abiotic conditions in these two habitats. In the high marsh, docks appeared to facilitate the landward expansion of *S. alterniflora* as all dock heights contained low densities while *S. alterniflora* was absent from unshaded plots. This shift in *Spartina* species was also observed under private docks in Maryland (Vasilas et al. 2011). Under natural conditions, *S. patens* outcompetes *S. alterniflora* in the high marsh zone of New England salt marshes (Bertness and Ellison 1987; Bertness 1991), but abiotic conditions associated with docks appear to reduce competitive advantage for *S. patens*. Since *S. alterniflora* was able to expand its range into the high marsh under docks in our study, the more extreme and rapid loss of vegetation that we observed under docks in the low marsh is probably due to interactive abiotic effects rather than an inherently lower shade tolerance for *S. alterniflora* relative to *S. patens* and *D. spicata*. Stress from regular tidal inundation (Gleason and Zieman 1981) combined with shade stress may produce a more rapid loss of vegetation under dock structures in the low marsh relative to the high marsh, where higher elevation and less frequent flooding provide less stressful growing conditions. The more frequent flooding occurring in the low marsh also imparts additional shading stress due to light attenuation in the overlying waters during flooding phases. In an experimental manipulation of light and salinity, *S. alterniflora* aboveground biomass losses under shading conditions were greater at a higher salinity (Medeiros et al. 2013), suggesting salinity stress may compound shading-induced loss of biomass. Kearney et al. (1983) reported the opposite trend, with greater reductions in stem density under docks of *S. patens* than *S. alterniflora*, although all of the docks in that study sampled over high marsh were relatively short (≤101 cm).

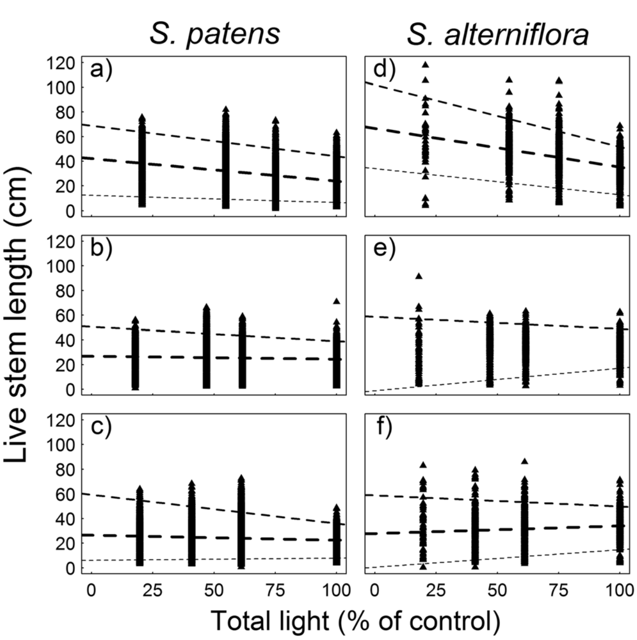


**Fig. 9** Live stem lengths (cm) of *Spartina patens* (**a**–**c**, high marsh) and *Spartina alterniflora* (**d**–**f**, low marsh) relative to total available light normalized to total light for control, unshaded plots. *Lines* are significant 95th quantile (*dashed*), mean (*long dash*), and 5th quantile (*dotted*) best fits for years 1 (**a**, **d**), 2 (**b**, **e**), and 3 (**c**, **f**)

For the high marsh, low docks in year 1 had lower stem density and biomass than high and intermediate docks, respectively, but not controls, which could have been due to short-term enhancement by the taller docks or natural variability. Reduced heat and associated salinity stress under moderate shading might produce increased stem densities for certain species (Bertness and Hacker 1994). *S. patens* is well adapted to heat stress (Duarte et al. 2016) and actually increases aboveground biomass (Gedan and Bertness 2010) and displaces co-occurring species (Gedan and Bertness 2009) under experimental warming conditions so dock shading is not likely to enhance *S. patens* production. Year 1 results alternatively could have been a result of natural variability between dock sites. While the randomized complete block design minimizes the risk of this source of error, we cannot exclude it as a possibility nor the potential for site differences to interact with annual variability (e.g., temperature, rainfall) to produce inconsistent results for some metrics and patterns.

Our observed negative correlation between maximum stem height and available light is consistent with results from studies of docks in the southeast (Sanger et al. 2004; Alexander 2012), mid-Atlantic (Vasilas et al. 2011), and northeast USA (Kearney et al. 1983; Colligan and Collins 1995). Previous studies demonstrating greater stem lengths under docks have proposed etiolation, the process in which plants put a greater proportion of energy towards vertical growth under low light conditions, as a likely explanation (Kearney et al. 1983; Vasilas et al. 2011). This response to low light conditions may allow plants to escape shading by growing above the shade source. Our results showed a relationship between light availability and stem height, which is consistent with an etiolation response.

We were able to detect changes in aboveground biomass at the elemental level that were consistent with shading stress. Seagrass stem % N and available light were also negatively correlated (van Lent et al. 1995; Grice et al. 1996; Moore and Wetzel 2000; Peralta et al. 2002). These shifts in elemental composition could result from a dilution process in which stored nitrogen resources are gradually depleted during growth due to faster utilization than uptake (Peralta et al. 2002). Shaded plants would have lower growth rates and consequently higher leaf nitrogen contents. These patterns could also be due to the disruption of carbon production and consequent accumulation of nitrogen at lower light levels. Analysis of % C and % N is inexpensive, routine, and only requires a small amount of dried material. Elemental composition analysis could potentially provide a rapid assessment of shading impacts in lieu of the more labor-intensive process of quantifying relative stem heights, densities, or biomass.

Some facets of our study may limit the transferability of results to other sites or structures. Since we conducted our study at a single field site, we cannot dismiss the possibility that observed reductions in vegetation might differ for other estuaries with different abiotic conditions (e.g., elevation, exposure to wave energy, salinity) or anthropogenic impacts (e.g., nitrogen loading, coastal development). Our results showing that dock height and H:W affect relative impacts to underlying marsh vegetation agree with data collected at private docks across a range of sites (Kearney et al. 1983; Colligan and Collins 1995), which provides support for the representativeness of our field site across other estuaries in the northeastern USA. *Spartina* stem densities in our control plots (mean ± standard deviation − high marsh, 1395 ± 517 stems/$m^2$; low marsh, 351 ± 124 stems/$m^2$) fell within the range of values reported in New England (Chaisson 2012) and other east coast estuaries (Havens et al. 1995; Sanger and Holland 2002; Alexander and Robinson 2004; Sanger et al. 2004) while aboveground biomass (high marsh, 83 ± 29 g/$m^2$; low marsh, 143 ± 35 g/$m^2$) was at or below the lower end of reported ranges (Castillo et al. 2010). Patterns that we observed in relation to dock H:W may not scale across a broad range of heights and widths. Bridges with heights (~7–20 m) and widths (10 m) that far exceed those of private docks and piers had minimal detectable losses in *S. alterniflora* biomass with H:W >0.7 (Struck et al. 2004); whereas, we observed significant *S. alterniflora* biomass losses for H:W up to 1.5:1.

Other facets of our study suggest that observed results are conservative estimates of potential dock impacts. Aside from the height of the low dock treatment, all experimental dock design attributes in our study met or exceeded best management practice guidelines (Bliven and Pearlman 2003) for dock construction over salt marsh in Massachusetts. All docks were set at a theoretically optimum north-south orientation, and docks with the same H:W set at different orientations might have greater shading impacts (Burdick and Short 1999). The 3-year timescale of our study also was short in relation to the lifespan of an actual private dock, and further impacts may occur over a longer timescale. In the high marsh, we only detected dock impacts on stem density at the end of the third growing season of shading, and these impacts may have intensified with additional years of shading.

The observed reductions in stem density and biomass under experimental docks could have broader ecosystem-scale impacts given the larger cumulative impacts that occur with dock proliferation (Needles et al. 2015). Reduced stem density under docks will decrease the sediment trapping capacity in these areas (Gleason et al. 1979), which could reduce accretion rates and consequently limit the marsh's capacity to keep pace with sea level rise (Morris et al. 2002). Shading likely also reduced belowground biomass under our docks based on laboratory results (Medeiros et al. 2013), which would further limit marsh resilience to rising sea levels (Deegan et al. 2012). These responses could trigger a cascade resulting in the complete loss of marsh habitat under docks constructed over low marsh and eventual conversion to creeks. In the high marsh, similar reductions in elevation would transform underlying areas to low marsh habitat. The observed expansion of *S. alterniflora* under our high marsh zone docks suggests this transformation may occur even without the compounding effects of sea-level rise. The cumulative loss of marsh biomass due to such shading impacts multiplied across all of the docks in an estuary will diminish available detritus for that system's food web, which could reduce higher trophic-level production (Alexander and Robinson 2006).

Our study only quantified impacts to underlying aboveground vegetation, but docks can have other environmental impacts. Docks can affect bird (Banning et al. 2009), benthic invertebrate (Struck et al. 2004), and infaunal (Weis and Weis 1992a) community composition. Docks constructed with pressure-treated wood can transfer toxic metals to epifauna and sediments (Weis and Weis 1992b; Weis et al. 1993, 1998).

## Conclusions and Future Research

Increases in dock height and H:W resulted in higher light levels and temperatures as well as reduced impacts to vegetation. Stem height and nitrogen content both increased in response to the decreasing light conditions under docks as H:W declined, consistent with etiolation and reduced growth responses, respectively. Reductions in aboveground production were greatest under low (0.5:1 H:W) docks, especially in the low marsh zone where stem density and biomass were each less than 15% of control values. Tall (1.5:1 H:W) docks had the least impact among tested H:W settings; high marsh zone production was equivalent to controls while low marsh was approximately 75% of control conditions. Intermediate docks set to match the 1:1 H:W guideline had approximately 50% of the vegetation biomass of unshaded marsh in both the high and low marsh zones after 3 years of dock shading.

The current 1:1 H:W best management practice guideline of the Massachusetts DEP (Bliven and Pearlman 2003) reduces but does not minimize impacts to marsh production. Our results indicate that a greater H:W (1.5:1) design further reduces vegetation impacts. Dock-induced reductions in salt marsh stem density and aboveground production diminish ecosystem services including marsh platform stability and detrital biomass for food webs. Given the current ubiquity of docks across US east coast estuaries and continued dock proliferation (Kelty and Bliven 2003; Patterson 2003a; Patterson 2003b), proper dock design is key to limiting the cumulative loss of underlying marsh production and associated ecosystem services.

Our study provides information for coastal resource managers to guide H:W designs for dock permitting over salt marshes, but other design characteristics also may affect light penetration and salt marsh production. Future studies should examine the effects of additional design attributes (e.g., orientation, decking spacing, decking type, width) to provide a more comprehensive understanding of the interplay among dock design, light transmission, and vegetation response. We quantitatively assessed vegetation responses to different dock H:W designs for docks set at a width typical of structures in Massachusetts, but H:W effects may vary across different widths. Studies evaluating vegetation responses across a H:W gradient for thinner or wider structures would provide resource managers with information that can be applied to permitting of smaller private catwalks as well as larger commercial or public walkways. Managers can apply such data to future permitting of new walkway structures over salt marsh as well as repairs and reconstruction of existing structures to reduce impacts to salt marsh production.

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