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Effects of Shading from Bridges on Estuarine Wetlands

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16. Abstract

Salt and brackish water marshes are integral parts of the coastal ecosystem, performing important nutrient cycling and hydrologic functions as well as providing habitat and breeding grounds for many coastal species. As human populations in coastal areas increase so does the need for an improved and more extensive infrastructure including bridging across estuaries and marshes when building roads. Very little research has been conducted to quantify the effects of shading on marsh function and productivity, and to determine the amount of mitigation that should be required to offset these effects. The objectives of this research were to determine the effects of bridge height and width on marsh productivity and function by directly assessing light attenuation under bridges, determining the effects of shading on the dominant salt marsh species and comparing benthic invertebrate communities beneath seven highway bridges with marshes outside of bridge-affected areas (reference marshes). Photosynthetically available light was measured. Plant samples were clipped, dried and weighed to determine aboveground biomass, average stem height, number of stems, number of flowers and basal area. Soil cores were taken to a depth of 30cm to determine soil C and N and below-ground biomass. Both bridge height and width heavily influenced the degree to which shading by bridges affected the underlying vegetation. All plant variables measured showed a strong bridge effect at HW ratios less than 0.5 and light attenuation less than 250 umol $m^{-2}s^{-1}$ under of the bridges. At a HW ratio of 0.68 bridge effects were still detected although it was greatly diminished. Of thirty-two comparisons between areas under and outside the influence of bridges having HW ratios greater than 0.7, only four significant differences were detected. Regression analysis showed a clear correlation between secondary productivity and bridge HW ratio, (r^2=.95). Low bridges, with HW ratio < 0.7 and light attenuation < 260 mol m^{-2} s^{-1} (photosynthetic photon flux units), had benthic invertebrate densities and diversity that were significantly lower than reference marshes. Density of benthic invertebrates at low bridges was 25-52% (29,685-72,920 organisms/m^2) of densities measured in adjacent reference marshes (119,329-173,351 organisms/m^2). Likewise, there were fewer taxa under low bridges (5.8 / 11.35 cm^2 core) as compared to the reference marshes (9.0 / 11.35 cm^2 core). Density of numerically dominant taxa (oligochaetes, nematodes) as well as surface- and subsurface deposit feeders also were reduced by shading of low bridges. Decreased invertebrate density and diversity beneath low bridges was attributed to diminished above- and below-ground macrophyte biomass that presumably resulted in fewer food resources and available refuges from predators. Data indicates that shading by bridges having HW ratios greater than 0.7 do not adversely impact the productivity or function of the underlying marsh and may not require compensatory mitigation.

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Summary

The effects of shading from bridging on primary and secondary production of tidal marshes were assessed by comparing plant growth, soil C and N, benthic invertebrates and light under seven bridges with adjacent reference marshes in North Carolina. Results indicated that each of these indicators was negatively impacted under three bridges with heights less than nine meters, and height/width ratios less than 0.7. There was no vegetation growing beneath the bridge that was the lowest (5.9 m) and widest (20.8 m) and it was the only bridge with significantly reduced soil carbon and nitrogen.

Invertebrate density, taxa richness, dominant taxa (oligochaetes, nematodes and *Capitella* sp.), and trophic feeding groups were negatively affected by bridges with a height/width ratio less than 0.7. Neither plant growth nor invertebrates were significantly affected under the four bridges that had height/width ratios greater than 0.7. Results suggest that low bridges adversely affect estuarine marsh productivity by reducing macrophyte growth and soil organic carbon, which in turn reduces density and diversity of benthic invertebrates.

Bridges with height/width ratio greater than 0.7, did not have a measurable effect on primary and secondary productivity. This suggests that mitigation for shading effects from high, narrow bridges is not warranted. With attention to bridge design, shading effects can be minimized.

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I. BRIDGE SHADING EFFECTS ON VEGETATION

INTRODUCTION

Wetlands are valuable natural resources providing a number of important ecological functions. Wetlands store organic carbon and are sinks for inorganic nutrients such as nitrogen and phosphorus. High primary productivity and rich organic soils make wetlands important contributors to the estuarine food web. Estuarine wetlands act as nurseries for many species essential to commercial fisheries, and many rare and endangered species of flora and fauna are also found in or adjacent to wetland habitat. In addition to providing habitat, wetlands also perform a number of critical hydrologic functions. Wetlands act as sponges or flood control devices by storing water during large storm events and improve water quality by filtering out pollutants and trapping sediments. Despite the many benefits of wetlands they continue to face degradation by many factors both human and natural. Loss of wetland areas has been recognized as a problem for many years resulting in laws allowing for no net loss of these areas.

Human populations continue to increase in coastal areas creating demand for further residential and industrial development. With increasing populations comes a need for improved infrastructure in the coastal region, resulting in construction projects in and near estuarine wetlands. In such cases the agency responsible for construction is required to mitigate to compensate for the effected wetlands. Of particular interest is the construction of bridges spanning estuarine wetlands. Presently, mitigation is required to alleviate the effects of shading from bridges spanning these areas; however, mitigation is expensive and increases construction costs. Little research has been conducted to quantify the effects of shading by bridges on marsh function and productivity. These effects must be quantified to understand how bridge height and width affect shading and underlying marsh vegetation. Should the effects of shading be minimal then mitigation requirements can be reduced, in turn reducing construction costs.

Light is one of the primary factors limiting growth and reproduction of vegetation (Smith 1996). Photosynthesis provides green plants with nearly all of their chemical energy and is therefore central to their ability to persist and reproduce. Photosynthesis is directly correlated with the amount of photosynthetically available radiation (PAR) at any given site until the saturation point is reached. Specifically photosynthesis is directly influenced by the amount of light striking the leaves of a particular plant. High levels of photosynthesis are not only important to the plants themselves but the ecosystem as a whole. Drake and Read (1981) found that carbon assimilated by photosynthesis has three possible pathways within the ecosystem. Carbon can be returned to the atmosphere through respiratory processes, accumulated in sediments, or exported out of the system as secondary production in the biomass of consumers. Each of these pathways returns energy to the system and is vital to its health. Studies of emergent marsh vegetation indicate that it is light limited during the growing season (Drake 1984, Drake and Read 1981). Thus, it can be expected that decreases in PAR may result in lower returns of energy to marsh systems therefore disrupting both marsh productivity and function.

Two different pathways of photosynthesis occur in nature under different light and moisture regimes (Mitsch and Gosselink 1993). These two pathways are the C_3 and C_4 pathways. Both of these pathways occur in coastal vegetation and are separated by gradients of varying light, salinity and temperature (Drake 1989). Plants using the C_3 pathway are adapted to moderate light and temperature levels and include most of the tree and shrub species. Plants with the C_3 pathway dominate the temperate regions of the world (Teeri and Stowe 1976). Plants using the C_4 pathway are better adapted to high light intensity, hot temperatures and low moisture (Teeri and Stowe 1976). Most C_4 plants occur in deserts or in the form of grasses. Many estuarine wetlands are dominated by vegetation that uses the C_4 pathway of photosynthesis (Drake 1989). High light intensity, hot summer temperatures and the water limiting osmotic effect of high salinity make wetlands suitable habitat for C_4 plants. Very high correlations exist between PAR, restricted water availability, high salinity, minimum average July daily temperature and the spatial distribution of C_3 and C_4 plants across the landscape (Teeri and Stowe 1976). These correlations result in a distribution where the dominance of C_4 plants increases with salinity towards the coast (Teeri and Stowe 1976). Due to their adaptive differences it can be hypothesized that C_3 and C_4 plants will respond differently to decreases in PAR due to the placement of man made structures.

The dominant C_4 species in southeastern coastal marshes is *Spartina alterniflora,* which possesses adaptations that allow it to compete very well in regions of physiological drought such as estuarine wetlands (Drake 1989). Specifically, *Spartina alterniflora* has the ability to photosynthesize at high light intensities and salt concentrations while using minimal fresh water (Giergevich and Dunn 1978, 1979). At the same time much research shows that C_4 plants experience greater reductions in growth in environments with reduced light intensity. Mitsch and Gosselink (1993) found that in C_4 plants the rate of photosynthesis increases in a linear manner with respect to increases in light, thus C_4 plants rarely become light saturated even in extreme conditions. Several studies have also shown that high light intensity is needed to maintain maximum levels of photosynthesis by C_4 plants (Longstreth and Strain 1977). This ability to increase photosynthesis up to very high levels of light is efficient in climates such as the southeastern United States where sunshine is abundant. However, this also suggests that at decreased levels of PAR, C_4 plants are likely to suffer relatively greater decreases in photosynthesis and net primary production than C_3 plants.

Many studies have been conducted to quantify reductions in photosynthesis and productivity associated with varying levels of illumination and soil nutrients. Longstreth and Strain (1977) collected numerous samples of *Spartina alterniflora* from North Carolina marshes and performed controlled growth experiments in which different nutrient and illumination treatments were applied. Growth at low illumination and high salinity resulted in a fifty percent decrease in growth compared to the control. Furthermore, plants grown at high salinity and high illumination showed significant increases in specific leaf weight and photosynthesis. Salinity treatments were increased until nearly equal with open ocean water and still no reduction was found as long as illumination was maintained at sufficiently high levels. Thus it was concluded that salinity has little effect on photosynthesis and would rarely if ever be a limiting factor in *Spartina alterniflora* growth (Longstreth and Strain 1977).

Light intensity interacts with factors other than salinity to regulate plant growth and productivity. Several studies have been conducted to evaluate the importance of nitrogen availability on the photosynthetic capabilities of C_4 plants such as *Spartina alterniflora*. Salt marsh ecosystems in general have been found to be nitrogen limited (Mendelssohn et al. 1982). Results of studies concerning photosynthetic capacity of *Spartina alterniflora* have shown a drastic decrease in photosynthesis under low nitrogen, low illumination conditions. Under low illumination high nitrogen conditions photosynthesis decreased less rapidly (Drake 1989). These studies suggest that in low nitrogen environments such as coastal salt marshes human induced shading by a bridge or other structure could significantly reduce photosynthesis and net primary production.

Plants using the C_3 pathway may act differently under conditions of reduced light. Although not as common in estuarine wetlands as C_4 plants, C_3 plants do play an important role on the composition of less saline brackish water marshes. These plants possess adaptations allowing them to flourish in temperate regions with moderate levels of sunlight and moderate temperature regimes. The water limiting effect of high salinity confines C_3 plants such as *Juncus roemarianus* to the less saline portions of coastal estuaries (Drake 1984).

Differences in light and salinity tolerance led to questions regarding varied response to decreased light availability in C_3 plants, which exhibit increasing photosynthesis with increasing light intensity up to the point of light saturation at approximately ¼ to ½ full sunlight suggesting that C_3 plants are adapted to lower light levels than C_4 plants and are less likely to suffer from decreased solar radiation (Mitsch and Gosselink 1993).

Currently, little data exists pertaining to the effects of bridge height, orientation and width on the shading of underlying emergent marsh vegetation. Information regarding height, width and orientation of boat docks with respect to submerged aquatic vegetation does exist. Walker et al. (1989) found that direct damage to sea grass beds by boat docks was minimal. However, the health of habitat under and adjacent to boat docks was compromised and more susceptible to damage. Studies conducted on *Zostera Marina* L. (eelgrass) beds under boat docks revealed that dock height above marine bottom, dock width, and dock orientation were influential factors in determining bed quality. Loflin (1995) and Burdick and Short (1999) found dock layout to be most influential and its significance is attributed to light levels and shading effects controlled by dock height and width. Recommendations have been made for the building of taller, narrower docks whenever possible (Loflin 1995, Burdick and Short 1999). A minimum dock height of three meters above the marine bottom oriented in a north-south direction was recommended as the best possible dock design.

OBJECTIVES

The overall objective of the research project was to determine the effects of shading from bridges, which span salt or brackish-water marshes, on ecosystem structure and function. Specific objectives were to:

1. Evaluate the effects of height and width of bridges on marsh productivity and function of emergent vegetation, soils, and benthic invertebrates.
2. Directly assess light attenuation by bridges using sensors to measure photosynthetic photon flux density under and near the bridges.
3. Compare the relative effects of shading on growth of the dominant species of salt marshes, *Spartina alterniflora* (a C_4 plant), with the growth of the dominant species in brackish marshes *Juncus roemerianus* (a C_3 plant).

MATERIALS AND METHODS

Seven bridges (Figure 1, Table 1) spanning either salt or brackish water marshes in eastern North Carolina were selected for sampling to determine their effects on marsh productivity. These sites provided opportunities to assess the effects of shading from bridges of various heights and widths on several types of marsh vegetation. Each marsh was sampled twice, once in October of 2000 and again in October 2001.

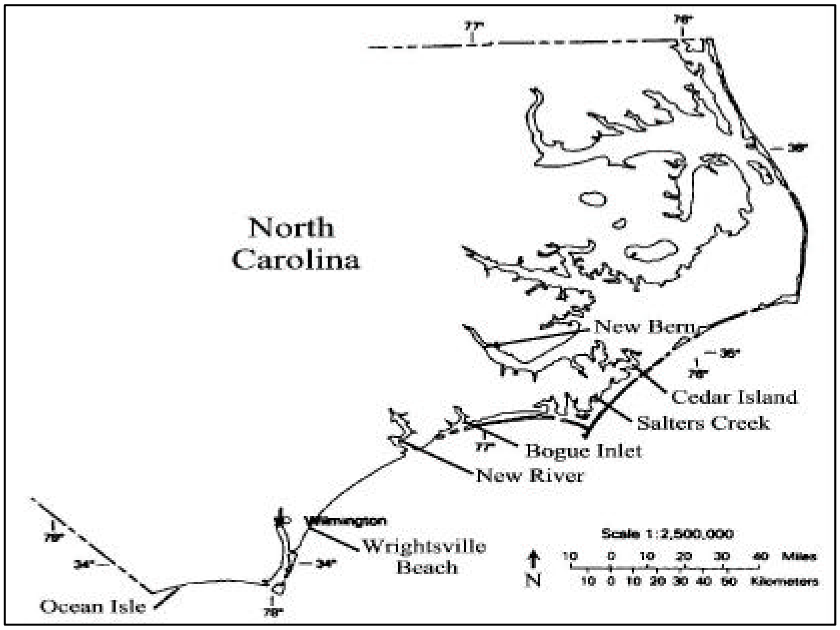


Figure 1. Locations of study sites for bridge shading effects.

Table 1. Bridge study sites with heights and widths of bridges at sampling transects.

Site	Plant species	Height (m)	Width (m)	HW Ratio	Age (years)	Salinity (ppt)	Orientation
Wrightsville Beach	*Spartina alterniflora*	5.85	20.82	0.28	44	32	125° E-SE
New River Low	*Spartina alterniflora*	7.32	10.73	0.68	7	4	176° S-SE
New Bern	*Spartina cynosuroides*	8.53	16.71	0.51	24.2	3	112° E-SE
Salter’s Creek	*Juncus roemerianus*	11.58	10.70	1.08	18	22	125° E-SE
New River High	*Spartina alterniflora*	14.63	10.73	1.36	7	4	176° S-SE
Ocean Isle	*Spartina alterniflora*	15.24	9.85	1.55	16	39	167° E-SE
Bogue Inlet	*Spartina alterniflora*	19.81	11.13	1.78	19	34	168° S-SE
Cedar Island Low	*Spartina alterniflora*	3.21	9.94	0.32	5	20	39° N-NE
Cedar Island Medium Low	*Juncus roemerianus*	4.98	9.94	0.50	5	20	39° N-NE
Cedar Island Medium High	*Juncus roemerianus*	6.15	9.94	0.62	5	20	39° N-NE
Cedar Island High	*Spartina patens*	15.52	9.94	1.56	5	20	39° N-NE

Sampling was conducted to compare productivity under and outside the influence of the bridges (Figure 2). A perpendicular line running from the center of the bridge to points outside the shading influence of the bridges was established at each study location.

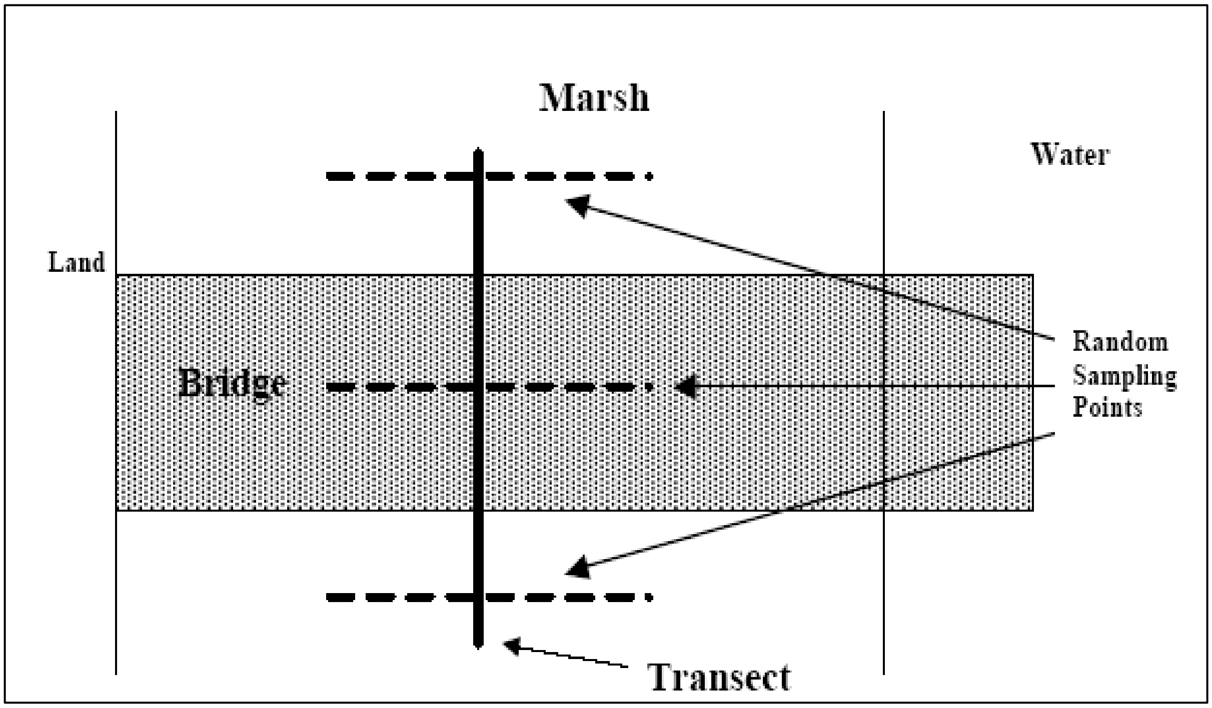


Figure 2. Sampling design used for sampling of vegetation and soils data during years 2000 and 2001.

Sampling quadrats were randomly selected on either side of the transect so that areas under and outside the influence of the bridge were sampled. When possible, samples were taken in unaffected areas on both sides of the bridges. However, at most locations it was only feasible to sample a non-shaded area on one side due to the presence of waterways or beaches.

Vegetation Samples

Vegetation samples were taken at the end of the 2000 and 2001 growing seasons. Sampling transects were located along a line running perpendicular to the bridge from the center outwards. Specific sampling plots were located along this line at points under and outside the influence of the bridges. At each sampling point a 0.25 sq. meter quadrat was placed on the marsh surface, all vegetative growth occurring within the plot was clipped. The number of stems, number of flowering stems, and basal area were recorded. Harvested vegetation was placed in a bag, labeled and returned to the laboratory, dried at 70° C in a forced air oven and weighed.

Belowground biomass measurements were taken from within the 0.25 sq meter plots after they were clipped. A soil corer 8.5 cm in diameter and 30 cm deep was used for obtaining samples. Each core was divided into two sections, 0-10 cm and 10-30 cm, returned to the laboratory and washed through a 2mm sieve. The root mass remaining on the sieve was bagged, air dried at 70° C in a forced air oven and weighed.

Soil Samples

A soil core 8.5 cm in diameter and 30 cm deep was taken from each quadrat for use in soil nutrient analysis. Each core was further divided into a 0-10 cm and 10-30 cm section, returned to the laboratory and sieved through a 2mm sieve. Samples were air dried before being sent to the Department of Soil Science Service Laboratory for Carbon and Nitrogen analysis using a CHN analyzer.

Light Measurements

Light Measurements were conducted at locations under and outside the influence of the shadow of each bridge. Measurements were taken along the same transects used for vegetation and soil sampling using hand held Apogee quantum meters. Apogee quantum meters measure radiation between 400 and 700 nanometers, which are the most important wavelengths for plant growth. Readings were taken simultaneously under and outside the bridges influence to assure an accurate comparison of solar radiation at each location. Three readings were taken at each measuring point at time intervals of one minute. All light data was collected during July of 2002 at or as close as possible to full sunlight.

Seedling Growth Experiment

A seedling growth experiment was conducted at the Cedar Island bridge location to assess the effects of varying levels of shading on dominant marsh vegetation types. The species selected for study were *Spartina alterniflora, Spartina cynosuroides* and *Juncus roemerienus.* Prior to planting at the bridge seedlings were transplanted to two-gallon pots containing a uniform mixture composed of 1/3 sand, topsoil and a standard potting medium. All pots were fertilized with an equal amount of Osmocote (14-14-14) fertilizer, and seedlings were grown for two weeks in a greenhouse prior to planting in the field.

Planting occurred at nine sections of the Cedar Island Bridge, ranging in height from 2.91 to 15.46 meters (Table 2). Three randomized blocks of seedlings were planted at each of the nine sections chosen. One block was located under the center of the bridge, a second under the edge of the bridge, and a third in the natural marsh outside the shadow of the bridge. Each block contained three pots of seedlings of each species for a total of nine pots per block.

Table 2. Height and Height Width (HW) Ratios for Cedar Island Bridge sections planted (2002).

Height (m)	HW Ratio
3.03	0.3
4.14	0.41
4.72	0.47
5.96	0.59
6.63	0.66
9.34	0.93
11.57	1.16
13.38	1.34
15.46	1.55

Pots were buried flush with the existing marsh surface. Planting occurred during May of 2002, all vegetative growth was harvested during October of 2002 at the completion of one growing season. Upon harvesting each plant was clipped and bagged, number of stems and height of the tallest stem was recorded. All samples were air dried at 70° C in a forced air oven and weighed.

Statistical Analysis

All data was analyzed under the supervision of the statistics department at North Carolina State University using Statistical Analysis Software (SAS Institute, 1985). An alpha level of 0.05 to indicate significance was chosen for all statistical analysis. Analysis of variance was computed using the following formula: $Y_{ijklm}=U+H_j+L_j+(H*L)_{ij}+(L*B)_{jk(i)}+T_l+(T*H)_{il}+(T*B)_{lk(i)}+(T*L)_{jl}+(T*L*H)_{ijl}+(T*L*B)_{jlk(i)}+E_{ijklm}$. Where: T=year, H=height or width, L=location, B=bridge, U=mean of population, E=random error in Y, Y_{ijklm} denotes the j^{th} response for treatment i etc.

Comparisons were made to determine significance in differences between data collected under and outside the influence of the bridges. Data from each year was examined independently and then pooled and examined. Analysis was conducted using t-tests along with the General Linear Model slice option to divide data into categories of low and high bridges. A height of nine meters was chosen to separate “high” and “low” bridges.

RESULTS AND DISCUSSION

Bridge Characteristics

Bridges at seven locations were used for sampling of plants and soils in October of 2000 and 2001. Vegetation at each bridge was sampled once at a particular bridge height at the conclusion of each growing season. A low and high transect was sampled each year at New River (Table 1).

Bridges range in height from 5.85 meters to 19.81 meters and in width from 9.85 meters to 20.82 meters (Table 1). Bridges were placed into height categories, either low or high (Table 1). Bridges < 9 meters in height were labeled low, and bridges > 9 meters were grouped into the high category. The low category consists of the bridges located at Wrightsville Beach, New River (low transect), and New Bern. The high category includes bridges located at Salter Creek, New River (high transect), Ocean Isle and Bogue Inlet. Bridge age was also determined for each location (Table 1). Bridges ranged in age from 5 to 44 years (NCDOT). Bridge orientations and the salinity of the marsh water were also recorded at every location (Table 1). The Cedar Island site was sampled once in 2001 at 4 heights for plant and soil variables. The seedling transplant experiment was also located at the Cedar Island site. (All Cedar Island data is presented in the Appendix).

Unlike other bridges sampled, the marsh Under the New River Bridge was severely disturbed during construction resulting in a change of vegetation from that in the surrounding natural marsh. During construction the area directly under and to the west of the New River Bridge was dredged and refilled with sand. Currently, the area disturbed during construction is occupied by *Spartina alterniflora* while the surrounding natural marsh is dominated by *Juncus roemerianus*. The change in soils and vegetation may be responsible in explaining some irregularities in belowground biomass data collected at the New River site. It is also important to note that all sampling was conducted within the area dominated by *Spartina alterniflora*.

A height-width ratio (HW ratio) was also calculated for each bridge transect sampled. The HW ratio was calculated by dividing bridge height by bridge width. The HW ratio combines the effects of both height and width into one number. Arranging bridges by increasing or decreasing HW ratios explains patterns in the data from New Bern and New River that are less clear when viewed against height alone.

Shading Impacts Under Bridges

Unless stated otherwise the data being discussed within the text and figures is the mean data for the growing seasons of 2000 and 2001. Statistical analysis showed that year of sampling was not significant in determining patterns within the data. In the few cases where the year was significant, the data is discussed separately and the data for each year is presented along with the mean data for the two years.

Light Data

Light was sampled at the seven bridges along transects where plant and soil samples were taken. Apogee quantum sensors were used to measure photsynthetically available light under and outside the influence of the bridges during July 2002. Table 3 shows light measurements collected under and outside the influence of the bridges in µmol $m^{-2}s^{-1}$, this data is shown as a percentage of the control in Figure 3.

Table 3. Light data collected on July 21 and 22 of 2002. Photosynthetic photon flux (PPF) was measured using Apogee Quantum sensors. Measurements were in µmol m $^{-2}$ s^{-1}.

Site (Time)	**Avg. PPF µmol m $^{-2}$ s^{-1} Outside (n=3,5)**	**Avg. PPF µmol m $^{-2}$ s^{-1} Under (n=3,5)**	**Percent of Control**	**Bridge Height (m)**
Wrightville Beach 1:30-1:40	1907	36	1.9	5.85
NR Low 11:55-12:15	1294	250	19	7.32
New Bern 2:05-2:15	1904	202	11.43	8.54
Salter C. N/A	2000	364	18	11.59
NR High 11:55-12:15	1543	1037	67	14.33
Ocean I. 3:15-3:20	1929	1816	94	15.24
Bogue I. 10:15-10:20	1658	1639	98	19.82

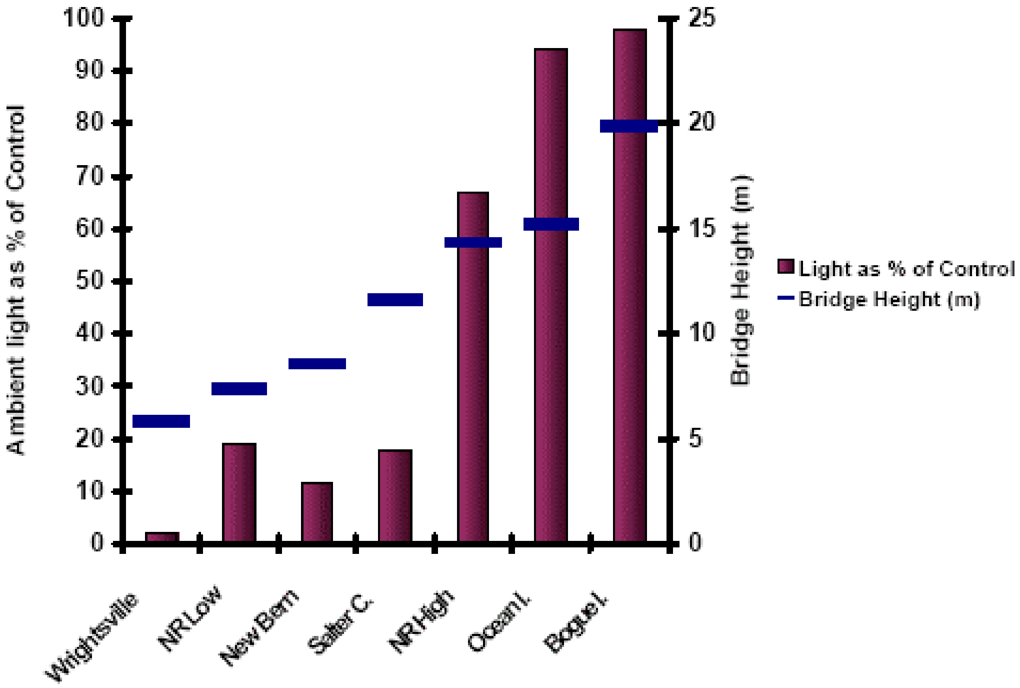


Figure 3. Representation of light data collected under bridges during July 2000 as percentage of sunlight outside the influence of the bridge. Means at each located based on n=5 measurements.

Figure 4 depicts aboveground biomass (gm^{-2}) and photosynthetic photon flux (PPF)(umol $m^{-2}s^{-1}$) measurements from under the bridges as a percentage of the control. Wrightsville Beach Bridge has a HW ratio of 0.28, the smallest HW ratio of all bridges sampled. Average PPF in the reference marsh at the time of sampling was 1907 umol $m^{-2}s^{-1}$, while the PPF measured at marshes located under the bridge averaged 36.25 umol $m^{-2}s^{-1}$ (Table 3). The PPF under the bridges at Wrightsville Beach was not adequate for vegetative growth (Figure 4). With a HW ratio of 0.51 New Bern was the next lowest and widest bridge. Average PPF outside the bridge was 1904 umol $m^{-2}s^{-1}$, PPF under the bridge averaged 217 umol $m^{-2}s^{-1}$ (Table 3, Figure 4). Reduced light levels reduced vegetative growth under the bridge to less than 50% of that occurring outside the bridges influence (Figure 4). As bridge HW ratio increases above 0.68 light as a percentage of the control

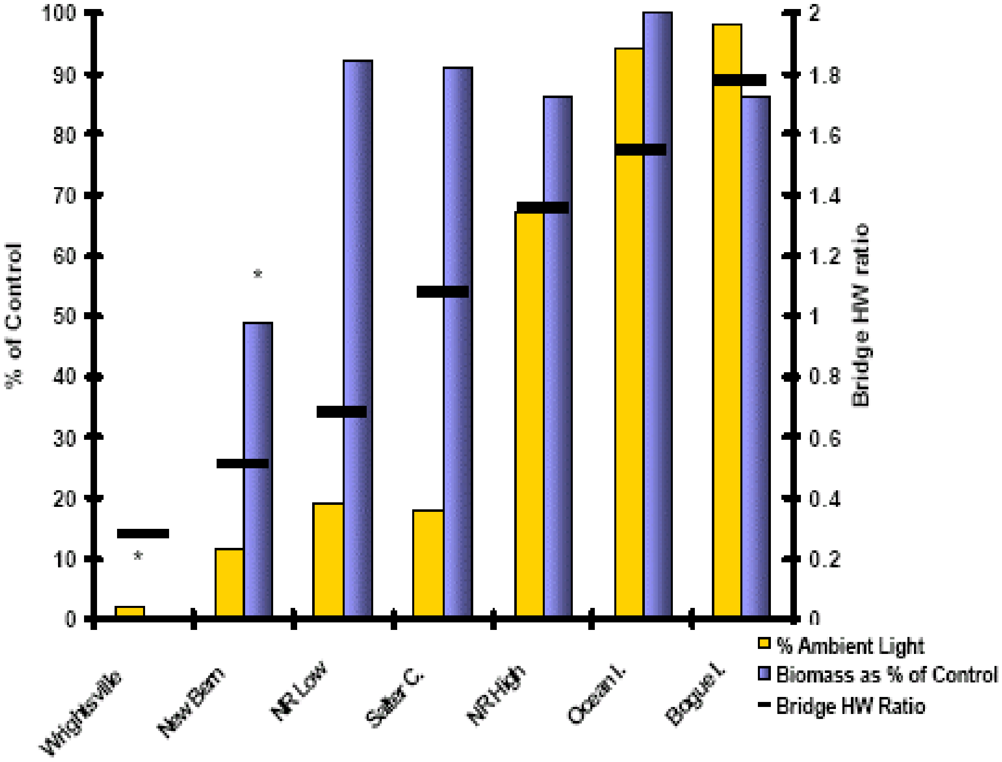


Figure 4. Comparison of ambient light and mean above-ground biomass represented as a percentage of the control at each bridge. Bridges are in order of increasing HW ratios. Asterisks indicate significant differences in biomass between areas under and outside influence of bridges at p<.05.

increases greatly and is sufficient to support vegetative growth under the bridges that is nearly equal to, or greater than the control.

Regression analysis indicates a significant relationship between light attenuation under the bridges and HW ratios (r^2=0.93) (Figure 5). This suggests that both height and width are important in determining the amount of light available to vegetation growing under any bridge.

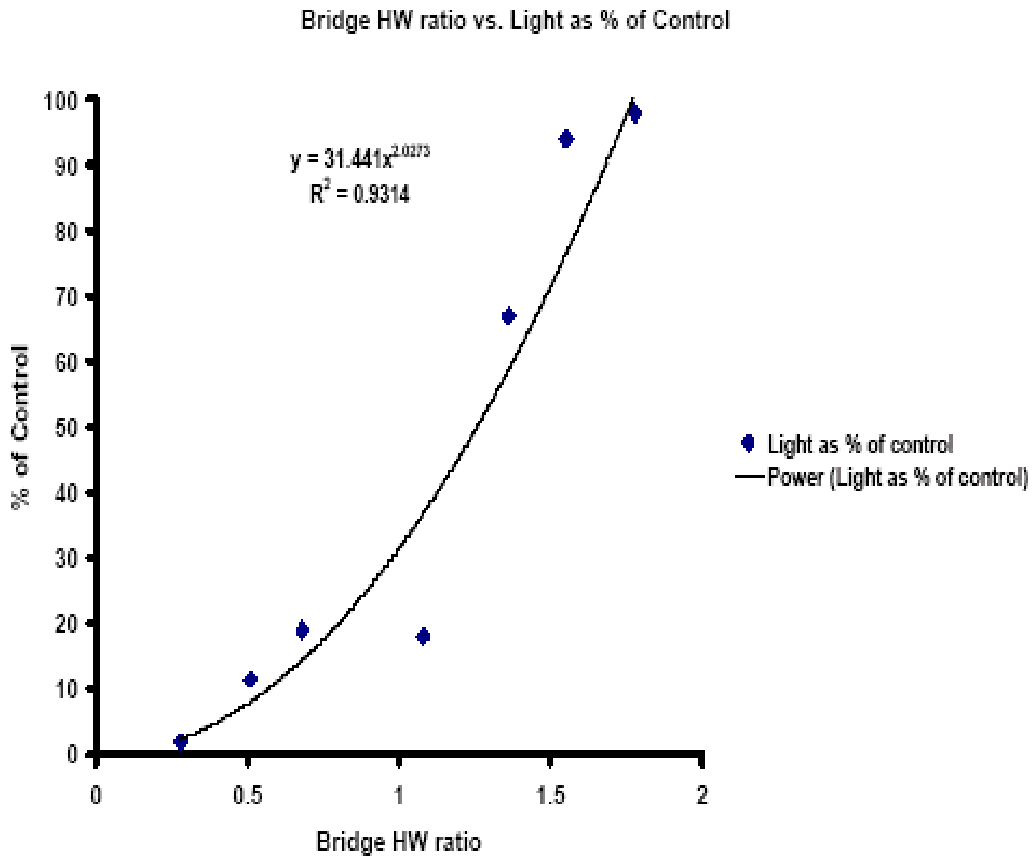


Figure 5. Regression analysis of percentage of ambient light reaching areas under bridges as a function of the bridges HW ratio.

Plant Growth Measurements

Sampling of vegetation under bridges from seven locations indicated that bridge height and width affected vegetative growth (Figures 6-11). Each of the growth measurements, aboveground biomass (gm^{-2}), number of stems per (m^{-2}), stem height (cm), flowers (m^{-2}), basal area (m^{-2}), and belowground biomass (gm^{-2}) demonstrated similar trends across increasing bridge heights and widths. Of the seven bridges studied, six had vegetation growing directly under the bridge, and all bridges sampled had vegetation growing outside the influence of the bridge.

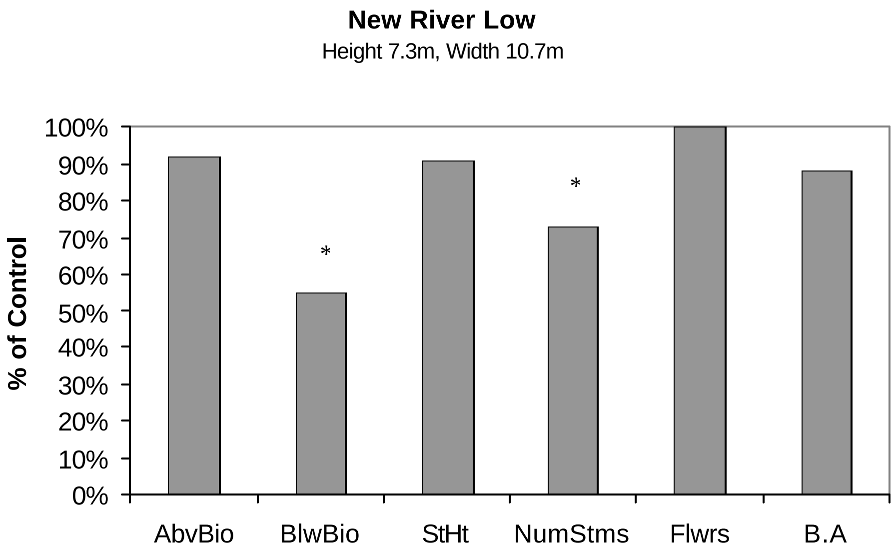


Figure 6. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, Flwrs = number of flowers. B.A = basal area.

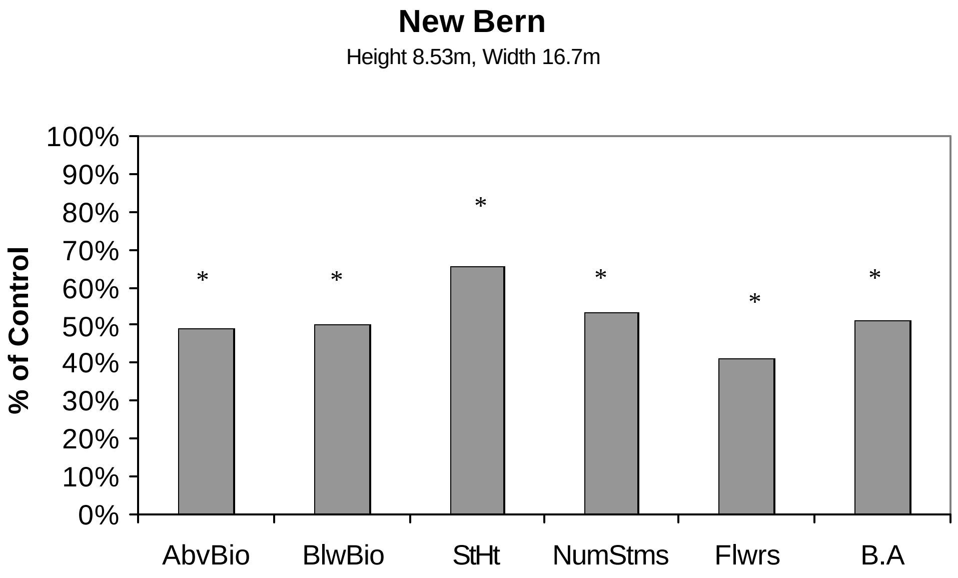


Figure 7. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, Flwrs = number of flowers. B.A = basal area.

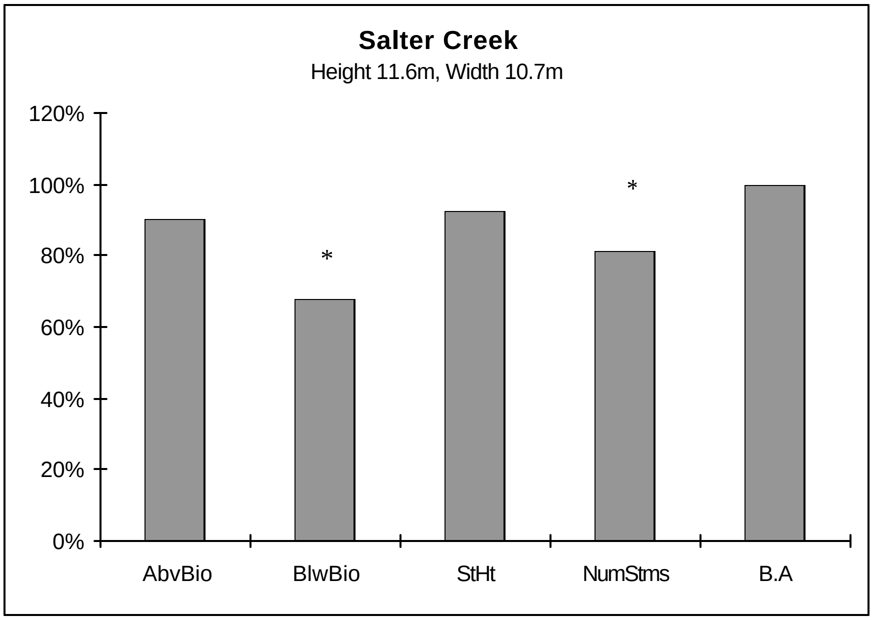


Figure 8. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, B.A = basal area.

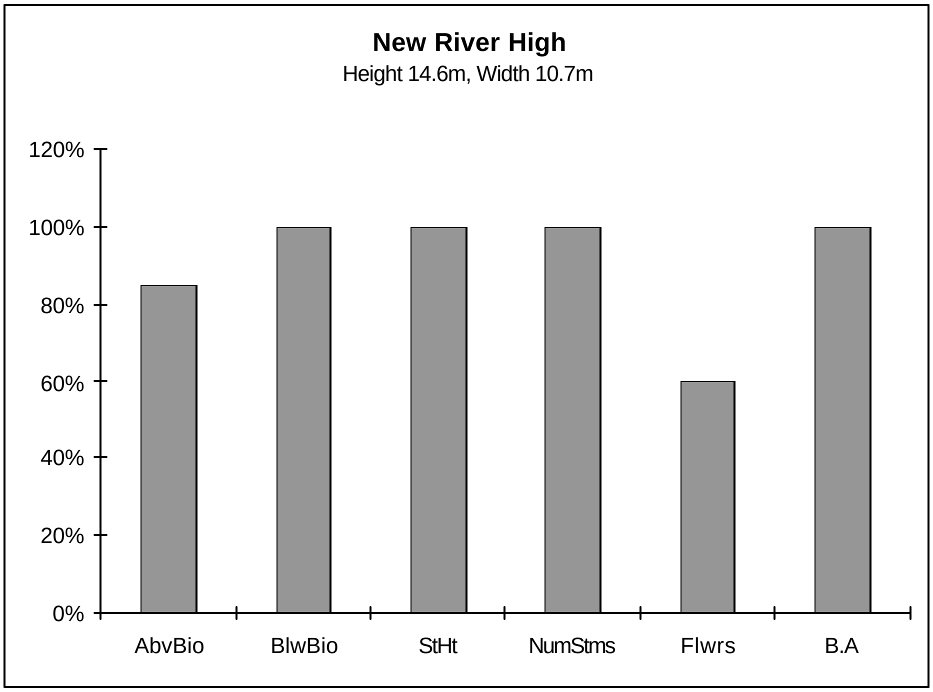


Figure 9. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, Flwrs = number of flowers, B.A = basal area.

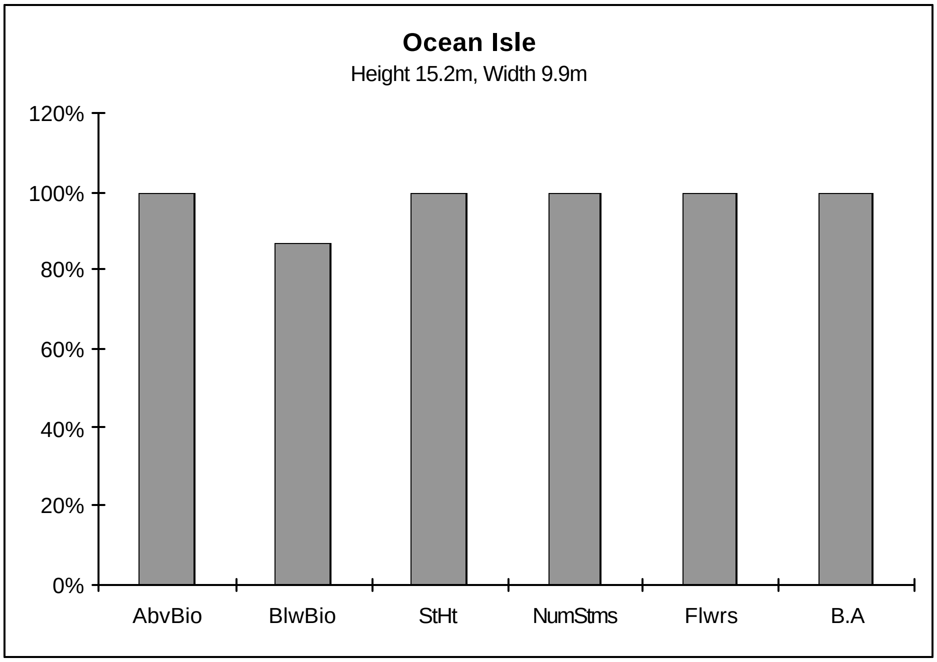


Figure 10. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, Flwrs = number of flowers, B.A = basal area.

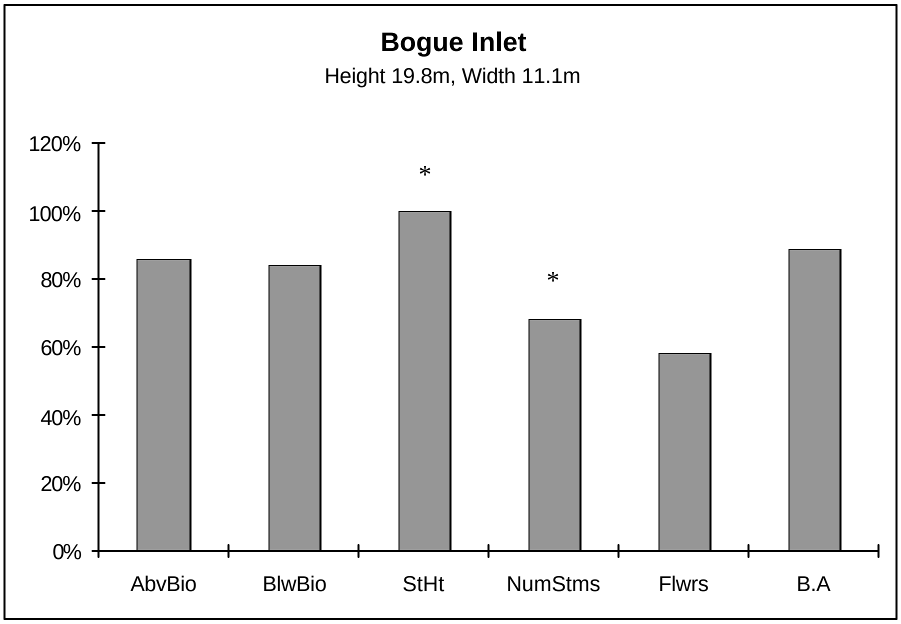
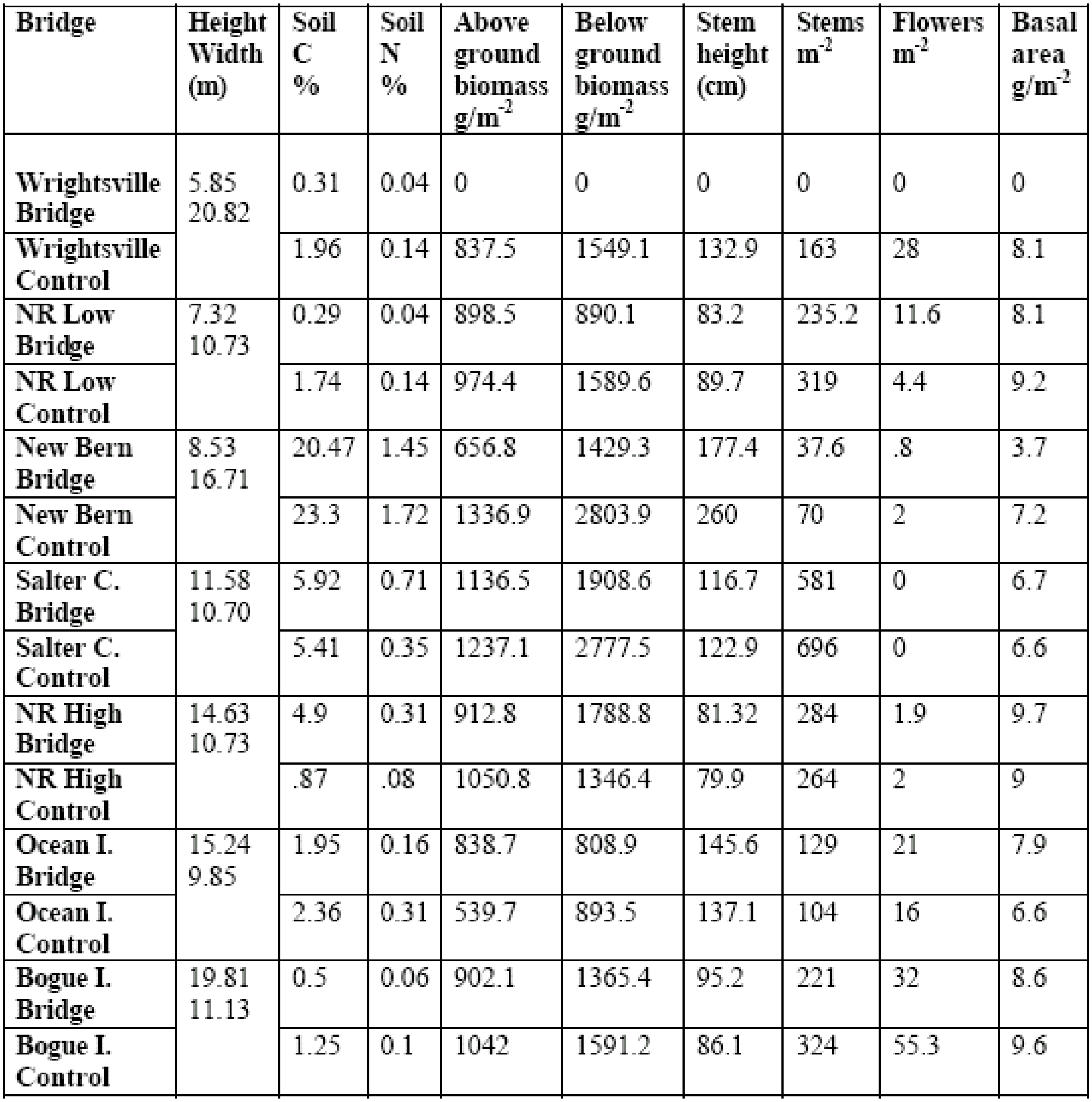


Figure 11. Mean plant growth measurements under the bridge for the years 2000 and 2001 expressed as a percentage of the control. Asterisks indicate significant differences between areas under and outside the influence of the bridge, p<.05. AbvBio = aboveground biomass, BlwBio = belowground biomass, StHt = average stem height, NumStms = number of stems, Flwrs = number of flowers, B.A = basal area.

At a height of 5.85 m and width of 20.82 m, Wrightsville Beach Bridge is the lowest and widest (Table 1), and has the lowest HW ratio at 0.28. No vegetation is present under the bridge, while outside the influence of the bridge *Spartina alterniflora* biomass averaged 837.5 g/m^2 (Table 4).

At a height of 7.3 m, New River (low transect) was the second lowest bridge sampled (Table 1), however, *Spartina alterniflora* biomass under the bridge was equal to that outside the bridge (Figure 4, Table 4). Although the low transect at New River is located where the bridge is only 7.3 meters tall, the bridge is narrow, only 10.7 meters as compared to the Wrightsville Beach bridge (20.8 meters) and New Bern bridge (16.7 meters). The narrower width and greater HW ratio (0.68) allows increased light availability that produces greater vegetative growth under the low transect at New River. The New Bern Bridge falls into the low height category (8.53 meters), and it is a four-lane bridge with a width of 16.7 meters, and HW ratio of 0.51. Measurements of aboveground biomass of *Spartina cynosuroides* revealed large differences between areas under and outside the bridge (Table 4). Mean biomass was less than half under the bridge (656.8 gm^{-2}), than outside the influence of the bridge where biomass was 1336.9 gm^{-2} (Table 4). All the growth measurements were significantly less under the bridge than outside the bridge (Figure 4). The reduction in plant growth can be attributed to the increased shading and low HW ratios associated with wide bridges.

Table 4. Mean plant and soil data collected in October of 2000 and 2001



Bridge	Height Width (m)	Soil C %	Soil N %	Above ground biomass g/m^{-2}	Below ground biomass g/m^{-2}	Stem height (cm)	Stems m^{-2}	Flowers m^{-2}	Basal area g/m^{-2}
Wrightsville Bridge	5.85 20.82	0.31	0.04	0	0	0	0	0	0
Wrightsville Control		1.96	0.14	837.5	1549.1	132.9	163	28	8.1
NR Low Bridge	7.32 10.73	0.29	0.04	898.5	890.1	83.2	235.2	11.6	8.1
NR Low Control		1.74	0.14	974.4	1589.6	89.7	319	4.4	9.2
New Bern Bridge	8.53 16.71	20.47	1.45	656.8	1429.3	177.4	37.6	.8	3.7
New Bern Control		23.3	1.72	1336.9	2803.9	260	70	2	7.2
Salter C. Bridge	11.58 10.70	5.92	0.71	1136.5	1908.6	116.7	581	0	6.7
Salter C. Control		5.41	0.35	1237.1	2777.5	122.9	696	0	6.6
NR High Bridge	14.63 10.73	4.9	0.31	912.8	1788.8	81.32	284	1.9	9.7
NR High Control		.87	.08	1050.8	1346.4	79.9	264	2	9
Ocean I. Bridge	15.24 9.85	1.95	0.16	838.7	808.9	145.6	129	21	7.9
Ocean I. Control		2.36	0.31	539.7	893.5	137.1	104	16	6.6
Bogue I. Bridge	19.81 11.13	0.5	0.06	902.1	1365.4	95.2	221	32	8.6
Bogue I. Control		1.25	0.1	1042	1591.2	86.1	324	55.3	9.6

At the taller bridges measured in the study, no significant differences were detected in aboveground biomass (Figure 12). It was concluded that bridges greater than 9 meters tall with HW ratios > 0.70 have no significant effect on biomass production under the bridge.

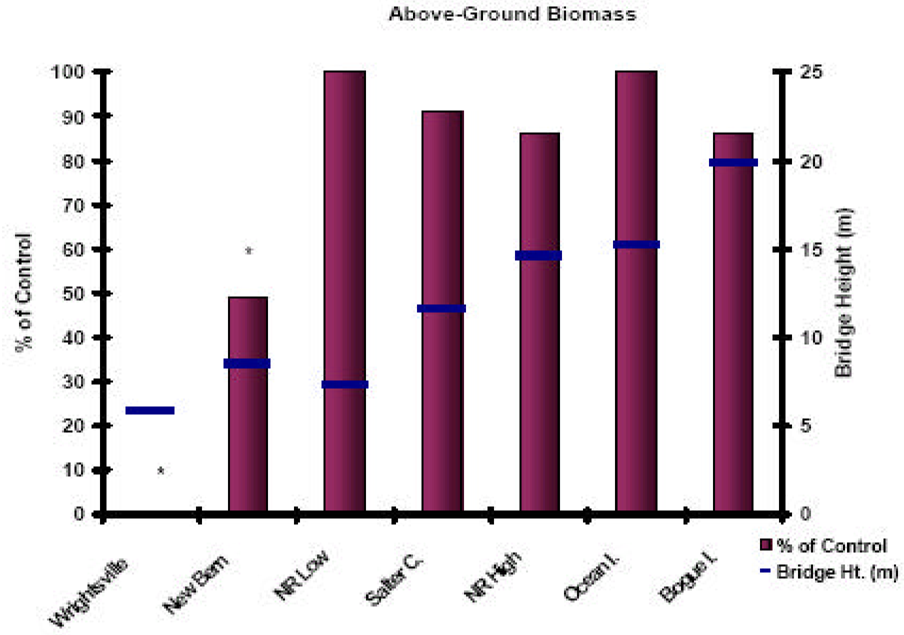


Figure 12. Mean above-ground biomass from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

Other indicators of aboveground growth, such as number of stems m^{-2}, stem height (cm), flowers (m^{-2}), and basal area (cm/m^2) demonstrated similar patterns related to bridge height and HW ratio as those exhibited by aboveground biomass measurements. The number of stems per m^{-2} differs significantly at Wrightsville Beach and New Bern (Figure 13). Salter Creek also exhibited a significant difference in the year 2001, but not 2000. At a height of 11.5 meters and HW ratio of 1.08 it is suspected that the difference occurring in the year 2001 was due to natural variation within the marsh rather than a bridge effect.

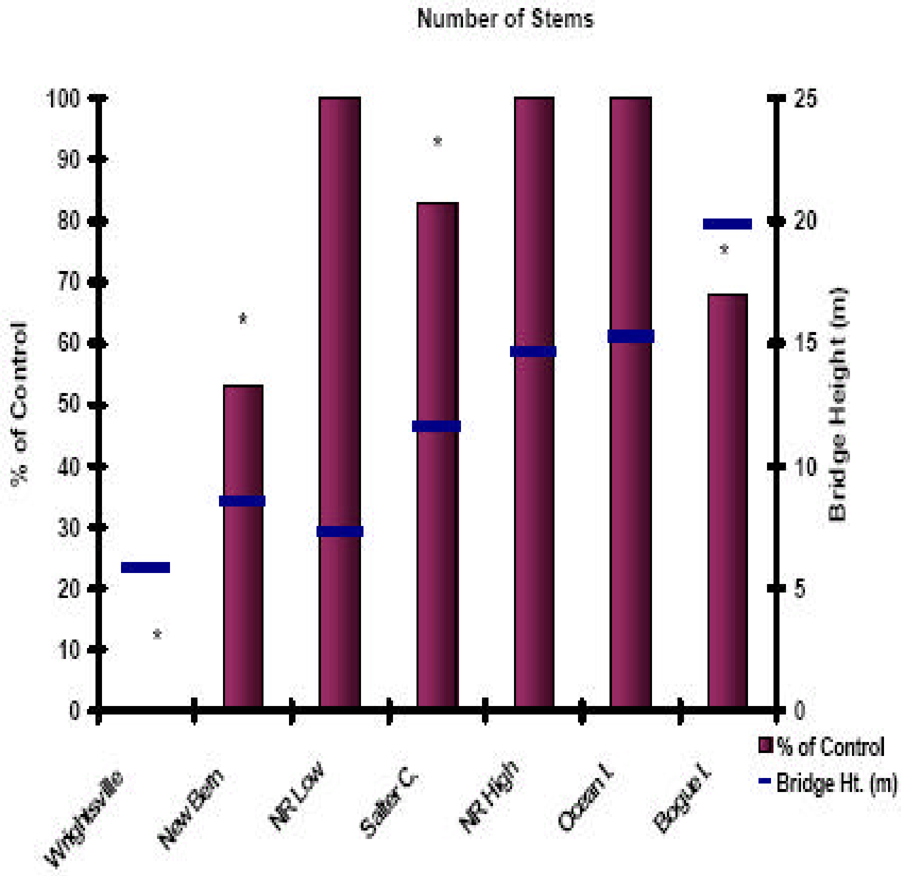


Figure 13. Mean number of stems from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

Significant differences in average stem height (cm) were detected at the two bridges having the lowest HW ratios, Wrightsville Beach and New Bern (Figure 14, Table 4,5). No significant differences occur at any of the bridges having HW ratios greater than 0.51. Three of the bridges in the tall category had greater average stem heights directly under the bridge.

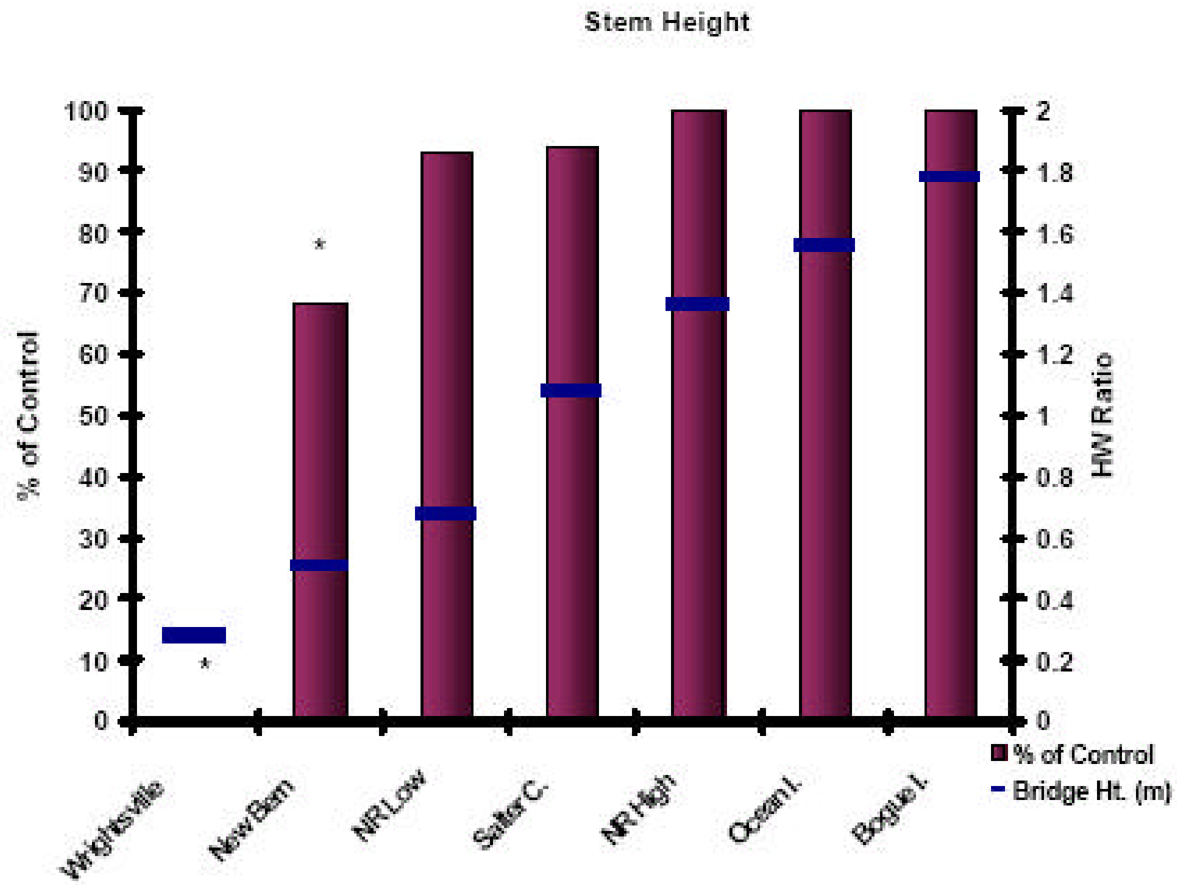


Figure 14. Mean stem height from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

Measurements of number of flowers m^{-2} revealed significant differences at Wrightsville and New Bern (Figure 15). Unlike other parameters measured number of flowers has significant differences occurring between the control and under the bridge at Bogue Inlet (Figure 15).

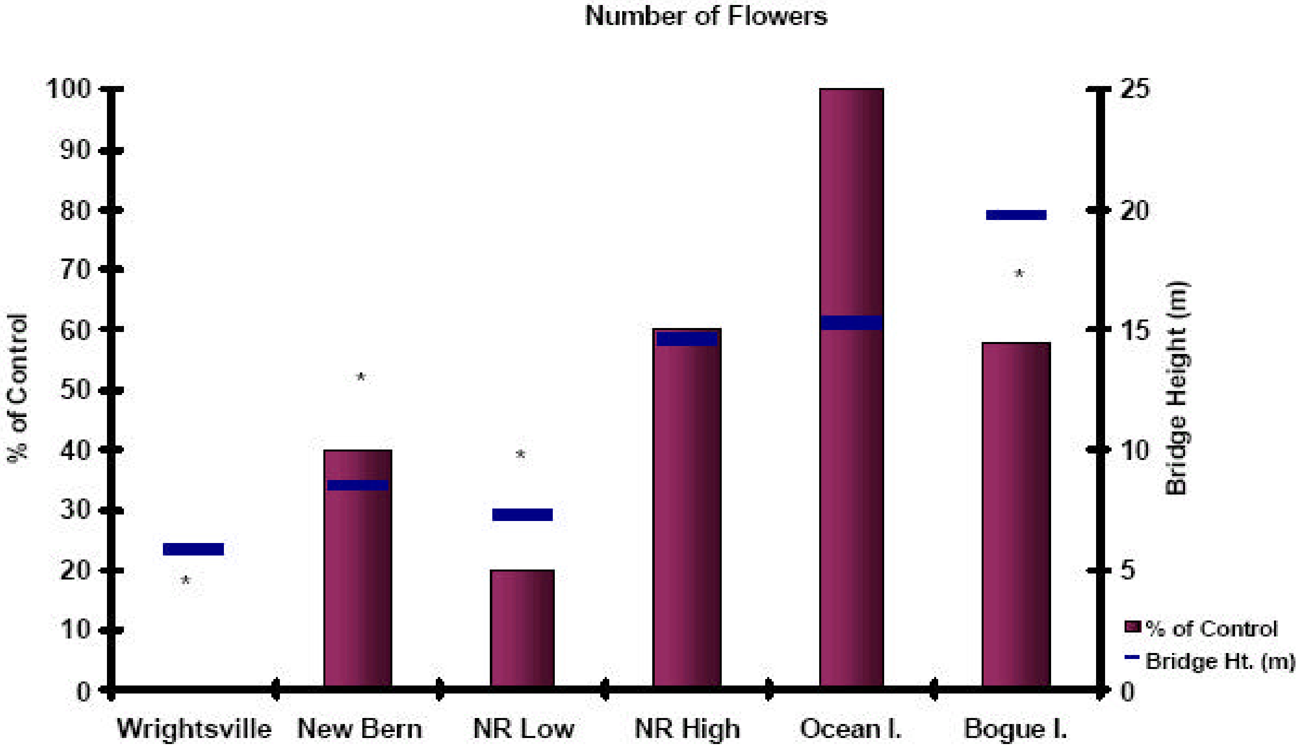


Figure 15. Mean number of flowers from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

Table 5. Bridges listed in order of height. Asterisks indicate significant differences at p<.05 between mean data collected under and to the outside of bridges over years 2000 and 2001.

Bridge	**Height**	**Soil C%**	**Soil N%**	**Above ground biomass g/m^{-2}**	**Below ground biomass g/m^{-2}**	**Stem height (cm)**	**Stems/ m^{-2}**	**Flowers/ m^{-2}**	**Basal area /m^{-2}**
Wrightsville	5.85	*		*	*	*	*	*	*
NR Low	7.32	*			*		*		
New Bern	8.53			*	*	*	*	*	*
Salter C.	11.58				*		*		
NR High	14.63								
Ocean I.	15.24								
Bogue I.	19.81						*	*	

Bogue Inlet is the tallest of all bridges sampled at a height of 19.81m. The difference in flowers m^{-2} may be a direct result of the significant difference in number of stems under and outside the influence of the bridge. The differences occurring at Bogue Inlet are more likely due to hydrological conditions at the site rather than shading effects of the bridge. Only a small area exists under the bridge where the water is not too deep for vegetative growth. Thus, growth in the sampling area was likely affected by factors unrelated to the bridge.

Basal area cm/m^2 has significant differences occurring at Wrightsville, and New Bern while locations with bridges having HW ratios of 0.70 or greater demonstrate no significant differences (Figure 16). All other bridges have basal area measurements under bridges that are equal to or exceeding those of the control (Table 4, Table 6).

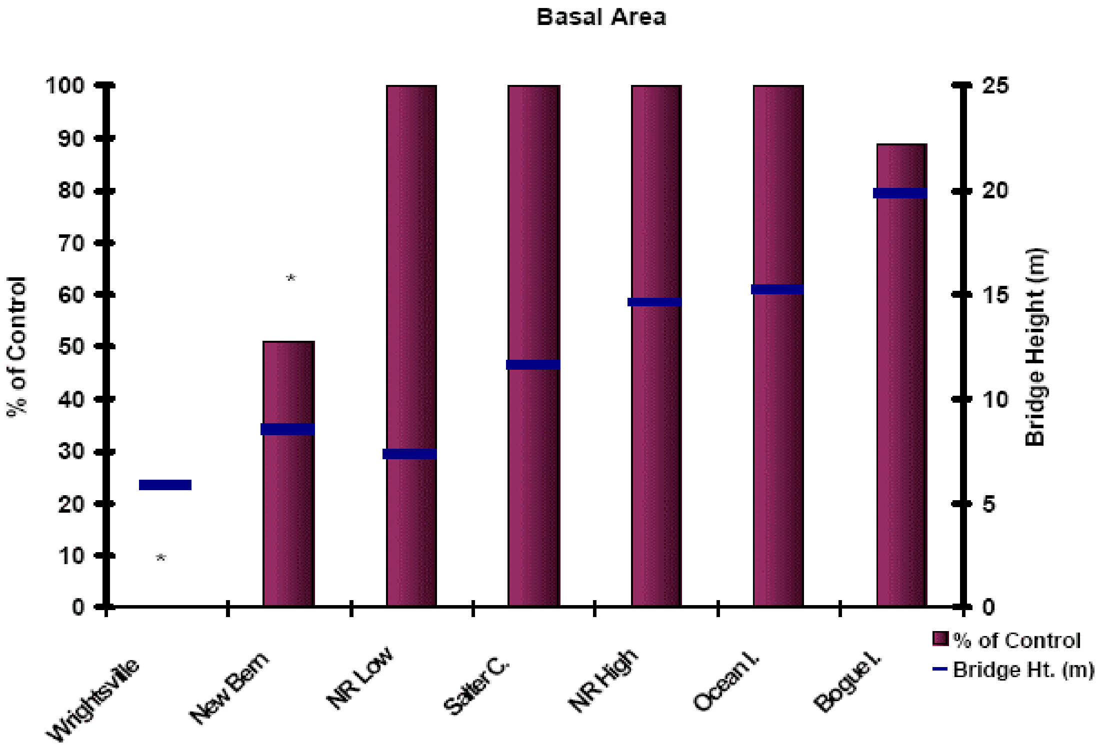


Figure 16. Mean basal area from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, $p<.05$.

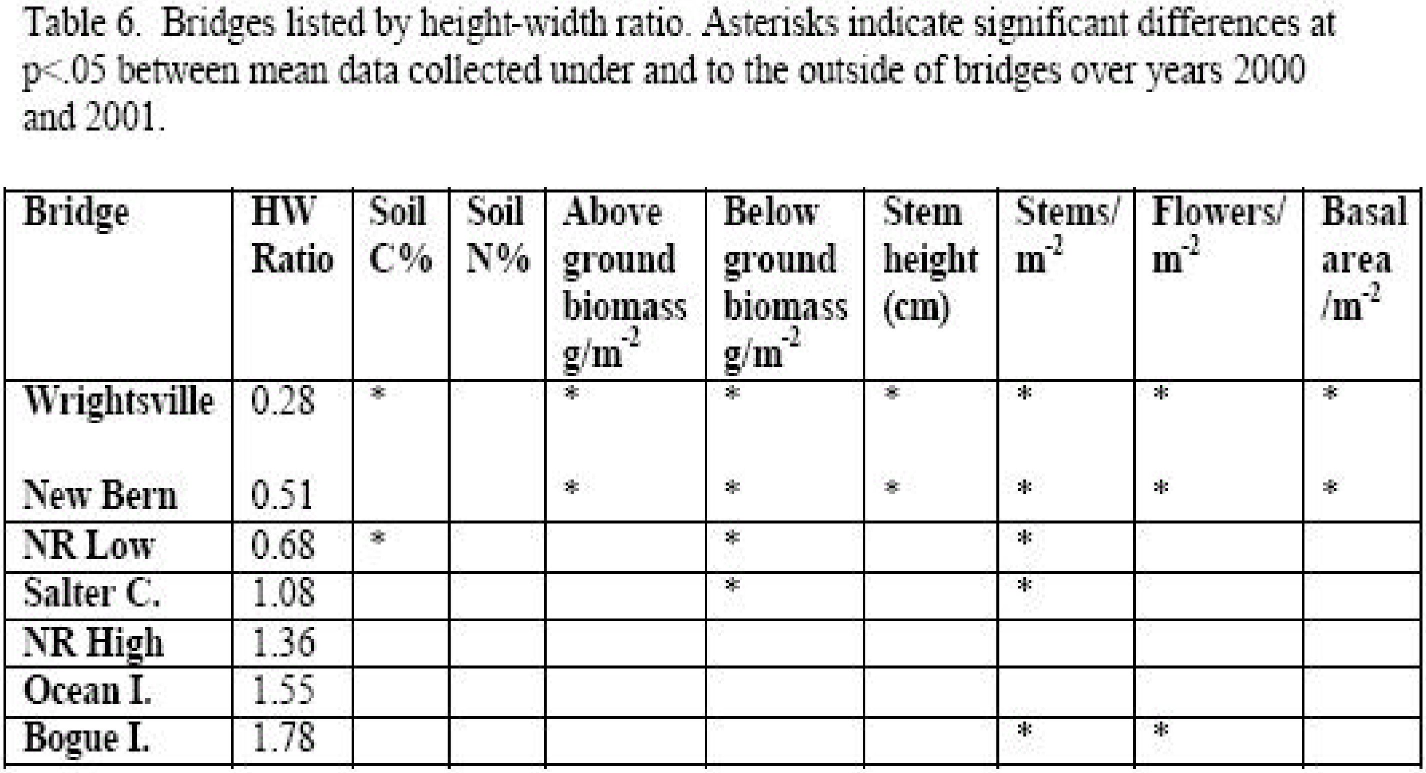


Table 6. Bridges listed by height-width ratio. Asterisks indicate significant differences at p<.05 between mean data collected under and to the outside of bridges over years 2000 and 2001.

Bridge	HW Ratio	Soil C%	Soil N%	Above ground biomass g/m^{-2}	Below ground biomass g/m^{-2}	Stem height (cm)	Stems/ m^{-2}	Flowers/ m^{-2}	Basal area /m^{-2}
Wrightsville	0.28	*		*	*	*	*	*	*
New Bern	0.51			*	*	*	*	*	*
NR Low	0.68	*			*		*		
Salter C.	1.08				*		*		
NR High	1.36								
Ocean I.	1.55								
Bogue I.	1.78						*	*	

Belowground biomass measurements display similar patterns to aboveground biomass across the seven bridges sampled (Table 4, Figure 17).

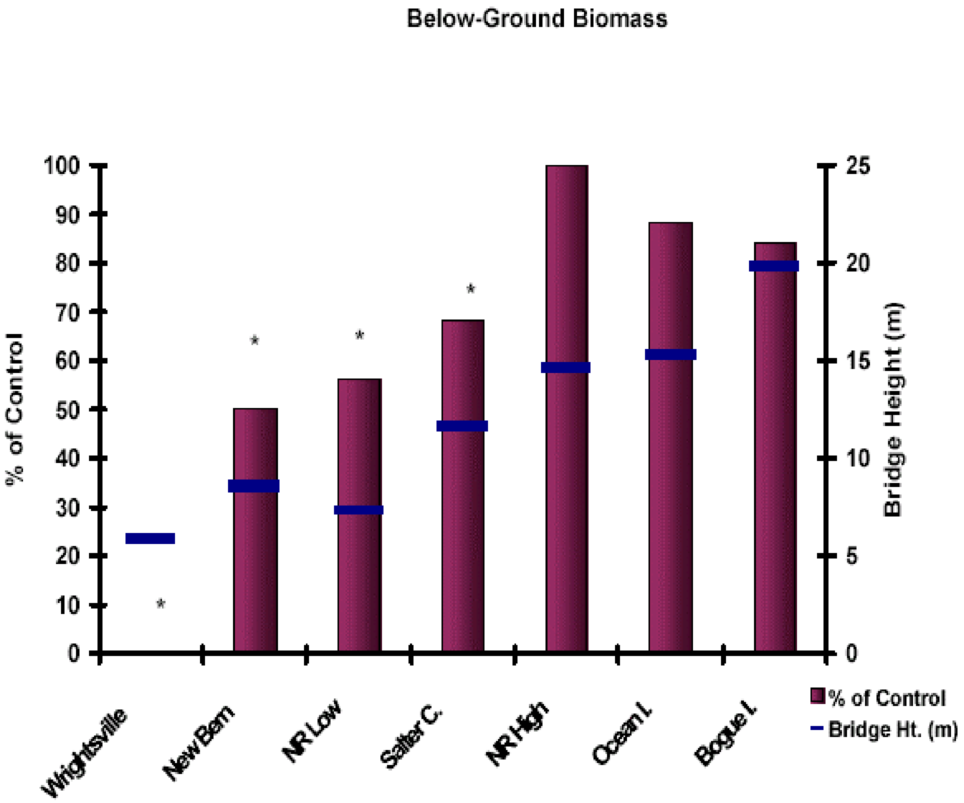


Figure 17. Mean below-ground biomass from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

All three bridges in the low category (Wrightsville Beach, New Bern and the low transect at New River) exhibit significant differences in belowground biomass between areas under and outside the bridges influence. Of the four bridges in the tall category, only Salter Creek exhibited a significant difference in mean belowground biomass over the two years of sampling. Mean belowground biomass under the bridge was 1908gm^{-2} while outside was 2777gm^{-2} resulting in a significant difference (p<.037). It should be noted that although the difference is significant when examining combined data from years 2000 and 2001 analysis of each year independently reveals a significant difference in 2001 but not 2000. Of the eight variables sampled at Salter Creek only one other is significant (number of stems) and is only so in 2001. Furthermore, C_3 plants such as *Juncus roemerianus* are adapted to moderate light levels and are not likely to be heavily affected by the shading of a tall narrow bridge such as Salter Creek. This suggests that the difference in belowground biomass at Salter Creek may result from sampling or natural variation rather than a bridge effect.

Measurements of belowground biomass were also examined by dividing the belowground cores into depth categories of 0-10 cm and 10-30 cm. Statistical analysis of the 0-10 cm-depth category revealed trends almost identical to those found when examining an entire core from 0-30cm. Significant differences between areas under and outside the bridges, occurred at Wrightsville, New Bern, and New River low transect (Figure 17). Data from the analysis of the 10-30 cm layer demonstrates patterns similar to those seen in looking at 0-30cm and 0-10. Significant differences occur at Wrightsville and New Bern. Unlike when examined on a 0-30 cm basis or 0-10 cm basis a significant difference occurs at the high transect at New River. It is highly unlikely that this results from bridge shading effect, as it is the only statistically significant difference occurring at this site. All other plant growth variables measured at the high transect of New River demonstrate no measurable bridge effect (Figure 9). This difference is likely due to the aforementioned dredging and refilling of the New River site.

Analysis of bridge height and width with each of the plant growth measurements used as a dependent variable revealed that bridge height and width are highly significant ($P<.05$) in determining the productivity of vegetation occurring under the bridges.

Soil Carbon and Soil Nitrogen

Soil C and N were not significantly affected by bridge height and width except at Wrightsville Beach where no vegetation was growing under the bridge. Evidence of the old root mat could still be detected but lack of marsh production over the last 44 years has decreased biomass inputs sufficiently to alter the percent of soil carbon (Figure 18) and soil nitrogen (Figure 19). A significant difference in soil carbon was also found at the low transect of New River bridge, this is likely the result of severe soil disturbances associated with the construction of the bridge.

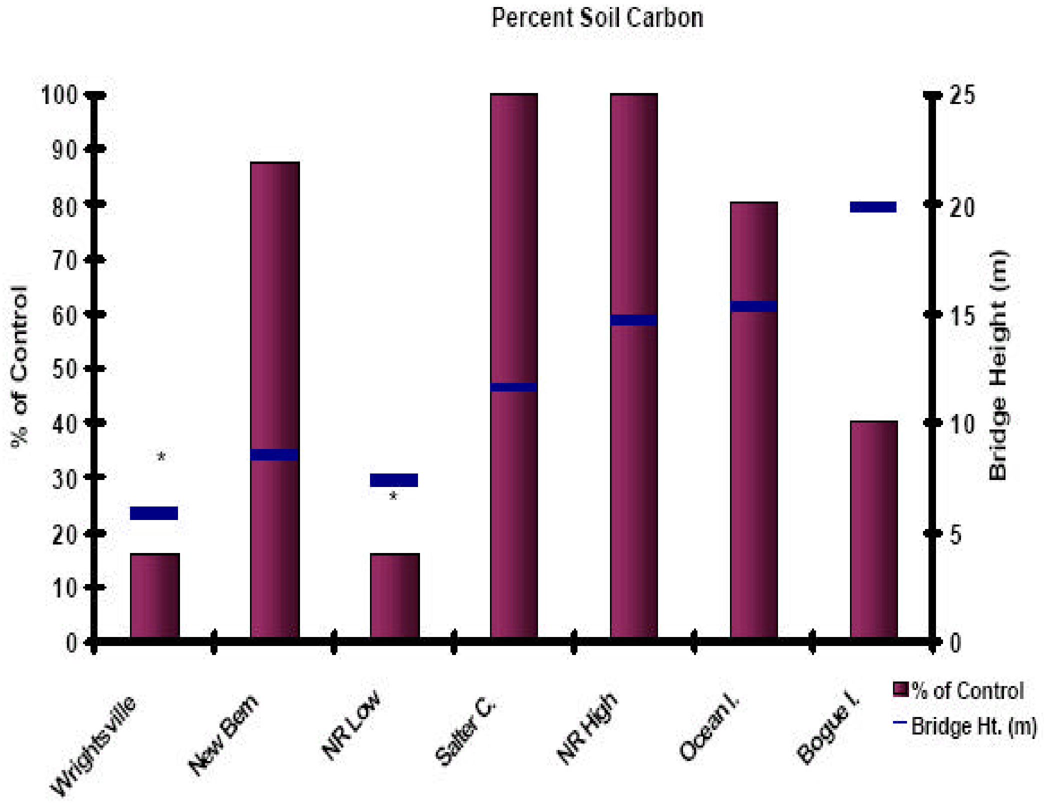


Figure 18. Mean soil carbon from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, p<.05.

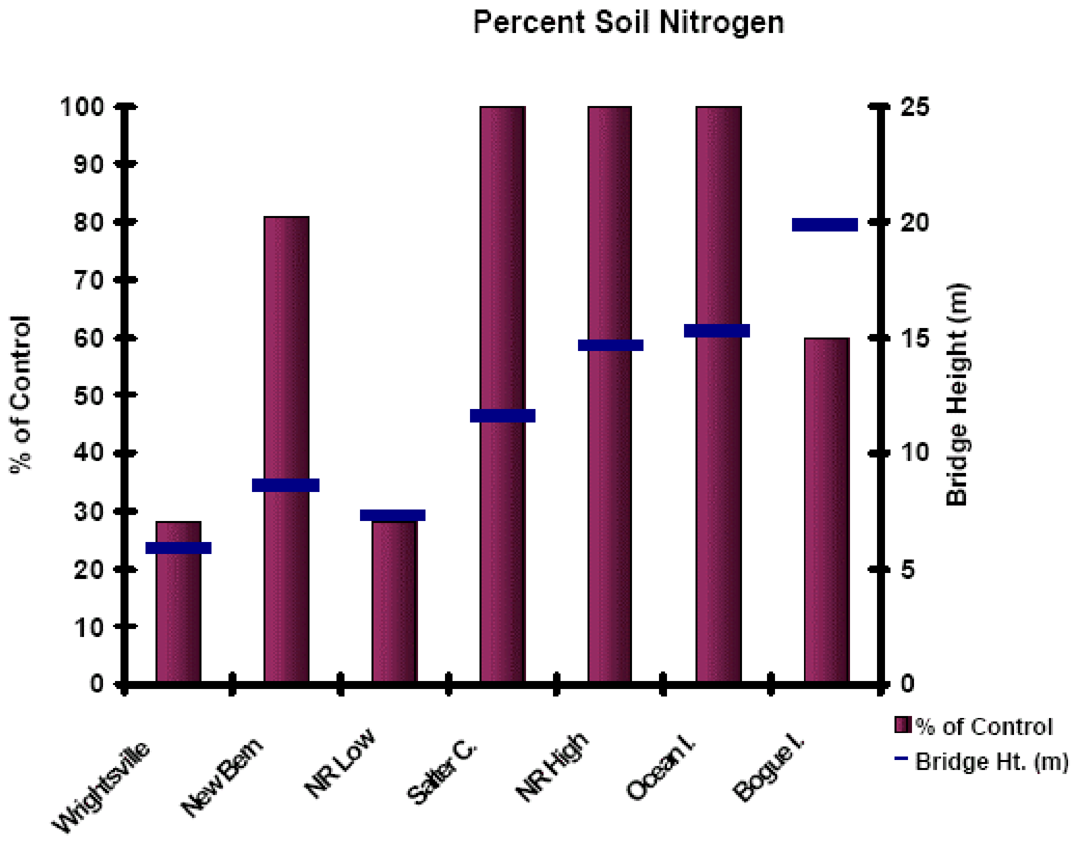


Figure 19. Mean soil nitrogen from years 2000 and 2001 expressed as a percentage of the control across seven bridges of varying heights. Asterisks indicate significant differences between areas under and outside the influence of the bridges, $p<.05$.

Bridge Height/Width Ratio

Arrangement of the bridges sampled using the HW ratio as opposed to height alone clarifies patterns seen in the data. Table 5 presents all the bridges sampled in order of increasing height along with the variables sampled, and whether a significant difference was detected. The order of the first three bridges when moving from lowest to highest is Wrightsville, New River low transect and New Bern. At Wrightsville (5.85 m) seven of the eight variables measured were significantly different under and outside the influence of the bridge. At New River low transect (7.3 m) three of the eight variables were significantly different, and at New Bern (8.53) six of eight variables were significantly different with four of the eight variables at 50% or less than that of the control (Table 5).

Rearranging the bridges by increasing HW ratios changes the order of the first three bridges to Wrightsville, New Bern, and New River low transect (Table 6).

This change is the result of the large difference in width between New Bern 16.71m and New River 10.7m and helps to explain why a taller bridge such as New Bern would demonstrate a greater bridge effect. By accounting for both height and width the HW ratio explains trends that height alone cannot. Viewing bridges in order of ascending HW ratios provides a more uniform trend and more clearly explains the decreasing bridge effect across the seven bridges studied (Table 5, Table 6). This indicates that width as well as height is an important growth-limiting factor.

SUMMARY

The data show a strong bridge effect occurring at the Wrightsville and New Bern sites as well as a smaller effect at the low transect at New River. All three of these bridges have heights less than 9 meters and HW ratios less than 0.7. Photosynthetic photon flux (µmol $m^{-2}s^{-1}$) averaged less than 20% of that recorded outside the influence of the bridge at all three locations. At Wrightsville ambient light measurements taken under the bridge were only 1.9% of those recorded outside the bridge's influence, consequently no vegetation is present under the bridge. In areas outside the bridge's influence, measurements of *Spartina alterniflora* biomass had a mean of $837gm^{-2}$ (Table 4). Using the HW ratio as opposed to height alone, the next bridge in ascending order is New Bern, HW ratio 0.51 and height of 8.53 meters. New Bern also exhibits a strong bridge effect with significant differences occurring in all six of the plant growth variables measured. Means of four of these variables under the bridge were less than 50% of the control. The low transect at New River is the next bridge with a HW ratio of 0.68. There was a diminished bridge effect, seen with three of the five variables being significantly different (Figures 15, Tables 4, 5, 6). Combining the three bridges grouped into the low category (<9 meters) twenty-four comparisons, were made between areas under and outside the bridges. Of these twenty-four comparisons sixteen were significant at $p<.05$ (Tables 5 and 6). Thus, 60% of the comparisons between areas under and outside the bridge were significant at HW ratios less than 0.68 and heights less than 8.53 meters. In the tall category four of the thirty-two comparisons made resulted in significant differences, this is only 12.5%. Furthermore, it is unlikely that any of these four differences can be attributed to a bridge effect. Regression analysis of the number significant differences occurring between areas under and outside the influence of the bridges as a function of bridge HW ratio shows a clear correlation ($r^2= 0.84$) between the two (Figure 20).

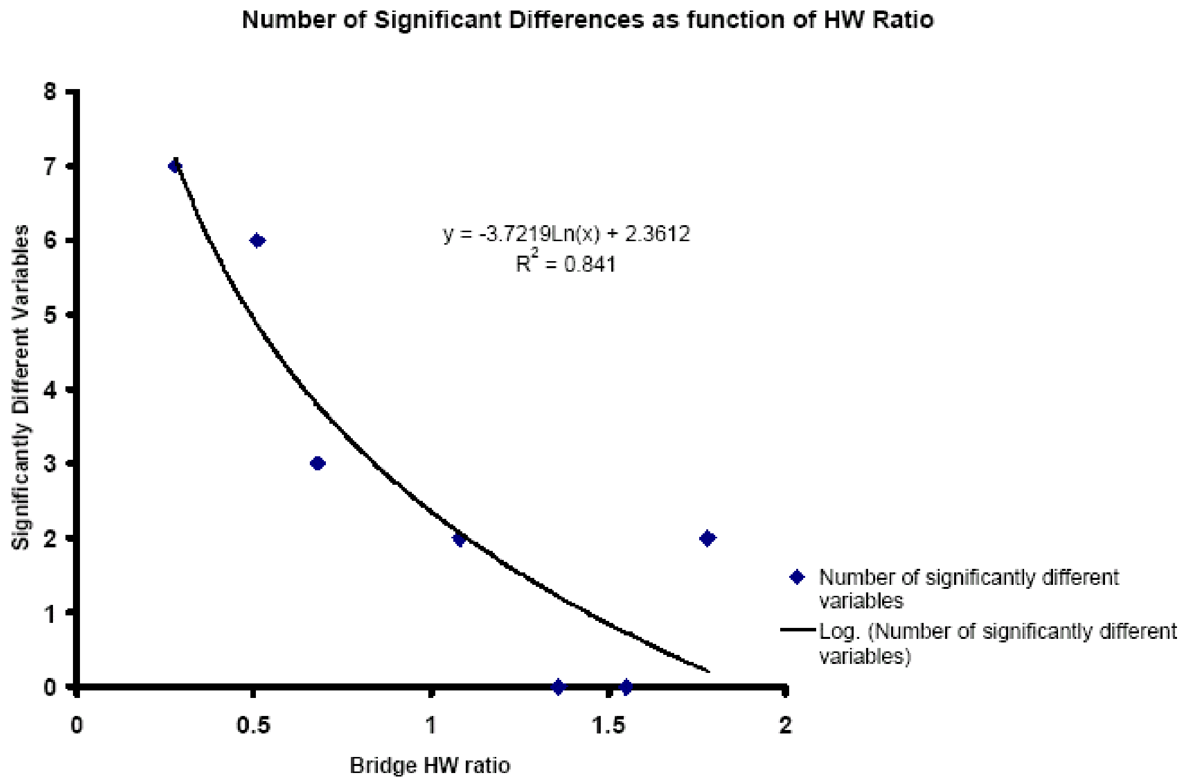


Figure 20. Regression analysis of decline in number of significant differences between variables under and outside influence of bridge as a function of bridge HW ratio.

Light measured under Bogue Inlet Bridge was 98% of the control at a HW ratio of 1.78, the highest of all bridges sampled, thus it is unlikely that these significant differences are due to a bridge effect. By assuming that the two significant differences occurring at Bogue Inlet are due to factors other than bridge effects, and deleting those values from the regression analysis, the relationship of number of different variables to bridge HW ratio becomes even more clear (r^2=0.95) (Figure 21).

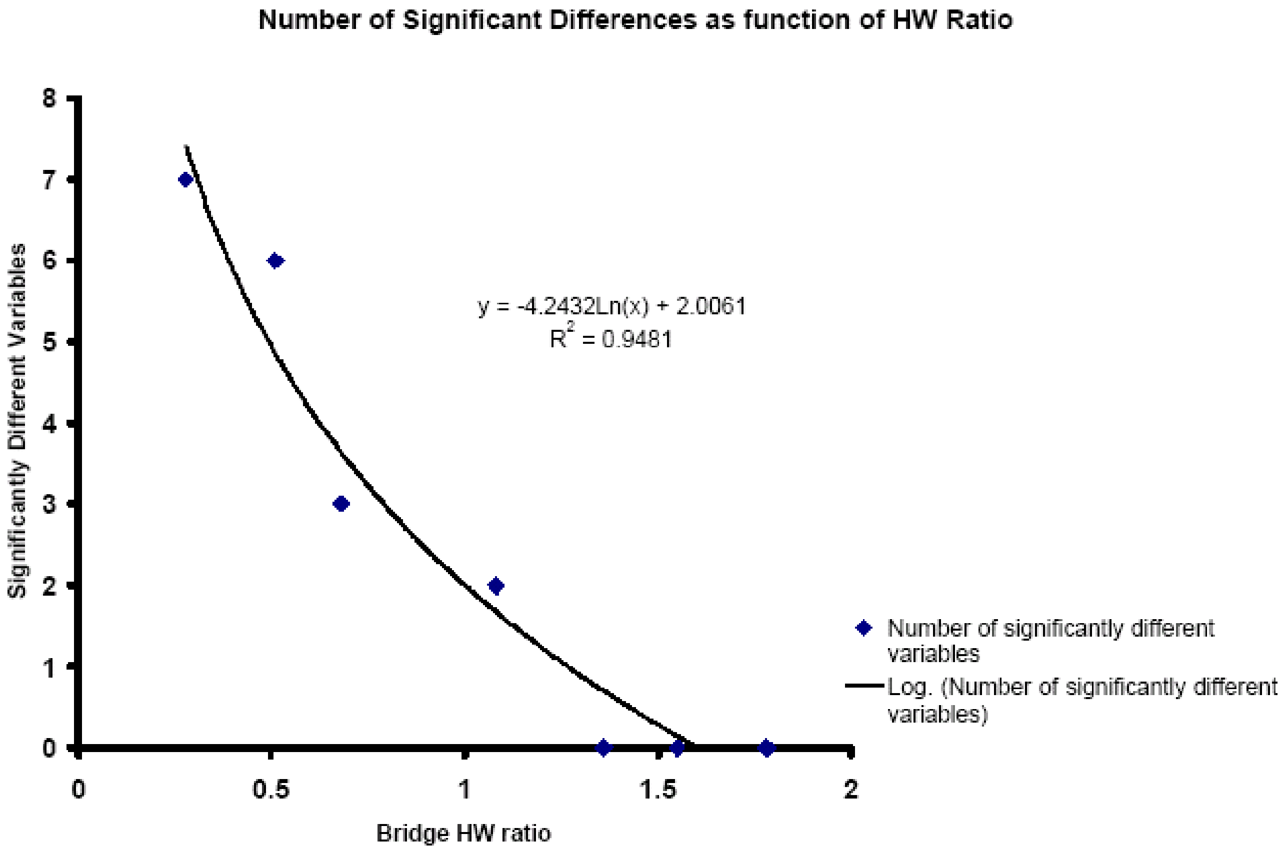


Figure 21. Regression analysis of decline in number of significant differences between variables under and outside influence of bridgez as a function of bridge HW ratio. (Bogue Inlet differences deleted).

This further supports the correlation between bridge HW ratio and the productivity and function of the underlying marsh.

CONCLUSIONS

Bridges spanning estuarine marshes can cause severe localized impacts to underlying vegetation. Impacts occur through shading from bridges as well as disturbances during construction. Under extreme circumstances shading by bridges may result in a complete loss of vegetation under the bridge. However, these effects tend to be small in area and only occur under the lowest and widest bridges (HW ratio <0.3).

Results suggest that bridges with HW ratios less than 0.5 affect marsh productivity and function under the bridges. At HW ratios between 0.5 and 0.68, bridge effects can be detected, although effects are greatly diminished. Above HW ratios of 0.70 the effects from shading by bridges are no longer measurable. Thus, it can be concluded that shading by bridges having HW ratios >0.7 do not adversely impact the productivity or function of the underlying marsh.

Portions of bridges with decks that are greater than 9 m above the surface of the underlying marsh, and that are narrow enough to keep the HW ratio greater than 0.7 allow sufficient light to support underlying vegetation with no measurable decline in productivity.

II. BRIDGE SHADING EFFECTS ON BENTHIC INVERTEBRATES

INTRODUCTION

Coastal wetlands provide an important interface between terrestrial and marine habitats. Salt, brackish, and tidal freshwater marshes reduce erosion by protecting coastlines from storm surges and wave action (Broome et al. 1986). Marshes serve as a sink in the global carbon cycle and sequester organic material and nutrients (primarily nitrogen) (Schlesinger 1977; Friedman and DeWitt 1978; Armentano 1980; Nixon 1980). Coastal wetlands play an important role in the human economy by offering habitat for commercially important juvenile fish and shellfish while contributing detritus to estuarine food webs (Teal 1962; de la Cruz 1973; Haines and Montague 1979; Peterson et al. 1986; Peterson and Howarth 1987).

With the expansion of human population and the demand for coastal dwellings and agricultural land, many coastal wetlands have been degraded or destroyed (Langis et al. 1991; Moy and Levin 1991; Zedler 1992). Continuous population growth demands new construction and improvements to many structures such as bridges, docks, and marinas. However, these structures can have an adverse impact on marsh structure and function. The initial construction of these structures may cause some harm to marshes, but longer-term shading may have a greater impact on overall structure and function than the initial construction. Light attenuation is one of the principal limiting factors of primary productivity (microalgae and emergent macrophytic vegetation) in shallow and intertidal estuarine habitats (Heip et al. 1995; MacIntyre et al. 1996; Underwood and Kromkamp 1999). Therefore, shading by such structures may adversely impact vegetation and overall net primary production (NPP).

Whitney and Darley (1983) found that microalgal communities in shaded areas are generally less productive than unshaded areas with productivity positively correlated with ambient irradiance. Likewise, net photosynthesis in *Spartina alterniflora, Juncus roemerianus* (Scheele), *Distichlis spicata* (L.), *Typha domingensis*, and *Cladium jamaicense* decreased with decreasing light intensity (Giurgevich and Dunn 1978; Giurgevich and Dunn 1979; Kemp and Cunningham 1981; Drake 1984; Pezeshki et al. 1996). Similarly, shading by boat docks resulted in a decrease in shoot density and biomass in temperate, tropical, and subtropical species of eelgrass (*Zostera marina* L., *Thalassia testudinum, Halodule wrightii*, *Posidonia australis*) (Walker et al. 1989; Czerny and Dunton 1995; Loflin 1995; Burdick and Short 1999; Shafer 1999).

While the decrease in microalgal productivity may be attributed to turbidity in pools and open water (Fitzpatrick and Kirkman 1995), physical structures such as bridges, docks, moorings and marinas can lead to a decrease in local productivity of emergent vegetation and algal communities. Such decreases can compromise the physical integrity of the remaining habitat, leaving it more susceptible to further habitat loss by erosion or invasions by other, less desirable or harmful species (Walker et al. 1989). In addition, heterotrophic communities dependent on organic matter for food, substrate, and refuges from predation, may be adversely impacted.

Benthic invertebrates are an important component of the salt marsh ecosystem, feeding on vascular plant detritus and associated bacteria and microflora in the soil (Craft 2000). These organisms are involved in the mechanical breakdown and consumption of primary production (Lopez and Levinton 1987), soil bioturbation (Bertness 1985), and salt marsh biogeochemical cycling (Alkemade et al. 1992). Levin et al. (1998) found macro invertebrates play an important role in the mechanical breakdown and consumption of primary production and increase bioturbation through feeding and burrowing activities contributing to the complex elemental cycling that occurs in salt marshes. Benthic invertebrates may be adversely affected by disturbances (e.g. shading) that reduce NPP because they are a heterotrophic community intimately linked to marsh primary production.

To date there have been relatively few studies exploring how shading may impact marsh macrofauna communities by reducing food sources and refuges from predators that algae and emergent vegetation provide. Stocks and Grassle (2001) used shading (up to 60 days with light reduced to 8% compared to controls) as a means of reducing microalgae as a food limitation in order to study the recolonization of benthic macrofauna within *in situ* salt-marsh pond mesocosms. They found the density of macrofauna in shaded plots was 62% lower than in controls with no shading effect on macrofaunal community diversity. However, the goal of the study was to determine if reduced microalgae, not shading, limited macrofaunal colonization and did not assess the effects of longer term shading or light attenuation on the estuarine benthic invertebrate community.

The objectives of this study were to investigate the effects of shading on marsh benthic macroinvertebrate community structure and function by comparing light attenuation and benthic invertebrate communities beneath seven highway bridges of varying heights and widths with marshes outside of bridges that are not influenced by bridge shading. This study hypothesized that a decrease in light availability would lead to a decrease in the amount of primary production. This, in turn, would result in a decrease in overall invertebrate density and taxa richness represented in samples collected under the bridge compared to nearby natural reference marsh samples. Functional capacity of the marsh was assessed through the analysis of four community attributes: total invertebrate density, invertebrate taxa richness, density of dominant taxa, and proportion of trophic feeding groups.

RESEARCH METHODS

Site Description

We sampled estuarine marshes adjacent to and beneath seven bridges along the North Carolina coast (Figure 22).

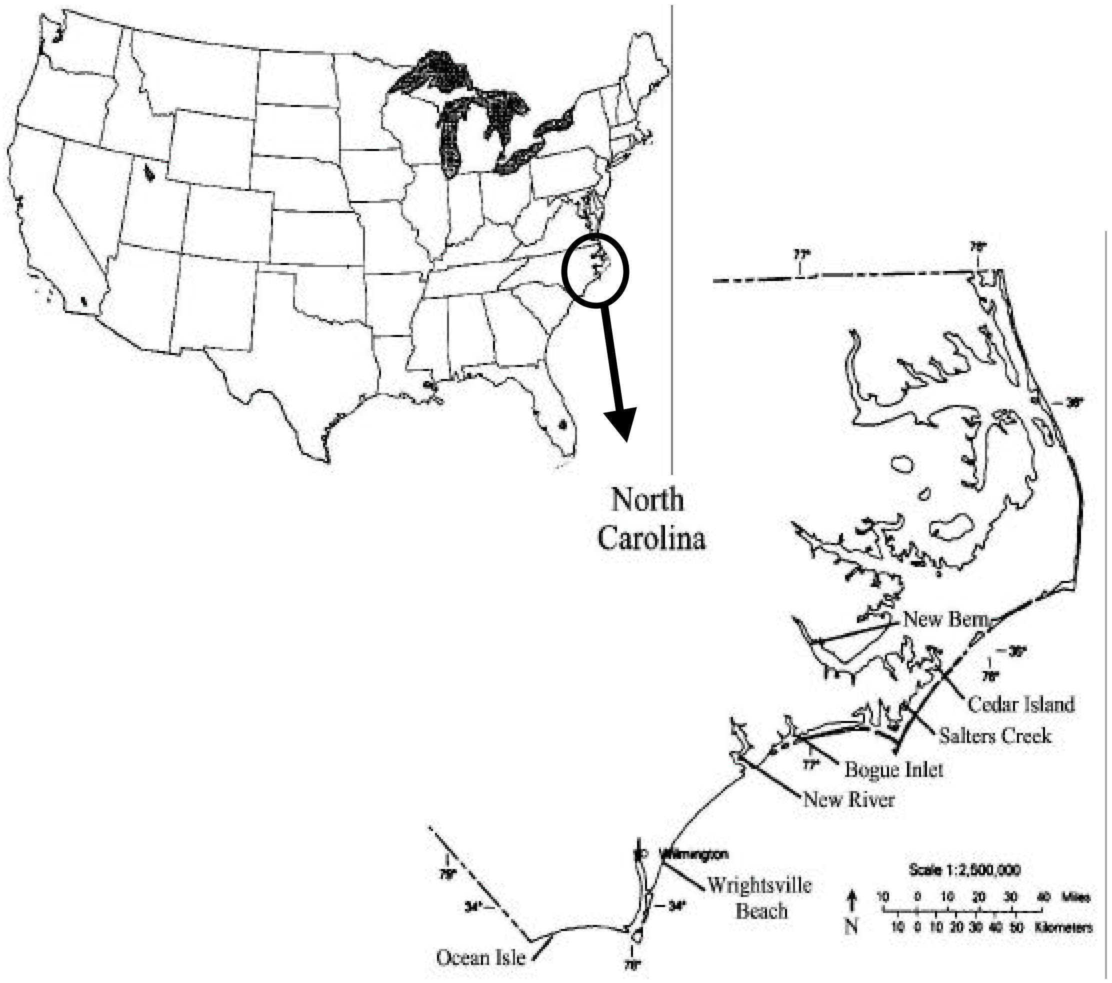


Figure 22. Map of eastern North Carolina showing the location of sampling sites. (Map modified from North Carolina Geological Survey 1984.)

Bridges were selected based on varying bridge height, width, orientation, and presence of marsh macrophytes (Table 7).

Table 7. Bridge parameters, salinity, and dominant vegetation used to evaluate effects of shading on established marsh invertebrate communities. Orientation is reported between 0º North and 180º South.

Location	Height (m)	Width (m)	HW Ratio	Age (yrs)[a]	Orientation	Salinity (g/l)	Dominant Vegetation
Wrightsville Beach	5.85	20.82	0.28	44	125º E-SE	32	*S. alterniflora*
Cedar Island	2.91	9.94	0.29	5	39º N-NE	29	*S. cynosuroides*
New Bern	8.53	12.59, 16.71[b]	0.68, 0.51[b]	24, 2[b]	112º E-SE	3	*S. cynosuroides*
New River - Low	7.32	10.73	0.68	7	176º S-SE	4	*S. alterniflora*
Salter's Creek	11.58	10.70	1.08	18	125º E-SE	22	*J. roemarianus*
New River - High	14.63	10.73	1.36	7	176º S-SE	4	*S. alterniflora*
Ocean Isle	15.24	9.85	1.55	16	167º S-SE	39	*S. alterniflora*
Bogue Inlet	19.81	11.13	1.78	19	168º S-SE	34	*S. alterniflora*

[a] Age is calculated as the number of years before initial sampling in 2000.
[b] The New Bern bridge was widened by 4.12 meters in 1998.

In 2000, benthic macroinvertebrates were sampled beneath each bridge as well as in unshaded reference marshes near each bridge. In 2001, one site (Cedar Island), along a gradient of varying bridge height, was intensively sampled to develop a predictive relationship between bridge height, width, light attenuation and benthic macroinvertebrate characteristics. Attempts were made to maintain similar conditions of vegetation, flooding depth and frequency, and sediment types between bridge sampling locations and in the nearby reference marsh of each site.

Field and analytical methods

Bridge Characteristics

Bridge width and height above the marsh soil surface were measured with a meter tape at each sampling point. A height/width ratio (HW ratio) was created by combining height and width variables because they both contribute to bridge shading. Orientation of each bridge was recorded with a hand compass and checked with digital orthophoto quadrangles (DOQ) of each bridge (U.S. Geological Survey, Reston, VA 20192 USA). Bridge construction and improvement data were obtained through construction records provided by the North Carolina Department of Transportation.

HW ratios ranged from 0.28 at Wrightsville Beach the second lowest but widest bridge, to 1.78 at Bogue Inlet, the highest measured bridge (Table 7). Bridge age varied from 5 to 44 years old. Bridge orientation of the seven bridges resulted in three bridges with roughly north / south orientations, three east-southeast / west-northwest orientations, and one with a northeast / southwest orientation (Table 7). Sample size and distribution of orientation measurements were not large enough to adequately assess the impacts of this variable.

Light Measurements

In July 2002, photosynthetically active radiation (PAR = 400-700 nm wavelengths), was estimated at each site by using a photosynthetic photon flux (PPF; μmol m^{-2} s^{-1} where 1 PPF = 5.01 foot-candles for sunlight) meter with a spherical quantum sensor (Li-Cor LI 190SA, Li-Cor, Inc., Lincoln, NE 68504, USA or BQM-SUN, Apogee Instruments, Logan, UT 84321, USA). Light data were collected simultaneously at or near the center of each bridge and outside of each bridge once during the growing season. Relative light attenuation, the percentage of surface irradiance compared to under bridge irradiance, was calculated by the quotient of paired "under bridge" light samples over "outside bridge" (natural sunlight) samples. Irradiance measurements were taken at thirty second intervals for at least 1.5 minutes when the ambient light outside of the bridge was in full or nearly full sunlight (1650 - 2000 μmol m^{-2} s^{-1}) between the hours of 1000 and 1500.

Benthic Invertebrate Sampling

Two soil cores each were collected from ten to twenty 0.25-m^2 plots sampled under each bridge and in reference marshes at the end of the growing season (early October) and to coincide with a period of maximal recruitment for the most common invertebrate species in the region (Watzin 1986; Levin and Huggett 1990). Cores were extracted with a stainless steel corer with a diameter of 3.8 cm from the upper 5 cm of soil resulting in a surface area equivalent to 11.35cm^2 per core. Samples were immersed in 10% buffered formalin containing Rose Bengal (to stain the organisms) in the field to preserve invertebrates. In the laboratory, samples were washed on a 250 µm sieve. Animals retained on the screen were sorted under a dissecting microscope and identified to the lowest possible taxon, counted, and stored in 70% ethanol. Invertebrate data were sorted into trophic groups (surface feeders, subsurface deposit feeders, carnivores, and unknown) based on feeding strategy (Sacco et al. 1994). The unknown feeding group included invertebrates in which food strategies were unknown in the literature or had several modes of feeding (i.e. nematodes, ostracods, copepods, acarina, and bivalves).

<u>Biomass and Soil C and N Measurements</u>

Aboveground biomass was measured by clipping five randomly selected 0.25-m^2 quadrants under each bridge and in unshaded reference marshes at the end of the growing season. Live standing material was dried in the laboratory at 70ºC, and weighed. A soil core (8.5 cm diameter by 30 cm deep) was collected from each clipped plot. Root material was separated from the soil by washing on a 2 mm diameter mesh screen. The remaining roots and rhizomes retained on the screen were dried at 70ºC and weighed.

A second soil core (8.5 cm diameter by 30 cm deep) was collected from each clipped plot and analyzed for total organic carbon and total nitrogen content. Soil material was air-dried, ground to a size allowing it to be sieved through a 2 mm-mesh diameter screen. An aliquot was treated with acid to determine whether carbonates were present. Organic C and total N were determined using a Perkin-Elmer CHN analyzer.

Statistical Analyses

Due to the variance in HW ratios, one-way ANOVA's were used to compare benthic macroinvertebrate community composition and richness, functional feeding groups, densities of the six most common invertebrates, above and belowground biomass, and soil carbon and nitrogen of under bridge samples (shaded) with natural reference marsh samples (no shading). A one-way ANOVA was used for 2001 data to compare changes in HW ratios and benthic invertebrate community characteristics, biomass and soil C and N at four bridge heights of varying light attenuation. Regression analysis was performed on the 2001 data using HW ratio and light data to evaluate the relationships between bridge HW ratio/light attenuation and invertebrate community composition. All tests of significance were made at a = 0.05. ANOVA analyses were performed using SPSS 10.0 (SPSS Inc., Chicago, IL 60606, USA).

RESULTS AND DISCUSSION

Shading Impacts on Benthic Invertebrates

Light Attenuation

Photosynthetic photon flux was lowest at bridge sites with HW ratios less than 0.70 with Wrightsville Beach, New Bern and New River-Low averaging 1.90% (36 μmol m^{-2} s^{-1}), 11.42% (218 μmol m^{-2} s^{-1}), and 19.43% (251 μmol m^{-2} s^{-1}), respectively (Table 8). These same sites had 8% - 100% less aboveground standing crop biomass and 25% - 100% less belowground biomass compared to respective reference marshes (Table 8).

Table 8. HW Ratio, irradiance, aboveground and below ground biomass, and soil organic carbon and total nitrogen under each bridge compared to natural reference marshes. Cedar Island biomass and soil cores were not collected in the first year of sampling. Cedar Island values for four bridge heights are shown in Table 5. Average natural irradiance was 1770 μmols^{-1}m^{-2} (full sunlight = 2000 μmols^{-1}m^{-2}). Values with an asterisk(s) indicate significantly lower values in under- bridge marshes versus natural reference marshes based on Student's t-test. "*", $p<0.05$; "**", $p<0.01$; "***", $p<0.001$. Values in italics indicate significantly ($p=0.05$) higher density in under bridge marshes versus natural reference marshes based on Student's t-test.

Site	**HW Ratio**	**Avg Irradiance Under Bridge (mmol m^{-2} s^{-1})**	**Available Ambient Light**	**Aboveground Biomass Under bridge (g/m^2)**	**Aboveground Biomass Natural Marsh (g/m^2)**
Wrightsville Beach	0.28	36	1.90%	0***	838
Cedar Island	0.29	18	0.93%	na	na
New Bern	0.51	218	11.42%	657**	1337
New River - Low	0.68	251	19.43%	898	975
Salter's Creek	1.08	364	18.20%	913	1051
New River - High	1.36	986	64.96%	1137	1237
Ocean Isle	1.55	1788	94.11%	*839*	621
Bogue Inlet	1.78	1639	98.85%	902	1043

Results by Giurgivich and Dunn (1979) are similar in which net photosynthesis was approximately 60% - 75% lower for the tall form and 66% - 82% lower for the short form of *Spartina alterniflora* when *in situ* plants were measured under low light (PAR approximately 250-300 μmol m^{-2} s^{-1}) conditions as compared to conditions of full sunlight (2000 μmol m^{-2} s^{-1}) in March, July, and September. Little or no vegetation growth would be expected as the photosynthetic capacity of plants declined with light availability to the point that net photosynthesis reaches zero (light compensation point). Burdick and Short (1999) found that the light compensation point for the submerged seagrass *Zostera marina* was approximately 2.5% (50 μmol m^{-2} s^{-1}) of ambient sunlight. Drake (1984) reported a light compensation point of 8.4% (167 μmol m^{-2} s^{-1}) in constructing a model using data for the brackish marsh species *Spartina patens*, *Distichlis spicata*, and *Scirpus olneyi.* Our light compensation point results are within these values with sampling points receiving less than 4.8% (96 μmol m^{-2} s^{-1}) ambient light lacking any aboveground macrophytic vegetation.

Bridges with HW ratios greater than 1.50, such as Ocean Isle and Bogue Inlet, had the lowest average percentage of light attenuation under each bridge with greater than 94% of ambient light reaching the marsh surface (Table 8). Likewise, there were no vegetation differences under these bridges with respect to the natural reference marshes. Salter's Creek bridge, with a HW ratio of 1.08 and light availability of 18.20% (364 μmol m^{-2} s^{-1}), had no significant difference in vegetation under the bridge compared to the reference marsh. However, this site consisted of a monotypic stand of the C_3 evergreen rush, *Juncus roemerianus.* Like most macrophytes, *J. roemerianus* typically increases net photosynthetic growth with increasing light intensity until a saturation point has been reached. However, *J. roemerianus* also has a longer seasonal photosynthetic capacity because of its ability to remain photosynthetically active at lower temperatures compared to C_4 marsh plants (Giurgevich and Dunn 1978). Thus, *J. roemerianus* can be metabolically active and undergo photosynthetic growth throughout the year unlike the responses of *Spartina alterniflora* and *Spartina cynosuroides* (C_4 species), the other marsh species sampled, which have a shorter growing season and senesce during colder temperatures at this latitude (Giurgevich and Dunn 1978).

Overall Invertebrate Density and Taxa Richness

There were no differences in benthic invertebrate densities in natural reference marshes and bridge shaded sites with an HW ratio greater than 0.70 (Salter's Creek, New River – High, Ocean Isle, and Bogue Inlet). However, bridges with an HW ratio less than 0.70 and ambient light less than 260 μmol m^{-2} s^{-1} contained significantly fewer ($p< 0.001$) benthic invertebrates than unshaded areas outside of the bridges. Density of benthic invertebrates at Wrightsville Beach (HW = 0.28), Cedar, Island (HW = 0.29), New Bern (HW = 0.51), and New River–Low (HW = 0.68), were 48-75% (67,506-108,171 organisms/m^2) of the density measured in adjacent reference marshes (Figure 23).

Bridges with low HW ratios (HW ratio < 0.70), had, on average, 45% less aboveground biomass compared to bridges with high HW ratios (HW ratio > 0.70) and 49% less aboveground biomass than the natural reference marshes. Likewise, belowground biomass was 51% to 61% less under low HW ratio bridges when compared to high HW ratio bridges and reference marshes, respectively (Table 8).

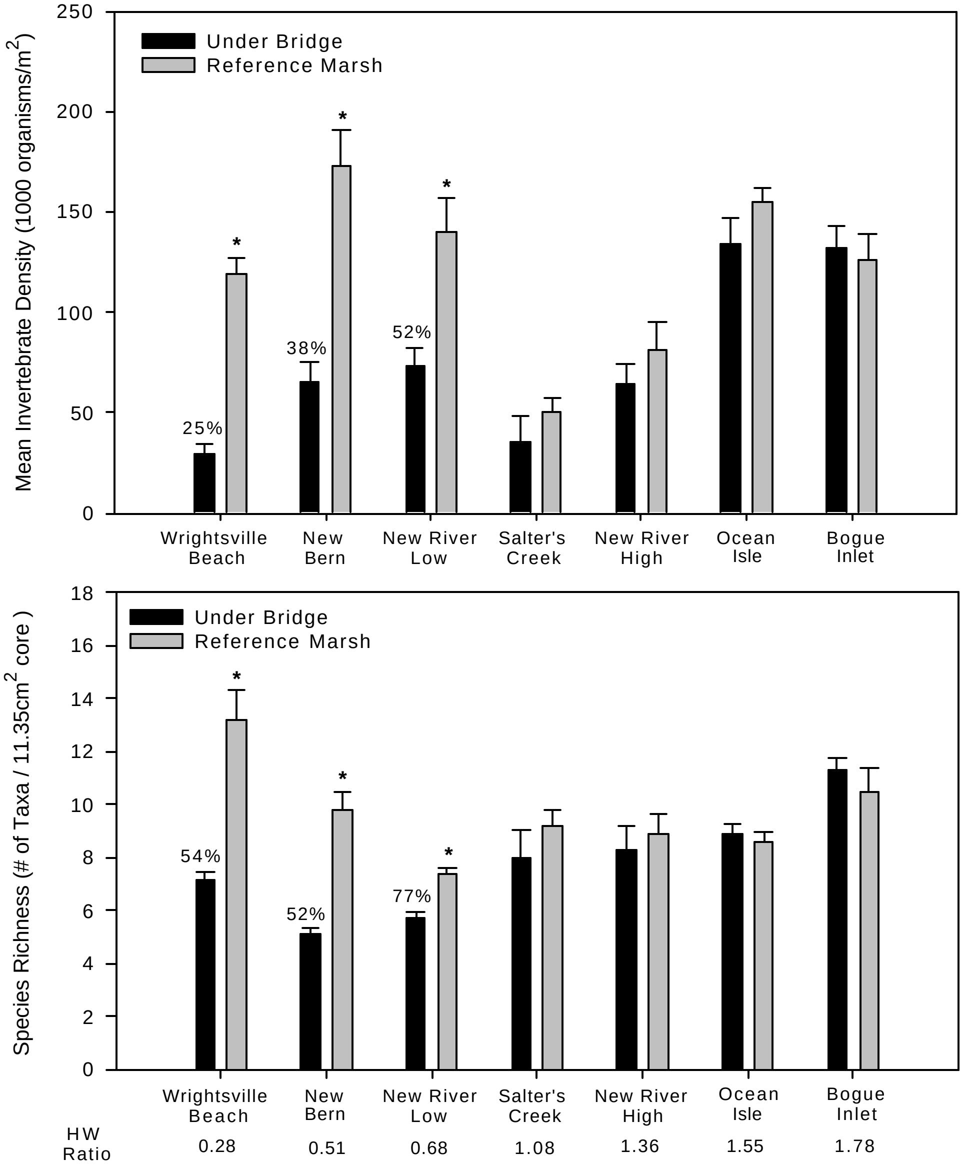


Figure 23. Composition of benthic invertebrate density and taxa richness under bridges (n = 10 for all sites except Wrightsville Beach and Bogue Inlet where n = 6; mean ± 1 standard error) of varying HW with natural reference areas outside of bridges (n = 10 for all sites except Bogue Inlet where n = 12; mean ± 1 standard error). Values with an asterisk indicate significantly ($p<0.05$) higher values in natural reference marshes versus under bridge marshes based on Student’s t-test. Percentages indicate the percent of invertebrate density and richness under “low” bridges compared to their reference marshes.

Soil organic C and total N showed similar trends. Wrightsville Beach and New River-Low had significantly less soil C (0.35% and 0.26%, respectively) and soil N (<0.04% and <0.04%, respectively) compared to unshaded reference marshes (Wrightsville Beach reference marsh, soil organic C = 2.02%, total N = 0.14%; New River-Low reference marsh, soil organic C = 0.53%, total N = 0.11%). New Bern also had less soil C and N under the bridge compared to the reference marsh (Table 8). Sites with reduced or absent vegetation and algae, would be expected to have fewer total macroinvertebrates, because salt marsh plants provide macroinvertebrates with protection from predation (Lopez and Levinton 1987), substrate and food, (Zajac 1986; Gremare et al. 1989; Marsh and Tenore 1990), while modifying temperature and humidity (Kraeter and Wolf 1974).

The low HW bridges exhibited a similar trend with taxa richness. There were, on average, fewer taxa represented under the bridge as opposed to the natural reference marsh at Wrightsville Beach, New Bern, and New River–Low (Figure 23). No differences were found in the remaining high HW ratio bridge samples.

Overall invertebrate densities ranged from 49,995-173,351 organisms/m^2. These invertebrate densities are similar to densities found in natural marshes of coastal North Carolina where nematodes were qualitatively enumerated (Craft and Sacco 2003) and in southern California *Spartina foliosa* marshes (Levin et al. 1998). These densities are higher than those reported in other natural marshes in North Carolina (Moy and Levin 1991; Levin et al. 1996). However, they reflect quantitative enumeration of nematodes that were retained on a 250um sieve or were in plant tissue that in other studies were excluded (Levin et al. 1996) or were classified as meiofauna that were sieved through a 63-300 µm mesh screen (Moy and Levin 1991).

Dominant Invertebrate Taxa

Bridges with an HW ratio less than 0.70 contained fewer dominant taxa than those with an HW ratio greater than 0.70. Significantly fewer oligochaetes were observed at Wrightsville Beach and New Bern under the bridges as opposed to natural reference marshes (Table 9). Wrightsville Beach also had significantly fewer *Manayunkia aestuarina*, *Streblospio benedicti*, *Capitella* sp., and nematodes under the bridge compared to the reference marsh and New Bern had significantly fewer *Capitella* sp. and nematodes (Table 9). In general, bridges with an HW

Table 9. Mean total density of six dominant taxa (number per m^2) of under bridge marshes and natural reference marshes. N is the number of samples collected each at under bridge and reference sites. Values with an asterisk(s) indicate significantly lower while values with a positive sign indicate significantly higher densities in under- bridge marshes versus natural reference marshes based on Student's t-test. "*", p<0.05; "**", p<0.01; "***", p<0.001. Values with a "+" indicate significantly (p=0.05) higher density in under bridge marshes versus natural reference marshes based on Student's t-test.

			Oligochaetes		***Manayunkia***		***Steblospio benedicti***	
Site	**HW Ratio**	**N**	**Bridge**	**Reference**	**Bridge**	**Reference**	**Bridge**	**Reference**
Wrightsville Beach	0.28	6	3233***	19692	0*	8377	2351**	17341
Cedar Island	0.29	10	3351*	23190	0	0	970	2028
New Bern	0.51	10	7759***	28480	0	0	0	0
New River - Low	0.68	10	5026	11992	0	0	0	0
Salter's Creek	1.08	10	11286	12344	1763	353	0	0
New River - High	1.36	10	9082	20986	0	0	8200	11198
Ocean Isle	1.55	10	24160	29362	0	0	16224	17106
Bogue Inlet	1.78	12	17044	16603	15431+	588	3233	4702
			Capitella sp.		***Nematodes***		***Nereidae sp.***	
Wrightsville Beach	0.28	6	1617**	12344	16312*	35417	1617	2351
Cedar Island	0.29	10	705	2204	3439	4144	529	176
New Bern	0.51	10	0***	1675	50348***	121593	1587	1852
New River - Low	0.68	10	1146	617	31302	47791	353	176
Salter's Creek	1.08	10	794	705	12168	9346	441*	2557
New River - High	1.36	10	4321	6613	28833	31831	803	88
Ocean Isle	1.55	10	2293	705	129705	160213	882	1411
Bogue Inlet	1.78	12	4115	3331	75095	79357	0	441

ratio less than 0.70 had 77% fewer oligochaetes and 51% fewer nematodes when compared to natural reference marshes. Bridges with an HW ratio greater than 0.70 had oligochaete and nematode densities that were not significantly different from the unshaded reference marshes (Table 9). These two taxa are numerically dominant, constituting nearly 60% of the total invertebrate density; therefore, they are likely to show the greatest decline in population with decreased food and less protection from predators.

Trophic Composition

Similar to total density and taxa richness, bridges with an HW ratio less than 0.70 adversely affected trophic composition. Wrightsville Beach, New River–Low, and New Bern sites contained fewer surface (52%-89%), subsurface (40%-84%), and unknown feeders (50%-64%) (Table 10). There was no significant relationship between the densities of carnivores found in under-bridge samples compared to reference marsh samples.

With the rate of soil organic matter accumulation dependent upon primary productivity and decomposition (Friedman and DeWitt 1978), the reduction or absence of plant biomass beneath bridges leads to reduced inputs of organic matter that serve as food sources for the suspension- and deposit- feeding detritivores, as those categorized in the surface and subsurface feeding groups. Similarly, reduced levels of soil N and C (with the exception of the high nutrient pools at New Bern) found under bridges versus the natural reference marshes may contribute to the reduction in benthic invertebrates beneath bridges. Craft (2000) reported that benthic invertebrate communities developed concurrently with accumulating soil organic carbon along a 25-year old chronosequence of created *S. alterniflora* marshes, emphasizing the role organic matter plays in benthic invertebrate structure and function.

Table 10. Mean total density of benthic invertebrate community feeding groups (number per m^2) in under bridge marshes and natural reference marshes. Values with an asterisk(s) indicate significantly lower density in under bridge marshes versus natural reference marshes based on Student's t-test. "*", p<0.05; "**", p<0.01; "***", p<0.001.

			Surface Feeders		Subsurface Feeders	
Site	**HW Ratio**	***N***	**Bridge**	**Reference**	**Bridge**	**Reference**
Wrightsville Beach	0.28	6	3968***	31008	5143***	32918
Cedar Island	0.29	10	2116	4144	3968*	25394
New River - Low	0.51	10	353*	3262	22749*	38180
New Bern	0.68	10	2028*	4232	7759***	30861
Salter's Creek	1.08	10	6437	10052	12697	14637
New River - High	1.36	10	10581	12609	15342	30156
Ocean Isle	1.55	10	20016	20456	26629	26717
Bogue Inlet	1.78	6, 12	20427	16753	23072	17782
			Carnivores		**Unknown Feeders**	
Wrightsville Beach	0.28	6	1470	2645	19105**	53199
Cedar Island	0.29	10	0	265	9699	6437
New River - Low	0.51	10	88	0	49730**	99373
New Bern	0.68	10	0	0	55374***	138258
Salter's Creek	1.08	10	0	0	16841	25306
New River - High	1.36	10	176	441	33771	34653
Ocean Isle	1.55	10	0	0	174762	197864
Bogue Inlet	1.78	6, 12	0	0	88909	91554

The unknown feeding strategy trophic group dominated with 63.5% of the total invertebrates collected. This is likely due to the number of organisms identified with multiple feeding strategies (classified as unknown) such as nematodes and copepods (63% and 12%, respectively) which are excluded or qualitatively enumerated from some trophic structure analyses (Craft and Sacco 2003). Subsurface (25.8%), surface (10.5%), and carnivore (0.2%) feeding groups comprised the rest of the trophic groups.

Predictive Relationship between Bridge Height and Benthic Invertebrates

Light Attenuation

Regression analysis of bridge HW ratio versus light attenuation along a gradient from low bridge elevation to high elevation at one site (Cedar Island) revealed a clear relationship between bridge HW ratio (hence, bridge height and width) and relative available light under the bridge (Figure 24).

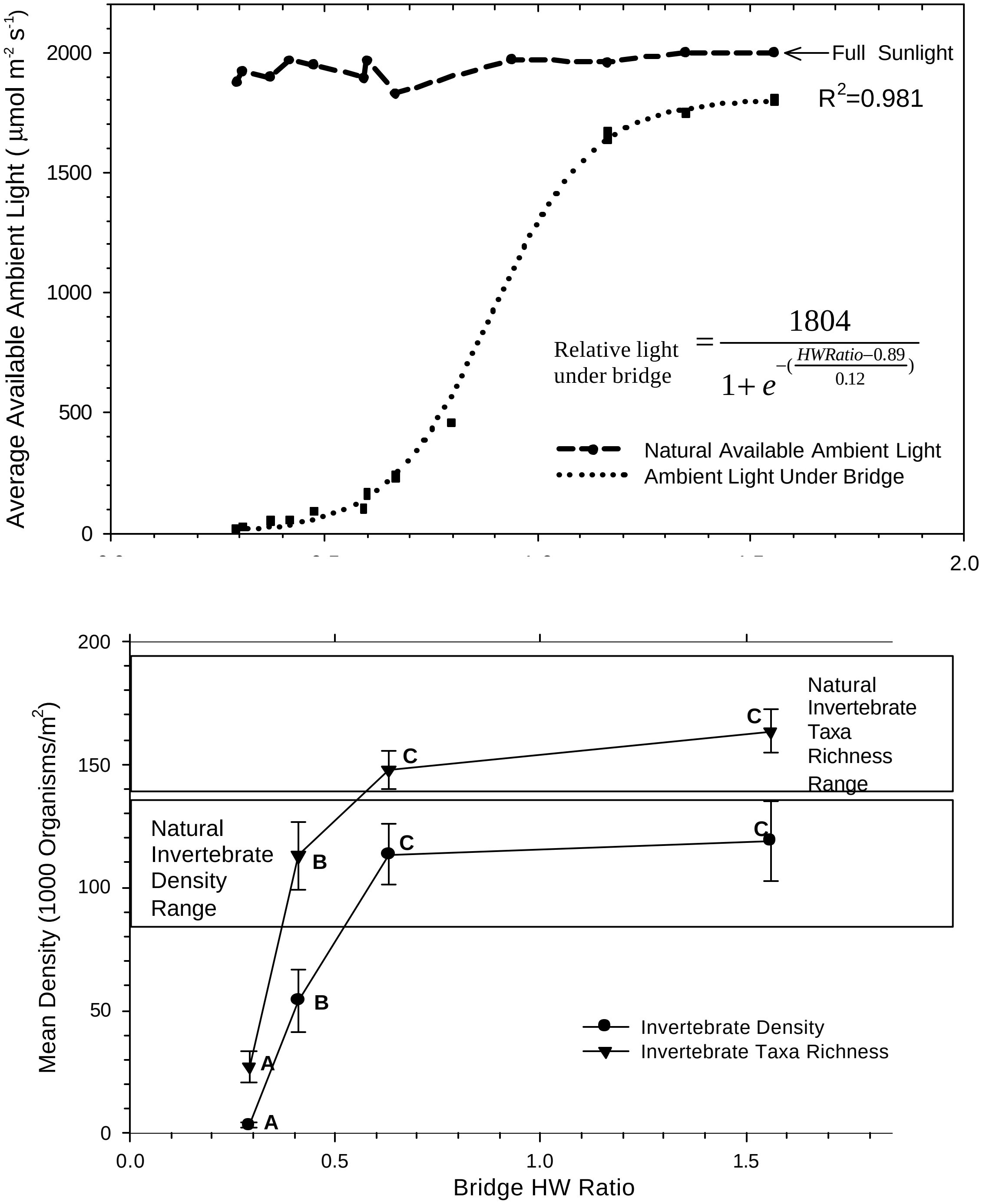


Figure 24. Relative available light and natural available light (top) and mean total density and taxa richness (bottom) for Cedar Island samples and nearby natural reference marshes. Capital letters denote significant differences ($p < 0.05$ using Student's t-test) from each mean. Error bars = ± 1 SE. Shaded areas represent the range of total density and taxa richness measured in the natural marsh.

Aboveground biomass was 0%, 62%, and 72% at the low, medium-low, and medium high sampling sites, respectively, compared to the natural reference marsh biomass (Table 11). These same sites had an average belowground biomass of 0%, 16%, and 21%, respectively, compared to the natural reference marsh. Soil organic C was 32% (low), 39% (medium-low) and 70% (medium-high) of the levels measured in the unshaded reference marsh (Table 11). Likewise, the percentages of soil total N at these, respective sites were 25%, 40%, and 62% of the soil nitrogen levels measured in the reference marsh.

Table 11. Percent organic carbon, percent total nitrogen, below and aboveground biomass of samples collected at four separate HW ratios (by increasing bridge height) and the natural reference marsh at Cedar Island in 2000. Lower case letters denote significant differences between sampling sites based on Tukey's HSD test.

Site	HW Ratio	*N*	Carbon in soil (%)	Nitrogen in soil (%)	Aboveground biomass (g/m^2)	Belowground biomass (g/m^2/30cm depth)	Average irradiance (mmol m^{-2} s^{-1})
Low	0.29	10	1.18 **a**	0.065 **a**	0.00 **a**	0.00 **a**	18
Medium Low	0.41	4	1.42 **a**	0.105 **a**	305.55 **a,b**	347.61 **b**	52
Medium High	0.63	6	2.54 **b**	0.163 **b**	352.57 **a,b**	467.58 **b**	200
High	1.56	10	6.41 **d**	0.481 **d**	474.65 **c**	2738.36 **c**	1803
Natural Marsh	na	10	3.63 **c**	0.265 **c**	490.84 **b,c**	2133.76 **c**	1936

Invertebrate Density and Taxa Richness

Total invertebrate densities were 4% of the reference marsh invertebrate density at the low (HW = 0.29) bridge site and 57% at the medium-low (HW = 0.41) bridge site (Figure 24). Similarly, invertebrate taxa richness at the low and medium-low bridge sampling locations were 16% and 70%, respectively, of the reference marsh taxa richness. Invertebrate density and taxa richness at the medium-high and high sites did not differ significantly from the reference marshes (Figure 24). The observed reduction in invertebrate density and species richness at low and medium-low bridge elevation is likely the result of reduced levels or even the absence of plant biomass and low levels of

soil organic carbon and nitrogen. These are needed to provide refuge from predation as well as to sustain food and substrate requirements for the heterotrophic community.

Dominant Invertebrate Taxa

As with total density, significantly fewer oligochaetes were present at the low bridge elevation compared to the reference marshes. Similarly, low and medium-low elevations had significantly fewer nematodes than were found in the reference marsh (Table 12). These two taxa are numerically dominant, making up 61% of the total invertebrate density (35% for oligochaetes and 26% for nematodes).

Table 12. Mean total density of dominant taxa (number per m^2) of a single marsh at four bridge heights and natural reference marshes. Values with an asterisk(s) indicate significantly lower density in under bridge marshes versus the natural reference marsh based on Student's t-test. "*", p<0.05; "**", p<0.01; "***", p<0.001.

Site	Height (m)	HW Ratio	*N*	Oligochaetes	Capitella sp	Nematodes
Low	2.9	0.29	8	2498**	882*	1470**
Medium Low	4.1	0.41	3	24689	4409	7054*
Medium High	6.3	0.63	5	45674	3527	32977
High	15.5	1.56	8	39127	13887	37474
Natural Marsh	na	na	16	39318	10856	33366
				Calanoid sp.	***Spitatella inflate***	**Acarina**
Low	2.9	0.29	8	220	0***	0**
Medium Low	4.1	0.41	3	1226	1470*	588
Medium High	6.3	0.63	5	1108	7936	705
High	15.5	1.56	8	2535	15982	2755
Natural Marsh	na	na	16	2149	11022	3086

In addition to oligochaetes, nematodes and *Capitella* sp., the meiofauna *Harpacticoid* sp., the gastropod *Spiratella inflata*, and the mite *Acarina* sp. were numerically important taxa in the Cedar Island samples. These species are more common in brackish marshes than salt marshes (S.D. Struck, unpublished data). Similar to other taxa, significantly fewer *Spiratella inflata* and *Acarina* species were observed at the low bridge sampling site compared to the reference marsh (Table 12). In addition to differences from the natural reference marsh, *Acarina* sp. had significantly fewer representatives at the low bridge samples compared to the high bridge samples.

Trophic Composition

Low and medium-low bridge elevations had lower densities of surface deposit (4% and 84%, respectively), subsurface deposit (5% and 62%), and unknown (2% and 50%) feeding strategists when compared to densities found in the reference marsh (Table 13). The low bridge elevation also had significantly fewer unknown feeding strategists compared to the medium-high and high bridge sites (Table 13).

Table 13. Mean total density of benthic invertebrate community feeding groups (number per m^2) of a single marsh at four bridge heights and natural reference marshes. Values with an asterisk(s) indicate significantly lower density in under-bridge marshes versus the natural reference marsh based on Student's t-test. "*", p<0.05; "**", p<0.01; "***", p<0.001.

Site	Height (m)	HW Ratio	*N*	Subsurface Feeders	Surface Feeders	Carnivores	Unknown
Low	2.9	0.29	8	1984**	772**	0	770***
Medium Low	4.1	0.41	3	26159*	4702*	294	23807*
Medium High	6.3	0.63	5	49554	12697	0	51318
High	15.5	1.56	8	55219	281056	0	47835
Natural Marsh	na	na	16	42489	17958	0	47229

Reduced plant biomass, organic C, and total N in the low and medium low bridge elevations are likely the reason for the trophic differences observed. Relative proportions of trophic feeding groups were similar between under-bridge and the reference marsh. Subsurface deposit feeders and unknown feeders, respectively, dominated the overall trophic feeding structure composing 46% and 42% of the under-bridge samples and 45% and 43% of the reference marsh samples at Cedar Island. As in the year 2000 sampling of invertebrates, there was insufficient data representing the carnivorous trophic feeding group to contribute to the analyses.

CONCLUSIONS

Bridges spanning salt and brackish water marshes in North Carolina with a HW ratio less than 0.70 and available light = 260 μmol m^{-2} s^{-1} have a negative impact on under bridge invertebrate density, taxa richness, dominant taxa (oligochaetes, nematodes, and *Capitella sp.*) as well as trophic feeding groups (surface and subsurface deposit feeders). Results from the year 2001 study of Cedar Island, assessing the role of bridge height, are similar, with additional impacts to densities of *Spiratella inflata* and *Acarina* species characteristic of more brackish marsh areas. Our results suggest that low bridges, that attenuate light to less than 260 μmol m^{-2} s^{-1}, may adversely affect estuarine marsh food webs by reducing macrophyte growth and soil organic carbon which adversely impact the density and diversity of benthic invertebrates. With a greater knowledge of bridge shading effects, bridge design and construction may be improved to reduce the impacts on estuarine marsh ecosystem structure and function.

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