Plant and Soil Characterizations in a *Spartina alterniflora* Saltmarsh Experiencing Dieback in Terrebonne Parish, Louisiana, USA.

Task II.4

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In Partial Fulfillment of:
DNR Interagency Agreement No. 2512-05-03

December 17, 2004

Acknowledgements

This report was prepared by Thomas C. Michot, R. Scott Kemmerer, and Jeremy J. Reiser, and was partially funded from the National Oceanic and Atmospheric Administration, U. S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the Department of Commerce. Additional funding was provided by USGS. The Louisiana Department of Natural Resources and the Barataria-Terrebonne National Estuary Project assisted in the administration of funding. We would like to acknowledge Mark Ford, Patricia Rafferty, Troy Olney, Ron Boustany, Rebecca Moss, and Patricia Lavin for their assistance with experimental setup, field data collections, laboratory assistance, and data management. Brian Perez, Christopher Swarzenski, and Bradley Segura provided additional logistical support for field trips. We thank Darren Johnson of JCWS for statistical analyses and review, and Connie Herndon, Christopher Swarzenski, Gregory Grandy, and an anonymous referee for technical and peer reviews.

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Abstract

We established five pairs of study sites in Terrebonne Parish, Louisiana, to investigate a dieback of *Spartina alterniflora* Loisel (smooth cordgrass) marsh. The dieback was first observed in May 2000. We established two sites in 2000 and three in 2001. Each study site pair consisted of a Dead site (impacted by the dieback) and an adjacent Live site or reference site (survived the dieback). We constructed boardwalks and established four permanent one-square-meter plots at each site. Site visits were made approximately every four to six weeks from October 2001 to September 2002. During each visit we collected vegetation and porewater chemistry data from each plot. Vegetation data included dead and live stem densities, dead and live stem heights, leaf characteristics, stress categories and a vegetation cover transect. Interstitial porewater data included salinity, sulfides, pH, NH_4, NO_2, PO_4, and redox potential (Eh) at 15 cm and 30 cm below the sediment surface. All impacted sites showed steady recovery over time, as evidenced by an increase in vegetation cover and stem densities, whereas reference sites showed no change; stem heights were variable at both sites. Our interstitial porewater data showed no trends that were consistent among sites and months. Salinities varied (12-30 ppt) but never exceeded tolerance limits for *S. alterniflora*. Porewater pH levels were near neutral (site means 7.1-7.4), and when treatment effects did occur, the dead sites had higher values than the reference sites (contrary to predictions). Sulfide levels were high (site means 1.4-6.4 mmol), with some significant differences among sites and months, possibly driven by hydrological factors. When treatment effects did occur, it was the reference sites that showed higher sulfide levels (contrary to predictions). Oxidation-reduction potential varied, presumably driven by hydrology, but appeared to be in the normal range for wetlands. At this time we cannot determine a probable cause for the dieback, though future comparisons with results from concurrent studies may provide additional insight and aid in our analysis.

Introduction

Dieback of *S. alterniflora* Loisel in Louisiana marshes was documented in 1968 (Smith 1970), and since that time it has been noted that relatively small areas of *S. alterniflora* or *S. patens* marsh dieback are common within the Louisiana coastal zone (Mendelssohn and McKee 1988, Webb and Mendelssohn 1996). The dieback of 2000, however, occurred on a much larger scale, and there was concern among managers that accelerated wetland conversion to open water could result. During a season when salt marshes, dominated by the perennial grass *S. alterniflora*, are typically healthy and support rapidly growing plants, we noted an unprecedented extent of stressed, dying, and dead vegetation beginning in May 2000. The dieback peaked in March 2001 and affected approximately 51,000 hectares (126,000 acres) in southeast Louisiana (Michot et al. 2004).

In an effort to characterize the dieback and to investigate potential causes, we established study sites at Bay Junop and Bayou du Large in the summer of 2000. Later, in 2001, we received funding to conduct the current study. At that time we established three additional paired sites, for a total of five paired sites. This document reports finding from the five sites during 2001 and 2002, but does not report on findings from the original two sites during the first year (2000-2001).

Methods

We established pairs of sites on adjacent dead (<15% live plants) and live (>85% live plants) marsh tracts at five locations in Terrebonne Parish, Louisiana (Figure 1). The Bay Junop (BJU) site was established in June 2000 and the Bayou du Large (BDU) site in September 2000. The other three sites, Bayou Sale (BSA), Lake Felicity (LFE), and Old Oyster Bayou (OOB), were selected in May 2001, and data collection began in October 2001. The sites were sampled every four to six weeks from October 2001 to September 2002.

At each site we established four one-square-meter permanent plots (quadrats) in random locations. From those plots we collected data on vegetation and interstitial (porewater) soil chemistry. We constructed wooden boardwalks at each site to facilitate access while minimizing damage to plants and substrate. Concurrent with our study, data were collected at the same sites by another group (Swarzenski et al. 2004) for hydrology, substrate elevation, and soil chemistry. As part of that study we determined absolute elevations for all of our sites, and hindcasted water level history over the dieback period (reported in Swarzenski et al. 2004).

We established permanent transects to measure vegetation adjacent to the boardwalk at each site. The boardwalks were oriented perpendicular to the bayou or waterway and extended into the interior marsh for a distance of approximately 20-40 m. Planks on the boardwalk were approximately 20 cm wide by 3 m long. We used the boardwalk at each site as a framework from which to estimate vegetation cover; thus, the boardwalk served as a reference structure for the permanent transects. We estimated percent cover of each plant species and of unvegetated substrate, adjacent and parallel to each board, out to a distance of approximately 20 cm on both sides of the board. Because we observed plants growing up to and touching the boards at all sites, shading effect was assumed to be minimal.

Vegetation present in the quadrats was divided into two classes: live (totally or partially green), and dead (no green tissue present). We classified live plants into three stress categories: >90% green, 50–90% green, and <50% green. For statistical analysis, we converted those values to a range of zero to one, where 0 = brown and 1 = green. We classified dead plants into four categories assumed to correspond to the length of time that the plant had been dead: standing dead stems with intact leaves, standing dead stems with frayed leaves, culms with no leaves, and stubble. For statistical analysis we converted those four values to a scale of zero to one, where 0 = dead and intact, and 1 = no stem present (only stubble). In each quadrat, we measured maximum and average plant height for live and dead stems and counted the number of dead and live stems per square meter. We also counted and recorded densities of snails (*Littorina irrorata*) in each quadrat.

We used a plastic tube and syringe to collect interstitial water samples in the center of each quadrat at depths of 0 cm (surface water, when present), 15 cm, and 30 cm below the sediment surface. These samples were used to determine salinity, temperature, pH, sulfides, and nutrients (PO_4, NH_4 and NO_2). Salinity and temperature were measured on site using a Yellow Springs Instruments model 85 salinity meter and probe. Measurements of pH were determined on site using a Hanna HI9025 digital pH meter standardized with a two point calibration using buffers of known pH values. For sulfide measurements we prepared a dilute sodium salicylate antioxidant buffer and standards in the laboratory prior to the field trip and stored them in airtight containers on ice (separate containers for each day) for field use within five days. Because loss of buffering capacity is indicated by dark coloration, we inspected the buffer solutions prior to each use and discarded them if a color change was detected. In the field we collected a 5-ml aliquot of interstitial water from each plot/depth, then treated it with the buffer. Within 24 hours we ran standards, field samples, and then standards again (to check for drift), using an Orion sulfide electrode and a Cole Parmer Digi-Sense digital pH meter with millivolt (mV) conversion capabilities (Lazar Research Labs, Inc., undated publication). Readings were then compared to standards using a log regression standard curve and converted from mV to ppm by multiplying the inverse log mV value by two (because samples are diluted 50% with buffer). We then divided the ppm values by the molecular weight of sulfur (32.06) to obtain concentrations in millimolars (mmol). As an additional quality control check on our sulfide methodology, we asked an independent laboratory at USGS-NWRC (from a separate study, using personnel not involved in our study) to run standards on their equipment, using their methodology. At the same time, our crew ran separate standards (from the same batch) using our methodology and equipment. They used a Lazar DJM-146 probe, while we used the Orion 9416 probe. Our results fell within 1 to 7 mV (0.1-1.0 %) of each other (n = 5), thus giving us confidence that our sulfide readings were reliable.

For nutrient analysis, we collected a 20-ml aliquot of interstitial water at each plot/depth and filtered it through GF/F filters. We then froze the samples until they were assayed for NO_2 and PO_4 nutrients, which we did using an Alpkem Flow Solution III autoanalyzer (Alpkem Corporation1992). Ammonium (NH_4) was assayed colorimetrically using a UV/VIS spectrophotometer (U.S. Environmental Protection Agency 1979). We also measured sediment oxidation–reduction (redox) potential (Eh) in each quadrat at 0 cm, 15 cm, and 30cm using platinum-tipped probes and a standard calomel electrode standardized with quinhydron. The probe was read with a Cole Parmer Digi-sense digital pH meter with millivolt (mV) conversion capabilities (Patrick et al. 1996). Redox probes were allowed to equilibrate for a minimum of 30 minutes prior to reading.

We used a four-way factorial analysis of variance (ANOVA) to assess effects of site, treatment (dead/live), depth (15 or 30 cm), and month for each dependent variable. Due to the Bonferroni effect, we set the alpha level for pairwise comparisons at 0.0001 to achieve an experimentwise Type I error rate of 0.05 (Day and Quinn 1989). Results of pairwise comparisons of means for significant model interaction effects are presented in graphic form.

Results

Vegetation

Percent cover. Colonization of unvegetated substrate occurred in all of our dead sites throughout the study (Figure 2). In October 2001, vegetation percent cover at the impacted sites varied from 15% (LFE) to 75% (OOB). Site differences were significant especially early in the study, from October 2001 through March 2002. From May through July 2002 only OOB and LFE were significantly different from each other, and by September 2002 there were no significant differences among sites (all were 80-90% covered with vegetation). OOB was the only site that did not die back in 2000 but died during the second year in 2001; it was also the site that consistently had the highest percent vegetation coverage. That is because the actual dieback patch size was smaller than the other sites. LFE maintained the lowest vegetation coverage throughout the study. Among the live sites (Figure 3) there were no significant site differences. The LFE Live site had a lower vegetation coverage (not significant) than the other sites because our transect ran through a small unvegetated pothole (about 10 m diameter) that appeared to be present before the dieback event. Early in the study (October 2001 to May 2002) vegetation coverage was higher on the Live sites than on the Dead sites for all except OOB. In June and July 2002 only BDU had a significant treatment effect (Live > Dead), and by September 2002 no sites showed a significant difference in treatments. Thus, all sites showed recovery over time. *Spartina alterniflora* was the predominant vegetation at the reference sites (65-100% coverage) and at the dieback sites (5-80%), but other species were present as well. These included *Spartina patens* (OOB Dead: 10-25% coverage; OOB Live: 2-4%; BSA Dead: 2-5%), *Distichlis spicata* (BSA Dead: 15-22%; OOB Live: 0-4%; BDU Live: 0-2%), *Salicornia virginica* (BJU Dead: 0-2%; BSA Dead: 0-3%), and *Batis maritima* (BJU Live: 5-20%; BJU Dead: 2-5%). Some of those species colonized the unvegetated substrates first and were later replaced by *S. alterniflora*.
Vegetation height and stem density. Statistical tests for this set of variables were hindered by the lack of live stems in some plots, thus creating missing cells in the analysis, so trends may be more important than statistical differences. Live stem densities were generally higher in the Live sites than in the Dead sites, though the differences were significant only for LFE and BSA (Figure 4). Dead sites showed higher live stem densities toward the second half of the study than in the first half, thus indicating revegetation of deadflats. Live sites, on the other hand, seemed to have higher live stem densities during the first half of the study than in the second half. Mean (Figure 5) and maximum (Figure 6) live stem heights were extremely variable. We found a significant treatment effect for some months at two sites, BDU (Dead > Live) and BSA (Live > Dead). Though observers noted that stems in the Dead sites seemed to be taller and more robust, this was not manifested in our data analysis, or at least was not consistent among sites.

Stem stress. We found no significant differences among site, treatment, or month for dead stem status (i.e., dead and intact, frayed leaves, culms only, or stubble). We did find significant main effects for treatment and month for dead stem densities (but no significant interactions). The Live sites had more dead stems (mean = 164/m^2) than the Dead sites (mean = 64/ m^2), and the number of dead stems (all sites combined) was lowest in winter and highest at the peak of the growing season in June. For live stem stress class (i.e., percent brown versus green on stem and leaves, with 0 = brown and 1 = green), we found significant interactions for site x month and site x treatment. Within sites (Table 2), only BDU showed a treatment effect, with live stems in the Live sites being browner (mean stress index = 0.67) than live stems in the Dead sites (mean = 0.73). This finding fits our observations that the plants that colonized the Dead sites seemed much greener and more robust than the plants in the Live sites; the latter often appeared to be stressed.

Snail herbivory. Density of shredder snails *(Littorina irrorata*) at BJU during late 2000 and early 2001 was often two to four times higher than at other times during the study (Figure 7). Densities at BJU (both Live and Dead sites) averaged 300-600 snails/m^2 during the peak of the dieback (late 2000 to early 2001), whereas densities were <200/m^2 after August 2001. The grazer activity may have functioned to speed the transition from brown standing vegetation to bare, unvegetated mudflats.

Soil porewater chemistry

Salinity. We found three significant three-way interactions for salinity: site x treatment x month (Figure 8), site x depth x month (Figure 9), and site x treatment x depth (Figure 10). Salinities over all sites and dates ranged from about 12 to 30 ppt (Table 1). Among sites, BJU consistently had the highest salinities (18-30 ppt), whereas the other four sites usually did not differ (12-22 ppt). All sites showed the same seasonal pattern, i.e., a decrease from November 2001 to December and January, then higher values from March through September of 2002. We found no significant differences in salinities due to depth within sites, treatments, and months. The treatment effect was significant for certain sites, depths, and treatments, but it was not consistent. Salinities at Dead sites were higher than Live sites for BJU (one month) and BDU (two months), whereas salinities at Live sites were higher than Dead sites for BJU (two months) and OOB (four months).

pH. Porewater pH levels rarely deviated substantially from neutral, with overall means for sites occurring from 7.1 to 7.4 (range 6.2 to 8.9; Table 1). We found a significant site x treatment x month interaction (Figure 11). Significant monthly variation was shown at some sites (e.g., BDU, BJU, OOB). Interestingly, in March 2002 we found our highest pH values at BDU and BJU Dead, whereas we found our lowest pH values at OOB that same month. We only found four instances of treatment differences (OOB 6/2002, LFE 3/2002, BJU 3/2002, BDU 12/2001), and the Dead sites had higher pH values than the Live sites for all four of those. For all other sites and months, however, there were no differences in treatments.

Sulfides. Porewater sulfides were variable, often reaching unusually high levels. Site means ranged from 1.4 mmol (BJU Dead) to 6.4 (OOB Live), with maxima ranging from 4.86 to 23.84 (Table 1). We found three significant three-way interactions: site x treatment x depth (Figure 12), site x treatment x month (Figure 13), and site x depth x month (Figure 14). Among sites, OOB had the highest sulfide values (Figure 12), primarily due to spikes in 3/2002, 7/2002, and 9/2002 (Figure 13). All sites showed a spike in 7/2002, but only OOB showed spikes in the other two months. When pooled over months (Figure 12), only BJU showed a significant treatment effect, with the Live site showing higher sulfide values (mean = 4.3 mmol) than the Dead site (mean = 1.4 mmol). That trend (Live > Dead) held up at BJU during the last four months of the study and also was noted at OOB for the last month (Figure 13). There were months where differences in sites (Figure 13) or depths (Figure 14) were significant, but the differences were not consistent across months. In general, BJU and LFE had lower sulfide values, whereas OOB and BSA had higher values.

Oxidation-reduction potential. Redox potential was widely variable, but the BDU Dead site was often substantially higher than the other three sites for which we had data (Figures 15 and 16). Our soils at 15 and 30 cm were all in the anaerobic, reducing state (i.e., no free oxygen at Eh < 400; Mitsch and Gosselink 2000).

Nutrients. Nitrite (NO_2) means varied between 1.0 and 1.5 micromoles (Table 1). We found a significant site x treatment x month interaction, but site and month differences were not consistent (Figure 17). Within sites there were no significant treatment differences in nitrite levels. For phosphates (PO_4) we found significant effects for month x treatment (Figure 18), site x treatment (Figure 19), and site x month (Figure 20). The Dead sites showed a spike in January 2002 (Figure 18). Only BDU showed a significant treatment effect, with phosphates being higher in the Live site than in the Dead (Figure 19); values were higher at BDU than at BSA, LFE, and OOB (Figures 19, 20). For ammonium (NH_4) we found significant effects for treatment x depth (Figure 21), site x depth (Figure 22), and treatment x site x depth (Figure 23). Dead sites generally had higher ammonium values than Live sites, and levels were higher at 30 cm depth than at 15 cm (Figures 21, 22). Ammonium levels were generally higher at BSA and OOB (Figure 22), but differences among sites were not consistent within months (Figure 23). Several sites showed a drop in ammonium in May 2002, but only one (BJU Dead) was significant (Figure 23).

Discussion

Recovery of impacted sites was slow until about March 2002; then revegetation of bare substrates increased steadily through the end of the study (August 2002). Differences among the five sites in terms of percent vegetation coverage were mostly due to differences that were present at the start of the study. By the end of the study, site differences diminished, because all sites were 80-90% recovered. It is noteworthy that at the LFE site a substantial area of substrate outside of our transect area remained unvegetated at the end of the study. We found that our ground sites were fairly representative of the southeast Louisiana coast in general in terms of recovery, based on an estimated 76% reduction in impacted acreage by August 2002 (Michot et al. 2004). Handley (2004) showed a similar trend in recovery from the dieback event. We found stem counts, heights, and stress levels to show a gradual recovery over time in the Dead sites, whereas our Live sites seemed to show stress over time. Snail densities at our sites seemed to track the availability of standing dead vegetation and, thus, were probably a response to the dieback rather than a cause, as was suggested by Silliman and Bertness (2002).

Site differences in salinity seemed to track basin differences in hydrology and distance from the coast (Swarzenski et al. 2004); the BJU site was closest to the Gulf of Mexico, and it had the highest salinities. The interstitial salinity values that we measured at all sites (10-32 ppt) were well below the lethal limits of *S. alterniflora* (83-115 ppt; Hester et al. 1998). In the previous year (September 2000) we found higher salinities (35-45 ppt) at BJU, but even those values were well below the lethal limits, so it is unlikely that high salinities alone were enough to trigger dieback conditions. Also, we found little or inconsistent differences between our Dead and Live sites, again downplaying the role of salinity as a factor in the dieback.

Although low pH values (<5) have been implicated by some researchers (e.g., Nyman et al. 2001) as having a role in dieback, we found field pH values to be near neutral (6.2-8.9), with little variation among sites. In addition, when we did find a treatment effect, our Dead sites had a higher pH than the Live sites, which is the opposite of what would be expected. McKee et al. (2004) also found most field sites to have near neutral pH, although they did mention one dead site with low (ca. 4) values. In addition, they found that, when oxidized, soils from dieback sites showed considerable acidification, whereas soils from reference sites did not, concluding that pH may have had a role in the dieback. Portnoy and Valiela (1997) found a similar acidification effect (down to pH 4.5) in *S. alterniflora* marsh soils when they were drained and aerated.

Interstitial sulfide levels in our study were higher than most published values. Most studies of *Spartina* marsh found values of <2 mmol (Koch and Mendelsshon 1989, Chambers 1997, Chambers et al. 1998, Carlson 1982). A few researchers, however, found higher values such as 2.7 mmol (King et al. 1982), 3.0 mmol (Lee et al. 1996), 4.5 mmol (DeLaune et al. 2002), 5.2 mmol (Portnoy and Valiela 1997), 8.1 mmol (Lee 1999), and 12-16 mmol (Kostka et al. 2002). Koch and Mendelsshon (1989) found a reduction in *S. alterniflora* root biomass when 1.0 mmol sulfide was added to the soil. McKee et al. (2004) found no differences in sulfide levels between dieback and reference sites. We did find considerable variation among sites and months, possibly related to hydrological differences (Swarzenski et al. 2004). When treatment effects were noted, the live sites had higher sulfide levels, which is opposite of the predicted response.

Redox potential on our sites was probably directly related to flooding events at the various sites. Our values were in line with others from the literature (Mendelssohn and McKee 1988, Bertness 1991, Mitsch and Gosselink 2000, Anastasiou and Brooks 2003, McKee et al. 2004). Our interstitial PO_4 levels (3-10 uM) were comparable to those found by Chambers (1997). Our NH_4 levels (200-400 uM) were much higher than those (7-62 uM) found by Chambers (1977), but comparable to those (200-600 uM) found by Webb and Mendelssohn (1996).

At this time we cannot identify a probable cause for the dieback. Our objective in this report was to present the results of our study and to put them in context. The next step in this process will be to compare our results to those of several concurrent studies that are just coming out (e.g., Swarzenski et al. 2004). At the same time, efforts are being made by researchers to summarize concurrent dieback studies, using modeling and a separate synthesis process, to draw general conclusions about what we can and cannot say about the dieback. At that point we hope to formulate hypotheses and conduct additional studies to test those hypotheses, and hopefully to focus in on the factor or factors that caused the dieback. Our ultimate challenge is to be in a better position to take management actions, and to know what actions to take, if dieback conditions reoccur.

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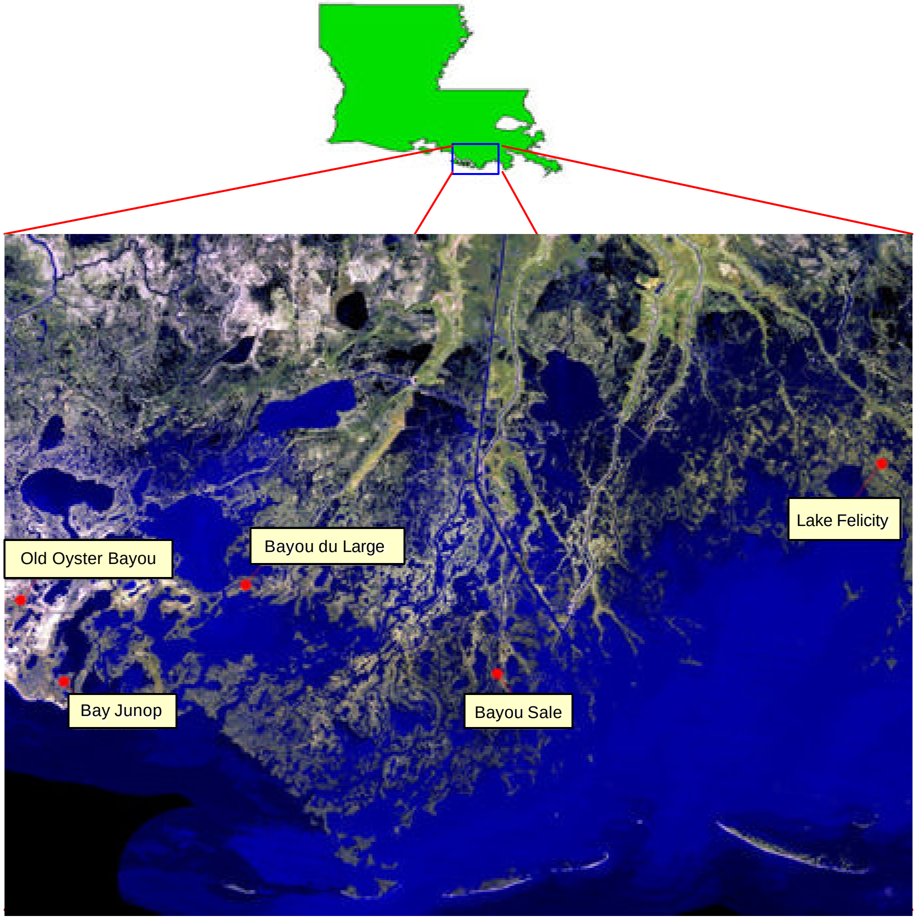
Table 1. Summary of data from soil porewater chemistry and vegetation measurements at the five pairs of live and dead marsh study sites; values were pooled over months and soil depths.

Site Abbreviations:

BDU = Bayou du Large
BJU = Bay Junop
LFE = Lake Felicity
BSA = Bayou Sale
OOB = Old Oyster Bayou

		BDU		**BJU**		**LFE**		**BSA**		**OOB**	
Parameter		Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
Salinity	n	60	59	52	59	59	57	60	62	59	57
(ppt)	Mean	19.0	21.4	25.6	26.1	17.1	17.8	16.1	15.9	17.4	15.2
	SE	0.2	0.24	0.54	0.49	0.41	0.38	0.32	0.32	0.27	0.22
	Max	21.6	24.0	31.4	32.1	22.4	22.2	19.7	19.4	25.6	18.4
	Min	15.2	16.3	11.2	17.1	9.6	11.8	11.1	9.4	13.8	10.7
pH	n	61	59	59	59	59	60	60	62	63	61
	Mean	7.29	7.39	7.34	7.38	7.11	7.26	7.21	7.27	7.12	7.12
	SE	0.05	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.05
	Max	8.86	8.23	7.68	8.11	7.53	7.61	7.71	7.68	7.45	7.73
	Min	6.72	7.00	6.97	6.83	6.16	6.65	6.83	6.83	6.33	6.23
Sulfides	n	58	58	60	60	61	57	60	62	60	64
(millimoles)	Mean	3.53	3.49	4.33	1.45	3.18	2.46	5.08	4.15	6.40	6.12
	SE	0.15	0.29	0.30	0.15	0.29	0.19	0.35	0.30	0.66	0.42
	Max	7.35	9.42	10.24	4.86	9.42	6.23	13.12	12.08	23.84	14.55
	Min	1.76	0.42	1.04	0.03	0.01	0.49	0.95	0.77	1.34	1.94
NO2	n	46	38	42	43	31	38	45	50	47	42
(micromoles)	Mean	1.28	1.23	0.97	1.31	1.02	1.25	1.34	1.31	1.30	1.39
	SE	0.04	0.05	0.06	0.08	0.11	0.06	0.07	0.07	0.06	0.09
	Max	2.20	2.41	1.40	2.54	1.65	4.56	2.83	2.81	3.48	4.05
	Min	0.51	0.55	0.45	0.57	0.30	0.57	0.57	0.76	0.67	0.73
PO4	n	46	38	42	43	31	38	45	50	47	42
(micromoles)	Mean	8.76	6.80	5.86	6.10	3.94	3.91	4.44	3.90	4.81	4.22
	SE	0.38	0.75	0.33	0.29	0.30	0.29	0.30	0.25	0.21	0.20
	Max	27.55	11.31	9.27	9.89	9.16	9.15	9.18	8.39	8.04	6.61
	Min	1.01	1.53	1.56	1.37	2.03	1.74	1.54	1.57	1.98	1.61
NH4	n	46	38	42	43	31	38	45	50	47	42
(micromoles)	Mean	127.36	346.87	203.97	291.56	137.29	231.89	273.48	263.04	286.47	427.04
	SE	0.40	0.70	0.93	0.09	0.31	0.40	0.61	0.59	0.68	0.63
	Max	401.93	639.84	546.43	843.57	299.00	736.48	759.05	714.90	561.19	860.46
	Min	17.81	11.94	5.49	17.11	18.45	54.83	44.97	23.91	19.68	78.21
Stem Density	n	93	59	61	22	46	22	62	24	63	64
(# stems / m^2)	Mean	107.0	88.4	231.6	20.0	382.3	62.5	223.2	36.6	219.7	43.0
(live stems)	SE	7.0	10.3	18.2	8.3	40.6	15.5	20.7	10.6	20.7	7.1
	Max	336	352	560	176	1376	240	688	192	816	288
	Min	16	0	16	0	48	1	16	0	2	1
Stem Heights	n	90	51	61	16	46	22	62	23	63	52
(cm)	Mean	38.0	55.5	37.1	46.4	39.7	46.5	53.9	45.5	32.9	31.9
(live stems)	SE	1.5	3.8	1.5	6.8	1.9	5.0	2.2	5.0	1.7	2.1
	Max	65	109	66	91	59	100	110	105	58	71
	Min	5	7	11	16	12	8	22	0	5	13
Stem Stress	n	60	38	33	15	33	19	42	22	38	24
(live stems)	Mean	0.62	0.51	0.69	0.52	0.62	0.53	0.58	0.53	0.55	0.55
1 = green	SE	0.03	0.04	0.02	0.06	0.03	0.05	0.03	0.04	0.04	0.04
0 = brown	Max	0.95	0.95	0.95	0.70	0.95	0.70	0.70	0.70	0.95	0.70
	Min	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25



Old Oyster Bayou
Coordinates: N 29^{0} 15’ 40.3”
W -91^{0} 05’ 41.2”

Bay Junop
Coordinates: N 29^{0} 12’ 13.5”
W -91^{0} 03’ 56.7”

Bayou Sale
Coordinates: N 29^{0} 12’ 06.2”
W -90^{0} 43’ 07.3”

Lake Felicity
Coordinates: N 29^{0} 21’03.1”
W -90^{0} 24’ 45.4”

Bayou du Large
Coordinates: N 29^{0} 15’09.0”
W -91^{0} 00’07.3”

Figure 1. Location of brown marsh study sites in Terrebonne Parish, Louisiana.

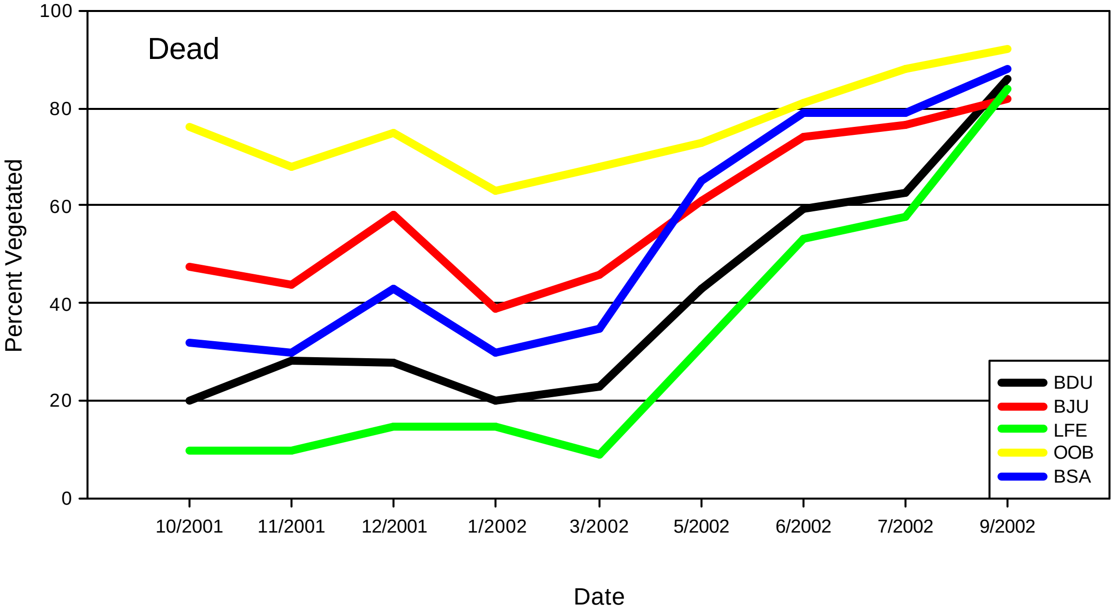


Figure 2. Mean percent vegetation cover for transects in dead sites, Terrebonne Parish, Louisiana, 10/2001 - 9/2002. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

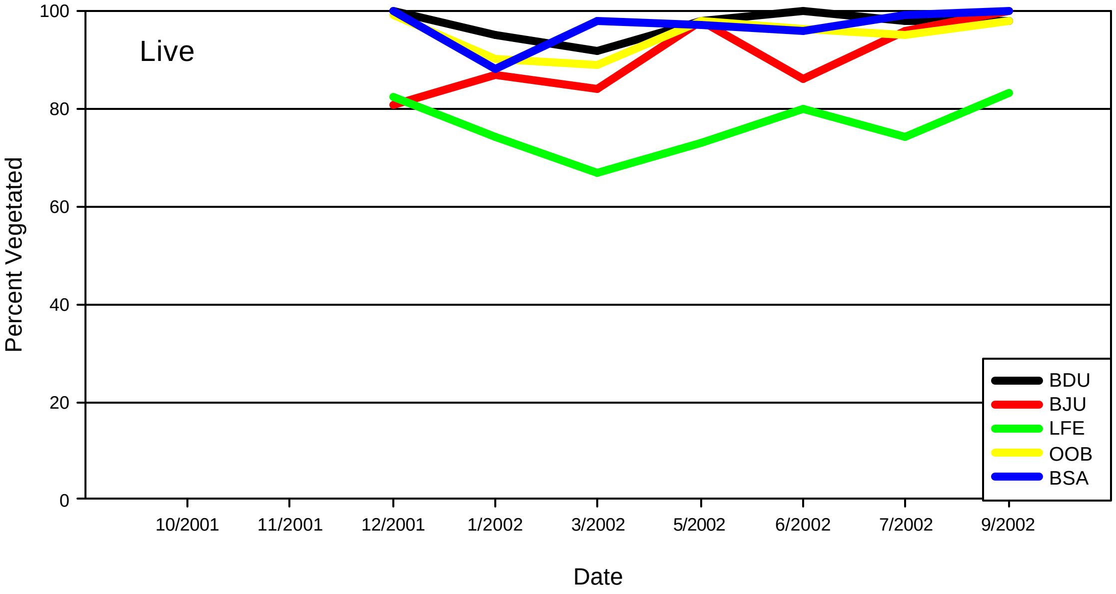


Figure 3. Mean percent vegetation cover for transects in live sites,Terrebonne Parish, Louisiana, 12/2001 - 9/2002. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

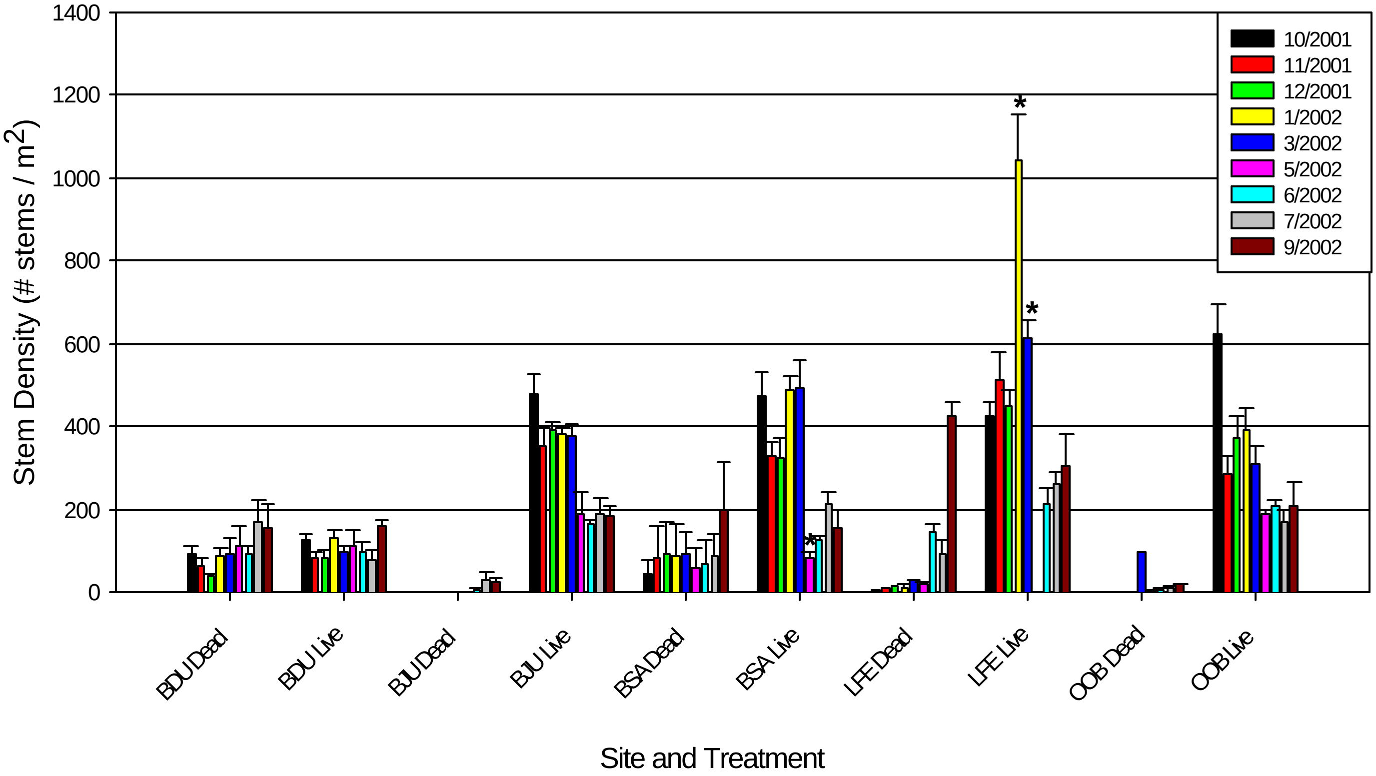


Figure 4. Mean live stem densities for *Spartina alterniflora* by site, treatment, and date for Terrebonne Parish, Louisiana, 2001-2002 (total n = 541; results are pooled over depth). Missing bars are due to absence of live stems for that sampling period (except for data missing for LFE Live 5/2002); error bars = SE; bars without SE had only one plot with live plants present. Treatment was significant for LFE (Oct through Mar) and BSA (Oct, Jan, and Mar). Asterisk (*) = mean is significantly different from previous month. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

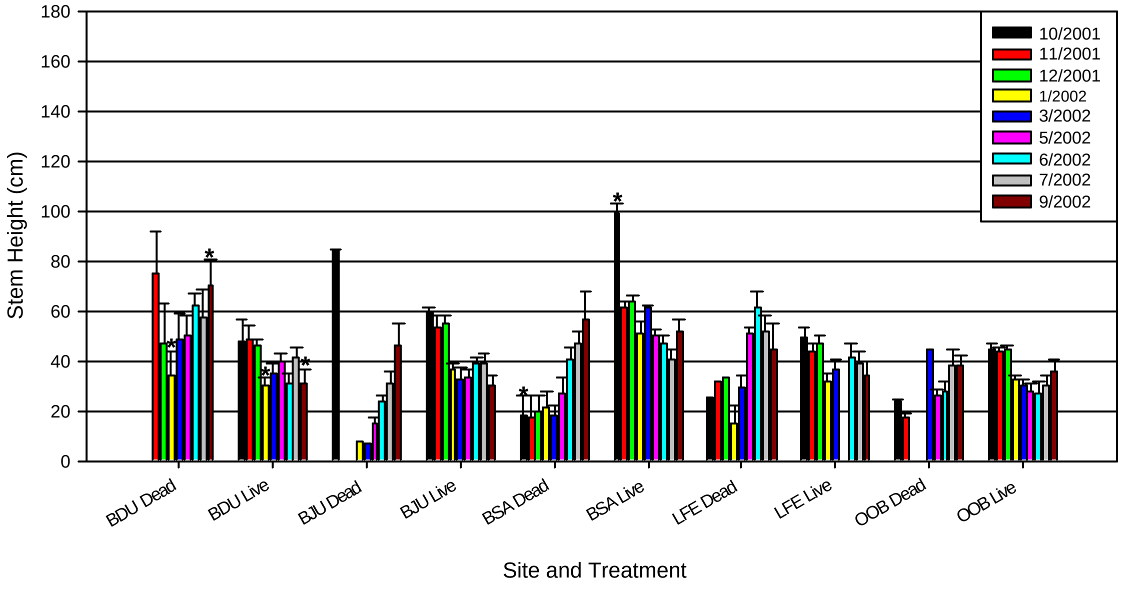


Figure 5. Mean live stem heights for *Spartina alterniflora* by site, treatment, and date, Terrebonne Parish, Louisiana, 2001-2002. Missing bars are due to absence of live stems for that sampling period (except data missing for LFE Live 5/2002); error bars = SE; bars without SE had only one plot with live plants present. Asterisk (*) = treatment effect is significant ($P \leq 0.0001$). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

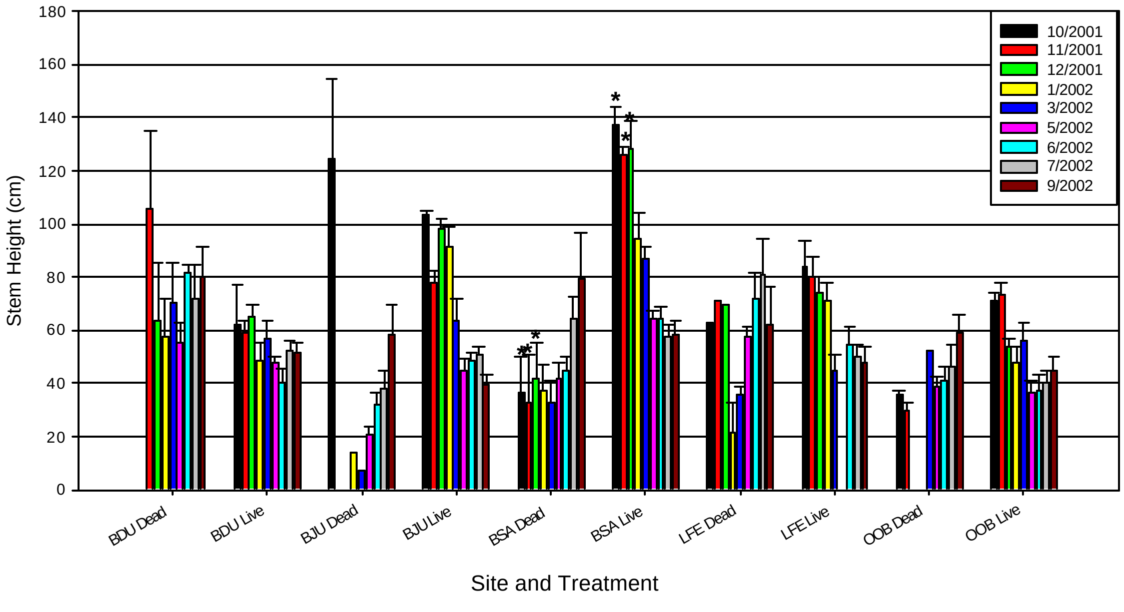


Figure 6. Maximum live stem height per plot for *Spartina alterniflora*, by site, treatment, and date, Terrebonne Parish, Louisiana, 2001-2002. Missing bars due to absence of live stems for that sampling period (except data missing for LFE Live 5/2002); error bars = SE; bars without SE had only one plot with live plants present. Asterisk (*) = treatment effect is significant ($P \leq 0.0001$). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

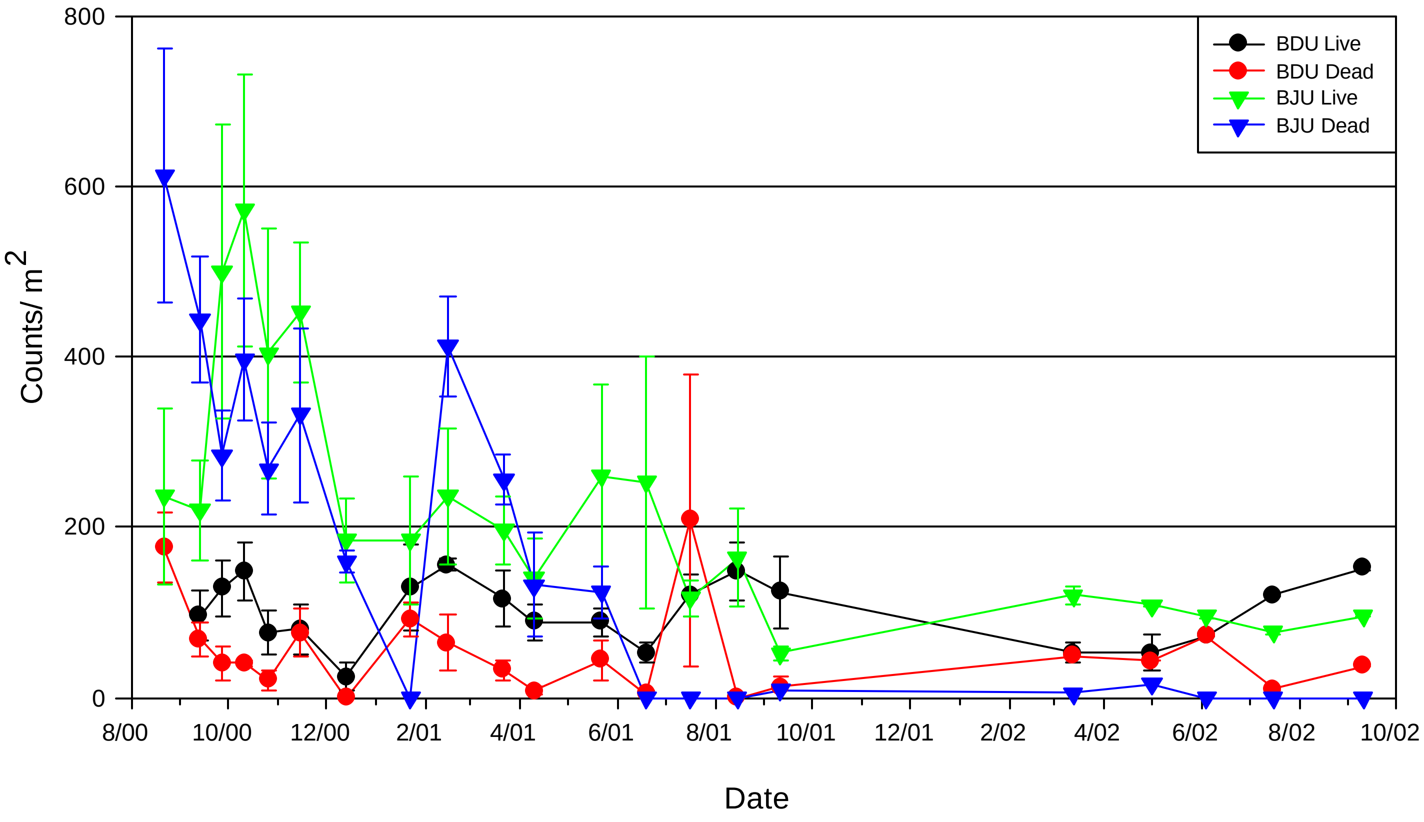


Figure 7. Mean snail density for Bay Junop (BJU) and Bayou du Large (BDU) sites in Terrebonne Parish, Louisiana, 2000-2002.

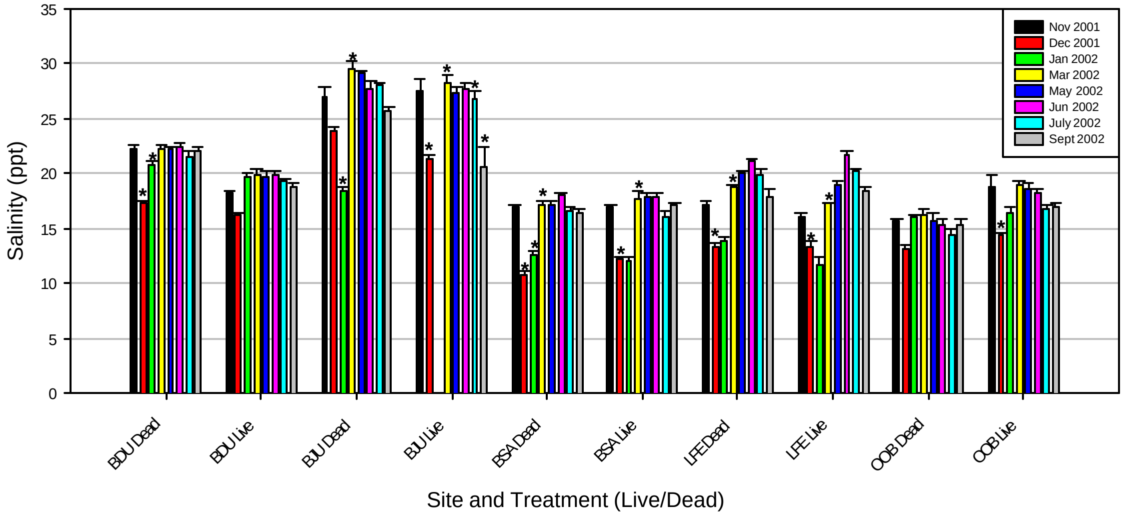


Figure 8. Mean salinity (ppt) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 528; Data missing for BJU Live 1/2002; results are pooled over depth; asterisk (*) = mean is significantly different from previous month). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

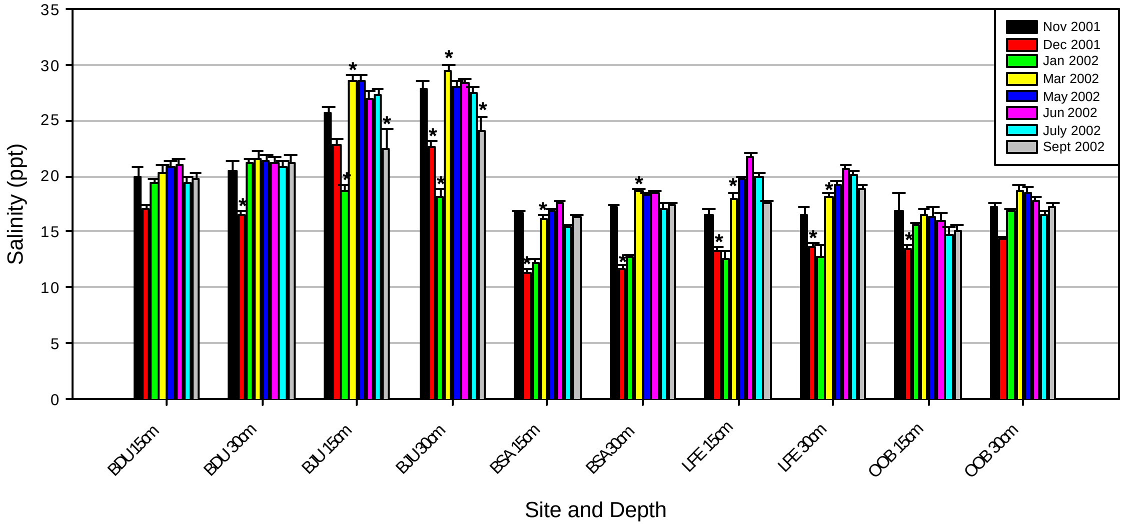


Figure 9. Mean salinity (ppt) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 528; results are pooled over treatment). Asterisk (*) = mean is significantly different from previous month. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

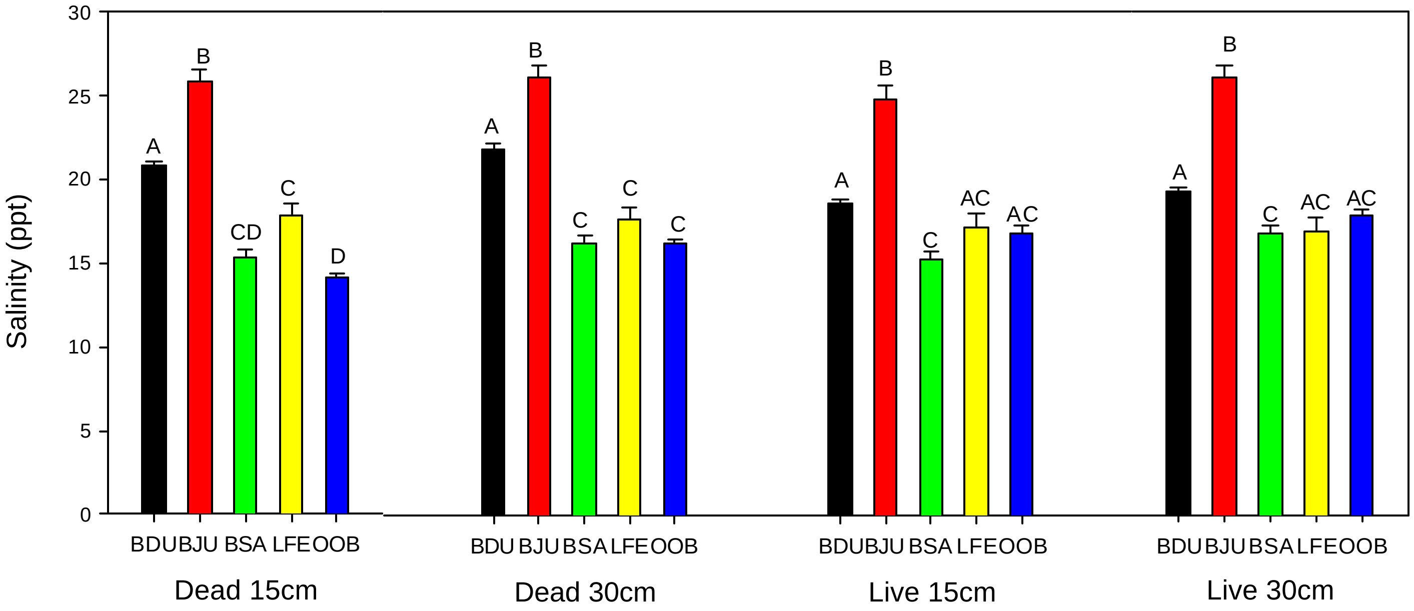


Figure 10. Mean salinity (ppt) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 528; results are pooled over months). Bars that share a common letter do not differ (P > 0.0001) within depth/treatment classes. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

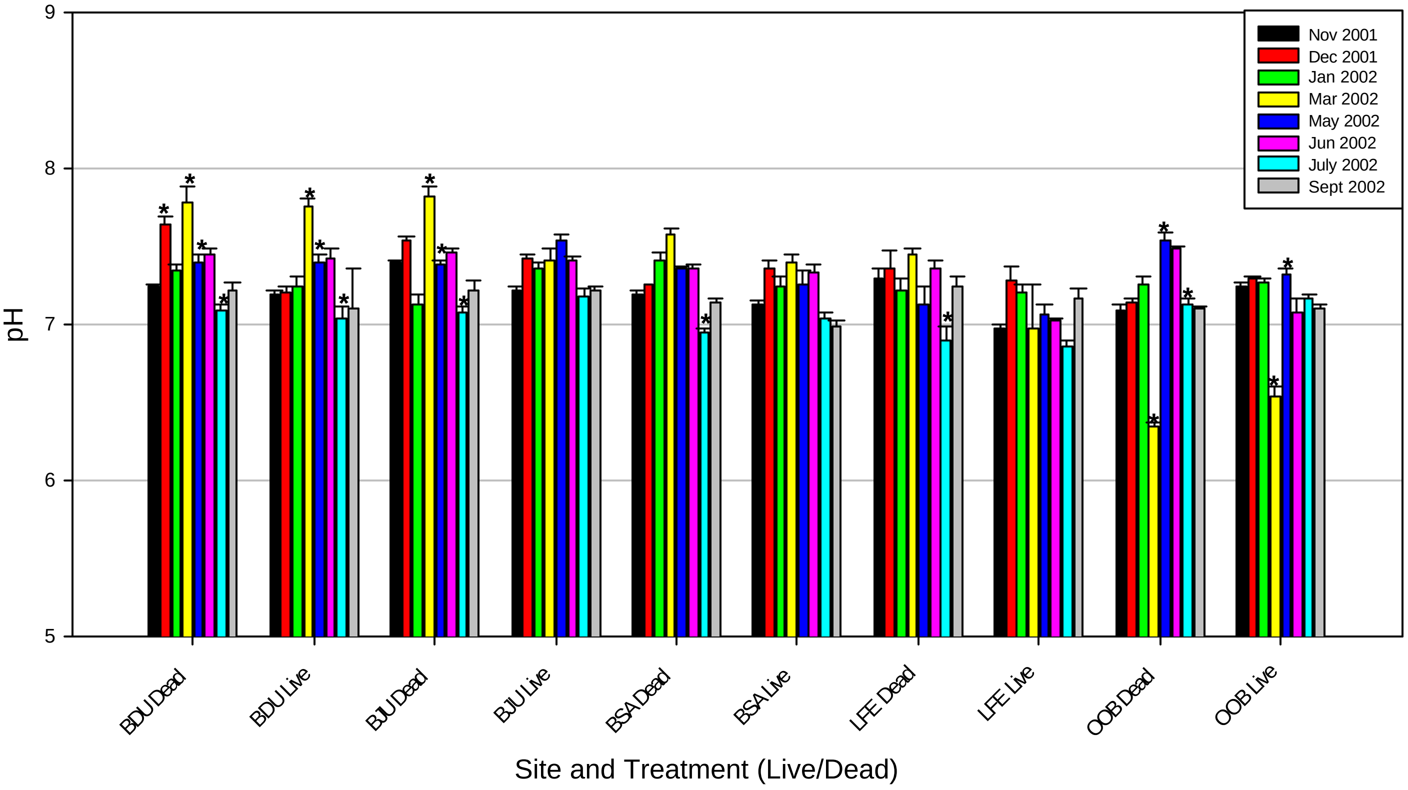


Figure 11. Monthly pH values from Terrebonne Parish, Louisiana, 2001-2002 (total n = 544; results are pooled over depth). Asterisk (*) = mean is significantly different from previous month. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

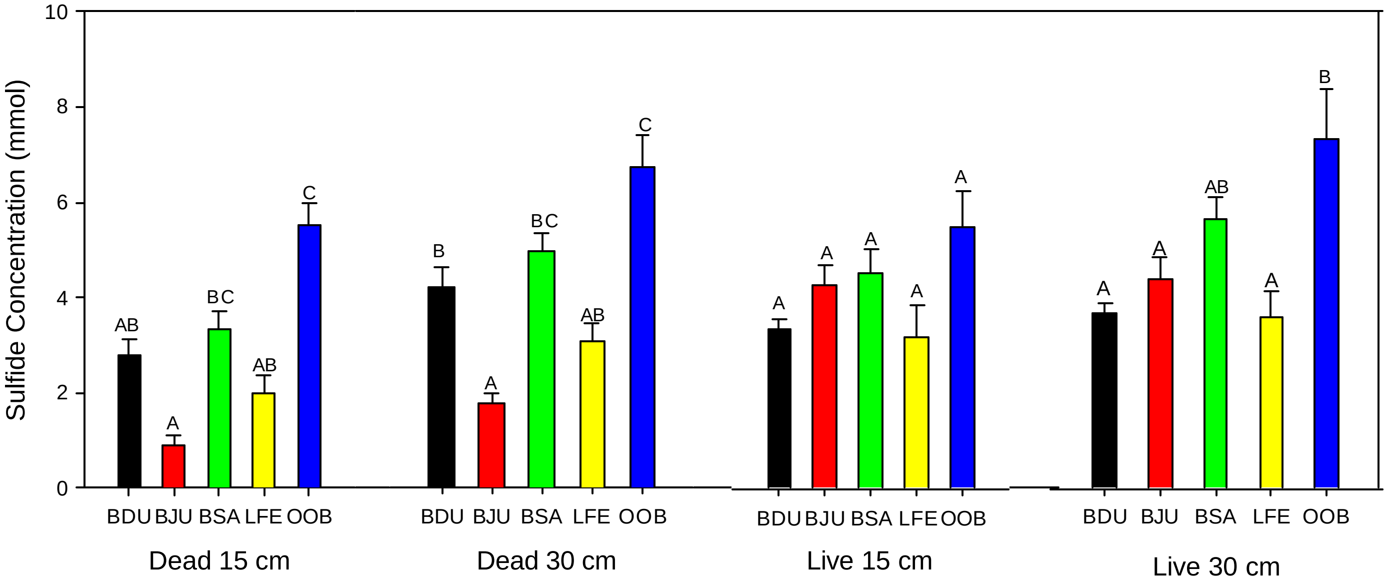


Figure 12. Mean concentration of sulfides (mmol) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 541; results are pooled over months). Bars that share a common letter do not differ (P > 0.0001) within depth/treatment classes. There were no significant differences in depths within site/treatment classes, and only the Bay Junop (BJU) site had significant differences in treatments (live > dead within both depth classes). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

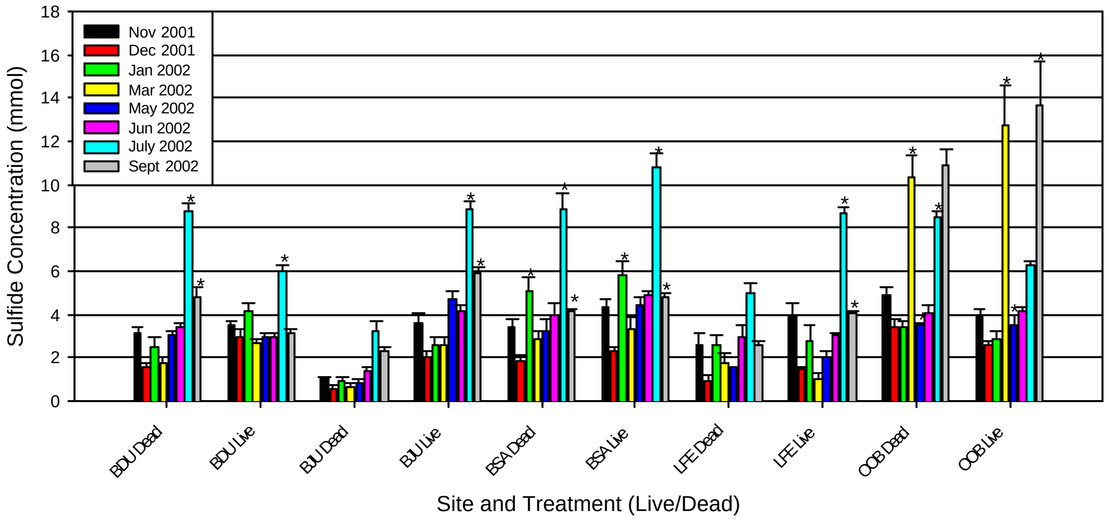


Figure 13. Monthly mean concentration of sulfide (mmol) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 541; results are pooled over depth). Asterisk (*) = mean is significantly different from previous month. Within month/site class, the Live mean was significantly greater that the Dead mean for BJU (5/2002, 6/2002, 7/2002 and 9/2002) and OOB (9/2002). Within month/treatment class, OOB was > all others sites for 3/2002 and 9/2002 (both treatments), and OOB was > BJU for 11/2001, 12/2001, and 6/2002 (Dead only). Site differences were also significant in 1/2002 (Dead: BSA > BJU; Live: BSA > BJU & LFE) and 7/2002 (Dead: BSA, BDU & OOB > BJU & LFE; Live: BSA > BDU & OOB). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

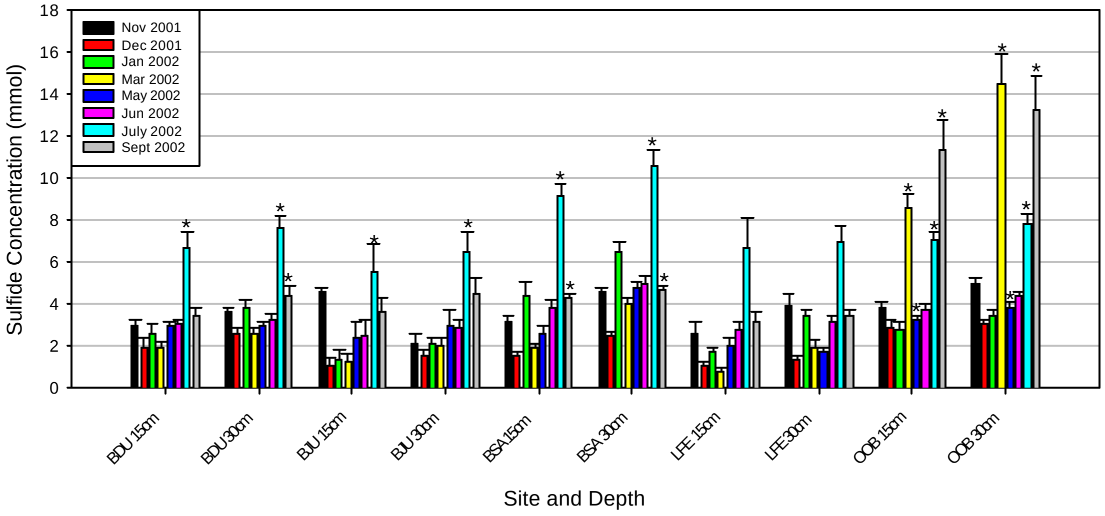


Figure 14. Monthly mean concentration of sulfide (mmol) from Terrebonne Parish, Louisiana, 2001-2002 (total n = 541; results are pooled over treatment). Asterisk (*) = mean is significantly different from previous month within site/depth class; depth effect was only significant for OOB, 3/2002 (30cm >15cm). In 3/2002 and 9/2002 OOB mean was significantly higher than all other sites (both depths), and in 7/2002 BSA was > BJU (both depths). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

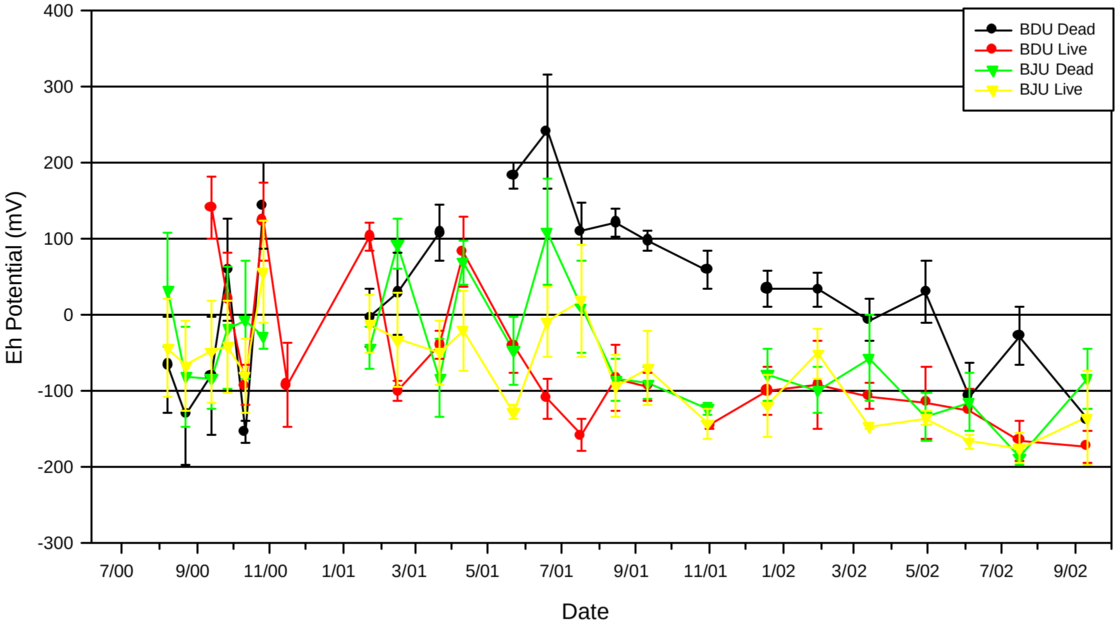


Figure 15. Mean redox values at 15 cm depth for sites in Terrebonne Parish, Louisiana, 2000-2002.
BDU = Bayou du Large; BJU = Bay Junop.

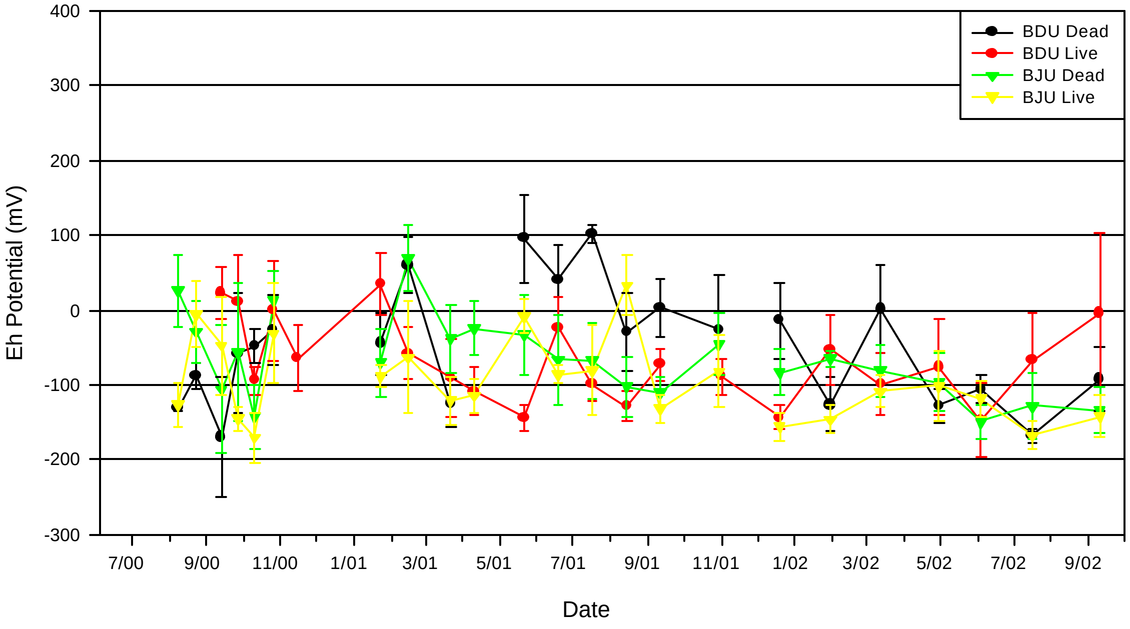


Figure 16. Mean redox values at 30 cm depth for sites in Terrebonne Parish, Louisiana, 2000-2002.
BDU = Bayou du Large; BJU = Bay Junop.

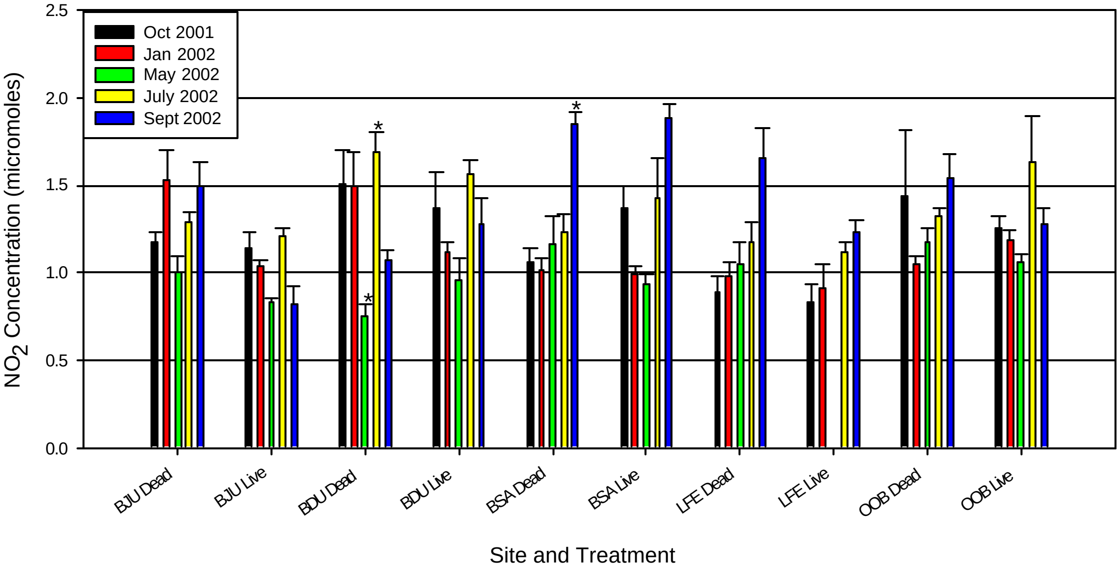


Figure 17. Mean NO_2 concentrations for Terrebonne Parish, Louisiana, 2001-2002 (total n = 242; results are pooled over depth; asterisk (*) = mean is significantly different from previous month; LFE Live data missing for 5/2002). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

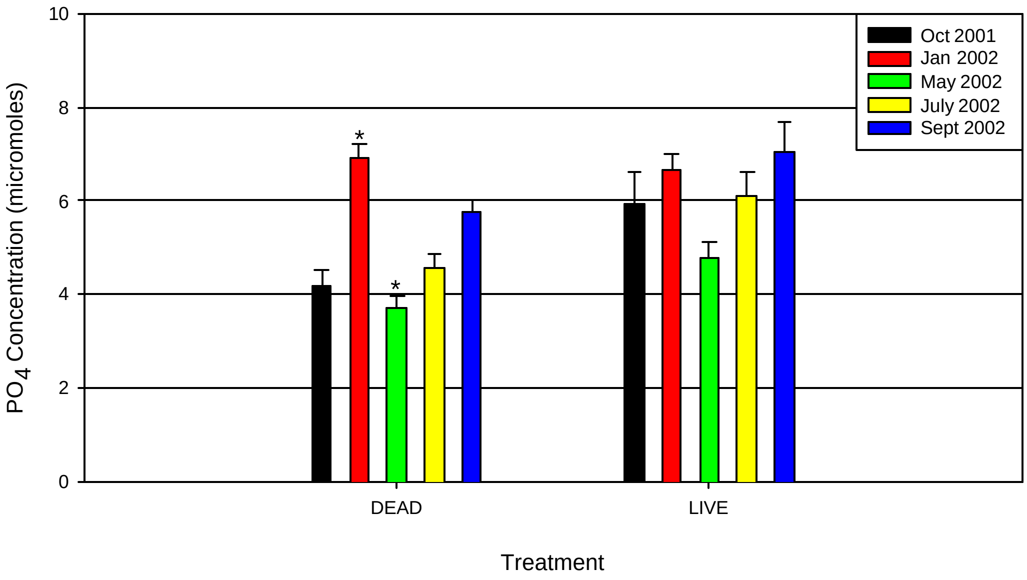


Figure 18. Mean PO_4 concentrations for dieback sites in Terrebonne Parish, Louisiana, 2001-2002 (total n= 242; results are pooled over site and depth). Asterisk (*) = mean is significantly different from previous month; no treatment differences were significant.

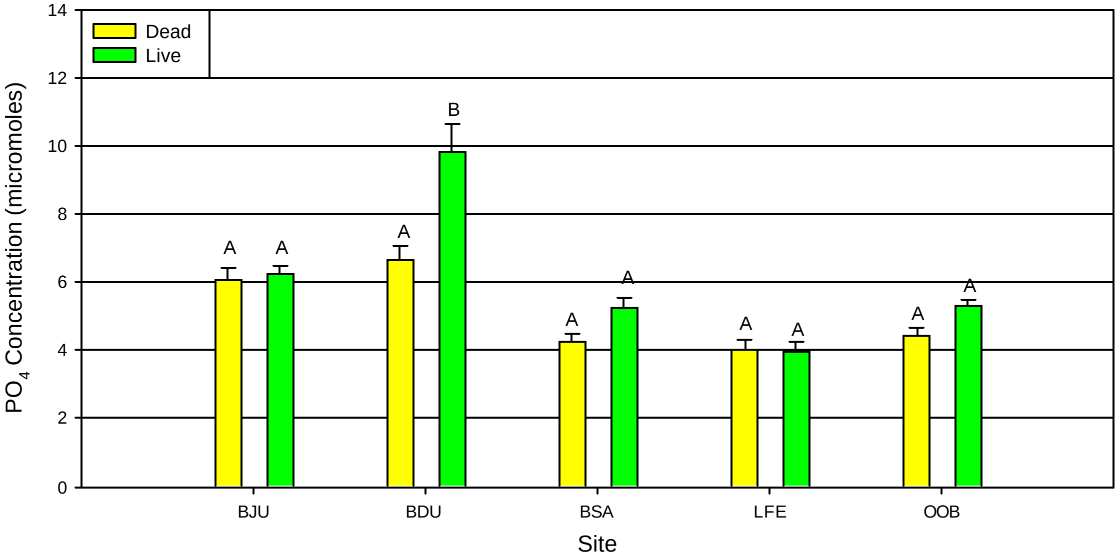


Figure 19. Mean PO$_4$ concentration for dieback sites in Terrebonne Parish, Louisiana, 2001-2002 (total n = 242; results are pooled over depth and date). Bars that share a common letter are not significantly different (P>0.0001) within sites. Within treatments, BDU Live was significantly different from all other sites, and BDU Dead was significantly different from all other sites except BJU Dead. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

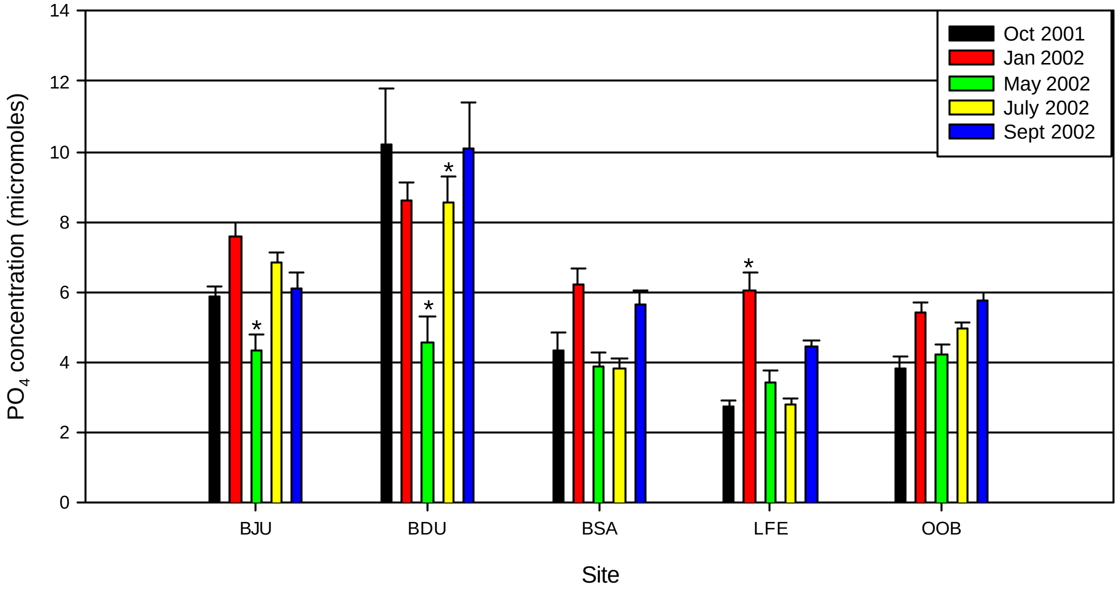


Figure 20. Mean PO$_4$ concentration for Terrebonne Parish, Louisiana, 2001-2002 (total n = 242; results are pooled over depth and treatment). Asterisk (*) = mean is significantly different from previous month. BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

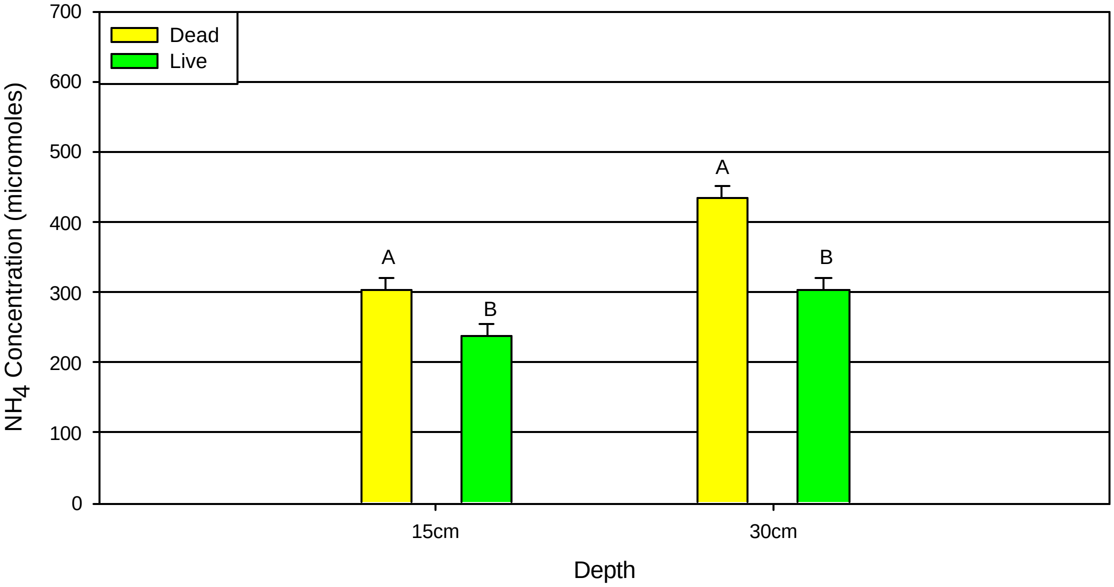


Figure 21. Mean NH_4 concentrations by site treatment for dieback sites in Terrebonne Parish, Louisiana, 2001-2002 (total n = 242; results are pooled over site and date). Bars that share a common letter do not differ significantly within depth groups; within treatments, depth differences were significant.

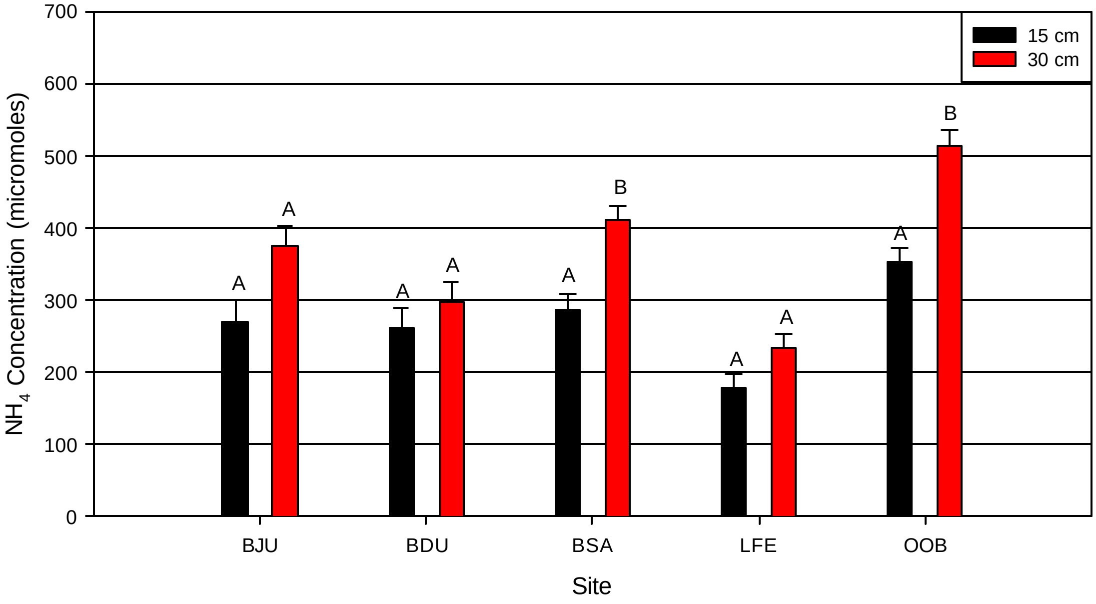


Figure 22. Mean NH_4 concentrations for dieback sites in Terrebonne Parish, Louisiana, 2001-2002 (total n = 292; results are pooled over treatment (Live/Dead); bars that share a common letter do not differ significantly within sites). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.

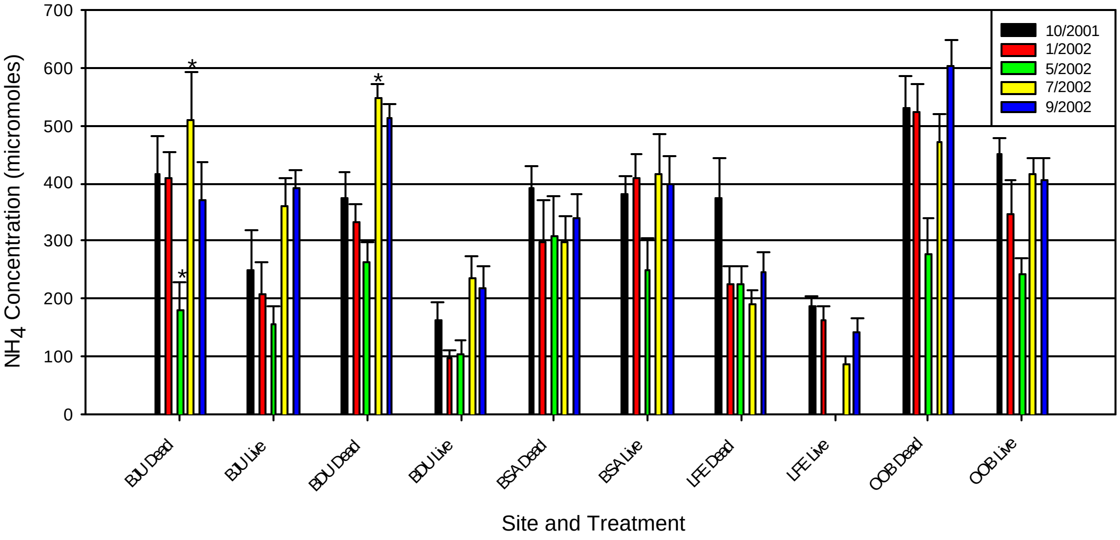


Figure 23. Mean NH_4 concentrations for dieback sites in Terrebonne Parish, Louisiana, 2001-2002 (total n = 242; results are pooled over depth; asterisk (*) = means are significantly different from previous month; LFE Live data missing for 5/2002). BJU = Bay Junop; BDU = Bayou du Large; BSA = Bayou Sale; LFE = Lake Felicity; OOB = Old Oyster Bayou.