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Interactive Effects of Salinity and Hydrology on Radial Growth of Bald Cypress (*Taxodium distichum* (L.) Rich.) in Coastal Louisiana, USA

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Abstract: Tidal freshwater forests are usually located at or above the level of mean high water. Some Louisiana coastal forests are below mean high water, especially bald cypress (*Taxodium distichum* (L.) Rich.) forests because flooding has increased due to the combined effects of global sea level rise and local subsidence. In addition, constructed channels from the coast inland act as conduits for saltwater. As a result, saltwater intrusion affects the productivity of Louisiana's coastal bald cypress forests. To study the long-term effects of hydrology and salinity on the health of these systems, we fitted dendrometer bands on selected trees to record basal area increment as a measure of growth in permanent forest productivity plots established within six bald cypress stands. Three stands were in freshwater sites with low salinity rooting zone groundwater (0.1–1.3 ppt), while the other three had higher salinity rooting zone groundwater (0.2–4.9 ppt). Water level was logged continuously, and salinity was measured monthly to quarterly on the surface and in groundwater wells. Higher groundwater salinity levels were related to decreased bald cypress radial growth, while higher freshwater flooding increased radial growth. With these data, coastal managers can model rates of bald cypress forest change as a function of salinity and flooding.

Keywords: bald cypress; salinity; hydrology; radial growth; coastal forest; saltwater intrusion; basal area increment

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1. Introduction

Bald cypress (*Taxodium distichum* (L.) Rich.) typically inhabits the most flooded freshwater forest habitats in the southeastern USA. It is one of the most flood-tolerant tree species, able to withstand prolonged deepwater flooding [1]. Inland bald cypress forests exist in riverine floodplain settings and are subject to variations in rainfall and river flow, making them susceptible to drought conditions. However, coastal bald cypress forests are so close to sea level that under most drought conditions, the root zone remains saturated [2]. For these sites, the lack of surface flooding increases groundwater salinity through evapotranspiration. This is common in tidal freshwater forested wetlands occurring throughout the coast of the southeastern USA, but especially common in coastal Louisiana, where the transition zone from salt marsh to tidal freshwater forests is very susceptible to saltwater intrusion [3]. Proximity to sea level also makes coastal bald cypress forests susceptible to hurricane and storm surges, which push saltwater far inland. In the early years of ecological research in Louisiana, bald cypress "ghost forests" (groups of dead trees) were encountered at the transition zone between coastal marshes and freshwater forests [3]. It was theorized that the trees died as a result of a saltwater surge from a strong hurricane. It may have been that the hurricane was just the tipping point after many years of slow encroachment by saltwater.

Saltwater intrusion affects freshwater wetlands near the coast of Louisiana. Sea-level rise, a profusion of man-made canals for navigation and oil extraction access, and climate change-induced increases in storm surges from hurricanes and other wind-driven surges have all contributed to increasing the intrusion of saltwater into surface water and groundwater of Louisiana's coastal wetlands, particularly bald cypress forests [1,4,5]. Tidal freshwater forests, including bald cypress swamps, are usually located at or above the level of mean high water [6]. In coastal Louisiana, some bald cypress forests exist below mean high water because these forests were established prior to the current levels of global sea level rise and local subsidence. This exacerbates the likelihood of saltwater intrusion as the elevation of the forest floor falls below the elevation necessary to maintain a freshwater head. Sustained freshwater input from precipitation and/or riverine input would be needed to keep salinity from rising in Louisiana's coastal forests. The construction of levees along the Mississippi River has limited the source of river water, thus Louisiana's tidal freshwater forests are dependent on precipitation [7].

Another result of the construction of Mississippi River levees is that a once reliable source of nutrients and sediments is no longer available to bald cypress forests in the deltaic floodplain [8,9]. Nutrients from the river water increase primary productivity, while sediment input counteracts subsidence rates of the swamp surface soils. The absence of nutrient input would tend to lower productivity from previous levels, while lack of sedimentation is more complicated. In an environment of rising sea level coupled with subsidence, lack of allochthonous sediment input shifts to increasing dependence on autochthonous organic soil buildup originating from forest primary productivity [9], which suffers from that lack of nutrient input. A lower soil surface elevation implies deeper levels of flooding, which is not normally a problem for flood-tolerant bald cypress if the floodwater is fresh but potentially lethal when the floodwater is increasingly salty.

Interactions between hydrology and salinity drive the growth and productivity of tide-influenced bald cypress forests in coastal Louisiana. In this study, we report tree growth from 2008 to 2016 in Louisiana bald cypress forest plots to investigate how hydrology and salinity in salt affected sites in Louisiana affect seasonal, annual, and inter-annual individual tree basal area increment. We hypothesized that tree growth is lower with different inter-annual patterns in salinity impacted sites than tree growth in fresher water sites.

2. Methods

2.1. Site Selection

Six sites were selected in coastal Louisiana between August 2004 and May 2006 in forested wetlands dominated by bald cypress (Figure 1). Other tree species present on all sites were water tupelo (*Nyssa aquatica* L.), ash (*Fraxinus* spp.), red maple (*Acer rubrum* L.), Chinese tallow (*Triadica sebifera* (L.) Small), and Wax myrtle (*Morella cerifera* (L.) Small). All six sites exhibit a tidal signature and are considered tidal freshwater forested wetlands (Figure 2). Three of the sites are predominantly freshwater, with mean annual salinity < 0.6 ppt. The freshwater sites all have a buffer zone of multiple hectares of contiguous forest. These freshwater sites will be referred to as Fresh sites. Three of the sites were chosen in areas experiencing saltwater intrusion, with mean annual salinity > 1.4 ppt. These three sites are all adjacent to thinning forests transitioning to marsh and will be referred to as Salt sites. All six sites have altered hydrology. The forests are situated amongst a complex system of interconnected bayous and canals. In some cases, these flow paths create longer and slower paths of flow to and from the coast, while in other cases, there is a more direct path to the coast that connects the forests to saltwater [7,10].

The Bayou Teche site (BT—Fresh) is near Atchafalaya Bay and has water levels affected by the Atchafalaya River (Figure 1) via the Gulf Intracoastal Waterway (GIWW) [11,12]. The Atchafalaya River is a distributary of the Mississippi River that mimics the flow season of the Mississippi River. These two rivers have similar flows because the Atchafalaya River is controlled by the Old River Control Structure (Figure 1), which supplies a nearly constant percentage of the Mississippi River flow into the Atchafalaya River [13]. The Mandalay site (MA—Salt) is also somewhat affected by the Atchafalaya River, but it is farther away along the GIWW and south of the GIWW, closer to coastal influence. Four sites, two Fresh (Bayou

Chevrieul [BC] and Jean Lafitte [JL]), and two Salt (Treasure Island [TI] and Fleming [FL]) are in upper Barataria Bay, totally cut off from riverine input by levees along the length of the Mississippi River to the east and Bayou Lafourche to the west. Freshwater input to these sites is solely from local precipitation.

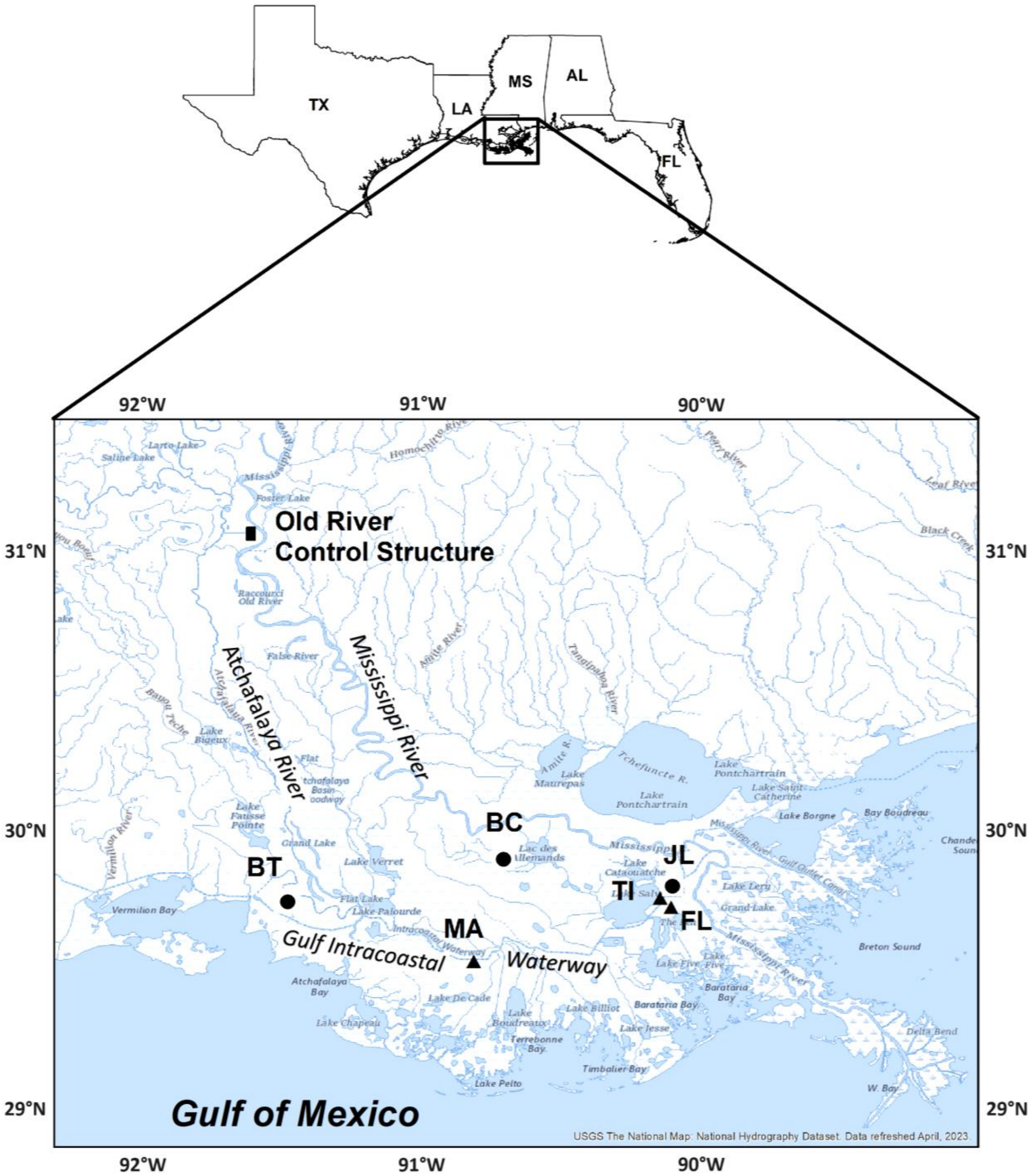

Figure 1. Location map of six study sites in Louisiana, USA. BT = Bayou Teche, MA = Mandalay, BC = Bayou Chevrieul, TI = Treasure Island, JL = Jean Lafitte, and FL = Fleming. Circles = freshwater sites. Triangles = saltwater sites. Top inset of USA states: TX = Texas, LA = Louisiana, MS = Mississippi, AL = Alabama, and FL = Florida. Map source: USGS National Hydrography Dataset. Available at https://www.usgs.gov/national-hydrography/national-hydrography-dataset (accessed 15 April 2023).

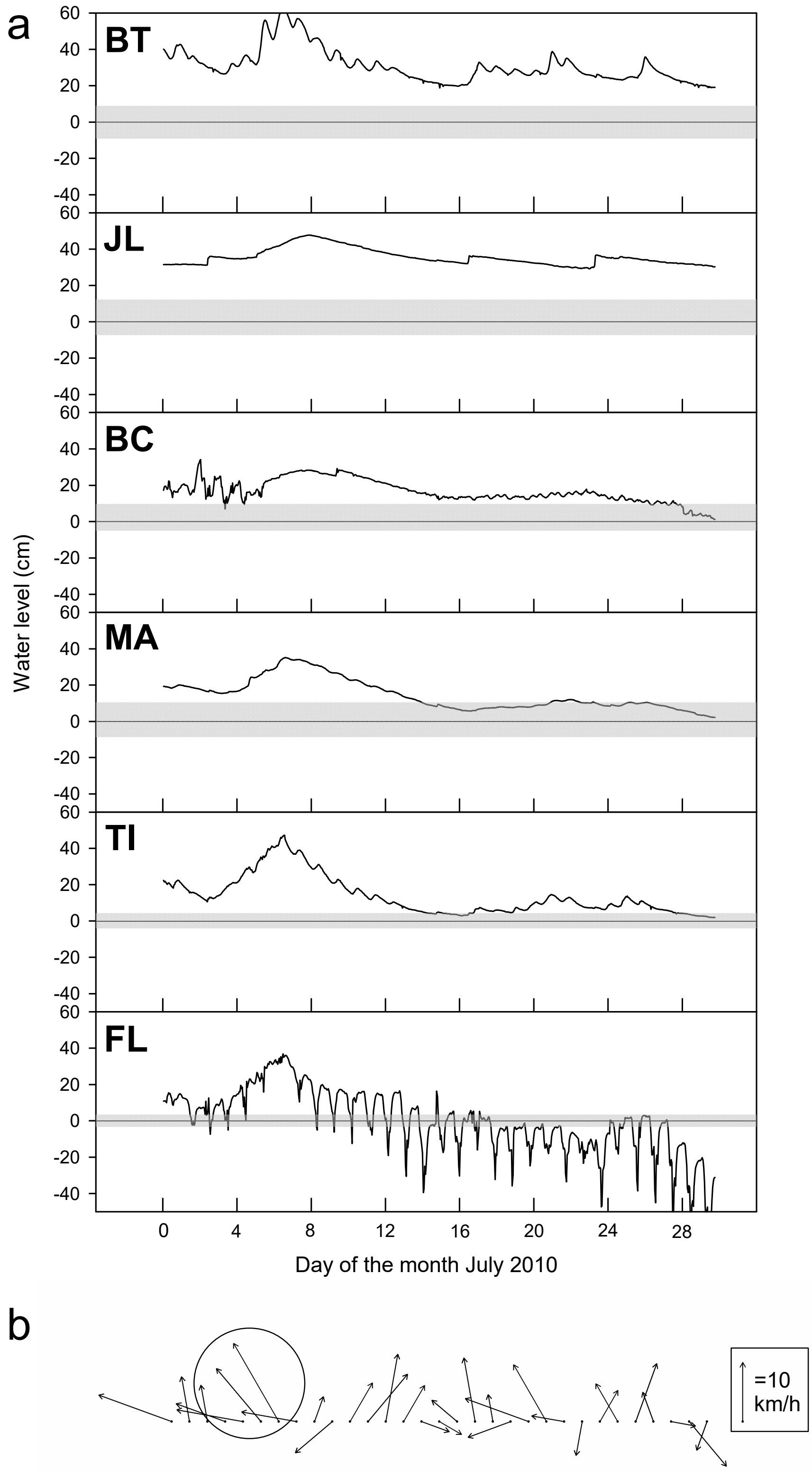

Figure 2. (**a**) 31-day hydrographs recorded by water level pressure sondes with hourly water levels of six study sites during the month of July 2010, (**b**) direction and velocity of wind (Meteorological station WBAN:53915 New Iberia, LA, USA) during maximum sustained wind speed for the day (e.g., an arrow pointing straight up represents wind coming directly from the south). The circle highlights strong sustained winds > 10 km/h for two days from the southeast, which resulted in high water levels at all sites depicted in Figure 2a. BT = Bayou Teche, JL = Jean Lafitte, BC = Bayou Chevrieul, MA = Mandalay, TI = Treasure Island, and FL = Fleming.

All six sites are adjacent to a natural or constructed berm. Two Fresh sites (BT, JL) are adjacent to high levees, separating them from canals that are pumped to drain water levels to elevations we surveyed and determined to be below sea level and approximately 2 m below the average water elevation within the forest plots at both sites. Two sites (BC—Fresh, FL—Salt) have the most natural hydrology. The BC site has a natural berm with openings to allow freshwater flow. The FL site is located behind a spoil bank of a dredged channel but is fully tidal because a breach in the spoil bank allowed a tidal creek to form.

2.2. Forest Plots

Forest plots were installed as described in a previous publication [5]. The sites were established using paired, rectangular plots 20 × 25-m encompassing a combined area of 1000 m^2 (0.1 ha) per site, except the BT site, which only had one 20 × 25-m plot (0.05 ha). In each site except BT, we installed a pressure sonde water level recorder between the pairs of plots, which takes an hourly reading, and four salinity wells for manual salinity measurement during each site visit. Site BT had the pressure sonde installed next to the single plot and only had three salinity wells. Height and diameter at breast height (dbh) were measured for all trees in each plot, and the results were published in a previous publication [5]. Stainless steel dendrometer bands were installed on at least ten codominant bald cypress trees per plot (20 per site) above any swell in the tree stem. Dendrometer bands exhibit the expansion of tree trunks as incremental circumference growth and are an effective measure of very small incremental growth [14]. Individual bald cypress trees were chosen to represent a range of sizes at each site to compensate for differences in trunk growth rate according to the initial dbh. The sites were visited monthly from August 2004 through March 2011 and quarterly from June 2011 through September 2016. During these sampling visits, the water level recorder was downloaded, salinity was measured in each of the four wells, as well as a random surface location in the plot and in the adjacent water body/canal, and each tree band was measured to the nearest 0.25 millimeter (mm). In order to sample the groundwater salinity, each well (approximately 61 cm deep) was pumped out and allowed to recharge before measuring instantaneous salinity using a YSI30 meter (YSI Inc., Columbus, OH, USA). Hourly water level data were recorded using an Infinity USA model #138 pressure water level data logger (Infinities, Port Orange, FL, USA). Dendrometer band readings were recorded as increments of the circumference, which were converted to individual tree basal area increments (BAI) in square centimeters (cm^2). Growth in circumference (C) for each time period (t) was converted to incremental growth of the tree trunk's basal area (BA) by using the calculation for the area of a circle:

$$\mathrm{BAI}_t = \mathrm{BA}_t - \mathrm{BA}_{t-1}, \text{ where } \mathrm{BA} = \pi\, \mathrm{r}^2, \text{ and } \mathrm{r} = C/(2\pi)$$

2.3. Statistical Analyses

The most complete data with the least missing values were for the years 2008–2016, so statistical analyses were run on this 9-year period. To equalize disparate sampling dates, growth rates were converted to BAI/day for monthly and seasonal analyses; then, we calculated the mean daily BAI of each individual banded bald cypress tree per site. The four seasons were defined as January–March, April–June, July–September, and October–December. For annual growth rates, we calculated the annual BAI from the January dendrometer band reading to the following year's January dendrometer band reading for each tree, then calculated the mean annual BAI of all trees per site. To analyze differences between monthly growth rates, we ran a 2-way ANOVA in PROC GLM with the dependent variable monthly BAI and independent variables Type (Salt, Fresh) and Month. To analyze differences between years, a 2-way ANOVA in PROC GLM was used with dependent variable annual BAI and independent variables Year, Site, Site × Year, Season, and Season × Year. The water level data were converted to the average ground level at the base of the banded trees, then the calculation of the percent time flooded above the base of the trees was used for analysis. We ran a regression model in PROC REG with dependent variable total 9-year BAI and independent variables 9-year mean Salinity, total 9-year Percent Flooded, and Salinity × Percent Flooded to ascertain the effect of flooding and salinity on tree growth. Finally, to analyze the effect of flooding on salinity, a regression model in PROC REG was used with the dependent variable Salinity and independent variables Type (Salt, Fresh) and Percent Flooded.

The level of significance for all tests was $\alpha = 0.05$. All statistical analyses were performed using SAS Version 15.1 (SAS 2018).

3. Results

3.1. Salinity

Mean groundwater salinity per site for the entire study period justified the a priori designations as three Fresh sites and three Salt sites (Figures 3, 4b, and 5b). The minimum, maximum, and mode salinity per site were all significantly higher at the Salt sites ($p < 0.0001$) (Figure 3). The major difference was the maximum extremes. Maximum salinity at Fresh sites never rose above 1.3 ppt, while Salt sites all peaked higher (3.8–4.9 ppt). Salt sites averaged 1.6–1.9 ppt, while Fresh sites means were all near 0.5 ppt (Figure 4b). Mean annual salinity varied slightly from year to year at Salt sites between 1.5–2.0 ppt, while Fresh sites remained nearly the same at 0.5 ppt (Figure 5b). Surface water within the forest site and surface water of nearby waterway salinity was always < 0.5 ppt at both Salt and Fresh sites.

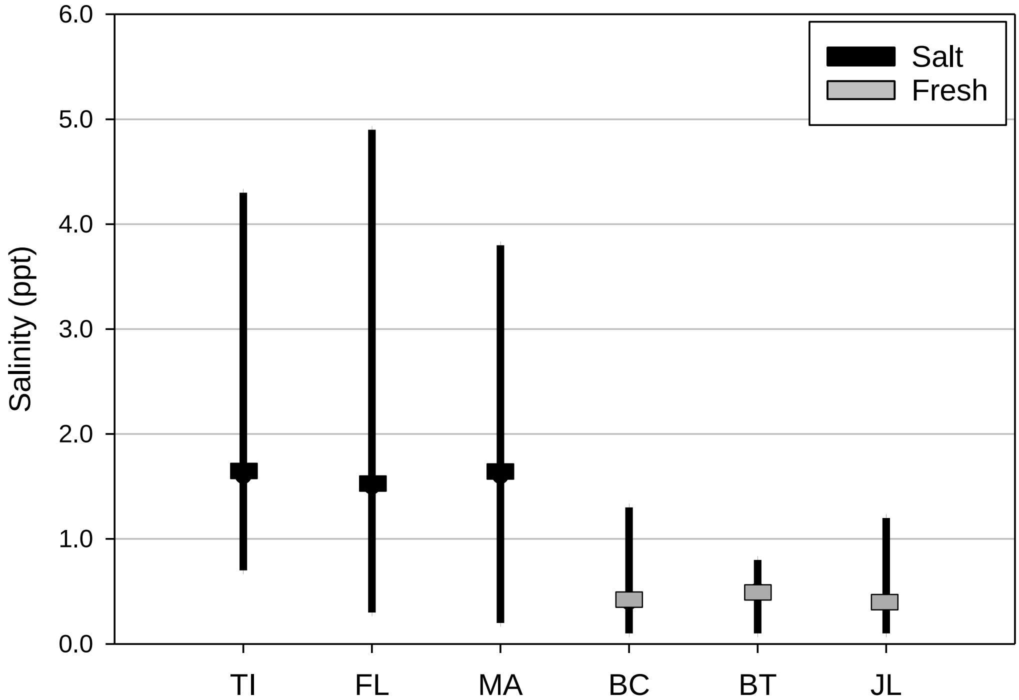

Figure 3. Salinity measured during the period 2008–2016: summary statistics showing mode (rectangles) plus maximum and minimum values (vertical bars) at six study sites in Louisiana. TI = Treasure Island, FL = Fleming, MA = Mandalay, BC = Bayou Chevrieul, BT = Bayou Teche, and JL = Jean Lafitte.

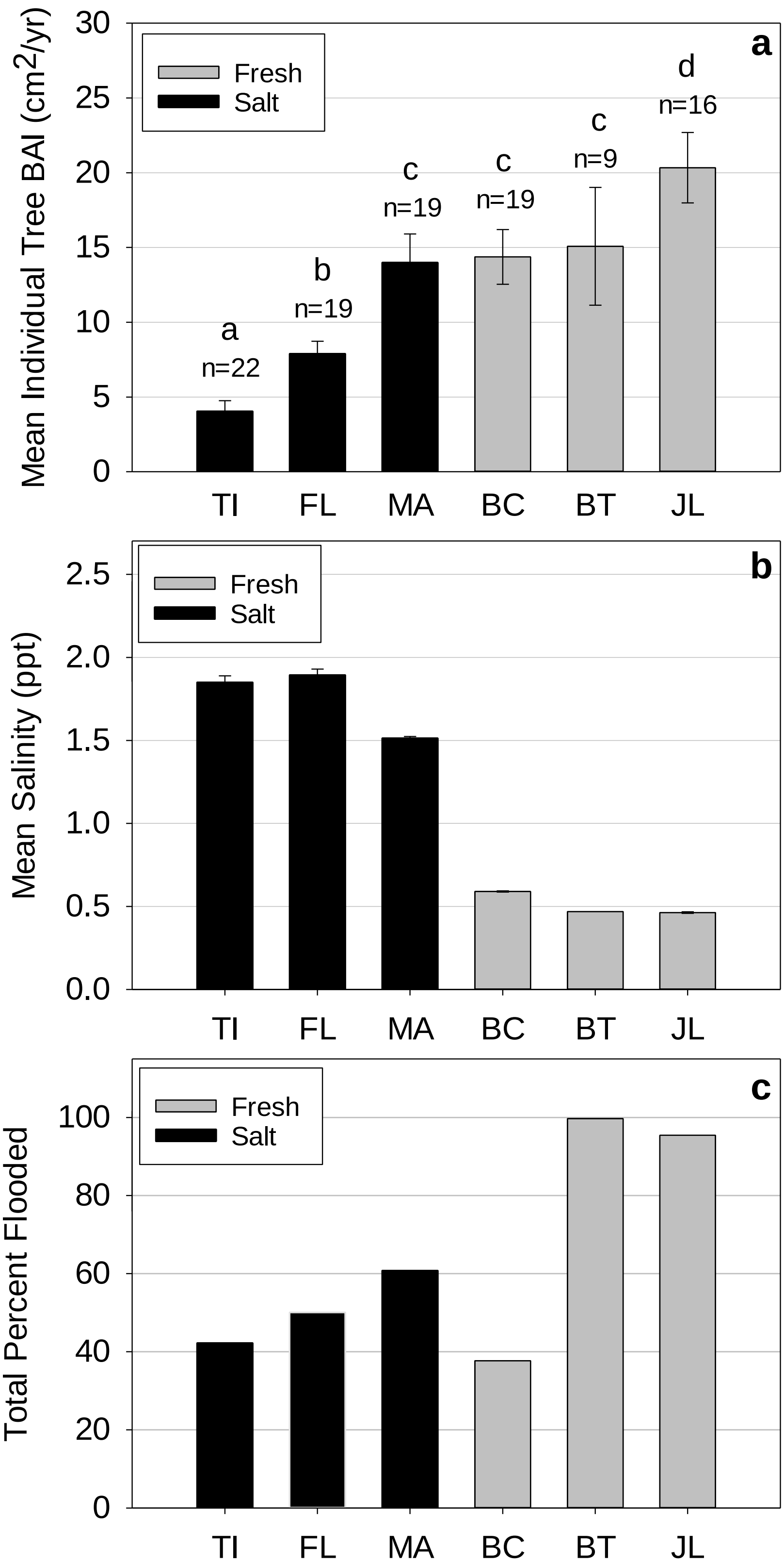

Figure 4. Flooding, salinity, and tree growth for six study sites in Louisiana (**a**) 9-year mean annual individual tree basal area increment (BAI) ± 1 SE, letters above the bars represent significant difference between sites from a 2-way ANOVA with dependent variable annual BAI and independent variable Site, (**b**) 9-year mean salinity ± 1 SE, (**c**) total percent time flooded above tree base. TI = Treasure Island, FL = Fleming, MA = Mandalay, BC = Bayou Chevrieul, BT = Bayou Teche, and JL = Jean Lafitte.

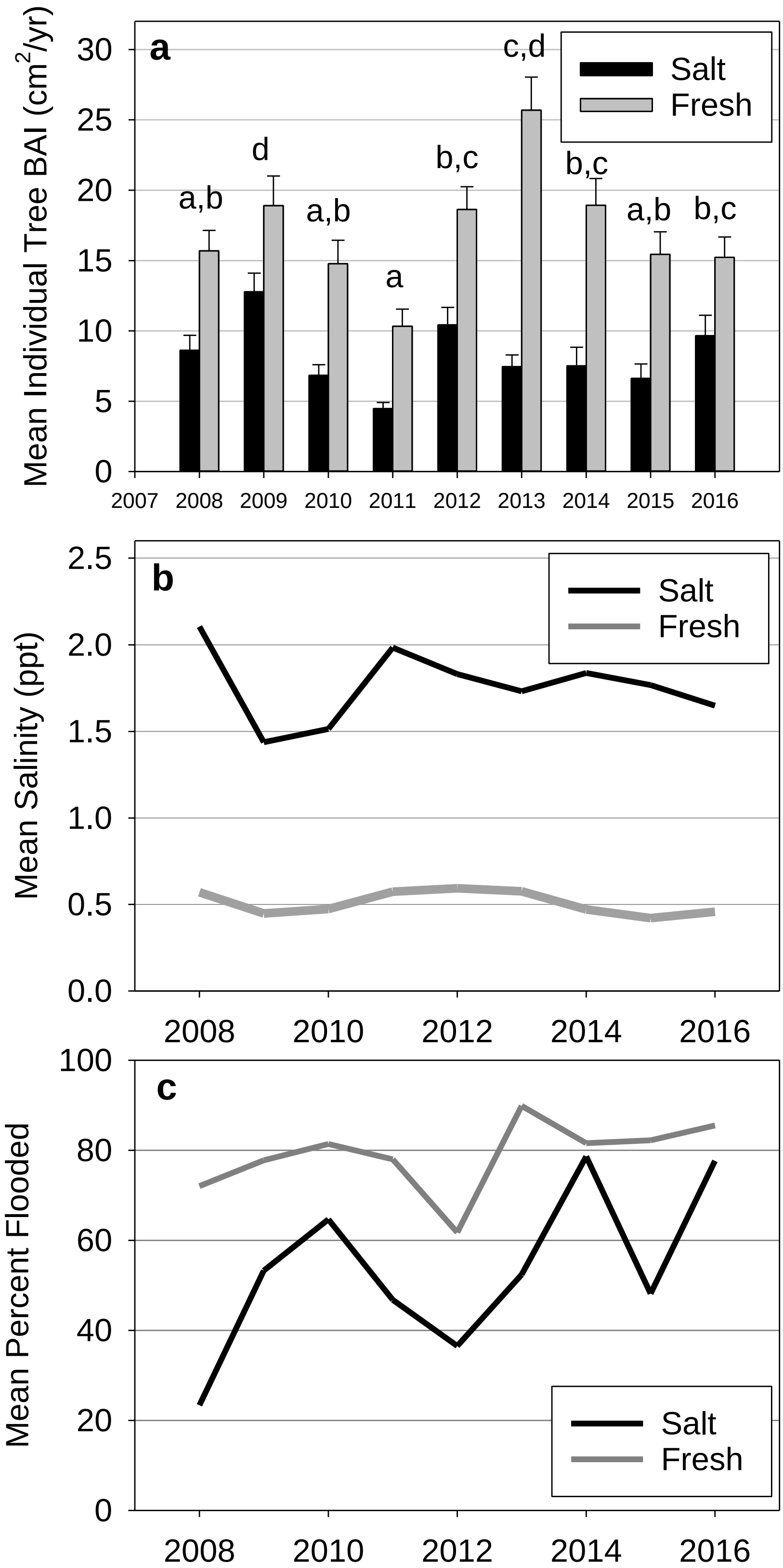

Figure 5. Annual means for six study sites in Louisiana (Salt = 3 sites, Fresh = 3 sites) (**a**) individual tree basal area increment (BAI) ± 1 SE (Salt = 60 bald cypress trees, Fresh = 44 bald cypress trees), letters above the bars represent significant differences between years for the combined Salt and Fresh pairings from a 2-way ANOVA with dependent variable annual BAI and independent variable Year, (**b**) salinity; (**c**) percent flooded.

3.2. Hydrology

Water levels at all six sites are affected by coastal tides, which at times can be strongly wind-driven (Figure 2). A hurricane may cause a sharp peak in the hydrographs of specific sites in its path, but a frequent occurrence is strong winds sustained for multiple days from the south or southeast, raising water levels at all six sites (Figure 2). The Salt sites exhibited coastal and tidal influence in their flooding rates, with total flooding above tree bases for the entire study period between 40 and 60% of the 9-year period (Figure 4c). The Fresh sites were more dissimilar. Two Fresh sites (BT and JL) were almost permanently flooded (>95% of the time) throughout the study period. The BC Fresh site had the lowest percent flooding among the Fresh sites at <40%. Pooled Salt and Fresh sites had similar temporal sensitivity patterns when comparing annual differences in percent flooding (Figure 5c). However, the mean percent flooding for the three Salt sites ranged from 20 to 80%, while Fresh sites were more flooded, ranging between 60 and 85%. The years preceding these analyses (2004–2007) were drier, with less percent flooding, and may have contributed to lower water levels (and higher salinities) at the beginning of this study (Figure 5b,c).

3.3. Radial Growth

We include the initial forest structural characteristics of each site to put the growth environment of the banded bald cypress trees into perspective (Table 1). The Fresh sites generally had taller trees, and the plots had higher tree density with greater basal area than the Salt sites. There was no significant difference ($p < 0.05$) between Salt and Fresh sites for the mean initial dbh of the trees chosen for dendrometer bands.

Table 1. Summary statistics for forest structure of six bald cypress (*Taxodium distichum* (L.) Rich.) forest sites in Louisiana (modified from [5]). * diameter at breast height.

	Forest Plot Structure				Banded Bald cypress
	Mean Forest Height	**Mean dbh ***	**Mean Basal Area**	**Total Tree Density**	**Mean dbh ***
	(m)	**(cm)**	**(m^2/ha)**	**(ind/ha)**	**(cm)**
Fresh					
Jean Lafitte (JL)	24.9 ± 0.6	29.9 ± 1.3	70.61	860	37.7 ± 2.1
Bayou Teche (BT)	17.0 ± 1.3	30.9 ± 2.5	53.35	600	38.1 ± 3.8
Bayou Chevreuil (BC)	23.5 ± 0.3	26.3 ± 1.1	56.19	890	36.2 ± 1.4
Salt					
Mandalay (MA)	19.1 ± 0.8	34.5 ± 4.2	26.85	220	44.1 ± 3.7
Fleming (FL)	18.9 ± 0.6	27.9 ± 1.4	36.06	520	33.5 ± 1.9
Treasure Island (TI)	16.9 ± 0.6	23.3 ± 1.1	36.89	750	29.3 ± 1.2

We did not use the first 6–8 months of the dendrometer band readings to allow the bands to tighten and begin to smoothly track the growth of each tree, so the analyses in this study began in the year 2007 after the last site was installed in 2006. The 9-year radial growth from the period 2007–2015 was significantly higher at Fresh sites (Table 2, Figure 4a). There were significant differences between mean annual BAI among years and for Type (Salt, Fresh) by year interactions ($p < 0.0001$) (Table 2, Figure 5a). The highest radial growth rate was >25 cm^2/year for Fresh sites in the year 2013, while the lowest rate was <5 cm^2/year for Salt sites in 2011. The highest significant growth rate for all six sites combined occurred in 2009, while the lowest significant growth for all six sites combined was in 2011 ($p < 0.0001$) (Figure 5a). The annual pattern of radial growth is exhibited in Figure 6. The trees initiate growth in April, followed by rapid growth peaking in June, steadily declining growth until December, then negative growth (shrinking) from January to March (Figure 6). While both Fresh and Salt sites showed significant differences in growth among seasons, Fresh sites grew faster in the growing season and shrank more in March ($p < 0.0001$) (Table 2, Figure 6). There was no significant interactive effect of Season × Year ($p = 0.4246$).

Table 2. Main effects of year, site, season, and interactions for annual basal area increments (BAI) of bald cypress (*n* = 104 trees) for six sites in coastal Louisiana over 9 years from a 2-way ANOVA with dependent variable annual BAI and independent variables Year, Site, Site × Year, Season, and Season × Year.

	Log (BAI + 1)		
Source of Variation	**d.f.**	***F*-Value**	***Pr* > *F***
Model	80, 874	8.93	<0.0001
Year	8, 874	6.73	<0.0001
Site	5, 874	81.45	<0.0001
Site × Year	40, 874	3.16	<0.0001
Season	3, 874	15.52	<0.0001
Season × Year	24, 874	1.03	0.4246

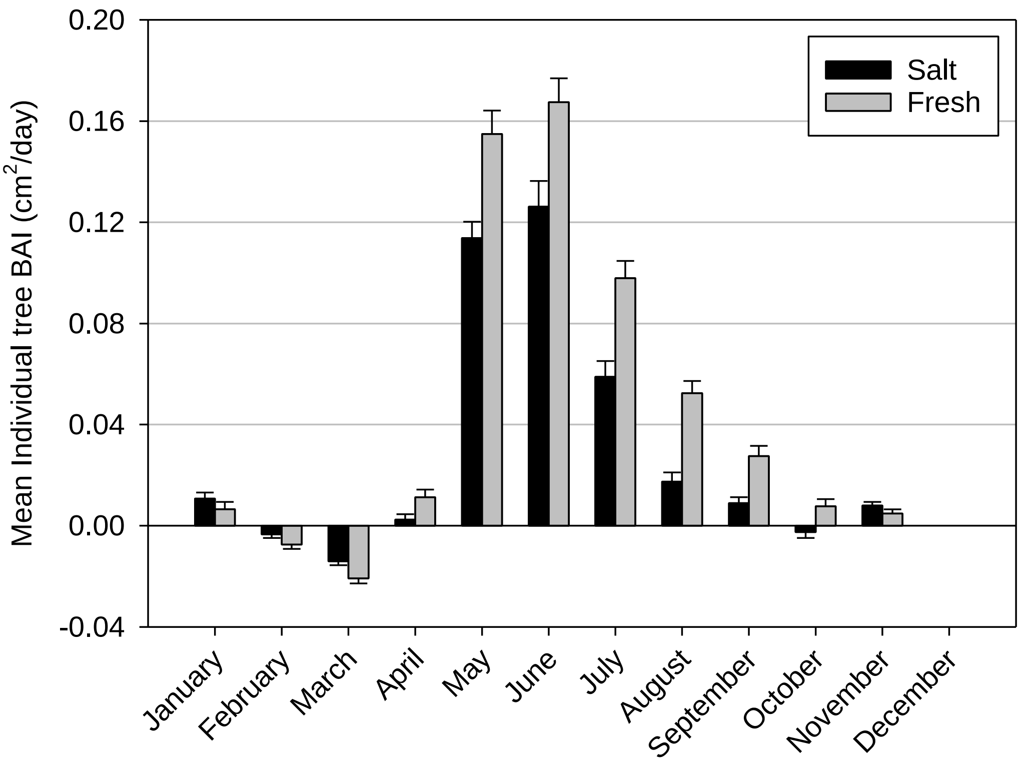

Figure 6. 9-year mean daily individual tree basal area increment (BAI) ± 1 SE. Salt = 3 sites and 60 bald cypress trees. Fresh = 3 sites and 44 bald cypress trees.

Regression analyses showed significant effects of percent time of duration of flooding and salinity level on BAI (Table 3, Figure 7). As salinity increased, BAI decreased ($r^2 = 0.653$, $p < 0.0001$) (Figure 7a). As percent flooding increased, BAI increased ($r^2 = 0.491$, $p = 0.0108$) (Figure 7b). There was also a significant interactive effect of salinity and percent flooding on BAI ($p = 0.0389$) (Table 3). The effect of percent flooding on salinity is significant ($p = 0.0304$) by Type (Salt and Fresh) (Table 4, Figure 8). The regression model indicates equal and parallel slopes by Type: as flooding increases, salinity decreases ($r^2 = 0.962$, $p < 0.0001$) (Figure 8).

Table 3. Regression analysis for BAI of bald cypress (n = 104 trees) with Percent Flooded and Salinity as predictors for six sites in coastal Louisiana over 9 years from a model with dependent variable total 9-year BAI and independent variables 9-year mean Salinity, total 9-year Percent Flooded, and Salinity × Percent Flooded.

	Log (BAI + 1)		
Source of Variation	**d.f.**	***F*-Value**	***Pr* > *F***
Model	3, 41	10.50	<0.0001
Salinity	1, 41	10.38	0.0025
Percent Flooded	1, 41	0.43	0.5163
Salinity × Percent Flooded	1, 41	4.55	0.0389

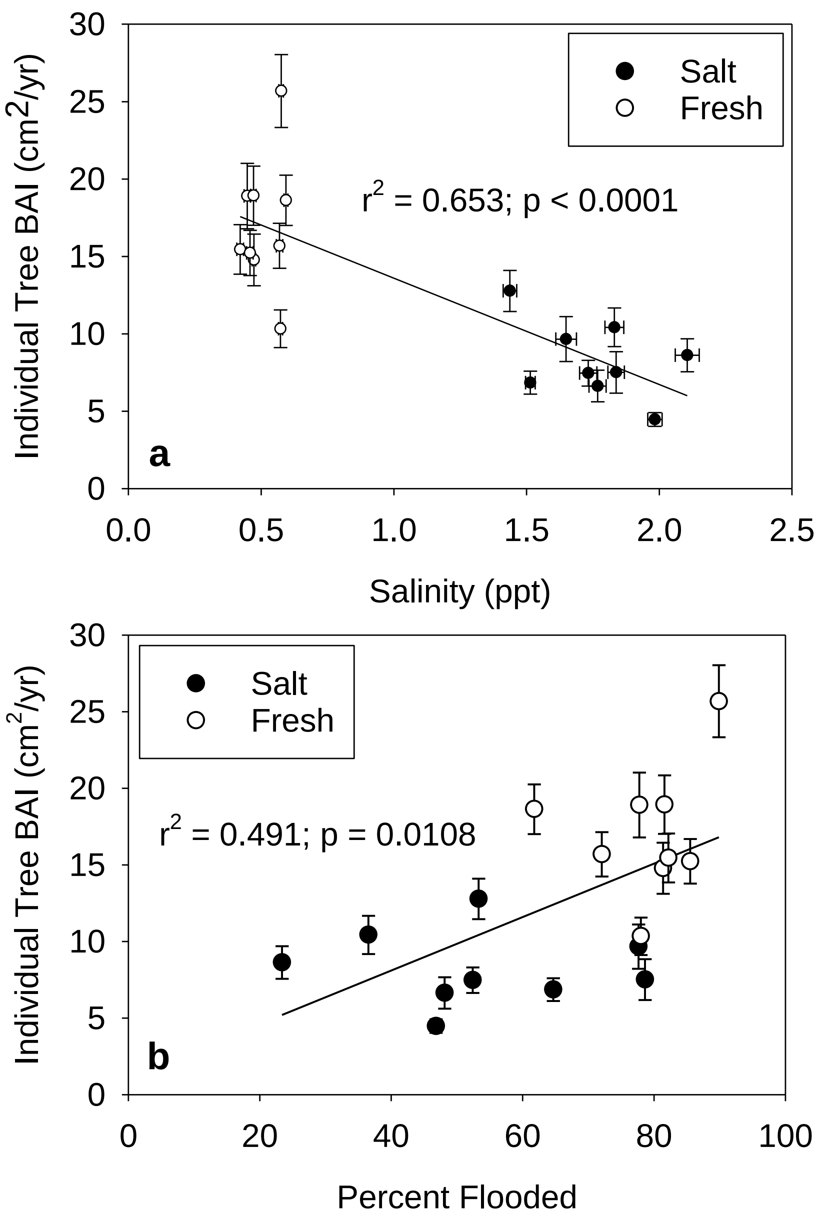

Figure 7. Relationships for (**a**) salinity (ppt ± 1 SE) and (**b**) percent flooded with mean annual basal area increment (BAI, cm^2/yr ± 1 SE) of bald cypress trees (Salt = 60 trees, Fresh = 44 trees) at six study sites in Louisiana (Salt = 3 sites, Fresh = 3 sites). Each point equals annual means for three sites combined.

Table 4. Results of a regression model with dependent variable mean annual Salinity and independent variables Type (Salt, Fresh) and Total Percent Flooded per site.

		Mean Salinity	
Source of Variation	**d.f.**	***F*-Value**	***Pr* > F**
Model	2, 15	188.56	<0.0001
Type (Salt, Fresh)	1, 15	149.69	<0.0001
Percent Flooded	1, 15	5.72	0.0304

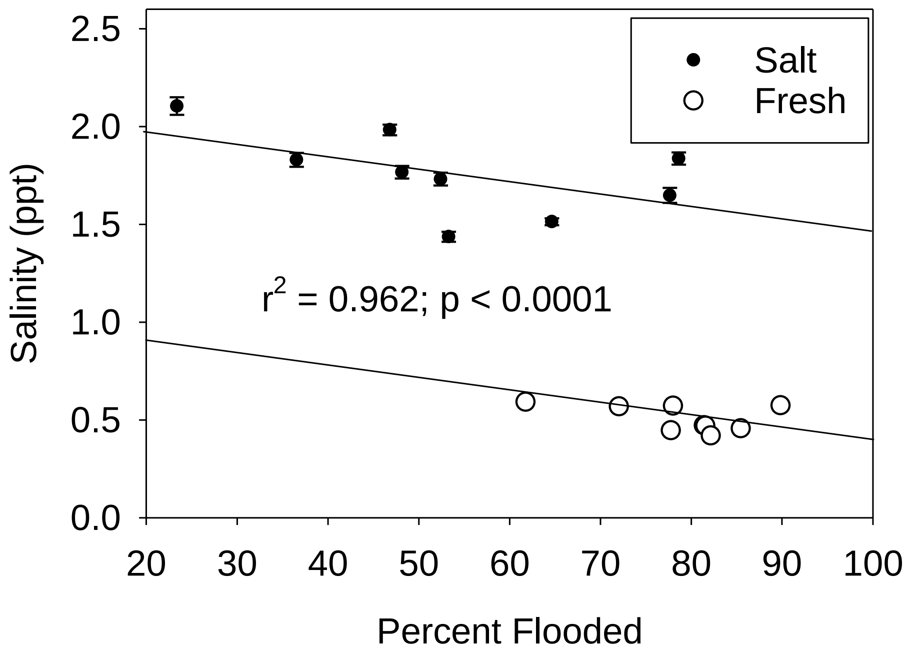

Figure 8. Relationship for percent flooded with salinity (ppt ± 1 SE) at six study sites in Louisiana (Salt = 3 sites, Fresh = 3 sites) over 9 years. Each point equals annual means for three sites combined.

4. Discussion

Tree growth of bald cypress in coastal Louisiana reflects the response of tidal freshwater trees to environments of coastal salinity and flooding and is poised to change in the future with predicted increases in coastal salinification.

4.1. *Salinity Effects*

Maximum, minimum, and modal values of salinity have a wide range at the Salt sites (up to 5 ppt) while maintaining long-term stable salinity closer to 2 ppt. Bald cypress has been shown repeatedly in lab and field studies to be salt tolerant to low salinity around 2 ppt [4,7,15–17]. In a greenhouse study, bald cypress seedlings exhibited reduced stomatal conductance while being shallowly flooded with water with salinities of 2–7 ppt but recovered within three weeks [18]. In another short-term experiment, bald cypress seedlings were watered daily with salt water (6 ppt) or once a week with fresh water (to simulate drought) and compared to controls watered daily with freshwater [19]. The salt and drought treatments showed similar results of survival with reduced diameter growth but increased wood density and greater resistance to xylem cavitation. Embolism resistance was also reported for upland conifer seedlings surviving a drought experiment [20]. Bald cypress seedlings from parent trees growing in salty sites have been shown to have more salt tolerance than seedlings from parent trees from freshwater sites, indicating genetic selection for salt tolerance [15,16]. Sapflow and water use were lower in mature bald cypress individuals in salty sites than in trees in fresher water sites, presumably due to shifts in individual-tree osmotic balance and water-use strategy to extend survival time [21]. It is clear that bald cypress seedlings, as well as mature trees, tolerate low levels of salinity. The bald cypress forests in the three Salt sites in this study in coastal Louisiana show resilience by persisting for years with chronic salinity close to 2 ppt. However, closer to the coasts and with higher salinity, there are ghost forests of dead bald cypress that have already succumbed to saltwater intrusion [3,22,23]. As sea level and storm frequency/intensity increase, the bald cypress forests within the sites in this study may reduce growth rates even further and even exceed their salt tolerance to eventual mortality.

4.2. Flooding Effects

Long-term studies of tree rings (fifty to hundreds of years) indicate that freshwater flooding is positively correlated with the growth of bald cypress [24–28]. In a detailed study of frequently flooded sites, the depth of annual flooding was positively correlated with growth that year but negatively correlated with growth in the following year [25]. Delayed effects are difficult to analyze in shorter-duration studies where the variation in annual flooding is not frequent enough to show such correlations. This study also shows a positive relationship between flooding and bald cypress growth, not only in deep freshwater swamps but also in salt-affected sites (Figure 7). Flooding increases radial growth rates of bald cypress in Fresh and Salt Sites.

The JL and BT sites in this study have the highest percentage of flooding and also exhibit high radial bald cypress growth. Another study showed that tree growth in freshwater bald cypress forests was not reduced, and healthy growth was maintained despite stagnant standing water conditions [24]. They hypothesized that rainwater put a higher downward pressure on the below-water soil surface, perhaps forcing more oxygenated water into the porewater and alleviating hypoxic conditions. The JL and BT sites are perched at least 2 m above the surface water on the opposite side of the levees at both sites. The JL and BT sites may have a constant downward flow of water into the porewater and under the levee, seeking the level of the surface water 2 m lower on the other side. This elevation difference may also contribute to the downward movement of the ground surface, leading to more rapid subsidence and, consequently, increased flooding.

4.3. Radial Growth Patterns

The pattern of tree growth during the growing season and shrinkage in the winter dictated by annual rhythms of temperature and sunlight inherent to coastal Louisiana is also a common characteristic of temperate and subtropical trees, which exhibit clear annual growth rings, with cellular growth during summer followed by lignification and dehydration of the woody cells as photosynthesis and sap flow slow in the winter [29–31]. In addition, flooding and salinity affect the magnitude of annual radial growth rates, and along with annual variations in temperature, solar radiation, and other meteorological parameters, result in tree growth responses to environmental change over the years [32]. Another factor affecting an individual tree's growth is the forest environment in which the tree is growing. Bald cypress is in the intermediate range on a scale of shade tolerance [33,34]. The openness of the canopy, as affected by the density of trees in a forest stand, affects individual trees by controlling the competition between trees for access to sunlight and nutrients, especially in bald cypress forests where salinity may be a factor causing declining health or death of older trees [35]. For example, the MA site (Salt) in this study has a relatively high rate of growth compared to the other two Salt sites (TI and FL) (Figure 4a). The MA site also has the lowest tree density at 220 trees/ha (Table 1). Within the context of a salt-affected site, individual trees at the MA site may have an advantage in the competition for resources (space, nutrients, light) as there are fewer trees with which to compete. This may partially offset the negative effect of salinity, which lowers growth, as we show here. The annual BAI differences reported here are affected by salinity levels and flooding rates and the interaction between salinity and flooding.

5. Conclusions

Salinity as low as modal values of 1.6–1.7 ppt lowers the growth rates of bald cypress in coastal Louisiana, while increased freshwater flooding increases bald cypress growth rates. The effect of high salinity coastal water flooding on bald cypress forests during hurricanes and other large tidal surges would imply that more flooding would increase the salinity of the sites. This occurs during the infrequent high salinity spikes experienced by the Salt sites. However, the overall significant effect of flooding lowering salinity at both Salt and Fresh sites suggests that salinity is controlled more often by the frequent input of freshwater from precipitation to dilute the groundwater salinity at the sites. This highlights the importance of climate change and increasingly extreme year-to-year differences in sustained precipitation to dilute groundwater salinity and the frequency of hurricanes to increase salinity through tidal surges. What salinity level is needed and for how long to result in the transition of a healthy bald cypress forest to a stand of dead trees in coastal Louisiana? Continuous monitoring of the sites in this study into the future can assist coastal managers in predicting these parameters. Long-term studies can produce sufficient data to support accurate modeling. The results of this study illustrate that complex interactions between hydrology and salinity drive the growth and productivity of tide-influenced bald cypress forests in coastal Louisiana. All data are available in From et al. [36].

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