Ecological response of forested wetlands with and without Large-Scale Mississippi River input: Implications for management

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**A B S T R A C T**

We investigated two adjacent wetlands in the Lake Pontchartrain basin, one of which receives periodic input of Mississippi River water and one which does not, to gain insight into how isolation from river input impacts wetland loss in the Mississippi delta. The LaBranché (LB) wetlands bordering Lake Pontchartrain are severely degraded due to saltwater intrusion, subsidence, leveeing of the river, and hydrologic alterations including partial impoundment. Directly adjacent is the Bonnet Carré (BC) spillway, a geomorphically similar area that contains healthy baldcypress swamp. The spillway carries river water to the lake during high discharge years and has been opened eleven times in 80 years, with flows as high as 9000 m\(^3\) s\(^{-1}\). The primary hydrologic difference between the two areas is the regular input of River water to the BC wetlands while the LB wetlands are isolated from the river. The interior of the LB wetlands is also isolated from sediment originating from Lake Pontchartrain. Long-term accretion, tree growth, and elevation were measured in these two wetland areas to determine impacts of riverine input. \(^{137}\)Cs accretion rates in the BC wetlands were 2.6–2.7 cm yr\(^{-1}\), compared to 0.43 and 1.4 cm yr\(^{-1}\), respectively, in the LB wetlands in areas without and with sediment input from Lake Pontchartrain. Baldcypress growth in the BC averaged about 2.3 mm ring width yr\(^{-1}\), compared to 1.4 mm yr\(^{-1}\) in LB. Trees of relatively the same age due to lack of recruitment and widespread logging. Tree height, an indicator of site quality, is about 20% less at the LB sites compared to BC, even though the trees are approximately the same ages. The average wetland elevation in the BC wetlands was about one meter with some areas higher than two meters, and was significantly higher than elevations in the LB (average sea level and 0.3 m, respectively, in areas with and without input from Lake Pontchartrain).

**1. Introduction**

Freshwater, sediments and nutrients from the Mississippi River formed the expansive network of deltaic wetlands in coastal Louisiana, including forested wetlands such as those that are the focus of this study (Roberts, 1997; Day et al., 2007; Törnqvist et al., 2006; Shaffer et al., 2009a). In the 20th century, there was a dramatic loss of about 25% of these coastal wetlands. This loss was due to a variety of factors such as pervasive hydrological alteration and enhanced subsidence, but there is broad consensus that isolation of the deltaic plain from riverine input is one of the primary factors contributing to this loss (Kesel, 1988, 1989; Mossa, 1996; Day et al., 2000, 2007). In an effort to restore marshes and freshwater swamps, water from the Mississippi River is being diverted into coastal wetlands, primarily in small-scale diversions less than 200 m\(^3\) s\(^{-1}\) such as the Caenarvon diversion (Day et al., 2009).

Previous research has shown that these small river diversions can increase marsh primary production, wetland surface elevation, and vertical accretion (DeLaune et al., 2003; Lane et al., 2006; Day et al., 2007, 2009). However, there is concern that these diversions are so small compared to pre-levee flooding of the Mississippi River that they are not making a significant contribution to coastal restoration and that they may make wetlands susceptible to hurricane damage (Turner, 2010; Howes et al., 2010). In the past, large...
crevasses on the Mississippi River were fairly common and they delivered large quantities of freshwater (generally with peak discharge between 5000 and 10,000 m$^3$ s$^{-1}$) and sediment to adjacent wetlands (Davis, 2000; Day et al., 2009). With larger river diversions planned for future restoration projects, it is important to understand how discharges of large volumes of water will impact wetlands.

One example of an area with large-scale riverine input is the Bonnet Carré spillway, which carries floodwaters from the river to Lake Pontchartrain Basin when high river levels threaten New Orleans (Fig. 1). The LB wetlands, located adjacent to the BC spillway and separated from it by an earthen levee, are an example of wetlands that have been isolated from the river by levees for more than a century. In this paper we compare baldcypress growth, sediment accretion, elevation in wetlands and other information in the BC wetlands with adjacent LB wetlands to determine impacts of an infrequent, large-scale diversion on forested coastal wetlands.

2. Objectives of research

We hypothesized that previous openings of the BC spillway have led to higher elevation, increased accretion, and increased cypress growth rates than in the LB wetlands that have been isolated from flooding from the Mississippi River for over a century. We also hypothesized that accretion rates in the BC wetlands are sufficient to offset current and projected increases in the rate of sea-level rise. To test our hypotheses, the objectives of this research were:

1) Utilize LIDAR data to determine and compare elevations between the two study sites;
2) Determine long-term patterns of sediment accretion in the BC and LB wetlands using $^{137}$Cs;
3) Determine long-term patterns of baldcypress growth in the study sites and relate patterns to environmental conditions such as precipitation, drought, and storms; and
4) Synthesize available information on the area to determine factors responsible for change over time.

3. Methods

3.1. Site description

3.1.1. Bonnet Carré Spillway

The BC Spillway was completed in 1931 in response to the great flood of 1927 (Barry, 1997). The purpose of the spillway is to decrease river stage to reduce flooding threat to New Orleans. The 3.4 km wide spillway is confined by two 8.6 km levees, and connects the Mississippi River to Lake Pontchartrain. A water flow regulation structure, consisting of 350 floodgates (each with twenty 20 cm $\times$ 30 cm creosoted wooden timbers 3.1–3.6 m in length), is located at the Mississippi River inlet. The structure is opened and closed by removing or replacing the timbers one at a time. Thus, it can take a week or more to completely open or close the structure. The spillway is located just downstream of the Bonnet Carré crevasse, one of the many natural crevasses that occurred in the 1800s, introducing up to 10,000 m$^3$ s$^{-1}$ of river water into Lake Pontchartrain during flood events (Kesel, 1989; Davis, 1993). The spillway has 1300 ha of forested wetlands; approximately 50% of the total spillway area (Lane et al., 2001). Although the spillway was designed for flood control, its use as a freshwater diversion to manage salinity levels for oyster production and to provide sediments and nutrients for wetland restoration has been considered (Lane et al., 2001).

Since 1931, the spillway has been opened eleven times during high water events of the Mississippi River, with flows ranging from 3100 to 9000 m$^3$ s$^{-1}$ (Table 1; Sikora and Kjerfve, 1985; Day et al., 1999; Lane et al., 2001). Spillway openings generally correspond to the peak hydrograph of the Mississippi River when snowmelt and rainfall in the upper basin increase flow and stage in the lower river. When open, water flows through the spillway into Lake Pontchartrain, flooding wetlands, creating a temporary water body, and returning water to the Mississippi River within a week.
Pontchartrain and then to the Gulf of Mexico. River water discharged into Lake Pontchartrain often tends to flow along the southern portion of the Lake in an easterly direction adjacent to the LB wetlands, exiting through Chef Menteur Pass and the Rigolets (White et al., 2009).

With each opening of the BC spillway, the river deposits an average of about 5 million m$^3$ of sediment, consisting mostly of silts and sands, in the spillway (Table 1; Lane et al., 2001). During an experimental opening of the spillway in 1994 (peak discharge was 396 m$^3$ s$^{-1}$), Lane et al. (2001) estimated that approximately 6.4 × 10$^6$ m$^3$ of Mississippi River water was diverted into Lake Pontchartrain over 42 days. During this time, there were 3.9 ± 1.1 cm of accretion in the spillway (Lane et al., 2001). Research by Snedden et al. (2007) indicated that sediment inputs are maximized when diversion events coincide with the hydrograph peak.

### 3.2. LaBranche wetlands

The 8100-hectare LB wetlands consist primarily of non-regenerating baldcypress-water tupelo (*Taxodium distichum* – *Nyssa aquatica*) swamp and freshwater herbaceous wetlands in the southern areas, grading to intermediate, brackish, and saline marsh and shallow open water ponds closer to Lake Pontchartrain. The wetlands border Lake Pontchartrain to the north while the rest of the area is bordered by flood control levees (Cramer et al., 1981; Pierce et al., 1985; Boumans et al., 1997). The major factors contributing to the deterioration of the LB wetlands are isolation from riverine input by Mississippi River levees, hydrologic alterations, erosion, saltwater intrusion, hurricanes, semi-impoundment, nutria herbivory, and soil subsidence (Pierce et al., 1985). These factors have interacted in a cumulative way to create non-sustainable ecosystems in much of the Pontchartrain Basin (Shaffer et al., 2009a, b).

The Mississippi flood control levees have eliminated most river input to Mississippi delta wetlands. Relatively healthy cypress swamps occur only in freshwater areas experiencing minimal daily tidal action and where the salinity range does not normally exceed two parts per thousand (ppt; Conner et al., 2007; Krauss et al., 2009; USACE, 2009). Fragmentation of the LB wetlands occurred due to digging of canals, oil and gas extraction, and construction of the Illinois Central Gulf Railroad in 1854 and highway I-10 in the 1960s. The railroad sits atop an embankment with seven small openings along a total length of approximately 10.4 km that severely restricts water exchange between Lake Pontchartrain and the wetlands south of the railroad. The dredging of several canals to Lake Pontchartrain and the opening of the Mississippi River Gulf Outlet (MRGO) east of New Orleans in 1963 caused saltwater intrusion into the wetlands (Shaffer et al., 2009b). A severe drought in 2000–2001 led to high salinities that killed large areas of cypress in the Labranche wetlands and other parts of the Pontchartrain Basin (Shaffer et al., 2009a).

In 1965, Hurricane Betsy caused a surge that overtopped the railroad and inundated the wetlands with salt water. This occurred again during hurricanes Katrina and Rita in 2005. The embankment associated with the railroad is a barrier to sheet flow and drainage, thus reducing sediment input from Lake Pontchartrain to wetlands south of the railroad (Pierce et al., 1985). The construction of Interstate I-10 altered hydrology of the wetlands through the excavation of permanent access canals and extensive borrow pits (Nesbit et al., 2004).

Natural water features such as Bayou Trepagnier and Bayou LaBranche and canals such as Parish Line Canal, Walker Canal, and several I-10 access canals serve as hydrological conduits for brackish and/or saline waters from Lake Pontchartrain into the LaBranche wetlands (Nesbit et al., 2004). Prior to disruption of the natural hydrology, there was regular riverine input and flow of fresh water through the LB wetlands before reaching the lake. Currently, because of isolation from the Mississippi River and the access canals, salinities in the LB wetlands can reach more than 10 ppt during drought, as occurred during the 2000–01 regional drought (Shaffer et al., 2009a). As a result of these changes, from 1952 to 1983, much of the interior marsh converted to open water in the LaBranche wetlands and portions of the swamp were reclaimed (Pierce et al., 1985, Table 2, Fig. 2).

The climate in the area is subtropical with hot summers and mild winters. Summers have an average daily temperature of 28 °C, average daily maximum temperature of 33 °C, and high average humidity (National Climate Data Center, New Orleans International Airport). Winters are influenced by cold, dry, polar air masses moving southward from Canada, with an average daily temperature of 12 °C and an average daily minimum of 7 °C. Estimated annual evapotranspiration is 108 cm and is relatively constant from year to year and annual precipitation averages 137 cm (USDA NARCS, 2002). Generally, water deficits occur in the summer growing season when evapotranspiration often exceeds precipitation.

Lake Pontchartrain is a 163,000-hectare oligohaline body of water with a mean depth of 3.7 m and approximate volume of 1.66 × 10$^9$ m$^3$. Tides are diurnal with a mean range of 1.1 cm (Sikora and Kjerfve, 1985). Although the average salinity of Lake Pontchartrain is less than 6 ppt, salinity can vary widely (e.g., from fresh

### Table 1

Opening dates of the Bonnet Carré Spillway, maximum water discharge, and estimated sediment deposition within the spillway (USACE, 2009). The 1994 opening was for experimental purposes and not for flood control.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dates spillway open</th>
<th>Maximum number of bays open</th>
<th>Maximum discharge (m$^3$ s$^{-1}$)</th>
<th>Sediment deposition (m$^3$)</th>
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</thead>
<tbody>
<tr>
<td>1937</td>
<td>Jan 28–March 16</td>
<td>285</td>
<td>5976</td>
<td>7,800,000</td>
</tr>
<tr>
<td>1945</td>
<td>March 23–May 18</td>
<td>350</td>
<td>9006</td>
<td>9,500,000</td>
</tr>
<tr>
<td>1950</td>
<td>February 10–March 19</td>
<td>350</td>
<td>6315</td>
<td>3,800,000</td>
</tr>
<tr>
<td>1973</td>
<td>April 8–June 21</td>
<td>350</td>
<td>5523</td>
<td>11,500,000</td>
</tr>
<tr>
<td>1975</td>
<td>April 14–26</td>
<td>225</td>
<td>3115</td>
<td>1,500,000</td>
</tr>
<tr>
<td>1979</td>
<td>April 17–May 31</td>
<td>350</td>
<td>6457</td>
<td>3,800,000</td>
</tr>
<tr>
<td>1983</td>
<td>May 20–June 23</td>
<td>350</td>
<td>7590</td>
<td>3,800,000</td>
</tr>
<tr>
<td>1994</td>
<td>May 16–26</td>
<td>30</td>
<td>400</td>
<td>–</td>
</tr>
<tr>
<td>1997</td>
<td>March 17–April 18</td>
<td>298</td>
<td>6797</td>
<td>6,900,000</td>
</tr>
<tr>
<td>2008</td>
<td>April 11–May 8</td>
<td>160</td>
<td>4531</td>
<td>1,500,000</td>
</tr>
<tr>
<td>2011</td>
<td>May 9–June 20</td>
<td>330</td>
<td>8940</td>
<td>7,200,000</td>
</tr>
</tbody>
</table>

### Table 2

Area (ha) of different habitats in the LaBranche wetlands quantified using aerial photographs (Pierce, 1985). See also Fig. 2.

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Year 1952</th>
<th>Year 1956</th>
<th>Year 1965</th>
<th>Year 1972</th>
<th>Year 1978</th>
<th>Year 1983</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water</td>
<td>108</td>
<td>151</td>
<td>1911</td>
<td>1893</td>
<td>1633</td>
<td>1722</td>
</tr>
<tr>
<td>Marsh</td>
<td>4353</td>
<td>4327</td>
<td>3647</td>
<td>3190</td>
<td>3385</td>
<td>3061</td>
</tr>
<tr>
<td>Swamp forest</td>
<td>4084</td>
<td>4036</td>
<td>3681</td>
<td>3260</td>
<td>3316</td>
<td>3417</td>
</tr>
<tr>
<td>Developed land</td>
<td>60</td>
<td>97</td>
<td>107</td>
<td>264</td>
<td>281</td>
<td>410</td>
</tr>
</tbody>
</table>
Changes in the areas of open water and wetlands in the LaBranche area between 1952 (left) and 1983 (right). The normal elevation of Lake Pontchartrain is about 0.1 m above mean sea level (MSL). At least 40% of the Pontchartrain basin consists of swamps and marshes. The dominant hydrological influence on the LB wetlands is the surface elevation of Lake Pontchartrain. Although the average tidal range in the lake is about 11 cm, during major storm events the surface elevation can range from 0.6 m above MSL during frontal passages to about 4 m or more above MSL during hurricanes. Elevated water levels can completely submerge the LB and BC wetlands (Nesbit et al., 2004).

3.3. LIDAR

Light Detection and Ranging (LIDAR) is an optical sensing technology that measures properties of scattered light to find range and/or other information of a distant target. LIDAR can be used to determine tree canopy heights down to bare earth elevations. The LIDAR image for the study area was derived from LIDAR data captured in 2002 (Source: http://atlas.lsu.edu). The LIDAR data are accurate to 15–30 cm root mean square error (RMSE). The bare earth returns were used to create the LIDAR digital elevation maps (DEMs) with a 5 m pixel size. Most LIDAR signal is absorbed by water and so gives fewer returns. The water areas within this collection of DEMs were assigned a value that was lower than the surrounding land (−0.6 m) and were therefore ignored. The LIDAR elevations are relative to 1988 NAVD (North American Vertical Datum). In the Lake Pontchartrain side of the project area the local MSL is −0.11 m below NAVD88 and on the Mississippi River side of the project area the difference is −0.16 m (http://vdatum.noaa.gov/welcome.html).

3.4. Accretion

Six sediment cores were collected for $^{137}$Cs dating to determine long-term accretion rates. Two cores were collected in each of

Fig. 3. Location of soil (SC1–6) and tree core (TC1–5) collection sites in the LaBranche wetlands and Bonnet Carré Spillway.
three areas between April and July 2009 (Fig. 3): BC wetlands (Cores 1 and 2), LB wetlands south of the railroad (Cores 3 and 4), and LB wetlands north of the railroad (Cores 5 and 6). Wetlands north and south of the railroad differ in hydrology because the railroad restricts surface water flow to wetlands south of the railroad. Thus, wetlands north of the railroad exchange water with Lake Pontchartrain while those south of the railroad have limited water exchange.

Cores were collected using 15 cm-diameter thin wall aluminum cylinders. Cores were extruded with a wooden plunger and sectioned at 3-cm intervals. Compaction as a consequence of the coring procedure was minimal as determined by DeLaune et al. (1990). Core sections were placed into individual aluminum foil cups, dried at 80 °C, weighed, and crushed with a mortar and pestle. Sediment bulk density (g cm⁻³) was calculated from the sediment dry weight and the known volume of each sediment section. $^{137}$Cs activity of the bulk sediment was counted with a Lithium-drifted Germanium detector and multichannel analyzer (DeLaune et al., 1978, 2003).

Sedimentation rates were calculated from initial $^{137}$Cs concentration in the profile that correlates to 1953, the year of the beginning of $^{137}$Cs fallout.

On January 3, 2006 recent sediment accretion due to hurricanes Katrina and Rita was measured at sites both north and south of the railroad from Bayou Labranche to the Pipeline Canal (Fig. 3). Cores were collected using 2-cm diameter piston corer to measure the depth of the unconsolidated root-free sediment layer due to hurricane sediment deposition. The upper recently deposited material readily separated from the lower part of the core that contained roots. We then measured the depth of this recently deposited material by gently pushing a thin metal ruler into the upper unconsolidated sediment until penetration was stopped by the underlying sediments that contained roots. This depth was measured at 55 sites north of the railroad and 50 sites south of the railroad. Several additional cores were collected using the piston corer to check against the measurements using the ruler and all gave the same results using the ruler.
3.5. Tree cores

Two cores were collected from each of 10–12 baldcypress trees at each of three sites in the LB wetlands and two sites in the adjacent BC spillway between January and March 2009 (TC1–5; Fig. 3). Sampled trees were in dominant or co-dominant crown positions, so that climatic and soil variations most likely affected tree ring variations more than did competition from neighboring trees. Trees from each area were growing in the same stand, so that a stand-scale estimate of annual growth variations was obtained. Cores were taken with a 5-mm diameter increment borer above the buttress base to avoid distorted rings. The cores were dried, glued to wooden mounts, and sanded using progressively finer sandpaper to 600-grit, so that individual cells were visible under the microscope at 10–100× magnification. Ring widths were then measured using a Velmx sliding stage (model A60, Bloomfield, New York) and recorded to the nearest 0.001 mm. The cores were crossdated to assign correct calendar year to each ring and to identify missing rings and then the crossdating was verified using the standard dendrochronological software COFECHA (Holmes, 1983; Grissino-Mayer, 2001).

ARSTAN (Cook, 1985) was used to create tree ring chronologies for each site (mean growth index 1.0), using only negative exponential detrending to account for age effects on ring width but to allow other long-term trends in growth (such as periods of poor or good growth) to remain. Correlations of tree growth to weather (data from the NOAA National Climate Data Center) and salinity in Lake Pontchartrain at Pass Manchac also were calculated using SAS. Surface water salinity was collected from the EPA STORE database (http://www.epa.gov/storpub/legacy/gateway.htm) for Pass Manchac in Lake Pontchartrain from January 1951 through April 1998. Palmer Drought Severity Index data (PDSI) were obtained from the National Climate Data Center (NOAA, 2010). PDSI is a meteorological drought index that is calculated based on precipitation, temperature, and available soil water content.

4. Results

4.1. LIDAR

The LIDAR image (Fig. 4) showed striking differences in wetland elevation between BC and LB. BC wetland elevations (transect line A–A’) ranging from less than 0 to 2.9 m MSL are higher than elevations (transect line B–B’) in the LB wetlands (ranging from about 0 to almost 1 m MSL), with the exception of the railroad embankment. The low areas in the spillway are due to periodic removal of sediment for fill material while low spots in the LB wetlands are due to subsidence and conversion to open water. It is interesting to note that in the LB transect, areas south of the railroad (average marsh elevation near sea level) are lower in elevation than areas north of the railroad (average marsh elevation about 0.2–0.3 m).

4.2. Accretion

The peak 137Cs distribution, representing 1963/64, was observed in two cores taken from the sites south of the railroad in the LB wetlands (Fig. 5). Based on this distribution, the accretion rate of the LB wetlands south of the railroad between 1953 and 2009 was estimated as approximately 0.43 cm yr⁻¹. Bulk density at these two sites was between 0.20 and 0.30 g cm⁻³ (Table 3), which is typical of highly organic marsh soils receiving little mineral sediment input (DeLaune et al., 1978, 1987). Accretion based on 137Cs profile distribution was much higher at sites north of the railroad, averaging 1.4 cm yr⁻¹ (Fig. 6).

In cores collected from the BC wetlands, the 137Cs activity in core profiles did not have a distinct 1963/64 peak because 137Cs was introduced primarily during spillway openings and 137Cs activity was measured throughout the core. Therefore, sediment was not sampled deep enough to reach a depth where no 137Cs was present (i.e., prior to 1953 when 137Cs first entered the environment; DeLaune et al., 1978). We therefore took deeper cores to determine where 137Cs activity ceased. Based on the profile distribution of 137Cs (assuming that the 140–160 cm depth was near the 1953 marker) we estimate accretion for the two east levee sites in the BC wetlands was approximately 2.6 and 2.7 cm yr⁻¹ (Fig. 7).
Results suggest appreciable sediment was obviously deposited during the openings of the spillway. The BC soil profiles had bulk density of over 1.0 g cm$^{-3}$ (Table 4), which is typical of mineral soils with low organic matter content or a depositional environment with high sediment input. Total $^{137}$Cs inventory in the BC soil profiles were also greater than the LB marsh sites suggesting the deposited riverine sediment was a source of $^{137}$Cs. $^{137}$Cs is readily adsorbed to silt & clay and transported to other sites such as the BC spillway.

Short-term sediment deposition due to hurricanes Katrina and Rita was significantly higher north compared to south of the railroad. Deposition north of the railroad was 4.7 ± 1.8 cm while that south of the railroad was 1.8 ± 1.8 cm.

### 4.3. Tree cores

Tree cores revealed that all sites were logged between approximately 1880–1920 and the majority of the cores are from regrowth since then. The average growth of baldcypress trees at the BC sites was about 2.3 mm ring width per year compared to 1.3 mm ring width per year for trees in LB wetlands (Table 5). Tree height was about 20% less at the LB sites than at the BC sites, even though the trees are approximately the same ages (Table 5).

Despite multiple missing and false rings typical of baldcypress (Ewel and Paredes, 1984), especially when growing under stressful conditions, crosstreeing for three of the five sites was sufficient to meet the stringent standard of less than 10% problem segments required for inclusion in the NOAA International Tree-Ring Data Bank (Table 6). Trees at site TC2 had up to 10 missing rings after 1960 (about 20% missing), so were essentially impossible to crossdate correctly in the period 1960–2008. The resulting ring widths used to estimate growth and corresponding ARSTAN chronologies are shown in Fig. 8.

The environmental variable most highly correlated with tree-ring chronologies was salinity in Lake Pontchartrain (Fig. 9). These correlations are high despite the fact that the measurement site for salinity was about 10–20 km from the sampling sites. The climate variables most correlated with tree-ring chronologies were precipitation and temperature during April and May (Fig. 10). Warm, dry spring weather reduces growth at these sites, but cool, wet spring weather increases growth. May PDSI was the single climatic variable most related to growth (Fig. 11).

### 5. Discussion

#### 5.1. Wetland accretion and elevation

Wetland elevation is directly influenced by a complex relationship between subsidence and accretion (Cahoon et al., 1995; Lane et al., 2006), and the BC spillway serves as an example of how a very large diversion can lead to high rates of accretion and elevation gain. The spillway has been opened eleven times since 1937 (Table 1). There were ten openings of the spillway for flood control (maximum discharge 4500–9000 m$^3$ s$^{-1}$) and a small experimental opening (400 m$^3$ s$^{-1}$) in 1994 (Lane et al., 2001). In addition, leakage through the spillway when river levels are high can deliver up to 300 m$^3$ s$^{-1}$. These openings introduce fresh water, sediment and nutrients into wetlands in the spillway. As sediments are introduced in the spillway, elevation increases as sediments drop out of

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**Table 4** Bulk density of Bonnet Carré sites.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Site 1</th>
<th>Site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–3</td>
<td>0.38</td>
<td>0.35</td>
</tr>
<tr>
<td>3–6</td>
<td>0.38</td>
<td>0.50</td>
</tr>
<tr>
<td>6–9</td>
<td>0.71</td>
<td>0.91</td>
</tr>
<tr>
<td>9–12</td>
<td>0.71</td>
<td>0.93</td>
</tr>
<tr>
<td>12–15</td>
<td>0.90</td>
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</tr>
<tr>
<td>15–18</td>
<td>1.28</td>
<td>1.36</td>
</tr>
<tr>
<td>18–21</td>
<td>1.08</td>
<td>1.29</td>
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<td>21–24</td>
<td>1.51</td>
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<tr>
<td>57–60</td>
<td>1.42</td>
<td>1.63</td>
</tr>
<tr>
<td>60–63</td>
<td>1.63</td>
<td>1.62</td>
</tr>
<tr>
<td>63–66</td>
<td>1.38</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 5** Tree characteristics at the sample sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Area</th>
<th>Trees</th>
<th>Cores</th>
<th>Age (yr)$^a$</th>
<th>Height (m)</th>
<th>Mean ring width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>TC1</td>
<td>LaBranche</td>
<td>10</td>
<td>24</td>
<td>130</td>
<td>190</td>
<td>17</td>
</tr>
<tr>
<td>TC2</td>
<td>LaBranche</td>
<td>11</td>
<td>20</td>
<td>120</td>
<td>130</td>
<td>19</td>
</tr>
<tr>
<td>TC3</td>
<td>LaBranche</td>
<td>12</td>
<td>24</td>
<td>120</td>
<td>130</td>
<td>16</td>
</tr>
<tr>
<td>TC4</td>
<td>Bonnet Carré</td>
<td>11</td>
<td>20</td>
<td>110</td>
<td>140</td>
<td>23</td>
</tr>
<tr>
<td>TC5</td>
<td>Bonnet Carré</td>
<td>11</td>
<td>20</td>
<td>110</td>
<td>140</td>
<td>21</td>
</tr>
</tbody>
</table>

$^a$Estimated from age at coring height and assuming 0.3 m height growth per year.
the water column. For example, sediment elevation near the center of the spillway increased by five to ten feet between 1936 and 1969 (Fig. 12). In the 1994 opening, Lane et al. (2001) reported that about 83% of total suspended sediments introduced from the river were deposited in the spillway. The percentage of sediments retained in the spillway during large flood control diversions is likely considerably less because of the high discharge.

Long-term accretion rates in the BC wetlands (2.6–2.8 cm yr⁻¹) are more than twice the rate necessary to keep pace with current relative sea-level rise (RSLR), the combination of subsidence plus eustatic sea level rise. RSLR is ≥1 cm yr⁻¹ in many areas of the Mississippi River delta (Day et al., 2007). The IPCC (2007) predicted an increase in eustatic sea level rise of about 40 cm and some projections are as high as one meter or more (i.e., Vermeer and Rahmstorf, 2009). The accretion rates measured in the BC Spillway can keep up with even these high rates (see also Coleman et al., 1998; Day et al., 2005). In contrast, accretion rates in the LB wetlands south of the railroad (0.36–0.40 cm yr⁻¹) are less than half of what is necessary to keep pace with current RSLR. Accretion rates in LB north of the railroad are sufficient to survive current RSLR but not predicted RSLR by 2100, which is 1.5–2.0 m based on the sea level projections cited above. Lane et al. (2006) reported that elevation gains at marsh sites at two smaller diversions were sufficient to offset local RSLR, as is also the case for the Atchafalaya Delta (Shaffer et al., 1992). Blum and Roberts (2009) predicted most coastal wetlands in the Mississippi delta will disappear by 2100 as a result of subsidence, eustatic sea-level rise, and reduced sediment load in the Mississippi River. The accretion rates measured in the spillway show that very large but infrequent diversions of river water will lead to accretion sufficient to keep up with predicted relative sea level rise.

Accretion was lower south of the railroad, indicating that the railroad acts as a barrier to water flow to wetlands to the south and this contributes to sediment deficits in this area. The seven openings under the railroad through which water can exchange have a total width of about 127 m and a cross section area of only about 150 m². The length of the railroad running through the LB wetlands is about 10,400 m. Thus, much of the water exchange is restricted to openings that total about 1% of the previous exchange area. The differences in sediment deposition south and north of the railroad during hurricanes Katrina and Rita also demonstrate the impact of the barrier formed by the railroad.

5.2. Forested wetlands

Baldcypress trees in the BC wetlands grew almost twice as fast as in the LB wetlands. By looking at cross-dated tree ring data it is possible to gain an understanding of fluctuations in growth of trees in the two sites (Fig. 11). Several milestone years in the history of growth in these sites have been accompanied by unusual spring weather. The 1963 spring drought, for example, occurred at the onset of the poor growth period of the 1960s. This period of poor growth also was correlated with the opening of the MRGO shipping channel that increased salinity levels in Lake Pontchartrain (Shaffer et al., 2009b). Other spring droughts occurred in 1999, 2000, 2001, and 2006, coinciding with periods of reduced tree growth in both areas (Fig. 11 bottom). High production years occurred in conjunction with cool, wet weather in the spring of 1919, 1939, 1961, 1991–1993, and 2005. Although it may not be intuitive that trees growing in wetlands grow better in rainy weather, this relationship has been found for baldcypress elsewhere in Louisiana (Keim and Amos, 2012), as well as in North Carolina (Stahle and Cleaveland, 1992), Arkansas (Cleaveland, 2000), and Mississippi because rain and flowing water increase oxygen to the root zone when compared to stagnant water (Davidson et al., 2006) and may increase nutrient loading from non-point source runoff (Shaffer et al., 2009a).

Long-term growth records from tree rings provide information to help understand the long-term implications of subsidence, increased flooding (Keeland and Young, 1997; Keim and
Amos, 2012), and saltwater intrusion on forested wetlands and to quantify the potential effects of river diversions. Subsidence can prolong flooding in wetlands and, when flooded by salt water, may intensify salt stress. Although there has been extensive research conducted to understand how forested wetlands respond to these stressors (e.g., Conner and Day, 1988; Conner and Day, 1992; Allen et al., 1996; Hoeppner et al., 2008; Shaffer et al., 2009a), few studies have combined productivity data with historical records of soil accretion and tree rings.

The openings of the BC spillway in 1937, 1945, 1950, 1973, 1975, 1979, 1983, 1997, and 2008 coincided with years of good growth in both the BC and LB sites (Fig. 11). Most of these openings occurred during times of wet weather. Fresh water from rainfall and from the spillway combats saltwater intrusion and the deposition of sediments during spillway openings counteracts subsidence so the BC wetlands are not as subject to saline intrusion and drain better than the LB sites. Even if the BC sites are inundated with salt water during storm surges, the generally higher elevations and frequent freshwater input appear to prevent retention of salinity for extended periods.

The combination of dry spring weather, drought, and hurricanes caused an extended period of poor growth in the 1960s and early 1970s in both the BC and LB wetlands (Figs. 8 and 11). As mentioned above, the opening of the MRGO in 1963 increased salinity in Lake Pontchartrain, which contributed to the growth declines in the LB wetlands at that time (Shaffer et al., 2009b). It increased salinities in wetlands as remote as the Manchac/Maurepas Swamp (Shaffer et al., 2009a). Similarly, the drought of 1998–2001 was responsible for the most recent period of poor growth. This drought also caused the mortality of a large number of baldcypress in the LB wetlands. Hurricane Katrina also acted in concert with a drought in 2006 to cause another period of poor growth, most likely due to saltwater intrusion.

Degradation of baldcypress—water tupelo swamps at the LB wetlands is not a unique phenomenon in coastal Louisiana (Keim et al., 2006). Declines have been measured in swamps from the edges of Lakes Pontchartrain and Maurepas to the deep interior (Hoeppner et al., 2008; Shaffer et al., 2009a). Reduced freshwater inflows to the Lake since the construction of levees over the past 100–200 years, and lack of accompanying sediment and nutrient additions to the wetlands have resulted in widespread decreases in tree growth and outright loss of wetland forests. For example, large areas of the Manchac land bridge between Lake Pontchartrain and Lake Maurepas were forests in the mid-20th century but today are largely treeless marshes and open water (Barras et al., 1994; Shaffer et al., 2009a).

5.3. Management implications

The health of baldcypress wetlands in the BC Spillway indicates that periodic, large diversions of river water can be effective in maintaining sustainable coastal forested wetlands. All other river diversions constructed thus far are at least one order of magnitude smaller than the BC Spillway and, thus, are inadequate to restore the coast on a large scale (see Day et al., 1999). The spillway delivers river water on both temporal and spatial scales that mimic historic crevasses along the river (Davis, 2000). Our research shows that a large-scale diversion would most likely benefit the LB wetlands and lead to sustainable management of the area.

Fig. 10. Correlation coefficient (r) between monthly climate variables and tree-ring chronologies from January of the year prior to ring formation through August of the year of ring formation.

Fig. 11. Time series of May PDSI superimposed on tree-ring chronologies.
Accretion rates in the LB wetlands compared to the BC wetlands show the effect of isolation of the area from the river while rates in the spillway demonstrate the effectiveness of periodic high riverine input. Although the spillway was opened only about once a decade, accretion in the BC wetlands is almost an order of magnitude higher than in the LB wetlands south of the railroad. Some areas of the BC wetlands are nearly two meters above sea level. This is sufficient to offset the highest predictions of sea-level rise for the 21st century. By contrast, large areas of the LB wetlands are near sea level. In addition, baldcypress production is much greater in the BC wetlands. Baldcypress in the LB wetlands are slowly dying out due to periodic intrusions of salt water during droughts, excessive flooding, and lack of recruitment.

Long-term restoration of the LB wetlands will require the reintroduction of Mississippi River water if the wetlands are to be sustainable into the next century. One possible location for a diversion is in the southeast corner of the wetlands because water would flow over most of the wetland before reaching Bayou LaBranche, the major conduit for water exchange between the north and south portions of the wetland. Water control structures in the openings under the railroad could be used to manage flow both south and north of the railroad. Pierce et al. (1985) also proposed a river diversion for the LB wetlands.

In summary, the BC Spillway serves as an example of the size of a river diversion that can maintain and build wetlands while the LB wetlands demonstrate the effects of hydrologic isolation and saltwater intrusion. Without large diversions such as the Bonnet Carré, we believe that there is little hope for successful restoration of the delta, especially with massive wetland losses projected as eustatic sea levels continue to rise (i.e., Blum and Roberts, 2009).

References