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Posthurricane Salinity in an Impounded Coastal Wetland (Bayou Sauvage, Louisiana, U.S.A.)

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ABSTRACT

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Coastal ecosystems can be structured by tropical cyclone disturbances, which interact with coastal management to reduce, magnify, or modify local effects on ecosystems. This research quantified the rate of recovery from salinification by impounded storm surge flooding by Hurricane Katrina at a natural levee ridge forest at Bayou Sauvage, Louisiana. Salinity measurements in soils and nearby pond sediments showed that elevated salinity remained 11 years after the flooding and persisted more at lower elevations. Rain events at the site created runoff of lower salinity relative to standing water, suggesting incomplete mixing and thus slow removal of salt. Recovery rates to prehurricane salinity were estimated to be at least two decades, on the basis of existing salinity, reports of salinity after the hurricane, and data from nearby long-term monitoring stations. The severity and length of storm surge effects have likely been exacerbated by the impounded conditions.

ADDITIONAL INDEX WORDS: *Hurricane Katrina, bottomland hardwoods, forested wetland.*

INTRODUCTION

Coastal ecosystems subject to disturbance by tropical cyclones can be structured by these large, infrequent events consisting mainly of wind and flooding. Cyclone winds affect broad coastal and inland areas (Stanturf, Goodrick, and Outcalt, 2007) and rapidly move forests to new successional states (Battaglia, Sharitz, and Minchin, 1999), but effects are generally similar to other disturbances, such as other wind events, logging, or pests (Everham and Brokaw, 1996). In contrast, coastal inundation from saline storm surges affects smaller, coastal areas in each storm, but each event has the potential to alter soils and groundwater fundamentally (*e.g.*, Williams, 1993) and is a much more pervasive disturbance with longer term consequences for ecosystems (Herbert *et al*., 2015).

Disturbance by coastal processes interacts with coastal management to reduce, magnify, or modify local effects on ecosystems. Management of coastal wetlands is particularly susceptible to producing unintended consequences in this regard, especially when water management structures are overwhelmed by storms. Impounded wetlands may retain saline surge water and salts for an extended period after storm passage, whereas wetlands retaining natural flow paths can drain quickly and experience much lower long-term salt loading (Conner *et al*. 1989).

One such impounded coastal wetland is Bayou Sauvage National Wildlife Refuge (BSNWR), the majority of which lies within the city limits and flood control levee system of the city of New Orleans, Louisiana, and which experienced dramatic changes as a result of inundation by storm surge from Hurricane Katrina in 2005. Before agricultural and urban development beginning in the 18th century, the area now designated as BSNWR was composed mainly of fresh and brackish marshes and swamp forests, except for a bottomland hardwood forest occupying the Bayou Sauvage distributary ridge (Penfound and Howard, 1940; Wall and Darwin, 1999; White and Skojac, 2002). Failure of levees surrounding BSNWR during Hurricane Katrina (Link, 2010) resulted in flooding with surface water salinity $\geq$17 ppt that persisted for 4 weeks (USFWS, 2009). This resulted in 68% mortality (Howard, 2012) of the forest occupying the natural levee of Bayou Sauvage and caused the forest to convert to a thicket of early successional shrub and invasive tree species.

Some remnant salinity from Hurricane Katrina remains in BSNWR. USFWS (2009) reported salinity 5 ppt in surface water, which is sufficient to prevent re-establishment of prehurricane vegetation communities. Of the previously existing forest on the distributary ridge, live oak (*Quercus virginiana*) is one of the few bottomland hardwood species that has persisted. Today, mostly salt-tolerant species persist, such as eastern baccharis (*Baccharis halimifolia*), palmetto (*Sabal minor*), and invasive Chinese tallow (*Triadica sebifera*), which have all expanded throughout BSNWR (Howard, 2012). Pre-event soil salinity is not known, but was likely $<$0.5 ppt, given that the species composition was similar to inland floodplain forests, and coastal forests of the region show the effects of salt at $<$0.7 ppt (Krauss *et al*., 2009).

The general objectives for this work are to quantify the rate of recovery from salinification, mainly on the ridge and marsh areas of the refuge, and to assess the potential for reforestation on the ridge in BSNWR. Specifically, this research was to measure the current salinity in soils of the distributary ridge and adjacent Blind Lagoon marsh and to use these data in conjunction with longer term monitoring data in nearby

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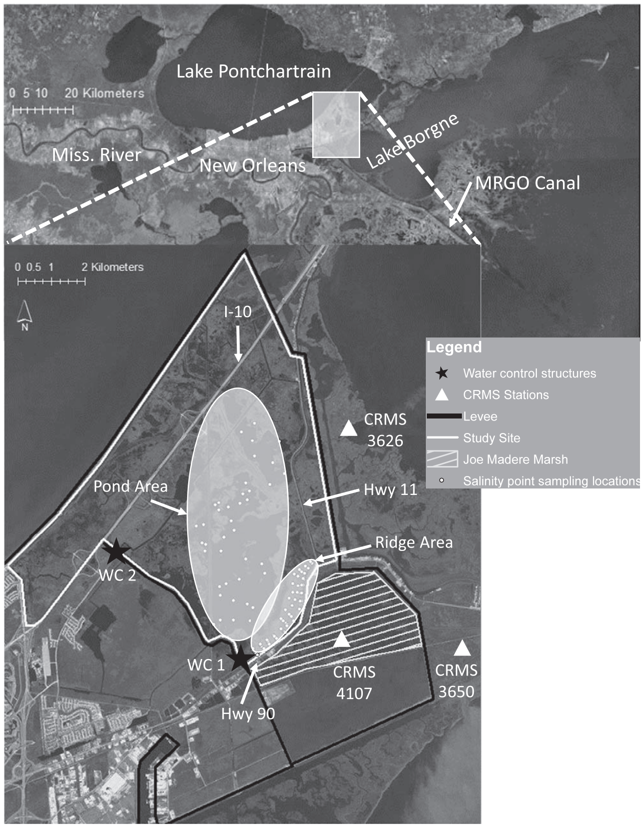

Figure 1. Area map of Bayou Sauvage, Louisiana.

wetlands and estimates of Katrina salt loads to model the recovery rates and long-term trajectory of salinity.

METHODS

The land cover of the study area is mostly intermediate-salinity marsh and open water with a small portion of deciduous forest wetland along the levee ridge. The forested ridge is about 1 m higher in elevation and gradually slopes into lower elevation intermediate marsh and open water. The boundaries of BSNWR are mainly composed of water-excluding structures. The eastern boundary is the New Orleans flood control levee and U.S. Highway 11. Two structures on the flood control levee that allow for movement of water are generally closed, supporting the assumption of no flow across this boundary. The SE boundary of the study area is the southern natural levee of Bayou Sauvage, which is also the location of U.S. Highway 90. No surface channels breach that natural levee, supporting the assumption of no flow across this boundary. The SW boundary of the study area is formed by the spoil bank of Maxent Canal, which is a part of the New Orleans stormwater drainage system. In two connections between the study area and Maxent Canal, this project installed water and salinity monitoring stations (WC 1, WC 2) (Figure 1). The NW boundary of the study area is formed by flood control levees that prevent exchange with Lake Pontchartrain. The choice to install monitoring equipment only along the SW boundary was made because these points are the most hydrologically connected to the forested ridge of interest, and they serve as the primary exit points for the entire area (USFWS, 2009).

Monitoring Salinity and Water Levels

Vented pressure transducer water level probes and data loggers (*in situ* Level Troll 500) were installed at the two main water control structures of the study unit (Figure 1). Each was mounted in a perforated 3-m polyvinyl chloride pipe section secured to each water control structure, and probe elevations referenced each water control structure. The probes recorded pressure head, temperature, and specific conductivity. Data were collected beginning June 2016 and lasted through September 2017.

Mapping Salinities

In January 2016, soil salinity was measured on the natural levee ridge forest and its surrounding waterbodies and wetlands. The combined total from all surveys was 181 soil samples.

One set of soil samples was collected along the ridge that runs parallel to the bayou. Fifteen transects ~400–600 m apart were established along the ridge, with four points per transect taken near the bayou, on the ridge on the side of the bayou, on the ridge on the side of the marsh, and close to the marsh at the back of the ridge. Samples were collected with a soil push tube at two depths: 30 and 60 cm.

Another set of samples was taken in three connecting marshes NW of the Bayou Sauvage Ridge in Blind Lagoon. Points were taken ~400–800 m apart from an airboat. At each location, a standard Ekman sediment sampler was used to collect a sample of surface sediments (~5–10 cm in depth), and a water quality meter (YSI EC300) was used to determine the water conductivity (as a proxy for salinity) at the time of collection. Water depth was not recorded, in part because the water bottom was an ill-defined transition between water and mucky sediments, but all sediment samples were obtained from about 0.5–1.0 m below the water surface.

In the laboratory, all soil samples were dried in a drying oven at 60°C for 3 days then finely ground using a mortar and pestle so that no aggregates were larger than 2 mm. One part soil subsample (20 g) and five parts deionized water (100 mL) were combined in a crucible. Samples were shaken for 3 minutes and left to settle for 1 minute, then the cycle was repeated three times and poured into a graduated cylinder. Electrical conductivity (corrected to 25°C) was then measured for each sample by a water quality meter (YSI EC300) to determine the salinity of this 1:5 slurry, $EC_{1:5}$. The $EC_{1:5}$ is an index of soil salinity, but it is highly diluted, so all values were converted to EC_e (electrical conductivity of saturated soil paste; dS/m) by multiplying a textural conversion of 8.6 for clay loam (Hardie and Doyle, 2012). These values were subsequently converted to salinity (ppt) by the standard conversion of Lewis and Perkin (1978) for salinity >2 ppt and the correction of Hill, Dauphinee, and Woods (1986) for salinity <2 ppt.

Analysis of Hurricane Flooding and the Salt Budget

Estimates of salt input to BSNWR, in combination with present salinity in soils and runoff, supported estimates of time to recovery from salt contamination. According to evaporation lines on trees in BSNWR, Howard (2012) estimated that inundation from hurricane surge water was 0.05–0.67 m, depending on their elevation on the ridge. This depth is slightly less than shorter term estimates obtained by other data. After levee failure in Katrina, water levels inside the New Orleans levee system equalized with Lake Pontchartrain, which remained higher than sea level for several days. Four days after the storm, this water level was 0.72 m (Gesch, 2007), which is sufficient to inundate the Bayou Sauvage ridge by 0.28–0.97 m according to elevations obtained by LIDAR by the Louisiana Oil Spill Coordinator's Office in 1999 (ArcGIS REST Services Directory, 1999). Floodwater remained for about 4 weeks (USFWS, 2009), giving salts ample time to diffuse into soils.

The salt content of soils after flooding by Hurricane Katrina is not known, but some likely scenarios from data collected nearby supported estimates of rates of recovery. Heitmuller and Perez (2007) reported post-Katrina salinity of Lake Pontchartrain to be 7.0 ppt, which is one reasonable estimate for BSNWR given high connectivity to the lake through breached levees after the storm. However, another reasonable estimate is that posthurricane soil salinity matched those reported by Doyle *et al*. (2007), who found pore water salinity of coastal forests increased to only ~3 ppt when inundated temporarily by a storm surge of 12 ppt—presumably because of dilution with pre-event water in soils. A final reasonable estimate of posthurricane soil salinity is that it matched local reports of surface water salinity between 17 and "high 20s" ppt (USFWS, 2009). Generally impounded hydrology and salt rings on trees (Howard, 2012) suggest long residence of salty floodwater and possible evaporative concentration.

This research compared measured salinity data and historical estimates to data from nearby marshes collected by the Louisiana Coastwide Reference Monitoring System (Folse *et al*., 2014). Specifically, this research used data from station 4107, which is in Joe Madere Marsh within BSNWR but south of the Bayou Sauvage ridge and out of the study area, and stations 3626 and 3650, both of which are outside the New Orleans flood control levee but near the study area (Figure 1).

To estimate the recovery rate of salinity in soils of the Bayou Sauvage ridge forest and adjacent marsh, this research first used salinity data from the nearby CRMS data in Joe Madere Marsh to parameterize a gamma distribution representing the expected time-dependent decay of salinity (S) after the slug addition from Hurricane Katrina at time $t = 0$ years:

$$S(t) = \frac{t^{a-1} e^{-\frac{t}{b}}}{b^{a} \Gamma(a)} \tag{1}$$

where, $\Gamma(\ )$ is the gamma function and a and b are fitted parameters. The gamma distribution has been found to be generally applicable for describing the residence time of contaminants in watersheds and is characterized by a "heavy tail" in which decay of contaminant concentrations in the watershed (in this case, the BSNWR) is rapid at first and then slower as time progresses (Kirchner, Feng, and Neal, 2000). The mean residence time in the watershed is given by $a \times b$. This research used numerical optimization to find the best values of a and b to fit the observed data; then, it used the model fit, in conjunction with salinity data, to infer the timescale of recovery for the soils of the ridge forest and marsh sediments.

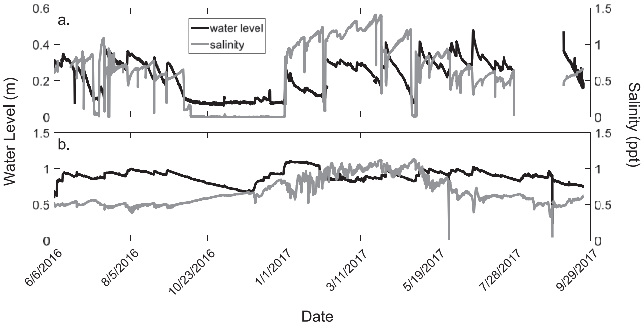

Figure 2. Water level and salinity recorded at locations (a) WC 1 and (b) WC 2. The location of each site is shown in Figure 1.

RESULTS

Water level in BSNWR was quite stable, varying by less than ~0.4 m in the 15 months of monitoring (Figure 2). Water level responded to precipitation events, and progressive declines of water level occurred between events. There were no seasonal trends in water level during the initial monitoring period. Instead, some longer timescale fluctuations occurred in response to manipulating the water control structures.

Similar to water level, salinity in BSNWR outflow water was also quite stable, varying by less than 1.5 ppt throughout the 15 months of monitoring (Figure 2). Salinity was also responsive to precipitation events: rainfall (inferred by rapid increases in water level) caused short periods of low-salinity water at the outflow structures, but salinity returned to pre-event concentrations rapidly. Thereafter, salinity slowly increased until the next precipitation event. Salinity was higher in the Bayou Sauvage outflow (WC 1) than at the western outflow (WC 2) by up to 0.4 ppt. A seasonal increase in salinity during the spring by ~0.5 ppt occurred at both monitoring locations. Correlation between salinity and water level was complicated by unrecorded manipulation of the water control structures, but generally there appears to be no correlation, except in immediate response to rainfall.

Mean soil salinity in the forested ridge along Bayou Sauvage in January 2016 was 1.3 ppt at 30 cm depth and 2.1 ppt at 60 cm depth (Figure 3). The spatial variability of soil salinity did not have an obvious pattern lengthwise along the ridge. However, samples taken adjacent to Bayou Sauvage (mean 2.4 ppt) or low elevations at the marsh side of the ridge (mean 1.8 ppt) showed a strong pattern of higher salinity, with lower salinity on the higher elevation, central portions of the ridge (mean 0.9 and 1.5 ppt at the highest and second-highest locations, respectively) (Figure 4).

Salinity in pond bottom sediments was much higher (mean 8.2 ppt) than in the soils of the forested ridge (mean 1.7 ppt) (Figure 5). The spatial variability of salinity in pond sediments had no discernable pattern, which is consistent with field observations of high variability in the mineral and organic content and density of the soil samples while sampling. Salinity

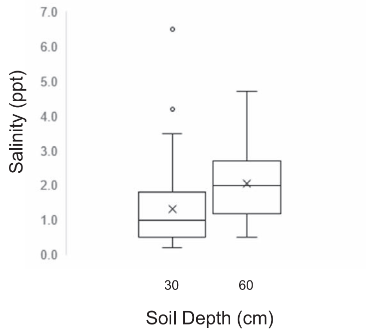

Figure 3. Soil salinity measured in January 2016 in forested ridge soils at two depths, pooled across all transect locations.

of sediments was substantially higher than the water in the ponds; during the field survey, mean water salinity was 1.1 ppt, and with low spatial variability (minimum 0.7 ppt and maximum 1.2 ppt).

Salinity in the upper 30 cm of marsh soils at three nearby Louisiana CRMS monitoring stations revealed long-term trends of declining salinity after their establishment in September 2007 (2 y after Hurricane Katrina). Salinity in 2007 was $\sim$9–12 ppt at these stations, and it is now $\sim$1–4 ppt (Figure 6). Salinity at the stations outside the flood levee was initially lower than inside the levee at the Joe Madere Marsh monitoring station (4107) by up to $\sim$2 ppt, but differences in salinity among the three stations are now small. Seasonal fluctuations in salinity of the marshes outside the levees are likely related to tidal and water circulation patterns shared by the two stations outside the levee, but temporal variability in salinity at the Joe Madere Marsh station is not coherent with the other stations.

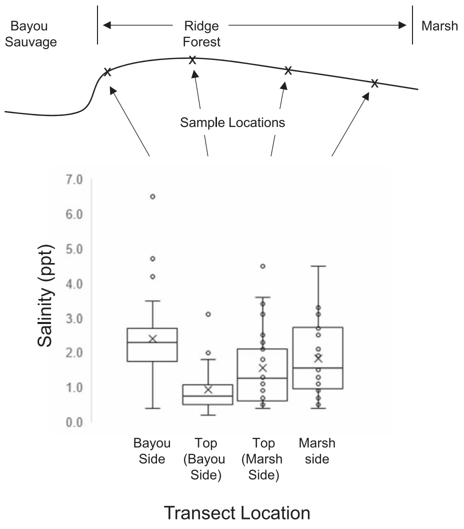

Figure 4. Soil salinity measured in January 2016 in forested ridge soils by transect location, pooled across two sampling depths.

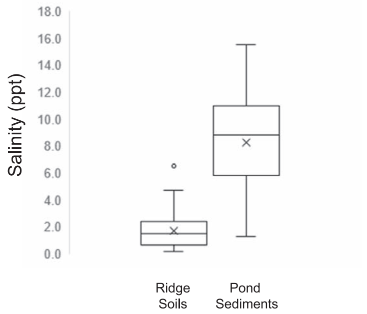

Figure 5. Ridge soil and pond sediment salinity, pooled across all samples within sites.

The best-fit gamma distribution to describe the temporal decay of salinity at the Joe Madere Marsh CRMS station (4107) after Hurricane Katrina was $a = 0.87$ and $b = 8.28$, indicating a mean residence of time 7.2 years, and suggests the initial concentration at the site was $\sim$20 ppt and that the concentra-

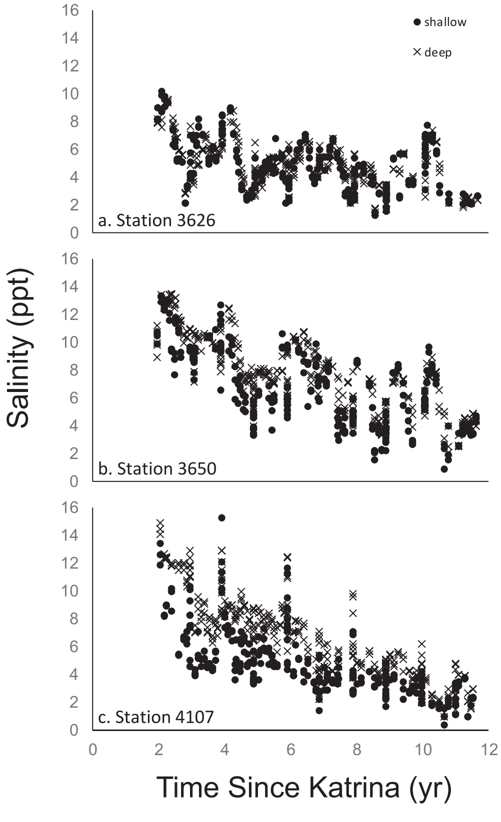

Figure 6. Salinity at three monitoring stations from the Louisiana Coastwide Reference Monitoring System used for comparison with the monitoring sites of this study. The location of each site is shown in Figure 1; stations (a) 3626 and (b) 3650 are outside the flood control levee and (c) station 4107 is inside the levee in Joe Madere Marsh. Each panel shows salinity data measured in shallow (10 cm) and deep (30 cm) soil pore water. Data span the dates September 2007–April 2017.

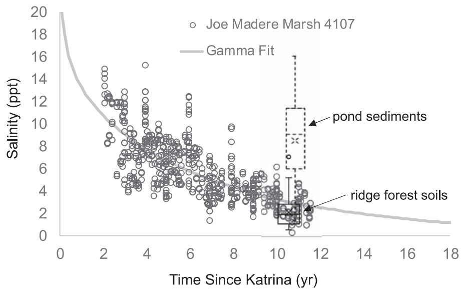

Figure 7. Best fit gamma model of salinity decline in Joe Madere Marsh after Hurricane Katrina in August 2005, with pooled Bayou Sauvage ridge forest soils and pond sediment samples superimposed.

tion will decline to 1 ppt by ∼19 years after the input and 0.5 ppt by ∼25 years after the input (*i.e.* by 2024 and 2030, respectively) (Figure 7). Salinity in the upper 30 cm of Joe Madere Marsh sediments is currently about the same as the soils in the forested ridge (∼2.5 ppt *vs*. 1.7 ppt, respectively) but is substantially less than the pond bottom sediments NW of the Bayou Sauvage ridge (∼2.5 ppt *vs*. 8.2 ppt).

DISCUSSION

The results of monitoring indicate that the general hydrology of the impounded BSNWR is characterized by rapid runoff after precipitation, with incomplete mixing between precipitation and pre-event water that is higher in salinity. A large residual reservoir of salt is apparent in pond sediments and, to a lesser extent, the lower soil column in the ridge forest.

The favorable hydraulic gradient of higher elevation areas forces infiltrating precipitation to come into contact with more saline soils, causing flushing during rain events by diffusion and mass transport. This contrasts with the situation in pond sediments, where fresh precipitation may remain at the surface, stratified above the denser, more saline water close to the sediment surface. The only mechanism for salt to be flushed from these sediments in that case is through diffusion and wind-induced turbulent mixing. These are slower pathways for salt removal than flushing, which probably at least partially explains the large difference between pond and ridge salinities.

The reason for higher salinity in deeper sediments with longer residence times is not clear. Some salinity may predate the levee system (from ∼1940s), and some may have later, nonhurricane origins. Before Hurricane Katrina, BSNWR was occasionally intentionally flooded by pumped water from Lake Pontchartrain during times of drought in an effort to prevent surface subsidence caused by desiccation and subsequent oxidation and compaction of organic soils (USFWS, 2009), as has happened in the adjacent drained land inside the levees (Jones *et al*., 2016). Thus, the spatial analysis of soil salinities suggests that higher elevation areas are recovering more rapidly than lower lying areas (Figure 4) if the majority of salinity originated in Hurricane Katrina, but that conclusion may not be correct if salinities in the pond and deeper sediments were higher before the storm, as well.

On the basis of multiple lines of evidence, it appears that salinity in the ridge forest soils was likely near 20 ppt at the cessation of flooding after Hurricane Katrina. First, the data and statistically derived estimate of 20 ppt initially in Joe Madere Marsh matches this high-case scenario and is completely independent of on-site estimates of 17 to “high 20s” ppt observed after the storm. Before Hurricane Katrina, the region was in a drought period that reduced local water tables and soil moisture, which reduced dilution and likely increased infiltration further into the soil. This condition is in contrast to the alternative case described by Doyle *et al*. (2007), wherein hurricane flood water had little effect on wet soils, probably because pore spaces were already occupied by fresher water. Related to this phenomenon is the final condition that makes high post-Katrina soil salinity more likely than low salinity; that is, storm surge flooding was retained in BSNWR for several days, or even weeks, during a time in which rainfall was low. This long residence time would have allowed for more complete mixing between event and pre-event waters by diffusion, so that salinity would likely increase even in previously saturated portions of the lower soil profile.

The Joe Madere Marsh monitoring (CRMS) site and the two similar stations outside of the New Orleans flood control system all showed similar declines in salinity over the 10 years after Hurricane Katrina. The stations outside of the levee experienced some spikes in salinity, which most likely represent either anomalous high tides or short drought events, that were not shared with the station inside the levee. The similarity in post-Katrina soil salinities among all stations would not have been expected according to previous work (*e.g*., Conner *et al.,* 1989) that found slower recovery for impounded areas subjected to storm surge compared with areas that were allowed to drain naturally. However Joe Madere marsh had slightly higher salinity compared with the two stations outside of the levee at the beginning of monitoring 2 years after the storm, which would not be expected because of decades of no connection to salt water. The apparently similar declines in salinity for sites both inside and outside the levee system may be explained by slightly different reasons: slow dilution from rainfall and regional declines in salinity, respectively. An important factor is likely the 2009 closure of the Mississippi River Gulf Outlet canal, which was a long-term source of salinity to the wetlands in the region of the BSNWR and has reduced salinity by 20% in Lake Borgne and eastern Lake Pontchartrain in the region of this research (van den Heuvel, 2010).

The pore water salinity of the upper sediments of Joe Madere Marsh are substantially lower than the measured salinity of shallow pond sediments (∼2.5 *vs*. 8.2 ppt). The majority of the Joe Madere Marsh surface is higher in elevation than the submerged areas sampled in the study pond area, which may explain some of the difference in pore water salinities between the two sites. However the discrepancy may be also related to the method of measuring “pore water salinity” by the paste method, which requires the use of an uncalibrated conversion factor. Regardless of the absolute differences in salinities between the two areas, however, the overall temporal trend at Joe Madere Marsh likely is representative of the ridge and pond sites because of similar hydrological conditions.

The severe effects of flooding on vegetation cover at the BSNWR are in stark contrast to the less severe effects of wind from tropical cyclones on coastal forest. Although salinity influx was the cause, the impounding of that salinity inside flood control structures appears to have played a strong role in the response of vegetation after the hurricane. The deviation in vegetative vigor after the storm was more pronounced for a longer period of time in BSNWR than it was in nearby wetlands, which are not impounded (Steyer, Couvillion, and Barras, 2013). Also, the duration of the disturbance was increased by the impoundment. At an impounded site in Germany similar to BSNWR that also received a slug of salinity influx from a storm, Selle *et al*. (2016) estimated a similarly long recovery period (>10 y) because of slow rates of flushing.

Estimating the salinity necessary for eventual recovery of ridge forest composition to that before Hurricane Katrina depends on soil and plant characteristics that are not fully understood. For example, live oak and sugarberry (*Celtis laevigata*) are partially tolerant to soil salinity of 2 ppt, but 2 ppt kills winged elm (*Ulmus alata*) and sweetgum (*Liquidambar styraciflua*) (Williams, Meads, and Sauerbrey, 1998) and at least damages seedlings of many bottomland oak species (Conner, McLeod, and McCarron, 1998). The presence of these less tolerant species before the hurricane suggests that pre-Katrina soil salinity was likely <1 ppt.

Salinity itself may not be the only or even the primary cause of tree mortality and ecosystem change in the natural levee, because seawater leads to other biogeochemical changes in soils. Specifically, sulfur in seawater can create toxic conditions. For example, Hackney and Avery (2015) found that sulfates are responsible for delimiting the edge of coastal forests in the Cape Fear Estuary in North Carolina. Although sulfur is unlikely to be in toxic form in the upper, oxidized portion of the soil profile on the natural levee, more toxic forms may be in the lower profile but still within the root zone of trees.

Soil characteristics likely play a role in determining the salinity threshold below which tree species can survive and the interpretation of salinity recovery after Hurricane Katrina. Data from this research show that pond sediments were highly variable, with some areas <2 ppt and other areas nearing the inferred post-Katrina salinity of ~20 ppt (Figure 5). The reasons for this variability are not known but may be related to varying soil properties such as organic matter. For example, organic matter was 55% ± 21% (SD) in a subsample of pond sediments. Also, salinity in the soil samples on the ridge was 1.4 ± 1.2 ppt in the shallow (30-cm) samples and 2.1 ± 1.1 ppt in the deep (60-cm) samples. Such large spatial variabilities can result in hotspots of high salinity that prevent or retard tree growth despite average salinity values that may be conducive for bottomland hardwoods. Although the exact mechanisms driving salinity spatial variability at BSNWR are unknown, transport of salinity may occur to create high salinities in areas once thought to be conducive for bottomland hardwood growth over time. For instance, the large temporal scatter in salinity taken at the Joe Madere marsh CRMS site (Figure 6) may have been caused by redistribution of high-salinity sediment pockets.

The Bayou Sauvage ridge forest could return to a pre-Katrina forest composition common along elevated ridges adjacent to degrading marsh in coastal Louisiana. This forest type is composed of species such as live oak, sugarberry, American elm (*Ulmus americana*), and common persimmon (*Diospyros virginiana*) in the canopy and deciduous holly (*Ilex decidua*) and hawthorn (*Crataegus* spp.) in the understory (Howard, 2012). However, return to this composition will be contingent on the management of the high abundance of invasive Chinese tallow. This species has higher salinity tolerance than most native species and has been reported to take over areas before storm surge flooding events (Howard, 2012; Neyland and Meyer, 1997). Management of this species and other native shrubs, such as rattlebox (*Sesbania drummondii*) and buttonbush (*Cephalanthus occidentalis*), that had success colonizing the ridge before Katrina will be important for reestablishing a pre-Katrina forest composition.

CONCLUSIONS

The saline storm surge flooding resulted in salinification of wetlands at Bayou Sauvage, Louisiana, because of impounding by flood control levees. Eleven years after the flooding, some parts of the formerly freshwater bottomland hardwood forest on the natural levee of Bayou Sauvage were still too saline to support species from the former community, and full recovery to prestorm salinity appears likely to require more than two decades. The impounded conditions at this site appear to have exacerbated the hurricane disturbance and caused greater shifts in the ecosystem than it would had the wetland still been connected to former drainage paths.

LITERATURE CITED

ArcGIS REST Services Directory, 1999. https://atlas1.ga.lsu.edu/arcgis/rest/services/elevation.

Battaglia, L.L.; Sharitz, R.R., and Minchin, P.R., 1999. Patterns of seedling and overstory composition along a gradient of hurricane disturbance in an old-growth bottomland hardwood community. *Canadian Journal of Forest Research*, 29(1), 144–156.

Conner, W.H.; Day, J.W., Jr.; Baumann, R.H., and Randall, J.M., 1989. Influence of hurricanes on coastal ecosystems along the northern Gulf of Mexico. *Wetlands Ecology and Management*, 1(1), 45–56.

Conner, W.H.; McLeod, K.W., and McCarron, J.K., 1998. Survival and growth of seedlings of four bottomland oak species in response to increases in flooding and salinity. *Forest Science,* 44(4), 618–624.

Doyle, T.W.; Conner, W.H.; Day, R.H.; Krauss, K.W., and Swarzenski, C.M., 2007. Wind damage and salinity effects of hurricanes Katrina and Rita on coastal baldcypress forests of Louisiana. *In:* Farris, G.S.; Smith, G.J.; Crane, M.P.; Demas, C.R.; Robbins, L.L., and Lavoie, D.L. (eds.), *Science and the Storms: The USGS Response to the Hurricanes of 2005*. Reston, Virginia: U.S. Geological Survey, *Circular 1306*, pp. 163–168.

Everham, E.M., III and Brokaw, N.V.L., 1996. Forest damage and recovery from catastrophic wind. *Botanical Review*, 62(2), 113–185.

Folse, T.M.; Sharp, L.A.; West, J.L.; Hymel, M.K.; Troutman, J.P.; McGinnis, T.E.; Weifenbach, D.; Boshart, W.M.; Rodrigue, L.B.; Richardi, D.C.; Wood, W.B., and Miller, C.M., 2014. *A Standard Operating Procedures Manual for the Coastwide Reference Monitoring System—Wetlands: Methods for Site Establishment, Data Collection, and Quality Assurance/Quality Control*. Baton Rouge, Louisiana: Louisiana Coastal Protection and Restoration Authority, 228p.

Gesch, D., 2007. Topography-based analysis of Hurricane Katrina inundation of New Orleans. *In:* Farris, G.S.; Smith, G.J.; Crane, M.P.; Demas, C.R.; Robbins, L.L., and Lavoie, D.L. (eds.), *Science and the Storms: The USGS Response to the Hurricanes of 2005*. Reston, Virginia: U.S. Geological Survey, *Circular 1306*, pp. 53–56.

Hackney, C.T. and Avery, G.B., 2015. Tidal wetland community response to varying levels of flooding by saline water. *Wetlands*, 35(2), 227–236.

Hardie, M. and Doyle, R., 2012. Measuring soil salinity. *In:* Shabala, S. and Cuin, T.A. (eds.), *Plant Salt Tolerance: Methods and Protocols*. Methods in Molecular Biology, Volume 913. New York: Springer Science+Business Media, pp. 415–425.

Heitmuller, P.T. and Perez, B.C., 2007. Environmental impact of Hurricane Katrina on Lake Pontchartrain. *In:* Farris, G.S.; Smith, G.J.; Crane, M.P.; Demas, C.R.; Robbins, L.L., and Lavoie, D.L. (eds.), *Science and the Storms: The USGS Response to the Hurricanes of 2005*. Reston, Virginia: U.S. Geological Survey, *Circular 1306*, pp. 231–238.

Herbert, E.R.; Boon, P.; Burgin, A.J.; Neubauer, S.C.; Franklin, R.B.; Ardón, M.; Hopfensperger, K.N.; Lamers, L.P., and Gell, P., 2015. A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. *Ecosphere*, 6(10), 1–43.

Hill, K.D.; Dauphinee, T.M., and Woods, D.J., 1986. The extension of the practical salinity scale 1978 to low salinities. *IEEE Journal of Oceanic Engineering*, 11(1), 109–112.

Howard, J., 2012. Hurricane Katrina impact on a leveed bottomland hardwood forest in Louisiana. *American Midland Naturalist*, 168(1), 56–69.

Jones, C.E.; An, K.; Blom, R.G.; Kent, J.D.; Ivins, E.R., and Bekaert, D., 2016. Anthropogenic and geologic influences on subsidence in the vicinity of New Orleans, Louisiana. *Journal of Geophysical Research Solid Earth*, 121(5), 3867–3887.

Kirchner, J.W.; Feng, X., and Neal, C., 2000. Fractal stream chemistry and its implications for contaminant transport in catchments. *Nature*, 403, 524–527.

Krauss, K.W.; Duberstein, J.A.; Doyle, T.W.; Conner, W.H.; Day, R.H.; Inabinette, L.W., and Whitbeck, J.L., 2009. Site condition, structure, and growth of baldcypress along tidal/non-tidal salinity gradients. *Wetlands*, 29(2), 505–519.

Lewis, E.L. and Perkin, R.G., 1978. Salinity: Its definition and calculation. *Journal of Geophysical Research*, 83(C1), 466–478.

Link, L.E., 2010. The anatomy of a disaster, an overview of Hurricane Katrina and New Orleans. *Ocean Engineering*, 37(1), 4–12.

Neyland, R. and Meyer, H.A., 1997. Species diversity of Louisiana chenier woody vegetation remnants. *Journal of the Torrey Botanical Society*, 124(3), 254–261.

Penfound, W.T. and Howard, J.A., 1940. A phytosociological study of an evergreen oak forest in the vicinity of New Orleans, Louisiana. *American Midland Naturalist*, 23(1), 165–174.

Selle, B.; Graeff, T.; Salzmann, T.; Oswald, S.E.; Walther, M., and Miegel, K., 2016. [Investigation of a renatured fen catchment on the Baltic Sea coast of Mecklenburg—Part II: Salt dynamics and water balance]. *Hydrologie und Wasserbewirtschaftung*, 60(4), 259–268 (in German).

Stanturf, J.A.; Goodrick, S.L., and Outcalt, K.W., 2007. Disturbance and coastal forests: A strategic approach to forest management in hurricane impact zones. *Forest Ecology and Management*, 250(1–2), 119–135.

Steyer, G.D.; Couvillion, B.R., and Barras, J.A., 2013. Monitoring vegetation response to episodic disturbance events by using multitemporal vegetation indices. *In:* Brock, J.C.; Barras, J.A., and Williams, S.J. (eds.), *Understanding and Predicting Change in the Coastal Ecosystems of the Northern Gulf of Mexico. Journal of Coastal Research*, Special Issue No. 63, pp. 118–130.

USFWS (U.S. Fish and Wildlife Service), 2009. *Bayou Sauvage National Wildlife Refuge Comprehensive Conservation Plan*. Atlanta, Georgia: U.S. Fish and Wildlife Service Southeast Region, 158p.

van den Heuvel, S., 2010. Modeling the Hydrodynamics and Salinity of the Pontchartrain Basin. Delft, The Netherlands: Delft University of Technology, Master's thesis, 126p.

Wall, D.P. and Darwin, S.P., 1999. Vegetation and elevational gradients within a bottomland hardwood forest of southeastern Louisiana. *American Midland Naturalist*, 142(1), 17–30.

White, D.A. and Skojac, S.A., 2002. Remnant bottomland forests near the terminus of the Mississippi River in southeastern Louisiana. *Castanea*, 67(2), 134–145.

Williams, K.; Meads, M.V., and Sauerbrey, D.A., 1998. The roles of seedling salt tolerance and resprouting in forest zonation on the west coast of Florida, USA. *American Journal of Botany*, 85(12), 1745–1752.

Williams, T.W., 1993. Salt water movement within the water table aquifer following Hurricane Hugo. *In:* Brissette, J.C. (ed.), *Proceedings of the Seventh Biennial Southern Silvicultural Research Conference* (Mobile, Alabama). New Orleans, Louisiana: USDA Forest Service, Southern Forest Experiment Station, *General Technical Report SO-93*, pp. 177–183.