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Key Points:
- Sources of carbon (allochthonous vs. autochthonous) for floodplain sequestration were successfully estimated using carbon isotope analyses
- Carbon deposition rates in the Atchafalaya Basin exceed all accounts for Blue Carbon and Tidal Freshwater Forested Wetland ecosystems
- Atchafalaya C sequestration is an important coastal area in trapping organic sediment and should be used in models of global C cycling

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Sediment Trapping and Carbon Sequestration in Floodplains of the Lower Atchafalaya Basin, LA: Allochthonous Versus Autochthonous Carbon Sources

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Abstract Recent studies suggest that about 2 Pg of organic C is stored on floodplains worldwide. The present study indicates the Atchafalaya River, fifth largest river in the United States in terms of discharge, traps 30 mm/year of sediment on average within its floodplain, which is the highest average nonepisodic rate of fluvial deposition on the U.S. Coastal Plain. We installed sediment sampling stations at 23 sites, normally in transect, in the Atchafalaya Basin; these sites represent the range of hydrogeomorphic conditions on the floodplain based on hydrologic connectivity with the river main stem. The rate of sedimentation translates into about 12.5 Tg/year and includes 694 Mg/year of organic C. Highest sedimentation rates are associated with areas of high connectivity to channels and prograding deltaic processes. The δ^{13}C content suggests that 35% of deposited C is derived from river-suspended sediment compared to litterfall in the basin. Thus, much of the organic C sequestered is allochthonous material. However, isolated interior sites with limited connectivity to the channel may generate and sequester large amounts of autochthonous C. The substantial trapping of both autochthonous and allochthonous C (392 Mg/year) make this freshwater-forested floodplain critical in storage of material before reaching the coastal delta and estuary. This C deposition rate (340 g C·m^{-2}·yr^{-1}) exceeds all other rates reported in recent Blue Carbon and Tidal Freshwater Forested Wetland studies. Atchafalaya C sequestration occurs in/near areas with tidal influence and like other coastal systems is an important site for trapping mineral and organic sediment and in global C cycling.

1. Introduction

Quantification of sediment trapping in floodplains has occurred only relatively recently. About 25 years ago, Johnston (1991) summarized the few published estimates of vertical accretion or mass accumulation of mineral sediment in wetlands within the United States; only four studies documented mineral sedimentation in forested wetlands. Since then, numerous reports of sediment trapping in freshwater wetlands, including forested floodplains, have been published (see summaries provided in Hupp et al. (2009) and Aust et al. (2012)). Rivers link many parts of the landscape and through hydrologic connectivity with their floodplain may transport, transform, or store about 2 Pg of organic carbon (OC) worldwide (Battin et al., 2008). Here we define hydrologic connectivity as the lateral exchange of water, sediment, and other suspended material between the main channels and various regions of the floodplain during periods of inundation. Although, there is a large range of estimated values of OC in watersheds (0.5 to 1.5 Pg (Aufdenkampe et al., 2011) and 0.9 Pg (Regnier et al., 2013)), some estimates in mountainous headwater streams indicate that riparian areas including floodplains may store about 25% of the total OC while occupying less than 1% of watershed area (Wohl et al., 2012). Sutfin et al. (2016) provide a comprehensive review of carbon storage in a wide range of alluvial areas.

Low-gradient, large rivers, such as those on the Coastal Plain of the southeastern United States, are particularly disposed to storage of previously eroded sediment and associated material including carbon (C; Hupp, 2000; Hupp et al., 2008; Noe & Hupp, 2009) somewhat in contrast to storage in alpine areas (Hoffmann et al., 2009; Sutfin & Wohl, 2017). Relatively deep burial of subsurface C emphasizes the

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importance of large alluvial systems in carbon sequestration; D'Elia et al. (2017) found alluvial subsurface soils (0–3 m) contained considerably more C than typical C stocks of 0–1 m deep, and Van de Broek et al. (2018) found a similar trend with soil depth in tidal marshes. High sediment loads from large watersheds combined with low-gradient fluvial processes that are characterized by prolonged inundation over broad floodplains facilitate the deposition and storage of substantial amounts of sediment and its constituent material such as carbon, nitrogen, and phosphorus. Much, to nearly the entire watershed sediment load may be trapped prior to entering major estuaries (Ensign et al., 2014; Hupp et al., 2009, 2015; Kroes et al., 2007; Phillips, 1992).

Recent studies have shown that temperate coastal lowlands may be an important sink for C (Aufdenkampe et al., 2011; Bridgham et al., 2006; Ensign et al., 2014; Ludwig, 2001; Noe & Hupp, 2005, 2009; Raymond & Bauer, 2001; Ricker & Lockaby, 2015) and associated nutrients (Hupp et al., 2008; Noe & Hupp, 2009), which may be stored in these systems as organic-rich sediment. Sediment and carbon sequestration are, thus, important functions of floodplain ecosystems (Aufdenkampe et al., 2011). The sources, location, and processes that enhance and maintain fluvial C sequestration of riverine C loads are poorly understood but increasingly studied (Battin et al., 2009; Wohl et al., 2017). Sediment trapping of C along temperate, large, low-gradient rivers has largely been unmeasured and overlooked by many models of global C flux (Battin et al., 2008, 2009; Cole et al., 2007) and the long-term coupling of carbon and sedimentation processes is poorly understood (Hoffmann et al., 2009). Lowland systems typically have high rates of primary productivity that may contribute to a large pool of autochthonous C (Cole et al., 2007), which may be likewise sequestered.

Identifying sources and measuring fluxes of the allochthonous and autochthonous C deposited in lowland floodplains is important for understanding watershed and global C budgets as well as floodplain ecosystem processes. Source analyses are particularly uncommon. Stable isotopes ($\delta^{13}C$, $\delta^{15}N$) have been used to identify the general sources of organic material in wetlands (Craft et al., 1988; Hackney & Haines, 1980), on floodplains (Martinelli et al., 2003; Robertson et al., 1999), and tidal marshes (Van de Broek et al., 2018) based on variance in plant utilization of C_3 versus C_4 photosynthetic pathways (forest vegetation/freshwater marsh—C_3, brackish/salt marsh vegetation—C_4) and fractionation of $\delta^{13}C$ between atmospheric and dissolved sources of CO_2 (emergent and terrestrial plants versus plankton and aquatic plants). For example, DeLaune (1986) and Matson and Brinson (1990) used carbon isotopes to estimate C sources in marshes, and Goni et al. (2014) measured C sinks in floodplains from a watershed perspective. Results from C isotope studies allow for the estimation of local vegetation OC inputs as separate from riverine sources derived from the watershed upstream.

The Atchafalaya Basin (AB, henceforth) has had several sedimentation studies over decades (Carlson et al., 2011; Demas et al., 2001; Doyle et al., 1995; Hupp et al., 2008; Kroes et al., 2015; Kroes & Kraemer, 2013). Results of these studies and the present study relate deposition patterns by hydrologic connectivity to sediment-laden river water in main channels. Thus, the degree of connectivity is reflected in suspended sediment concentration, which decreases with distance from main channels and from natural and man-made blockage of streamflow. The present and most completed studies have/had the general objective to document and interpret complex patterns of sediment deposition along natural and man-made bayous and canals in the central and lower AB including the determination of important flow paths for sediment and nutrient trapping to facilitate management. The present paper also has the specific objective to estimate the amount and character of sediment and associated C sequestered from allochthonous and autochthonous sources in the lower AB.

2. Methods

2.1. Site Description

The AB (Figure 1; area = 2,400 km^2) includes wetlands adjacent to the anastomosing network of channels associated with the Atchafalaya River, and contains the largest relatively intact, functioning riparian area in the lower Mississippi Valley. Approximately 25% of the Mississippi River discharge (drainage area about 3,200,000 km^2) and all of the Red River (drainage area about 233,000 km^2) flow in the Atchafalaya River, a distributary of the Mississippi River, on an annual basis. The entire suspended- and bed-sediment load of the Red River and as much as 35% of the suspended and 60% of the bed-sediment load of the Mississippi River (Mossa & Roberts, 1990) are now diverted through the AB. As a result, the AB experiences exceptionally high

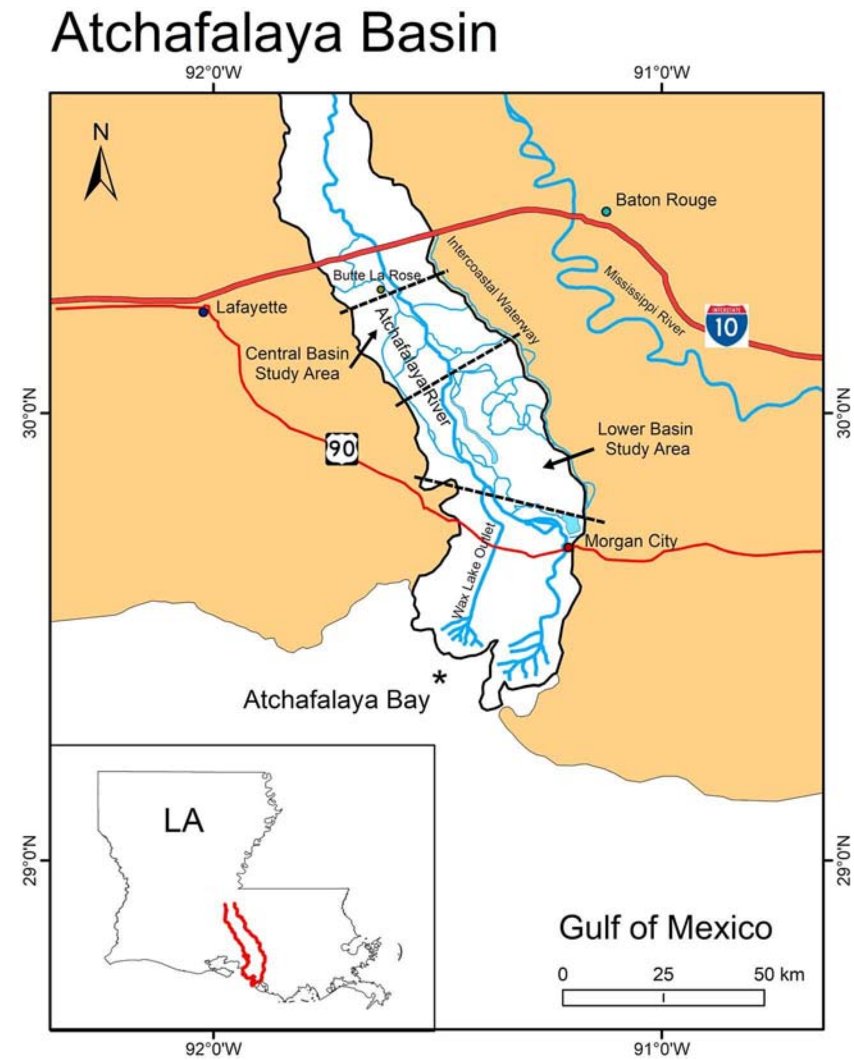

Figure 1. Map of study area with State of Louisiana inset. Both the earlier central basin study area and the present lower basin study area are shown, delineated by dashed lines. Main stream gage at Butte La Rose within the basin and sampling areas (asterisk) of Gordon and Goñi (2003) near Wax Lake and Atchafalaya River mouths are shown. A natural levee from deltaic process crosses the lower basin along U.S Highway 90; this levee is breached naturally by the river near Morgan City and cut during the construction of the Wax Lake outlet.

sedimentation rates at sites with high connectivity to the main river (Hupp et al., 2008). Initial results (Hupp et al., 2008) suggest that the central AB may conservatively trap 6.7 Tg of sediment annually, which is approximately 15% of total load entering the AB, of which over 820,000 Mg is organic material. As the AB continues to fill with sediment, simultaneously more sediment is likely to be exported to the coast where estuarine deltas are prograding into the Gulf of Mexico (Hupp et al., 2008). This process would help offset regional land loss due to subsidence and export of Mississippi River sediment to the deep Gulf of Mexico (Day et al., 2000).

Most of the AB (Figure 1) is partly blocked from the Gulf of Mexico by a natural levee that creates a high ground that is perforated, naturally by the Atchafalaya River near Morgan City, LA, and by the constructed Wax Lake navigation canal. The term Atchafalaya River refers to the actual main channel of the river here and henceforth. Accreting land surfaces (floodplains or bars) are rapidly colonized by woody vegetation upon emergence above elevations around the 25% flow duration. Although the AB is nearly completely freshwater above these outlets, the river channel is affected by tides that may range nearly 0.5 m in the central part of the basin near Butte La Rose, LA, during low flow (U.S. Geological Survey streamflow gage

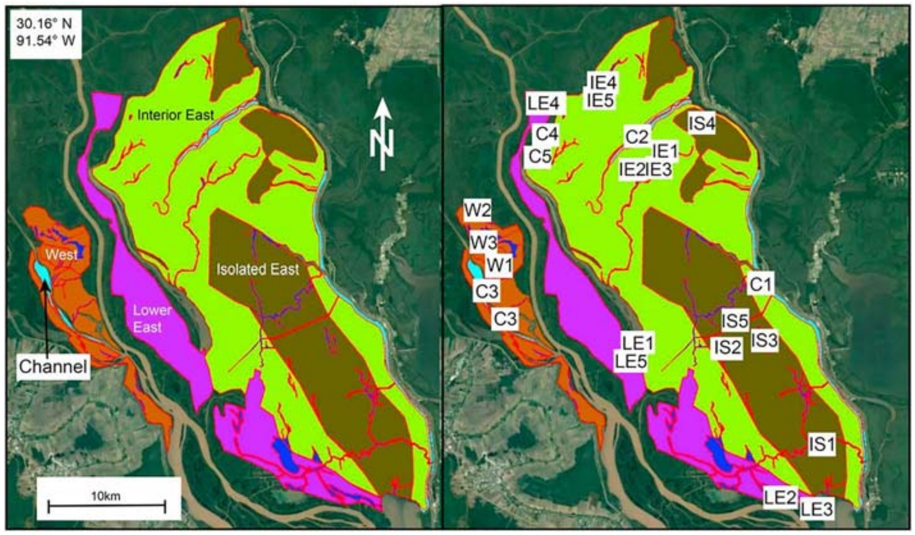

Figure 2. Aerial view of the lower, present study area, on left showing the hydrologic regimes used to partition the analyses into a gradient of connection to the Atchafalaya River. From Channel, through Lower East, West, Interior East to Isolated East regimes, the connection to the river diminishes. Site locations are shown on right figure.

#07381515; Figure 1). Parts of the lower AB are located around the head of tides and immediately upstream of the more classical tidal freshwater-forested wetlands (TFFW) where distinct, pronounced microtopographic landforms may occur presumably from diurnal tidal inundation of the soil surface. TFFW ecosystems are now considered, by some, to be part of the Blue Carbon (Krauss et al., 2018; Mcleod et al., 2011) group; to date, this ecosystem has had limited recognition (Conner et al., 2007), and limited basic research on sedimentation (Ensign et al., 2015; Kroes et al., 2007) and nutrient/C sequestration (Jones et al., 2017; Noe et al., 2016). However, OC burial in TFFW may be substantial (Krauss et al., 2018). Coastal Carbon or the marketing term Blue Carbon refers to OC that may be sequestered in vegetated coastal tidal ecosystems.

2.2. Hydrogeomorphology and Regime Selection

The present study is a continuation of AB efforts that first documented sedimentation patterns in relation to hydrologic regime and connectivity to sediment-laden water in the central AB that were published by Hupp et al. (2008). The present investigation is focused further south where sedimentation rates appear higher than the initial study; the present study design, upstream of the high ground along U.S. Route 90 (Figure 1), also added measurement of C sequestration rates and sources. The general study area in the lower part of the AB (Figure 1) is characterized by a network of numerous meandering natural bayous, constructed channels, extensive floodplain, and filling lakes where active lacustrine deltaic progression is obvious and dominant. We established 23 new sites for monitoring sediment accretion and its characteristics on the floodplain, including OC. These sites were chosen to characterize five common hydrogeomorphic regimes in the area (Figure 2) that form a decreasing gradient of hydrologic connectivity from the channel to interior sites. Typical sites are a floodplain transect with three or more sampling locations using feldspar clay pads as marker horizons (see Hupp et al., 2008). Here briefly, sites are established to characterize a regime according to their general connectivity to river water. We usually established a “transect” only to facilitate finding marker horizons for subsequent sediment deposition measurement; more detail follows. Some interior sites were always inundated; in this case, we deployed plastic tubs “pinned” to the bottom substrate through large holes to allow free drainage of water.

Floodplain hydrologic/depositional (hydrogeomorphic) regime areas were determined by frequency of water turbidity versus blackwater as determined by Allen et al. (2008), by flow patterns measured by Kroes (2012), and by the elevation of floodplain surface (U.S. Geological Survey, 2013) relative to characteristic channel low-water elevation determined from U.S. Geological Survey stage gages. Middle Fork Bayou Long (gage #295447091191500; not shown) is representative of water levels on east side of the main Atchafalaya River channel (most of study area); only the West and part of the Channel regimes lie on the west side of the river. The delineation of the five floodplain hydrogeomorphic regimes reflects the determination of the hydrologic connectivity (Figure 2) in order of degree of connectivity to main river channels, and can be characterized as (1) Channel regime (highest connectivity, elevation range 1–3 m); these sites are directly adjacent to main channels or in primary distributary channels, which includes areas within 150 m of main sediment-laden channels that are regularly inundated, have high sedimentation rates, and obvious levee development (Kroes & Kraemer, 2013). This regime does not include some land adjacent to the main river channels (Figure 2), which is typically a high levee that rarely floods (in some places the channel may be incised). (2) Lower East and (3) West regimes are regions where there are many previously filled or filling lakes. The primary source of sediment is the channel of the main Atchafalaya River, sedimentation rates are relatively high, and levee development may occur (these two regimes overlap in connectivity but are distinguished by flow conditions and water sources). The Lower East (elevation range 0.7–2 m) is most affected by filing lakes (lacustrine progradation), whereas the West (elevation range 0.7–3.5 m) is most affected by channel processes (lateral accretion) and West water levels are best related to Chico Pass stage gage (#073815450; not shown). (4) Interior East (elevation range 0.7–1 m) regime mostly occurs along secondary and tertiary channels that are regularly inundated by turbid water, although less so than the above regimes, lacks levee development, and may go dry during low-flow periods. (5) The Isolated East regime (elevation <0.7 m) is hydraulically disconnected from the river both by distance and/or spoil banks or natural channel blockages to flow; most area in this the regime is typically flooded or saturated at all times and shows little to no turbidity. The hydrology of these sites is dominated by backwater or extremely low-flow velocities dictated by downstream water levels as a result of upstream blockages to flow and by flow paths that were long with slow flow velocities (<0.01 m/s) and clearly reflect conditions typical of blackwater systems (Hupp, 2000). These five regimes form a gradient from levee/island formation processes in the Channel Regime, to characteristic alluvial (brownwater, Hupp, 2000) floodplain processes in the Lower East and West Regimes, to a transitional regime that reflects conditions typical of Bottomland Hardwood swamps in the Interior East Regime, to lastly, a characteristic blackwater system in the Isolated East Regime. Note that most of the present study area is east of the Atchafalaya River, which flows relatively close to the west protection levee as opposed to the central part of the AB (studied previously; Hupp et al., 2008) where the river flows near the middle of the study area (Figure 1).

2.3. Sediment Deposition and Sampling

Each of the 23 sites/transects was surveyed using a survey grade elevation GPS (elevation ± 20 mm with real-time kinematic correction) using a cellular data link to a local continuously operating reference site. Clay pads (at least 3, up to 12) were placed at each site, except as noted above, and are a layer of white feldspar clay approximately 20 mm in original thickness over an area of 0.5 m^2 on the soil after removal of coarse detritus. This clay becomes a fixed marker after absorption of soil water and permits accurate determinations of net vertical accretion over short periods (Baumann et al., 1984; Hupp & Bazemore, 1993; Kleiss, 1996). Clay pads were surveyed for elevation using a standard survey rod and rotating laser level with ±3.8 mm/100-m accuracy and ultimately tied to the elevation GPS. Sampling locations were measured for deposition rates over a three-year period (2011–2013) during the study. PVC poles were driven into the ground adjacent to clay pads for aid in relocating the pads and also as a backup deposition (or erosion) marker by measuring the distance from the top of the pole to the ground surface at time of placement. Pole height measurements are useful at sites with particularly high sediment deposition rates, where determining depth to clay pad is difficult. Mean deposition rates and standard errors by regime are provided in Table 1. An ANOVA with Fisher's LSD post hoc tests was performed to test for difference in deposition rates among regimes; only significant ($\alpha = 0.05$) differences are included in the results.

Suspended sediment in Atchafalaya River channel surface water, floating water hyacinth, and senesced tree leaves (no contact with surface water) were sampled from the basin to provide environmental end members of potential organic sediment sources. Suspended sediment samples from the river were collected after settling in the dark (30 days) from four 20-L surface grabs (80 L) of water from the upper 1.7 m of depth in the center of the river adjacent to the distributary channel Bayou Sorrel during the ascending limb of a flood wave on the Atchafalaya River; we assumed that the river flow was well mixed and did not require depth integration. Although this is a common and well-founded assumption during flooding (high) discharges, we acknowledge that suspended sediment concentrations and other organic compound concentrations

Table 1
Major Parameters Analyzed at the 23 Sites Across the River Connectivity Gradient From Channel Regime to Isolated East Regime

Site	Channel	Lower East	West	Interior East	Isolated East
Area (km^2)	14.82	101.22	47.59	321.32	333.12
Number of transects/sites	5	5	3	5	5
Mean deposition rate (mm/year)	79	23	9	12	28
Standard error (mm/year)	23.65	3.97	2.09	2.33	7.18
Mean bulk density (g/cm^3)	0.73	0.65	0.54	0.38	0.18
Mean percent organic (LOI)	6.5	9.9	12.7	12.8	32
Mass ($kg{\cdot}m^2{\cdot}yr$)	57.63	14.88	4.83	4.47	5.19
Mass organic ($g\ C{\cdot}m^2{\cdot}yr$)	880	530	240	240	710
Long-term equivalent ($g\ C{\cdot}m^2{\cdot}yr$)	624	376	170	170	504
Mass autochthonous organic ($g\ C{\cdot}m^2{\cdot}yr$)	460	338	170	160	670
Total deposition mass (Mg)	854	1506	230	1438	1727
Total deposition, organic C (Mg)	13.01	54.10	11.25	78.14	237.59
Total deposition, autochthonous organic C (Mg)	6.76	34.18	7.95	50.13	223.18
Total deposition, allochthonous organic C (Mg)	6.25	19.92	3.30	28.01	14.41
Percent river C	49	36	35	28	3

Note. Most values refer to recently deposited floodplain sediment. The long-term equivalent is an adjustment to reflect compaction during long-term burial of organic C (DeLaune et al., 2003). LOI refers to sample weight loss on ignition. Autoch, alloc, and depo are abbreviations for autochthonous, allochthonous, and deposition, respectively. Percent river C refers to the amount of sediment likely derived from suspended river sources is the mean of all sites in the regime, which ranged from 0 to 79%; note consistent decline with decreasing river connectivity, a trend shared with bulk density, as would be expected.

may be underestimated. This stage (14.3 ft in February 2012, at the Butte la Rose gage) resulted in the inundation of all of the soil sampled locations; this stage is also the annual flood with a 1-year return interval. Water hyacinth was collected from an isolated backwater area in March 2012. Fresh leaf litter was collected from a Cypress-Tupelo swamp north of the town of Butte La Rose in a location that had not been inundated by flood events during the study. Samples of sediment deposited on the floodplain were taken adjacent to or above the artificial marker horizon, within the top 20 mm of soil surface; we used a 75-mm-diameter sleeve for bulk density cores. These samples were returned to the laboratory and dried at 60 °C until they reached a constant mass and weighed for bulk density. We used 60 °C because of the tendency of organics in peats to volatilize above 60 °C. For comparison, O'Kelly (2004) found that the rate of organic matter loss was greater above 60 °C than the error created by latent porewater. Coarse organic material larger than 1 mm was removed and the remaining sample ground to pass through a 1-mm sieve; we chose not to include material >1 mm because it is unlikely to be transported large distances. Subsamples of the deposited sediment were subsequently analyzed for organic content using the loss on ignition technique (550 °C for 4 hr; Nelson & Sommers, 1996). Subsamples of deposited sediment, river suspended sediment, floodplain tree leaves, and floodplain water hyacinth leaves were acidified using HCl vapor digestion (Hedges & Stern, 1984) to remove carbonates and then analyzed for the isotopic abundance of OC and nitrogen ($\delta^{13}C$, $\delta^{15}N$), total organic carbon (TOC), and total nitrogen (TN) using an elemental analyzer (Carlo Erba NC 2500, CE Elantech, Lakewood, NJ, USA) connected to a continuous-flow isotope-ratio mass spectrometer (Delta V Isotope Ratio Mass Spectrometer, ThermoFisher Scientific, Waltham, MA, USA).

2.4. Organic Sediment Source Analysis

We considered vegetation (tree leaves, "floodplain") on the AB floodplain as representative of autochthonous organic material and suspended sediment in well-mixed river water ("riverine") as representative of allochthonous organic material. The proportion of these two sources contribution to organic sediment deposited on the floodplain ("deposited") was calculated as a linear, two source mixing model (Kwak & Zedler, 1997) and was calculated as

$$\%\text{Floodplain source in deposited sediment} = 100\%\times\left(\delta^{13}C_{\text{deposited}}-\delta^{13}C_{\text{riverine}}\right)/\left(\delta^{13}C_{\text{floodplain}}-\delta^{13}C_{\text{riverine}}\right)$$

and

$$\%\text{Riverine source in deposited sediment} = 100\%-\%\text{Floodplain source in deposited sediment}$$

In addition to the samples collected in this study, published values of four river suspended-sediment samples

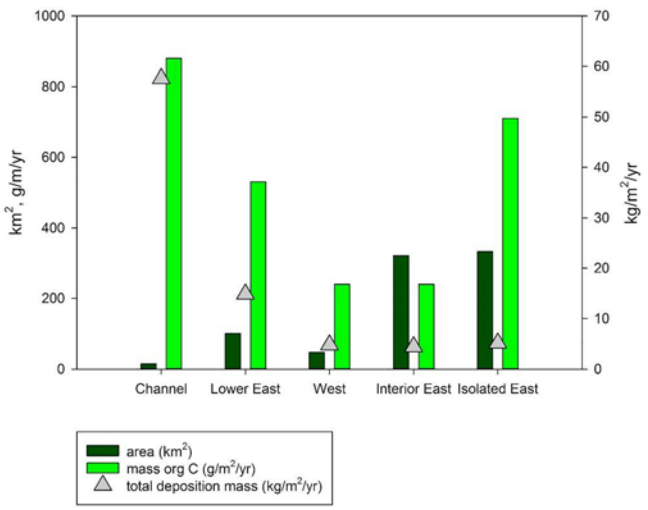

Figure 3. Graph showing trends along the river connectivity gradient, left to right, of area (dark bar), annual mass of organic carbon deposited in g/m^2 per year (light bar), and total mass of sediment deposited in kg/m^2 per year (red line).

collected (March and April 1998) at the mouth of the Atchafalaya River during a river discharge essentially equal to that of February 2012 (about 10,000 m^3/s) when our river samples were collected (Gordon & Goñi, 2003), downstream of the natural levee on the southern AB boundary (Figure 1), were included for a more robust characterization of that potential source. First, the ability of binary combinations of δ^{13}C, δ^{15}N, TOC, and TN to discriminate the potential sources was assessed to determine whether the potential sources bounded the deposited sediment fingerprint. The combination of δ^{13}C and TN successfully separated suspended sediment, tree leaves, and hyacinth leaves, whereas other combinations did not graphically separate tree and hyacinth leaves. The δ^{13}C and TN content of deposited sediment was clearly a mixture of suspended sediment and tree leaves, so hyacinth leaves were excluded as a potential source of organic sediment. With hyacinth excluded, δ^{13}C provided a clear gradient in organic sediment sources.

3. Results

3.1. Sedimentation by Hydrogeomorphic Regime

Sediment deposition rates are relatively high near the channel and in biologically productive isolated areas. Mean sediment deposition rates by site regardless of regime ranged over 3 orders of magnitude from 7 to 153 mm/year, with an average of 30 mm/year over the entire lower AB. Mean deposition by hydrogeomorphic regime ranged from 9 (SE = 2) to 79 (SE = 24) mm/year with the greatest rates occurring in the Channel (79 mm/year; SE = 24) and Isolated East (28 mm/year, SE = 7) regimes and lowest rates in the West regime (9 mm/year, SE = 2; Table 1). The Channel regime has significantly higher deposition rates than all other regimes ($p = 0.05$, Fisher's LSD) while the West regime has a significantly lower deposition rate than the Isolated East regime. The Channel regime is dominated by mineral deposition (6.5% organic) while the Isolated East site is considerably more organic (32%; Table 1) than all other regimes.

Sediment accumulation rates (kg·m^2·yr) generally decreased from the highly connected Channel regime to the Interior East regime with limited river connectivity (Table 1). The Isolated East regime had an intermediate mean deposition rate with a low mass accumulation rate (similar to the West and Interior East regimes). This result is expected given the highly organic and low bulk density nature of the sediment (Table 1 and Figure 3). However, OC sedimentation rates in the Isolated East regime were among the highest measured. Mean accumulation rate of sediment mass, when weighted by area of the regimes was 17.4 kg·m^2·yr. Mean accumulation of OC for the whole study area was 795 g·m^2·yr which converts to 564 g·m^2·yr after correction for long-term C loss during storage (organic matter accumulation rates measured using 1-year feldspar marker horizons versus ^{137}Cs dated soil cores; DeLaune et al., 2003). The area occupied by each hydrogeomorphic regime generally increased along the same gradient provided earlier regarding river connectivity, from the Channel to the Isolated East and ranged from 14.8 to 333.1 km^2, respectively (Table 1 and Figure 3), for a total sampling area of 818 km^2. The total annual amount of sediment trapped by the five hydrogeomorphic regimes in the lower AB is nearly 5,755 Mg. The Channel regime is by far the smallest area, but with the highest deposition rate yields 854 Mg/year of sediment accumulation (Table 1). Conversely, the Isolated East regime, with a relatively low deposition rate, yields 1727 Mg/year owing to the large areal extent of this regime (Table 1 and Figure 3).

3.2. Carbon Sources

The ^{13}C to ^{12}C ratio (δ^{13}C) of deposited sediment was variable among sampling locations and ranged between the two end-members that were sampled, the Atchafalaya River sample of suspended sediment along with the four previously published river samples and the five floodplain leaf samples, unaffected by river water, taken from swamp tree species (Figure 4). The river samples of suspended sediment represent C in the basin that should be the most allochthonous end-member, whereas senesced leaves should be the most autochthonous; together these samples roughly form a gradient that allows for inference on C sources of deposited floodplain sediment. Leaves of water hyacinth had clearly different elemental and isotopic

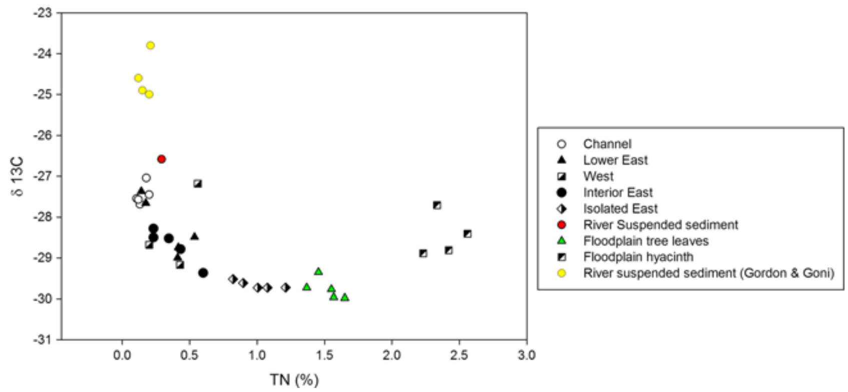

Figure 4. Scatter diagram of δ^{13} C content and percent N shown to identify sources of organic C for 23 site locations distinguished by hydrologic regime, 1 river-water suspended sediment, 5 basin leaf samples, 4 interior floodplain hyacinth samples, and 4 river-water suspended sediment samples near river mouth (Gordon & Goñi, 2003). Note the end-member clusters of the river and river mouth suspended sediment samples and leaf samples along the main gradient.

composition than that of deposited sediment and were not considered further as an important source of C (Figure 4). The river suspended sediment samples were enriched in δ^{13}C content compared to the leaf samples (t test, $p < 0.001$), with the suspended sediment having a mean δ^{13}C content of −24.98 (SE = 0.41) and the leaf samples having a mean content of −29.76 (SE = 0.11). The floodplain deposited sediment samples ranged in δ^{13}C content from −26.00 to −30.22 (Table 2 and Figure 4).

The mixing model with δ^{13}C indicated that the organic matter in the deposited sediment samples ranged from 21% to 100% from the floodplain source, with an average among sites of 37% autochthonous (or 63% allochthonous riverine source). Thirty-five percent of the samples had a >50% riverine source. The percent riverine contribution of deposited sediment OC decreased continuously from Channel to Lower East, West, Interior East, and to the Isolated East regimes (Figure 5). Percent riverine (allochthonous OC) ranged from 79 in the Channel Regime to 0 in the Isolated East Regime. Similarly, the allochthonous riverine OC sedimentation rate (g·m^2·yr) decreased continuously along the same gradient (Figure 5). The autochthonous floodplain organic sedimentation rate similarly decreases along the gradient, with the exception that the highest rates were found in the Isolated East (Figure 5).

Accounting for the different OC-sedimentation accumulation rates (g OC·m^2·yr) and areas (km^2) of the regimes, the Isolated East regime traps the largest amount of total OC (238 Mg/year), which is an order-of-magnitude greater that all other regimes that range from 11 to 78 Mg/year (Table 1).) Differences in OC sources further distinguished the five hydrogeomorphic regimes with the Isolated East annually trapping the largest mass of autochthonous floodplain C. Channel sites with high connectivity sequester about 6.76 Mg/year of autochthonous OC, whereas Isolated East sites sequester about 223 Mg/year of autochthonous OC (Table 1); other sites with intermediate river connectivity trap between 8 and 50 Mg/year of autochthonous OC. Although the highly connected Channel regime trapped 421 g·m^2·yr allochthonous OC, with a small area it sequesters the second lowest amount, 6.25 Mg/year. The West regime (small area and low trapping rate) sequesters the least allochthonous OC, 3.30 Mg/year (Table 1). The remaining regimes trapped between 14.41 and 28.01 Mg/year of allochthonous OC. The total mass of autochthonous floodplain C trapped annually in the southern AB is 323 Mg/year, and the allochthonous C mass is 72 Mg/year (i.e., 19% riverine allochthonous OC), for a total of 395 Mg/year of OC.

4. Discussion

The lower Atchafalaya Basin, part of the largest contiguously forested floodplain wetland in the United States, experiences sustained sediment depositions rates (average 30 mm/year), which may be the highest average annual river deposition rate (not including single-event maxima) on the Gulf and Atlantic Coastal Plains (Aust et al., 2012; Hupp, 2000); single-event rates of sedimentation can be episodically higher. Aust et al. (2012) in review of bottomland sedimentation rates provides a high estimate of 53 mm/year (Kesel et al., 1974), also in Louisiana. Hupp et al. (2008) reported a high of 42 mm/year and a sustained rate of

Table 2
The δ^{13} C Content, Percent N, Deposition Rate in mm/year, Percent OC, and Number of Clay Pad/Tubs (Pads) for 23 Floodplain Sediment Sampling Sites/Transects Organized by Hydrologic Regime

Regime/Substrate	Site Full Name	Site Abbreviation	δ^{13}C	%N	mm/year	%OC	Pads
Channel	OldRiverSET	C1	−27.55	0.11	27.9	1.22	3
	Little Bayou Pigeon	C2	−27.45	0.20	30.4	1.47	5
	Long Island	C3	−27.69	0.13	77.7	1.67	12
	Hop Island Spit	C4	−27.04	0.18	105.7	1.60	9
	Flat Lake Pass	C5	−27.57	0.12	153.1	1.66	3
Lower East	Little Bayou Long	LE1	−28.49	0.54	8.5	4.15	4
	Dog Island Pass	LE2	−28.74	0.42	25.9	5.33	5
	Flat Lake	LE3	−27.65	0.17	31.1	1.81	5
	Coon Trap	LE4	−27.37	0.14	28.1	2.06	3
	East Grand Lake	LE5	−29.00	0.41	20.8	4.61	8
West	Lower Mud Cove	W1	−29.17	0.43	10.5	4.99	7
	Buffalo Cove SET	W2	−27.18	0.56	11.4	6.60	3
	Mud Cove Upper	W3	−28.68	0.20	4.7	3.10	5
Interior East	Big Bayou Pigeon	IE1	−29.37	0.60	6.9	9.74	6
	Turkey Bayou	IE2	−28.79	0.43	7.5	5.56	5
	Brokeback Dan	IE3	−28.52	0.35	14.0	4.29	6
	Cross Canal	IE4	−28.28	0.23	19.5	3.38	4
	CrossCSET	IE5	−28.50	0.23	10.3	4.20	3
Isolated East	LBSSET	IS1	−29.52	0.82	16.4	11.24	3
	21-in. canal	IS2	−29.73	1.01	33.3	15.07	3
	21-nr big fork	IS3	−29.73	1.08	42.0	15.07	3
	Pigeon SET	IS4	−29.62	0.90	6.8	12.32	3
	byu N of 21	IS5	−29.73	1.21	43.0	15.07	3
Atchafalaya River Sediment		ARS	−26.58	0.29			
Leaves	Leaves 1	L1	−29.96	1.57			
	Leaves 2	L2	−29.77	1.55			
	Leaves 3	L3	−29.73	1.37			
	Leaves 4	L4	−29.98	1.65			
	Leaves 5	L5	−29.35	1.46			
Hyacinth	Hyacinth 1	H1	−28.81	2.42			
	Hyacinth 2	H2	−27.71	2.34			
	Hyacinth 3	H3	−28.41	2.56			
	Hyacinth 4	H4	−28.89	2.23			
Literature	Gordon and Goni (2003)	GG1	−25.00	1.84			
		GG2	−24.90	1.43			
		GG3	−23.80	1.88			
		GG4	−24.60	1.14			

Note. Also shown are one main basin Atchafalaya River suspended sediment sample, five leaf samples from within the AB, four hyacinth samples from the interior floodplain, and four suspended sediment samples from areas near the mouth of the Atchafalaya River (Gordon & Goñi, 2003).

11 mm/year in the central AB. About 40 mm/year along the lower Roanoke River in northeastern North Carolina was measured by Hupp et al. (2015) as part of an episodic legacy sediment deposition that can be quite rapid (James, 2013). The present study measured as much as 79 mm/year along channel filling bars over a range of 0 to 650 mm of depth, which characterize prograding deltaic processes occurring in the AB (Hupp et al., 2008; Tye & Coleman, 1989). Delta progradation occurs both within the AB and perhaps more typically seaward along the two AB outlets leading to the Atchafalaya Bay (Figure 1). Deltaic deposition likely represents significant organic material burial on the coastal shelf (Gordon & Goñi, 2003; Shields et al., 2017) and upstream in the AB proper. High rates of deposition, measured in the present study (Table 1), suggest that the AB and its coastal fringe may sequester some of the greatest amounts of sediment and associated C annually along the southeastern U.S. coast (Aust et al., 2012; Hupp, 2000; Krauss et al., 2018). Even higher rates (up to double) of deposition in the Atchafalaya Basin may occur based on total suspended sediment measurements (Rosen & Xu, 2015).

Our study of the lower AB confirms, like other recent studies, that coastal lowlands may be an important sink for carbon (Aufdenkampe et al., 2011; Bridgham et al., 2006; DeLaune & White, 2012; Gordon &

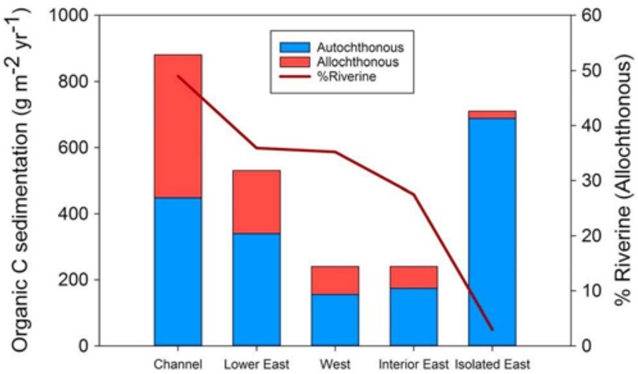

Figure 5. Graph showing trends in partitioning of allochthonous versus autochthonous organic C (bars) sedimentation rates along the river connectivity gradient and continuous decline (line) in percent of sediment from riverine sources.

Goñi, 2003; Krauss et al., 2018; Noe et al., 2016; Noe & Hupp, 2009). Hupp et al. (2008) demonstrated that the central AB may conservatively trap 6.7 Tg of sediment annually (approximately 15% of total load entering the AB), of which about 820,000 Mg are organic material. The lower AB may trap 5.8 Tg of sediment annually (Table 1), of which about 915,000 Mg are organic material. The sediment trapping estimate for the lower AB is also conservative; in that, unlike the central AB, many areas are underwater all or most of the time annually, which had hindered sampling efforts. We are presently sampling several of these locations using submerged sediment traps.

4.1. Trends by Hydrogeomorphic Regime

The hydrogeomorphic regimes display depositional trends along a gradient of connectivity to river water. The expansive nature of the lower AB bottomland, combined with the majority of river water flowing through only a few main routes (the river or other navigation channels) even during periods of high inundating flows (Kroes et al., 2015), leads to a consequence of increasing area for floodplain regimes more distant from the channels. Thus, proceeding from the relatively narrow Channel regime through the broad Interior to the Isolated regime, the areal extent of each generally increases (Figures 2 and 3). Previous studies have shown that connectivity to sediment laden river water strongly facilitates mineral sediment deposition (Hupp, 2000; McManus, 2002; Walling & Owens, 2003; Malmon et al., 2005; Hupp et al., 2008; Kroes et al., 2015; Ricker & Lockaby, 2015), which is clear in the present study where the rate of mass of deposition decreases through to the Interior East (Table 1 and Figure 3) with a small increase in the Isolated East regime. The mineral content as indicated by loss on ignition decreases completely across the gradient (Table 1) suggesting a replacement by organic material deposition that in the most isolated regime is high; total mass of autochthonous OC sequestered follows a similar pattern. Similarly and related, bulk density decreases consistently across the gradient; mineral content/bulk density provides an additional quantitative assessment of hydrologic connectivity (Table 1). Indeed, the annual rate of mass of OC deposited in this isolated regime is second only to that deposited in the Channel regime (Table 1 and Figure 3). Thus, primary productivity in these isolated areas is great and substantially contributes to overall mass of organic sediment deposited, most of which may be internally derived. The sheer size of a hydrogeomorphic regime more than compensates for deposition rates that may be greater in nearby regimes in terms of annual sediment (Hupp et al., 2015; Noe & Hupp, 2009) and C trapping/sequestration. It should be noted that postdepositional soil processes may limit OC sequestration in tropical lowland rivers (Omengo et al., 2016). Although this study was conducted over a relatively short period (three years), which may limit interpretation of long-term sedimentation and C sequestration trends, the study period includes a wide range of flows including some of the highest flows (2011) over several decades (Carlson et al., 2011; Kroes et al., 2015). The hydraulics of the study area during high flows limit potential sediment accretion owing to a hydraulic gradient that forces river water away from isolated areas; banks and levees in the area are rarely overtopped by flood flow (Kroes et al., 2015).

4.2. Carbon Sources

The present study is among a few to estimate OC accumulation rates and identify the amounts of autochthonous and allochthonous OC in forested freshwater wetlands using carbon isotope and nitrogen analyses (Craft et al., 1988; Hackney & Haines, 1980; Martinelli et al., 2003; Robertson et al., 1999; Van de Broek et al., 2018). The separation of the 23 floodplain sites displays a logical trend along the gradient of hydrologic connectivity from Channel regime sites to Isolated East sites, ranging from near river water with a large amount of OC from allochthonous sources to highly isolated autochthonous sites with little connection to river water and mineral sediment (Table 2 and Figure 4). The regime with the greatest range of connectivity to the main stem, West regime, generally plots in the central portion of the gradient and $\delta^{13}C$ axis (Figure 4), suggesting that elements of both river and floodplain C source end-members may be at play. Whereas, the Lower East regime with similarities in connectivity to the Channel regime and the Interior East with connectivity similar to Isolated sites align nearer the two endpoints, respectively (Figure 4). The samples from the Atchafalaya River seaward of the AB proper, associated with Gordon and Goñi (2003) study, had slightly

Table 3
Comparison of C Sequestration (Burial Rate) for Several Aquatic and Wetland Ecosystems

Ecosystem	C Burial Rate ($g\ C\ m^{-2}\ yr^{-1}$)	Global Area, Maximum (km^{-2})	Sources
Seagrasses	138	600,000	Duarte (2002) and Duarte et al. (2010) Kennedy et al. (2010)
Salt marshes	218	400,000	Chmura et al. (2003) and Duarte (2002)
Mangroves	226	152,361	Chmura et al. (2003) and Bird et al. (2004) Lovelock et al. (2010)
Tidal forests (MD, SC, GA)	93	?	Noe et al. (2016) and Ensign et al. (2015) Craft (2012)
Atchafalaya floodplain	340[a]	818	this paper
Danube River	290	104,000	Tockner et al. (1999)
Temperate floodplains	3–290	?	Sutfin et al. (2016)
Nontidal forested wetlands	188	?	Bernal and Mitsch (2012)
Nontidal riverine marshes	166	?	Bernal and Mitsch (2012)

Note. Estimates of global area for three blue-carbon ecosystems are provided, and area information for other ecosystems is unavailable. Tidal forest, usually freshwater, ecosystems are shown and now are also considered part of the blue carbon group. Nontidal wetlands are provided for comparison, including floodplains worldwide as reported by Sutfin et al. (2016).
[a]The Atchafalaya forest burial rate has been corrected for long-term burial.

enriched δ^{13}, containing allochthonous river suspended sediment and material including phytoplankton, seston, and *Spartina alterniflora* detritus from saltmarshes, all of which have a higher $\delta^{13}C$ (DeLaune, 1986; Peterson et al., 1980). Hyacinth dominated sites were continuously flooded, highly disconnected sites, which tended to have a low δ^{13} C and distinctly high percent TN, as would be expected in this isolated, eutrophic situation dominated by vegetal material.

The portion of OC sedimentation attributed to allochthonous sources by δ^{13} C analyses decreased continuously from the connected Channel Regime through the hydrogeomorphic regimes to the Isolated East from 49 to 3% (listed in Table 1 and Figure 5) and strongly supports the large role that connectivity to river water plays in OC sediment sources. This decrease in riverine sources with distance from main channel is supported by the results of Martinelli et al. (2003) on tropical floodplains along the Amazon River. Disconnected isolated sites receive the great bulk of OC from autochthonous sources, 97% (Figure 5). Thirty-five percent of sampling sites had >50% riverine sources of deposited OC (Table 1). The AB is a significant trap for allochthonous OC, removing 72 Mg/year from the Atchafalaya River channel (which includes some of the lower Mississippi River flow; Table 1). However, as suggested by Cole et al. (2007), the present study also finds a substantially great amount of autochthonous OC deposition, 323 Mg/year, trapped in the lower AB. The very high rates of deposition in smaller floodplain areas and the lower rates in very large areas of floodplain combine to make the AB a globally important region for carbon sequestration. Regardless of source, the distinct location (Figure 1) of the δ^{13} C values (Figure 4) from the Gordon and Goñi (2003) study indicates that saltmarsh/phytoplankton OC is not diluted by the lower values found within the waters of the AB proper. This suggests that a considerable amount of OC derived from in and upstream of the AB is sequestered before reaching the coastal marshes and river mouth and underscores the potential importance of the AB in C sequestration.

4.3. Relation to Blue Carbon Ecosystems

Carbon sequestration is a major component of the global carbon cycle. Tidal coastal ecosystems (Blue Carbon) may have the highest rates of carbon sequestration in sediments worldwide (Laffoley & Grimsditch, 2009). Thus, many reports suggest that these ecosystems have the potential to be singularly important in climate change mitigation, although considerable gaps in knowledge exist (Battin et al., 2009; Grimsditch et al., 2013; McLeod et al., 2011). Tidal saltmarshes, mangroves, and seagrass beds sequester OC at high rates relative to nontidal wetlands (Table 3) and 2 to 3 orders of magnitude greater than most other terrestrial ecosystems (Laffoley & Grimsditch, 2009).

Originally, the term Blue Carbon included only mangrove forests, seagrass beds, and salt marshes. However, the TFFW ecosystem is not typically listed among these blue carbon systems, although its vegetated tidal condition would warrant inclusion (Krauss et al., 2018). The TFFW ecosystem has high rates of C fluxes and sequestration compared to other blue carbon ecosystems (Krauss et al., 2018). Tidal wetland primary productivity is among the highest of all global ecosystems (Bridgham et al., 2006; Chmura et al., 2003) and both supports marine food webs and generates organic biomass (ultimately root bound) that may accrete with sea level rise. Interception and trapping of terrestrial sediments can provide a sink for upland carbon before it reaches the ocean (Ludwig, 2001; Raymond & Bauer, 2001). The lower AB lies in an area with limited tidal influence on floodplain topographic form and vegetation; although at the head of tides, it may not be considered a TFFW. However, the AB like other coastal river systems (Ensign et al., 2015; Ensign & Noe, 2018; Hupp et al., 2015; Kroes et al., 2007; Noe et al., 2016) traps most of the watershed derived sediment load (including OC) before reaching tide dominated regions, an important consideration for management and understanding regional and global elemental and sediment transport and cycling.

Although much of the Louisiana coastline is subsiding rapidly, the lacustrine and coastal deltas along the Atchafalaya Basin are actively trapping sediment and growing (Coleman et al., 1998). The lower AB, a region at the upstream edge of TFFW, may on average sequester more OC than TFFW and standard blue carbon systems (converted to an estimated long-term sequestration rate of 340 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$; Table 3). Unfortunately, many coastal ecosystems may suffer from human activities that degrade or diminish their ability to trap OC, such as channelization and levee construction as on the AB (Hupp et al., 2008). More study is needed to assess anthropocentric impacts on these globally critical areas.

5. Conclusions

The lower AB, over the relatively short-term, experiences the highest sustained fluvial sediment deposition rates (average 30 mm/year) in alluvial-forested wetland ecosystems of the United States (see previous synthesis papers by Hupp (2000) and Aust et al. (2012)). These high rates of deposition suggest that the large AB and its coastal fringe may sequester some of the greatest amounts of sediment and associated C annually along the southeastern U.S. coast. Previous studies have shown that connectivity to sediment-laden river water strongly facilitates sediment deposition, which is evident in the present study where mass of deposition decreases from the channel to interior and isolated areas.

This may be the first study to estimate OC accumulation rates and identify the amounts of autochthonous and allochthonous OC in near-tidal forested freshwater wetlands using carbon isotopes and total nitrogen analyses. The separation of the 23 floodplain sites closely tracks a gradient of decreasing hydrologic connectivity from Channel regime sites to Isolated East sites, ranging from allochthonous river water to highly isolated autochthonous sites with little to no connection to river water. The portion of OC sedimentation attributed to allochthonous sources decreased consistently from the connected Channel Regime to the Isolated East from 49 to 3% and strongly supports the large role that connectivity to river water plays in OC sediment sources. Thus, a considerable amount of OC, from both within and upstream of the AB, is sequestered in the AB before reaching the river mouth, coastal marshes, and Gulf of Mexico and underscores the potential importance of temperate coastal ecosystems in C sequestration and global climate patterns and trends in general.

The lower AB, a region at the upstream head-of-tide and transition to TFFW, may on average sequester more OC than other standard Blue Carbon systems and TFFW (converted to an estimated long-term sequestration rate of 340 g $C{\cdot}m^{-2}{\cdot}yr^{-1)}$. The distal upstream end of the tide spectrum is sometimes ignored in tidal wetland studies. These low-tidal areas may experience a near permanent hydroperiod owing to extremely low hydraulic gradients and large drag coefficients over large areas, facilitating high rates of deposition and sustained anoxic conditions. In the lower AB, these conditions have resulted in the burial of large volumes of organic material over millions of years. This historic storage of organic material is manifested as a booming natural gas extraction industry in this part of Louisiana. The carbon storage conditions that created this carbon extraction industry are likely still present.

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