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Spatial Analysis of Large Wood Storage in Coastal Plain Rivers of the Southeast US

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ABSTRACT

Large wood (LW) is widely recognized as a significant driver of geomorphic and ecological processes in river systems, but research on LW has been focused largely on low-order streams in high-gradient catchments. By comparison, there have been relatively few studies examining the channel-scale distribution of LW in higher-order, low-gradient river systems, such as those in the Coastal Plain of the Southeast US. Here, a field survey of LW in three Coastal Plain rivers in Alabama and North Carolina was conducted. Total wood loads were calculated, LW characteristics were examined, and Ripley's *K* analysis was used to investigate the channel-scale spatial distribution of LW in the study rivers for all pieces and for subsets based on stability and decay class. Results indicate that the range of LW loads in the study rivers (9.6–20.8 m^3 per 100-m channel length) is generally in line with loads reported for other temperate forested sites. Over half of the surveyed LW pieces were oriented perpendicular to the channel, and substantial proportions (36%–44%) were pinned, favoring the formation of jams. Ripley's *K* analysis showed that, on two of the three study rivers, LW was significantly clustered at short distance intervals, with higher degrees of clustering for pinned pieces, indicating the concentration of these pieces in jams. Older LW pieces (as indicated by decay class) were generally more clustered than new ones, potentially indicating the role of transport in moving pieces with longer residence time to favorable deposition locations during mobilizing flows.

1 | Introduction

Large wood (LW, generally defined as pieces of dead wood at least 1 m in length and 10 cm in diameter, located in the active channel) has long been recognized as a significant driver of physical and ecological processes in river systems (Zimmerman, Goodlett, and Comer 1967; Keller and Swanson 1979). Nevertheless, as noted by Wohl (2017), most knowledge of LW in rivers is based on studies of small- to medium-sized streams in steep headwater catchments, notably in the Pacific Northwest and Rocky Mountains of the United States, as well as in large gravel-bed rivers such as in Europe (e.g., Gurnell et al. 2001). The importance of LW for invertebrate habitat in low-gradient floodplain rivers, such as the Coastal Plain of the southeastern United States, has been established (Benke et al. 1985). There have, however, been a relatively few studies of the abundance and distribution of LW in higher-order rivers in low-gradient floodplains.

In part, the lesser focus on larger rivers is because previous research has found that LW loads decrease downstream within watersheds due to increasing channel width and transport capacity (Chen et al. 2006). However, this finding may partially be the result of a lack of data on larger rivers, as well as changes in LW abundance resulting from human activities such as timber harvest and river regulation (Collins, Montgomery, and

Haas 2002). Many large rivers once had extensive LW, as evidenced by historical accounts (Wohl 2014) and observations of buried wood (Davies, Gosse, and Rybczynski 2014). For example, Triska (1984) examined the massive log rafts that formed on Louisiana's Red River until the turn of the twentieth century and found that the debris led to blockage and flow reversals in tributary channels, overflowing onto the floodplain to form lakes, and a significant narrowing of the main channel. Following navigational improvements—snagging, levee construction, dredging, and logging—by 1904, the river had been transformed into a wide meandering channel very different from its previous form. Some unregulated large rivers still have significant LW loads (Webster et al. 2002; Boivin, Buffin-Bélanger, and Piégay 2015). Given these findings, there is a need for the analysis of LW distribution in high-order, low-gradient floodplain rivers to better understand the overall abundance of LW in these systems, the extent to which contemporary LW loads have been altered by human activities, and the ways in which recruitment and transport affect spatial patterns of LW storage.

The spatial distribution of LW can be characterized at multiple scales. At a basin scale, Massé and Buffin-Bélanger (2016) found that LW jams were more concentrated in the headwaters of a Québec river and decreased downstream because of the widening and deepening of the channel. Within the channel, LW is affected by discharge (Marcus et al. 2002), the presence of obstacles within or along the channel (Bocchiola, Rulli, and Rosso 2006), and cross-sectional geometry and planform (Downs and Simon 2001). LW storage tends to be higher in complex river segments (Gurnell et al. 2000; Wohl and Cadol 2011) with a lower unit stream power (Wyżga and Zawiejska 2005; Rigon, Comiti, and Lenzi 2012).

As with LW research in general, most previous studies of the channel-scale LW spatial distribution have been conducted in lower-order, higher-gradient streams. One exception is Magilligan et al. (2008), who surveyed LW in coastal Maine rivers and found that the frequencies and volumes of LW were relatively low, the LW was generally oriented parallel to flow rather than spanning the channel, and pool formation associated with LW was generally lacking. In contrast, Gurnell and Sweet (1998) analyzed the distribution of LW on a low-gradient river in the UK and found that the spacing of LW dams and pools was like that found in many steeper North American streams. Martin et al. (2018) applied spectral analysis to LW deposition locations on the low-gradient, variably confined Big River in Missouri, finding little correlation with channel-scale morphological features but significant periodicity. In the low-gradient San Antonio River in Texas, Curran (2010) found that LW pieces are frequently mobilized but that jams often re-form in the same locations. In one of the few prior studies focusing on LW in a Southeast US Coastal Plain river system, Wohl, Polvi, and Cadol (2011) examined the channel-scale distribution of LW in South Carolina's Congaree National Park. They found that LW loads were lower than in other temperate forests, which they attributed to higher decay rates in the humid subtropical climate as well as to higher transport rates resulting from frequent mobilizing flows. They also found a weaker relationship between channel geometry and LW deposition locations and fewer channel-spanning logjams compared to more laterally constrained channels (Wohl, Polvi, and Cadol 2011).

Here, we examined spatial patterns of LW at a channel-segment scale in three rivers of the Coastal Plain of North Carolina and Alabama, USA. The objectives were to (1) determine the total LW storage and wood characteristics in the study rivers, (2) analyze the spatial distribution for all LW pieces, and (3) examine differences in spatial distribution based on stability and decay class to assess the relative roles of recruitment and transport in determining patterns of LW storage. In its exploration of LW distribution in Coastal Plain rivers, the study contributes to the literature on LW dynamics in understudied higher-order, low-gradient rivers.

2 | Methods

2.1 | Study Sites

The research was conducted on three relatively large low-gradient floodplain rivers: the Lumber River in southeastern North Carolina (a tributary of the Pee Dee River, which flows into Winyah Bay in South Carolina), the Sipsey River in west-central Alabama (a tributary of the Tombigbee River, which joins the Alabama River to flow into Mobile Bay), and the West Fork Choctawhatchee River in southeastern Alabama (a tributary of the Choctawhatchee River, which flows into Choctawhatchee Bay in Florida) (Figure 1). All three rivers are in the Coastal Plain physiographic province and have humid subtropical climates (a mean annual temperature of 20°C–23°C, a mean annual precipitation of 1162–1451 mm). The humid subtropical climate of the study area is a large-scale control that affects LW dynamics because wood decomposition rates are expected to be higher in the study area than in cooler or drier climates (Harmon 1982). Another element of the Southeast climate that affects LW dynamics is the frequency of tropical cyclones, which can result in mass recruitment and transport of LW (Van Lear 1996; Phillips and Park 2009). The study river segments flow through extensive unconfined floodplains with second-growth forest (< 75 years in age) (Figure 2). Dominant floodplain canopy tree species include *Taxodium distichum* (bald cypress), *Nyssa aquatica* (water tupelo), *Liquidambar styraciflua* (redgum), *Nyssa sylvatica* (black gum), *Quercus nigra* (water oak), *Populus heterophylla* (swamp cottonwood), *Ulmus americana* (American elm), and *Quercus laurifolia* (laurel oak). Forest type also exerts a large-scale control on LW dynamics because of the higher mortality among hardwood trees (Harmon and Hua 1991), which dominate much of the riparian zones of the Coastal Plain, as well as the propensity for the wood of some species to sink (Wallace and Benke 1984).

The Lumber River experienced its highest and second-highest flows in the 100-year record of its United States Geological Survey (USGS) gage (02134500) during Hurricane Matthew in October 2016 and Hurricane Florence in September 2018. As a result, much of the accumulated LW in the Lumber River may have been transported downstream, but it is also possible that blowdown from the hurricanes recruited a large amount of additional LW. The largest recent flood on the Sipsey River, with a recurrence interval of ~10 years, occurred in January 2009, and the largest recent flood on the West Fork Choctawhatchee River, with a recurrence interval of ~11 years, occurred in December

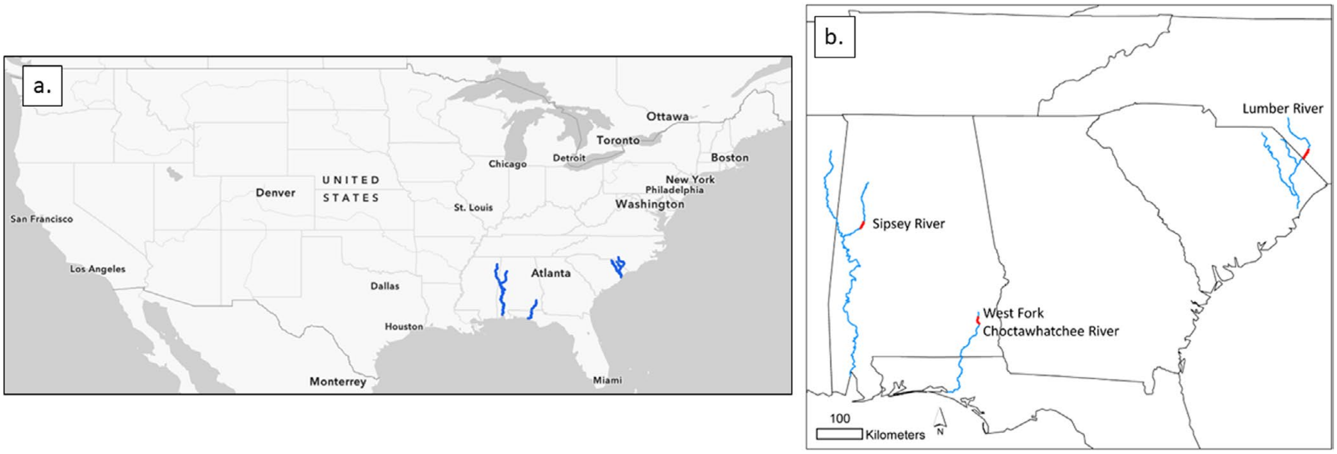

FIGURE 1 | (a) Location of study rivers in the United States. (b) Location of study segments on the three study rivers. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 | Study segments on the (a) Lumber River, (b) Sipsey River, and (c) West Fork Choctawhatchee River. [Color figure can be viewed at wileyonlinelibrary.com]

2009. It is therefore expected that LW on these two rivers has been relatively stable recently.

We selected these study rivers in part because all three are relatively large low-gradient floodplain rivers with fine-grained substrates, which are understudied when it comes to LW dynamics. The study segments of the Sipsey and West Fork Choctawhatchee rivers are both fourth-order rivers, and the Lumber River segment is a fifth-order river. The drainage areas upstream of the study segments (3204 km^2 for the Lumber River, 1242 km^2 for the Sipsey River, 227 km^2 for the West Fork Choctawhatchee River) are near to or substantially larger than the ~500-km^2 upper limit of drainage areas of rivers featured in most previous LW studies surveyed by Wohl (2017). The average channel slopes for the three study segments range from 0.0002 to 0.0013. All three rivers have a substrate of sand and finer grains. Use of these study rivers allows for the analysis of LW dynamics in relatively large, low-gradient, fine-grained floodplain rivers.

Another factor in site selection was that all three rivers are relatively intact physically and ecologically. Both the Sipsey River and West Fork Choctawhatchee River were listed as Strategic Habitat Units (SHUs) (United States Fish and Wildlife Service 2024). SHUs are river corridors with geomorphologically stable channels, no major dams or diversions, good water quality, a diversity of channel substrates, and few or no invasive species, which provide a habitat for listed and imperiled aquatic species. The Lumber River is listed as both a National Wild and Scenic River and a North Carolina Natural and Scenic River, both designations intended to protect free-flowing rivers and their outstanding natural, scenic, recreational, and other values (National Wild and Scenic Rivers System 2024). The rivers' location in remote protected areas (Lumber River State Park for the Lumber, the Alabama Forever Wild Land Trust for the Sipsey, Blue Springs State Park for the West Fork Choctawhatchee) minimizes the risk of individuals interfering with LW, and the relative lack of human impact on the study rivers allows for the examination of LW dynamics in the absence of recent large-scale timber harvest, flow regulation, and other activities that might otherwise obscure or eliminate the natural patterns and processes.

Legacy land use and other human impacts are major drivers of fluvial and forest processes that affect LW dynamics, and the three study rivers are not free of such impacts. On the Lumber River in the late 1800s, a reported 200 rafts carrying over 1000 m^3 of timber per year were floated down to the Pee Dee River and its port in Georgetown, South Carolina (United States Army Corps of Engineers [USACE] 1977). The Lumber River was never a major navigational waterway, however, with steamboat traffic on the Pee Dee River extending only as far as its confluence with the Lumber. The only documented federal navigation project on the Lumber River was a snagging and clearing project completed in 1897 from the river's mouth to Lumberton (USACE 1977). More recently, state-funded snagging operations have occurred following hurricanes Matthew and Florence but only for the portion of the river from the state line to Fair Bluff, downstream of the study segment (Smith 2019). The Sipsey River was also never heavily used for navigation, with steamboat traffic on the downstream Tombigbee River but not on the Sipsey itself. In 1908, the United States Army Corps of Engineers reported that "the only attempts to navigate this stream have been floating log rafts down river to sawmills by individuals" and made a recommendation to Congress that "the river is not worthy of improvement" (Congressional Record 1908). Nevertheless, snagging was implemented for 3 km of the river in 1940 (with 12,862 m^3 of debris removed) (USACE 1940), on 10 km in 1941 (with 18,063 m^3 removed), and on 51 km in 1974 (USACE 1974). The mainstem Choctawhatchee River experienced log rafting, and 177,599 snags were removed from 350 cumulative kilometers from 1874 to 1912 (Wohl 2014). The West Fork, however, is too small for navigation and has not experienced any channel improvements. Overall, compared to other Coastal Plain rivers (many of which are dammed and/or have ongoing timber harvest activities), the free-flowing and protected status of the study rivers makes them relatively less altered regarding LW loads.

2.2 | Wood Survey

In June and October 2022, we performed systematic field-based surveys of LW on each of the three study rivers. We conducted the surveys using a protocol implemented by Martin, Pavlowsky, and Harden (2016), which was based on the Level II survey protocol outlined in Schuett-Hames et al. (1999). We counted each visible individual piece of LW, measured its diameter using calipers and length using a stadia rod, and noted its orientation, stability, and decay class (Table 1). For pieces with multiple trunks or large branches, we measured the length and diameter of each trunk/branch separately and summed them to calculate the total volume. We also recorded the location of each LW piece with a real-time kinematic global positioning system (RTK-GPS). While we acknowledge the importance of root wads and LW jams, they were excluded from the inventory in order to simplify transport analyses and focus on individual piece transport. However, root wads were noted when still attached to trunks because of their influence on piece stability.

2.3 | Statistical Analysis

To quantify wood loads, we used the length and diameter measurements to calculate the volume of each LW piece, assuming a cylindrical shape. We summed the volumes for all pieces on each river and divided by the segment length to calculate normalized LW loads for each river.

To characterize the spatial distribution of LW storage locations within the channel, we used Ripley's K, a form of point pattern analysis that relates the number of neighbors found within

TABLE 1 | Field LW survey methods.

Attribute	Description
Length (m)	Distance from end to end
Diameter (m)	Diameter at middle
Orientation class	1: Parallel to flow
	2: Perpendicular to flow
	3: Intermediate angle to flow
Stability class	Buried
	Pinned
	Root wad attached
	Unstable
Decay class	1: Contains leaves, branches, and all bark
	2: No leaves, contains branches and > 50% of bark
	3: Few remaining branches, > 50% of bark
	4: No branches, < 50% of bark
	5: No bark, soft wood
Location	Measured with survey-grade RTK-GPS

varying distance intervals to the average concentration of features throughout the study area:

$$\hat{K}(t) = \lambda^{-1} \sum_{i \neq j} \frac{I(d_{ij} < t)}{n}$$

where d_{ij} is the Euclidean distance between the ith and jth points in a dataset of n points, t is the search radius, λ is the average density of points, and I is the indicator function (Ripley 1976). The Euclidean distance is determined based on the x and y locations of the data points within a Cartesian coordinate plane, which often introduces error when working with river data that are limited to a linear but sinuous boundary, calculating distances between points regardless of the channel boundary, crossing meander bends, and thus producing erroneous distance measurements. As such, spatial data transformations have been developed to convert the Cartesian coordinates of such data into a channel-centered coordinate system that eliminates such distance measurement errors (Legleiter and Kyriakidis 2007). However, for this study, the relatively short lengths of the study segments and the resulting lack of meandering that occurs within those short segments render such concerns negligible, and therefore no transformations were conducted.

We implemented Ripley's K using the Multi-Distance Spatial Cluster Analysis tool in ArcGIS Pro, using a manually delineated study area that encloses the river channel, five distance bands scaled to the study area, and Ripley's edge correction formula. For each analysis, we generated 999 permutations of random points so that a 95% confidence envelope for the observed distribution could be computed. If K is higher than expected, the pattern is clustered. If K is lower than expected, the pattern is dispersed. If observed K and expected K are equal, the distribution is random. To simplify the visual interpretation of Ripley's K output, a transformation is applied to $\hat{K}$ that yields a value $L(d)$, which represents a linearized $\hat{K}$, allowing for visual comparison to the diagonal line representing the expected outcome for complete spatial randomness. Therefore, the output is plotted on a Y axis of $L(d)$ and an X axis of distance. The $L(d)$ transformation is performed using the following equation:

$$L(d) = \sqrt{A \frac{\sum_{i=1}^{n} \sum_{j=1, j \neq 1}^{n} K_{i,j}}{\pi n(n-1)}}$$

where d is the distance, n is equal to the total number of features, A represents the total area of the features, and $k_{i,j}$ is the weight. If there is no edge correction, then the weight will be equal to one when the distance between i and j is less than d and will equate to zero otherwise. Using a given edge correction method will modify $k_{i,j}$ slightly.

We performed Ripley's K analysis on all LW locations for each river to determine whether they were clustered or not, to see whether there is some spatial control on LW locations. We also conducted separate Ripley's K analyses for different stability and decay classes to assess whether "old" LW pieces (those that have been in the river for a relatively long period of time) are more clustered than "new" pieces (those recently recruited). Decay class is certainly controlled by a variety of factors, i.e. time since recruitment, state of decay prior to recruitment, or species-specific rates of decay; however, for the purposes of this study, we are assuming that if pieces are more decayed, then they have been in the channel longer than those that are less decayed. Therefore, if old pieces are more clustered than new pieces, that would suggest that transport is likely a stronger control on LW locations than recruitment because pieces that have been in the river for a longer period have had the opportunity to be transported to favorable depositional locations by mobilizing flows. If, in contrast, new pieces are more clustered than old pieces, that would indicate that pieces are not being transported far from their site of recruitment.

3 | Results

3.1 | Total Wood Loads and Characteristics

The normalized frequency of LW ranged from 17.0 pieces per 100-m channel length on the Lumber River to 38.9 pieces per 100-m channel length on the Sipsey River (Table 2). Normalized LW volumes ranged from 9.6 m^3 per 100-m channel length on the West Fork Choctawhatchee River to 20.8 m^3 per 100-m channel length on the Sipsey. The mean length of LW pieces was 5.0 m (West Fork Choctawhatchee) to 10.2 m (Sipsey), and the mean diameter was 0.20 m (West Fork Choctawhatchee) to 0.26 m (Lumber) (Figure 3). On all three rivers, the dominant orientation (53%–69% of total pieces) was perpendicular to the channel. The three rivers differed in their dominant stability class: pinned for the Lumber River (44%), unstable for the Sipsey River (37%), and buried for the West Fork Choctawhatchee River (40%). On the Lumber and Sipsey rivers, the dominant decay class was 2 (moderately low decay) (31% and 61%, respectively). On the West Fork Choctawhatchee River, the dominant decay class was 4 (moderately high decay) (41%).

TABLE 2 | Characteristics of LW from the field survey.

Attribute	Lumber River	Sipsey	West Fork Choctawhatchee
Segment length (m)	836	126	374
Total number of LW pieces	142	49	121
Normalized frequency (no./km)	17.0	38.9	32.3
Normalized volume (m^3/100 m)	11.2	20.8	9.6
Mean LW length (m)	6.5	10.2	5.0
Mean LW diameter (m)	0.26	0.24	0.20

3.2 | Ripley's *K* Analysis

When applied to all LW pieces, Ripley's K analysis found significant clustering for the Lumber River at distances of up to 27 m and on the West Fork Choctawhatchee River for distances of up to 14 m (Figure 4). On the Sipsey River, LW pieces were randomly distributed at all distance intervals.

Looking separately at clustering patterns by stability class (Figures 5 and 6), buried pieces on the Lumber River were significantly clustered for the first distance interval only (13 m) and were randomly distributed at all distance intervals for the Sipsey and West Fork Choctawhatchee rivers. Pinned pieces, in contrast, were significantly clustered for the first four distance intervals (up to 53 m) on the Lumber River and the first three distance intervals (up to 21 m) on the West Fork Choctawhatchee River while being randomly distributed on the Sipsey River.

We also compared the spatial patterns of pieces in varying states of decay by aggregating decay classes 1 and 2 into a single "low-decay" class and classes 4 and 5 into a single "high-decay" class (Figures 7 and 8). On the Lumber and Sipsey Rivers, low-decay pieces were significantly clustered for the first distance interval only (13 and 3 m, respectively) and were randomly distributed on the West Fork Choctawhatchee River. High-decay pieces, meanwhile, were significantly clustered for the first three distance intervals on the Lumber River (up to 40 m) and for the first distance interval (7 m) on the West Fork Choctawhatchee River. There were too few highly decayed pieces on the Sipsey River to complete the analysis.

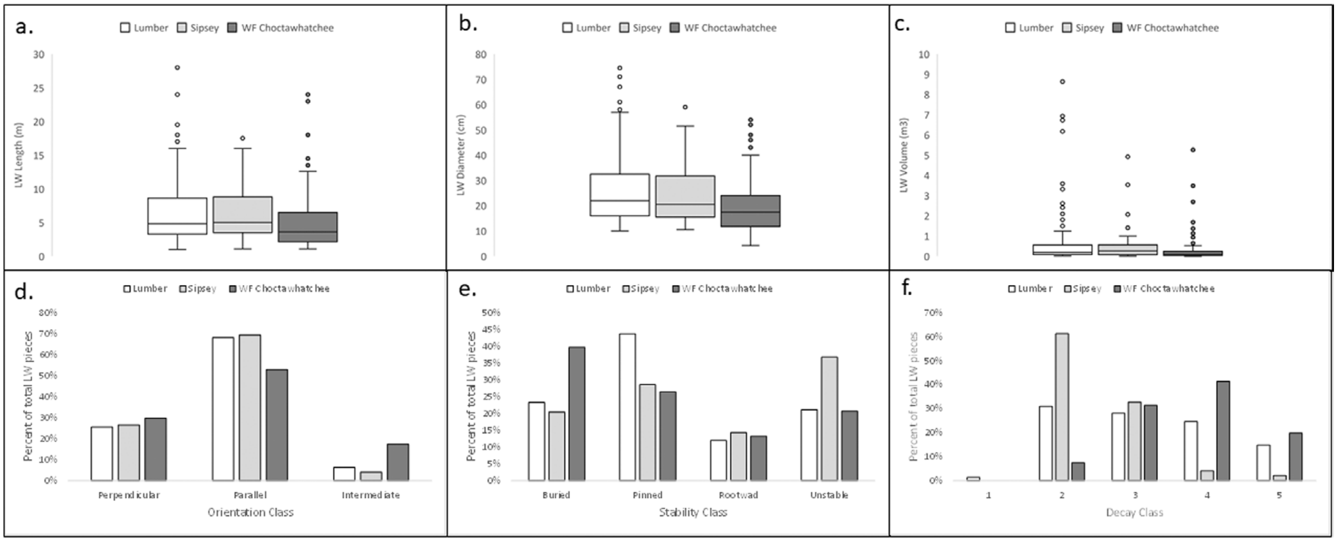

FIGURE 3 | Characteristics of LW pieces measured in the field survey. (a) LW length, (b) LW diameter, (c) LW volume, (d) orientation class, (e) stability class, and (f) decay class. The line within the boxes of the boxplots represents the median value, and the box represents the 25th to 75th percentile.

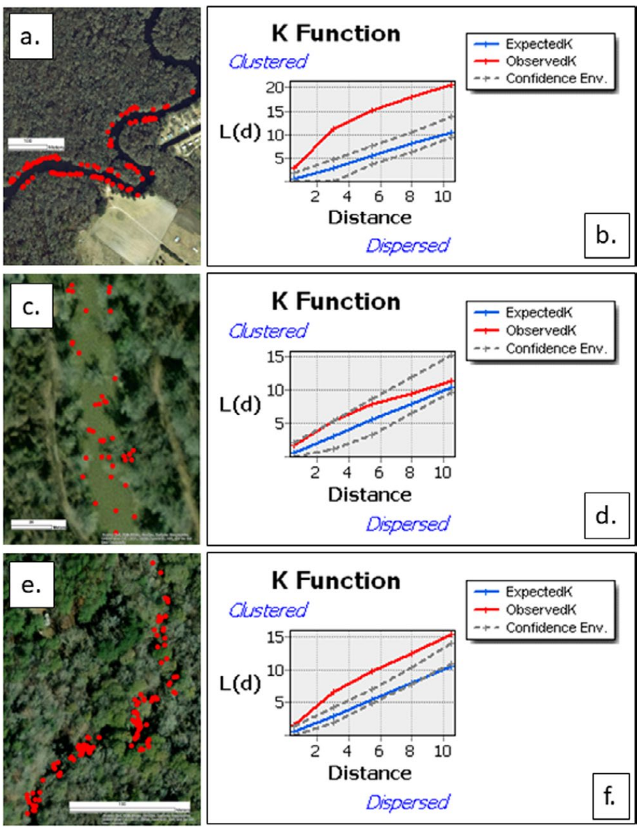

FIGURE 4 | (a) Locations of all LW pieces on the Lumber River study segment; (b) Ripley's *K* function for all LW pieces on the Lumber River study segment; (c) locations of all LW pieces on the Sipsey River study segment; (d) Ripley's *K* function for all LW pieces on the Sipsey River study segment; (e) locations of all LW pieces on the West Fork Choctawhatchee River study segment; and (f) Ripley's *K* function for all LW pieces on the West Fork Choctawhatchee River study segment. [Color figure can be viewed at wileyonlinelibrary.com]

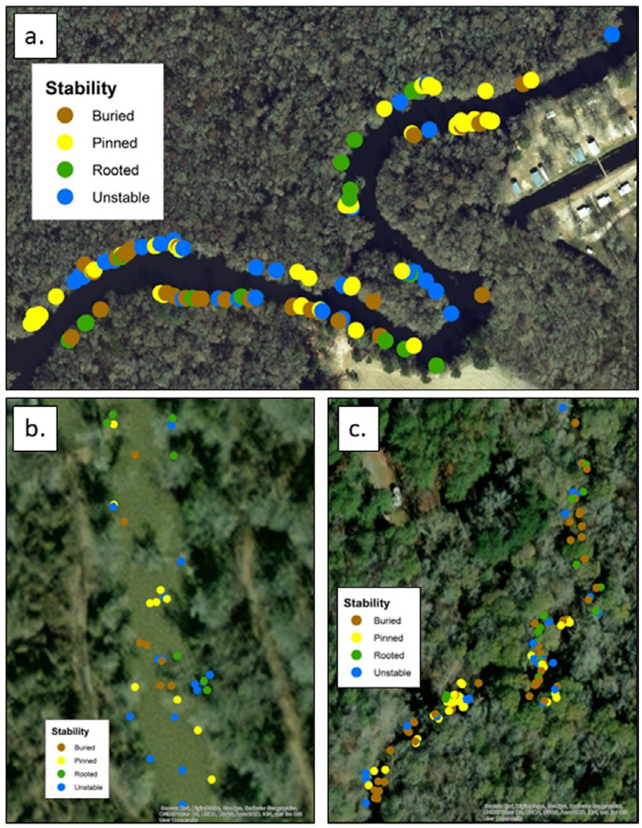

FIGURE 5 | LW pieces by stability class on study segments of the (a) Lumber River, (b) Sipsey River, and (c) West Fork Choctawhatchee River. [Color figure can be viewed at wileyonlinelibrary.com]

4 | Discussion

4.1 | LW Loads

The LW loads found for our three study rivers (9.6–20.8 m^3 per 100-m channel length) overlap with those found by Wohl, Polvi,

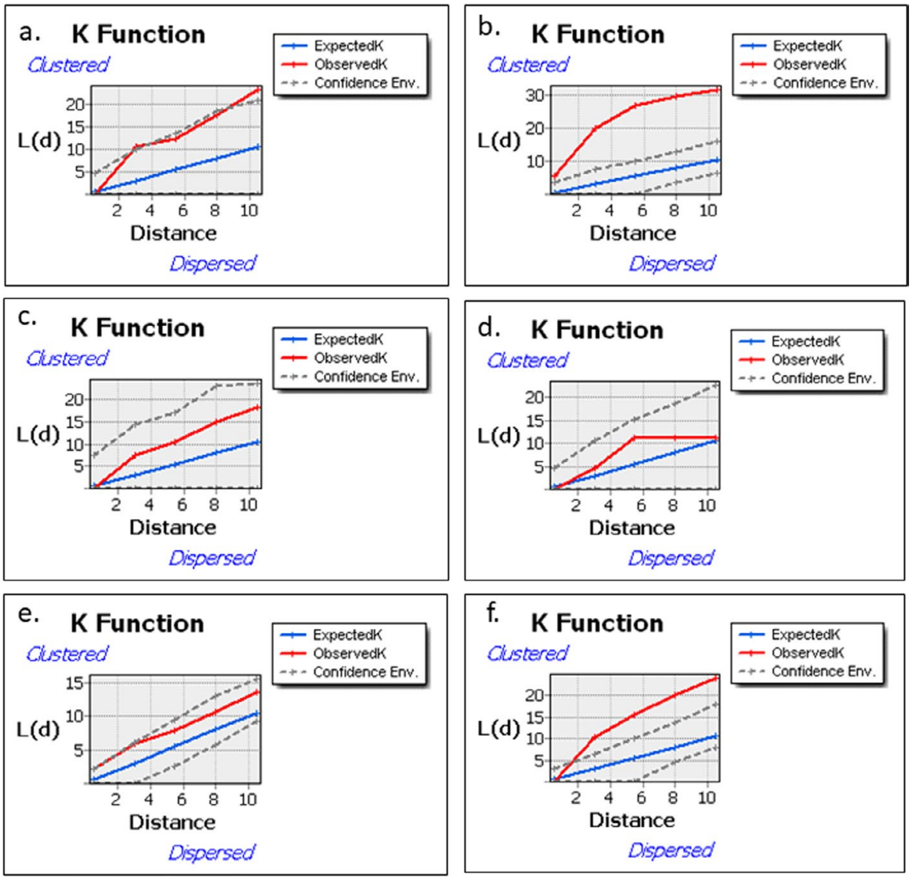

FIGURE 6 | Ripley's *K* function for (a) buried LW pieces, Lumber River; (b) pinned LW pieces, Lumber River; (c) buried LW pieces, Sipsey River; (d) pinned LW pieces, Sipsey River; (e) buried LW pieces, West Fork Choctawhatchee River; and (f) pinned LW pieces, West Fork Choctawhatchee River. [Color figure can be viewed at wileyonlinelibrary.com]

and Cadol (2011) for Congaree National Park in South Carolina (9.4–18.6 m^3 per 100-m channel length). Like the Congaree, our sites were all in bottomland hardwood forest of the Southeast US Coastal Plain. Unlike the Congaree, which is dominated by old-growth forest, our sites are characterized by second-growth forest that has been logged within the past century. The finding that our wood loads are nonetheless similar to those found by Wohl, Polvi, and Cadol (2011) for the Congaree contrasts with the expectation that instream wood loads would increase with forest age (Morris, Goebel, and Palik 2007; Warren et al. 2007, 2009). Another difference with the Congaree is that our study sites have much larger drainage areas (227–3204 km^2) than the sites used by Wohl, Polvi, and Cadol (2011) (110–270 km^2). Generally, LW loads are expected to decrease with increasing drainage area (Marcus et al. 2002). However, the Wohl, Polvi, and Cadol (2011) study examined both instream wood and floodplain wood, while our focus was solely on instream wood. Wohl, Polvi, and Cadol (2011) found significantly higher instream LW loads compared to floodplain LW loads, so the entire span of our data should be compared with the upper end of theirs. Accordingly, the LW loads found for our study rivers are in fact generally lower than the Wohl, Polvi, and Cadol (2011) findings for instream wood in the Congaree, consistent with the expectation that our loads would be lower because of younger forest and larger drainage area.

Wohl, Polvi, and Cadol (2011) also compiled previously published estimates of wood loads for old-growth forests in a variety of locations and settings. Our findings for this study overlap with LW loads reported for temperate deciduous forest in Michigan, USA (7–62 m^3 per 100-m channel length; Morris, Goebel, and Palik 2007), subantarctic to subtropical rainforest in New Zealand (4–49 m^3 per 100-m channel length; Meleason et al. 2005), temperate *Nothofagus*/*Araucaria* forest in Chile (3.8–236 m^3 per 100-m channel length; Andreoli, Comiti, and Lenzi 2007), subantarctic *Nothofagus* forest in Argentina (1–24 m^3 per 100-m channel length; Mao et al. 2008), and subalpine conifer forest in Colorado, USA (0.2–32 m^3 per 100-m channel length; Wohl and Cadol 2011). Like the Wohl, Polvi, and Cadol (2011) findings for the Congaree, however, the loads for our study rivers are generally at the low end of the estimates for temperate forests. This is likely the result of a combination of high wood mobility in Southeast US Coastal Plain rivers and higher decay rates in the region's subtropical climate compared to rivers in cooler or drier climates. Rivers in tropical wet forests in Costa Rica, which have similarly high wood mobility and a climate even more favorable to decay, have a similar reported range of LW loads (3–35 m^3 per 100-m channel length; Cadol et al. 2009). The coniferous temperate forest of the Pacific Northwest of North America, in contrast, has substantially higher loads of up to 305 m^3 per 100-m channel length (Fox

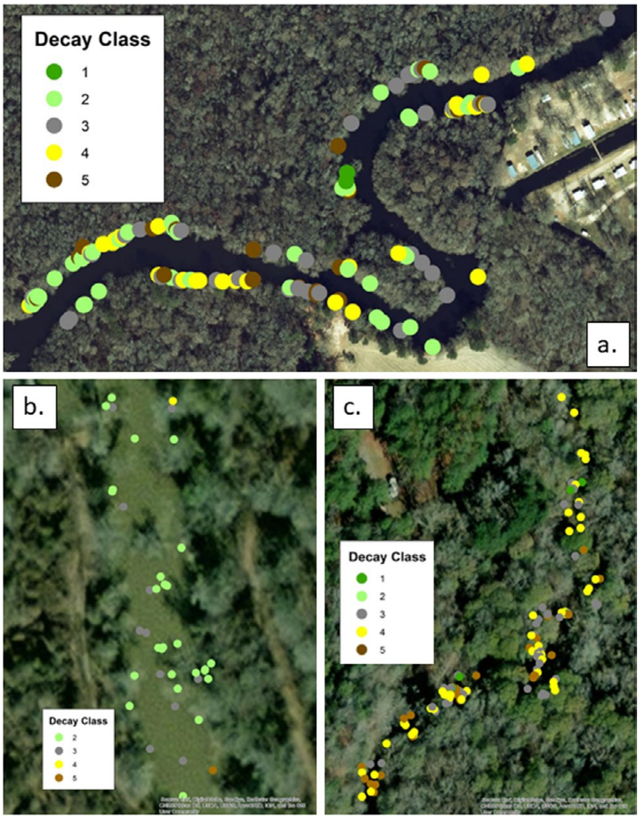

FIGURE 7 | LW pieces by decay class on study segments of the (a) Lumber River, (b) Sipsey River, and (c) West Fork Choctawhatchee River. [Color figure can be viewed at wileyonlinelibrary.com]

and Bolton 2011). Nevertheless, our findings suggest that LW loads are relatively abundant in Southeast US Coastal Plain rivers, comparable to those in tropical forest and not substantially lower than in most temperate forests.

4.2 | LW Characteristics

There were some differences among our study rivers in terms of the relative stability and decay class of LW. Both the Lumber and Sipsey Rivers had relatively high percentages of less-decayed wood (32% of all pieces on the Lumber River and 61% of all pieces on the Sipsey River were in decay class 1 or 2) and wood that was either pinned (44% of all pieces on the Lumber and 29% of all pieces on the Sipsey) or unstable (21% of all pieces on the Lumber and 37% of all pieces on the Sipsey). The West Fork Choctawhatchee River, in contrast, was more dominated by highly decayed wood (61% of all pieces were in decay class 4 or 5) and buried wood (40% of all pieces). This difference potentially indicates an abundance of wood recently recruited by individual tree mortality, bank erosion, or windthrow on the Lumber and Sipsey Rivers, while a greater proportion of the wood load on the West Fork Choctawhatchee may have been subjected to fill and subsequent scour during large flow events. Wohl, Polvi, and Cadol (2011) found that 46% of LW pieces on the Congaree River were buried, similar to the West Fork Choctawhatchee. Additionally, the higher percentages of less-decayed wood on the Lumber and Sipsey Rivers could partially be explained by the larger channel sizes, which allows for higher rates of transport and subsequent sorting; i.e. pieces that have been in the system for a longer period of time (more decayed) and have been subjected to more transport events may have become submerged or completely buried on the channel bed or deposited on floodplains. LW that is completely submerged, buried, or deposited on floodplains was not accounted for with the inventory protocol used here and therefore could introduce decay class bias related to channel size.

With regard to the orientation of LW, Wohl, Polvi, and Cadol (2011) found that instream wood was more likely to be preferentially aligned than floodplain wood, with over half of their channel transects exhibiting distributions of wood orientations that were significantly different from a uniform distribution. Similarly, over half (53%–69% across the three rivers) of the LW measured was oriented perpendicular to the channel, a nonrandom orientation. These perpendicular orientations are a characteristic of ramps and bridges resulting from individual treefalls in which the wood completely or partially spans the channel. On the Congaree, Wohl, Polvi, and Cadol (2011) found that ramps and bridges were relatively rare, making up only 13% of all pieces. The high concentration of perpendicularly oriented LW pieces in our study rivers likely results from bank undercutting leading to frequent toppling of trees into the channel. Bank erosion is the dominant mechanism of LW recruitment on sand-bed Coastal Plain rivers like our study rivers (Phillips and Park 2009).

The relatively high frequency of ramps, bridges, and other perpendicularly oriented pieces on our study rivers has implications for both LW mobility and geomorphic effects. In terms of mobility, perpendicularly oriented pieces are often pinned on one or both ends by living trees or other obstacles on the banks, making them generally less likely to experience fluvial transport. Wohl, Polvi, and Cadol (2011) attribute the expected high mobility of LW on the Congaree River in part to the relatively low instream retention due to the observed low frequency of ramps and bridges. LW on our study rivers, in contrast, exhibited relatively high rates of pinning (44% of all pieces on the Lumber, 29% of all pieces on the Sipsey, 26% of all pieces on the West Fork Choctawhatchee). This high frequency of pinned pieces means that, contrary to the expectation of low instream retention and consequent high mobility of LW in low-gradient floodplain rivers, wood mobility may potentially be lower than expected on some Coastal Plain rivers where perpendicular orientations and pinning are common. Further research that includes direct tracking of LW movement on Coastal Plain rivers is needed to verify this possibility.

The geomorphic implications of relatively high frequencies of perpendicularly oriented and pinned LW are that these pieces are potential sites for the formation of channel-spanning logjams. Wohl, Polvi, and Cadol (2011) found that geomorphologically effective channel-spanning logjams—those that elevate the local water surface elevation through backwater effects—are rare on the Congaree River because of the lack of lateral confinement. We also observed few such jams on the Lumber River, the largest of our three study rivers. This paucity of channel-spanning jams in the Lumber is mostly the result of a channel that is wide

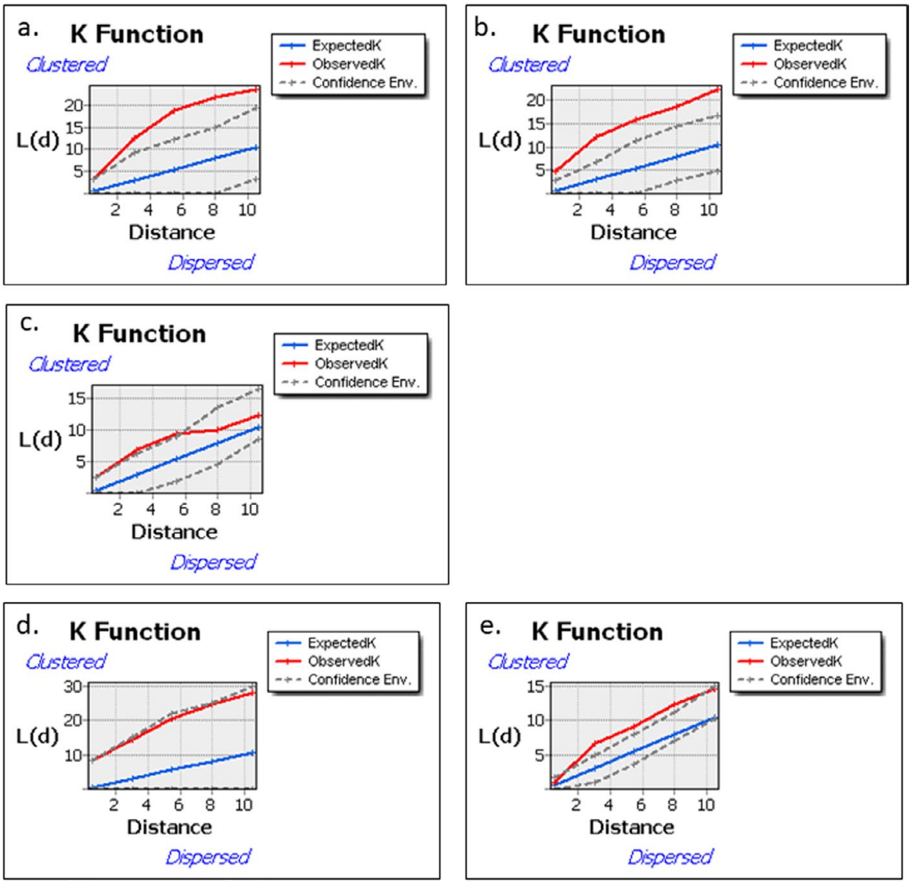

FIGURE 8 | Ripley's *K* function for (a) low-decay LW pieces (classes 1 and 2), Lumber River; (b) high-decay LW pieces (classes 4 and 5), Lumber River; (c) low-decay LW pieces (classes 1 and 2), Sipsey River; (d) low-decay LW pieces (classes 1 and 2), West Fork Choctawhatchee River; and (e) high-decay LW pieces (classes 4 and 5), West Fork Choctawhatchee River. [Color figure can be viewed at wileyonlinelibrary.com]

enough (average bankfull width of ~23 m) that only the tallest trees can completely span it. Also, the Lumber is managed as a recreational river by Lumber River State Park, so major channel obstructions are typically removed. We did, however, observe many channel-spanning jams, complete with upstream backwater and downstream scour pools, on the Sipsey and especially on the West Fork Choctawhatchee. This difference is partly the result of the smaller channel sizes (average bankfull width ~15 m for the Sipsey and ~7 m for the West Fork Choctawhatchee) and partly because these two rivers are not managed for recreation, are not popularly used for boating, and experience only infrequent and informal wood removal by individuals. The presence of frequent channel-spanning jams on the Sipsey and West Fork Choctawhatchee Rivers suggests the potential for persistent LW that significantly affects sediment transport and channel morphology in relatively small and less-managed Coastal Plain rivers like these, but future research is needed to specifically examine the geomorphic effects of LW in Coastal Plain rivers.

4.3 | Ripley's *K* Analysis

The tendency toward jam formation is reflected in our Ripley's K analysis results. When looking at all LW pieces, they were significantly clustered at localized distance intervals (14–27 m) on the Lumber and West Fork Choctawhatchee Rivers, indicating the concentration of pieces to form jams. This finding contrasts with Wohl, Polvi, and Cadol (2011), who applied Ripley's *K* analysis to LW pieces on the Congaree River and found generally random distributions, especially at distance intervals < 20 m. Several other studies have also used Ripley's *K* analysis to examine the spatial distribution of LW in rivers. Similar to our results, Kraft and Warren (2003) found that LW was clustered at localized spatial scales (up to 40 m) on streams in the Adirondack Mountains of New York, and Wohl and Cadol (2011) found that LW was highly clustered at all analyzed length scales in streams of the Colorado Front Range. Other studies have found the opposite pattern, with random patterns at local scales and clustered patterns at distance intervals of hundreds to thousands of kilometers as a function of stream-valley geomorphology (Morris, Goebel, and Palik 2010; Wohl and Jaeger 2009).

The only one of our three study rivers that exhibited generally random LW distributions in Ripley's *K* analysis was the Sipsey River. This difference is partly due to the Sipsey's smaller sample size (49 pieces surveyed on the Sipsey, compared to 142 on the Lumber and 121 on the West Fork Choctawhatchee) and shorter sample segment (126 m surveyed on the Sipsey, compared to 836 m on the Lumber and 374 m on the West Fork Choctawhatchee). Also, we surveyed the Lumber and West Fork Choctawhatchee in June 2022 during relatively high flows, while we surveyed the Sipsey River in October 2022 during low flows. As a result, many more pieces of LW were exposed on the dry riverbed on the Sipsey, while some pieces on the Lumber and West Fork Choctawhatchee were submerged. While we attempted to include all pieces in our LW survey, some deeply submerged pieces were impossible to measure, and some were undoubtedly not even visible and were therefore missed entirely in our survey. Accordingly, the datasets for the Lumber and West Fork Choctawhatchee are likely missing some submerged pieces, which are more likely to be randomly distributed than the pieces that are concentrated on channel margins, bars, and other low-energy environments. These potentially missing submerged pieces are a limitation of our dataset. However, because much of the geomorphic effects of LW are accomplished by channel-spanning pieces, pieces that form jams, and pieces that line banks, missing some individual submerged pieces from deep parts of the channel is not necessarily a major omission in terms of the overall effects of LW on channel morphology.

Examining differences in Ripley's *K* analysis by stability class, buried pieces were mostly randomly distributed. Buried pieces are likely to be legacy LW that has been recently exposed by scour, so it is logical that there is little clustering of buried pieces. Pinned pieces, in contrast, were highly clustered at localized scales for the Lumber and West Fork Choctawhatchee Rivers, indicating that these pinned pieces can serve as key pieces in jam establishment.

In terms of decay class, Ripley's *K* analysis found that highly decayed pieces were more consistently clustered than low-decay pieces on the Lumber and West Fork Choctawhatchee Rivers. In general, decay class is an indicator of residence time (Russell et al. 2014). Low-decay pieces were recently recruited into the channel and therefore may not have experienced a mobilizing flow yet, so they are more likely to be randomly distributed, not having moved far from their site of recruitment. Highly decayed pieces often have had a longer residence time in the river and therefore are more likely to have experienced mobilizing flows. Assuming that they are not initially pinned, buried, or otherwise incapable of transport, these highly decayed pieces have potentially already moved to a favorable deposition location, such as becoming part of a jam. The finding that highly decayed pieces are more clustered than less-decayed pieces can be interpreted as a potential indicator that transport is a significant factor in determining LW deposition locations, as many pieces that have been in the river for a substantial amount of time have seemingly experienced fluvial transport based on their clustering pattern.

5 | Conclusions

This study examined LW loads, characteristics, and spatial distributions in three low-gradient, higher-order rivers in the Coastal Plain of the Southeast US. Among the major findings were that LW is a substantial component of Coastal Plain rivers, with loads generally in line with rivers in other temperature forested environments, despite the general lack of research attention to these types of rivers in the extensive LW literature. Many LW pieces formed channel-spanning jams on two of our study rivers, providing preliminary evidence that LW may affect sediment transport and channel morphology of smaller and less-managed Coastal Plain rivers. Ripley's *K* analysis revealed a generally high degree of localized clustering of LW pieces, with older pieces more clustered than newer ones, potentially indicating a high mobility of wood in the study rivers. Additional research on mobility and geomorphic effects of LW in low-gradient, higher-order rivers such as those in the Southeast US Coastal Plain will expand the understanding of the varied environments in which LW helps to shape river systems.

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Data Availability Statement

Data supporting this research are publicly available through CUAHSI Hydroshare: http://www.hydroshare.org/resource/46bbd0dff2a6412f89553bb548c90bf7.

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