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Instream Woody Debris and Riparian Forest Characteristics in the Sabine River, Texas

Matthew McBroom[1,*], Michael Ringer[1], and Yanli Zhang[1]

Abstract - We examined instream large woody debris (LWD) dynamics on the Sabine River, TX. All wood >10 cm in diameter and >2 m long was measured on four river meanders (meander wavelengths) below the dam on Toledo Bend Reservoir. We determined LWD species, degree of decay, bank orientation, jam association, and stage contact. We also measured riparian vegetation characteristics on each meander. LWD volumes were significantly greater at the site immediately below Toledo Bend Dam, due to the relatively steeper channel gradient and higher rates of channel erosion. Based on mass balance estimates, between 11 and 21% of total annual recruitment came from upstream fluvial transport, and the remainder resulted from bank erosion and tree mortality. We estimated average LWD residence time to be 12–14 years. The lower Sabine River is transport-limited for sediment, and the same is true for LWD. Based on these measurements, it is unlikely that Toledo Bend Reservoir is having a significant impact on LWD dynamics at the measurement reaches due to lacustrine wood storage. Of greater concern in the study system are riparian forest degradation and invasive species spread, which may dramatically affect future LWD loadings and residence times, and thus, riverine biota.

Introduction

Large woody debris (LWD) is an extremely important structural and functional component for aquatic ecosystems (Wallace et al. 1993). While LWD habitat may only be a small part of the total habitat surface in southeastern US rivers (≈4%), it may support over 60% of the total invertebrate biomass for a river stretch (Benke et al. 1985). In addition, fish species obtained at least 60% of their prey biomass from snag habitat (Benke et al. 1984). Ecologically, LWD provides a reservoir for nutrients and energy vital to the detrital food chain, nutrient cycling, plant growth, and productivity (Goodburn and Lorimer 1998, Harmon et al. 1986, Huston 1993, Muller and Liu 1991). Stable debris slows fine organic matter transport and allows greater opportunity for biological processing of fine organic detritus (Swanson et al. 1976). Invertebrates and aquatic insects utilize LWD as direct and indirect food sources, attachment sites for feeding and retreat or concealment, material for larval cases, a substratum for pupation and emergence, and sites for egg deposition (Wallace et al. 1993). Consequently, management practices that alter LWD dynamics may have dramatic effects on aquatic ecosystem productivity.

LWD, including trees, snags, and logjams, has been shown to also influence stream morphology (MacDonald et al. 1982, Mutz, 2000, Shields and Nunnally 1984). Nunnally and Keller (1979) found that standing riparian trees play a vital

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role in slowing bank erosion. Wood in natural quantities results in complex flow regime patterns (Mutz 2000). Keller and Swanson (1979) add that tree root-wads in a hardwood forest were found to protect a length of bank five times the trunk diameter. The hydraulics of stream river systems are in a perpetual state of dynamic fluctuation as the flow of energy is distributed through the drainage basin, shaping channel morphology. Removing debris from streams increases current velocity and reduces the amount of material that can provide protection to the bank. These changes cause an acceleration of bank erosion and a wider channel (Nunnally 1978). Also, woody debris helps control river gradient. Abbe et al. (2003) reported that clearing wood from the Red River in Louisiana caused portions of the river to incise more than 4 m. LWD provides additional roughness and resistance (Shields and Gippel 1995) as it redirects the flow of water, slows velocity, increases depth, and creates backwaters, local scour, and various types of pools (Robison and Beschta 1990). The number of morphological structures, such as bars, is also increased by the presence of LWD (Harmon et al. 1986, Keller and Tally 1979). Because of the additional flow resistance created by LWD in the stream system, there can be a net increase in sediment storage, changes in bed texture, and changes in sediment transport (Smith et al. 1993). These combined factors can change the local and reach-average hydraulic conditions, which may affect channel bank stability (Bilby 1984, Trimble 1997).

While the importance of LWD to ecosystem structure and function in the Southeast is widely accepted, very little empirical information exists to quantify LWD biomass and dynamics in low-gradient rivers in the region (including Texas). However, rapid population growth in recent years coupled with greater demands on limited water resources has generated concern about the health and viability of river systems in the southeastern US. This concern prompted our examination of LWD dynamics in southeastern rivers to quantify possible management effects on LWD dynamics. Because woody debris is critical for proper function of aquatic ecosystems, it is imperative that woody debris budgets be evaluated in order to ensure that adequate habitat for aquatic biota is maintained in lower coastal plain rivers. The purposes of this study were to: 1) measure LWD loadings and riparian vegetation volumes in the lower Sabine River; 2) determine if significant differences exist among sites in measured variables like relative degree of decay, bank orientation, jam association, root-wad presence and likely origin; and 3) conduct a basic mass-balance calculation for instream LWD downstream of the largest reservoir in the southeastern US, Toledo Bend.

Methods

Field-site description

This study was conducted on the lower Sabine River downstream of Toledo Bend Reservoir on the boundary between Texas and Louisiana (Fig. 1). The total drainage area of the Sabine River is 25,267 km^2. Located in the Gulf Coastal Plain physiographic province, the region has a humid subtropical climate (Phillips 2003). The Sabine has the greatest total flow of any river in Texas, with average annual flows ranging from 402 cms in 1975 to 30 cms in 2011, with an overall average flow of 220 cms for the 1961–2011 period of record at the downstream-most US Geological Survey (USGS) gauge at Deweyville, TX.

The soils surrounding the lower Sabine River were mostly light-colored, fine, sandy loams with subsoils that were loamy sand to plastic clay in texture, and yellow to red in color. The vegetation was mostly composed of a mixture of *Pinus taeda* L. (Loblolly Pine) and various hardwoods like *Quercus nigra* L. (Water Oak), *Quercus phellos* L. (Willow Oak), and *Liquidambar styraciflua* L. (Sweetgum). Wet

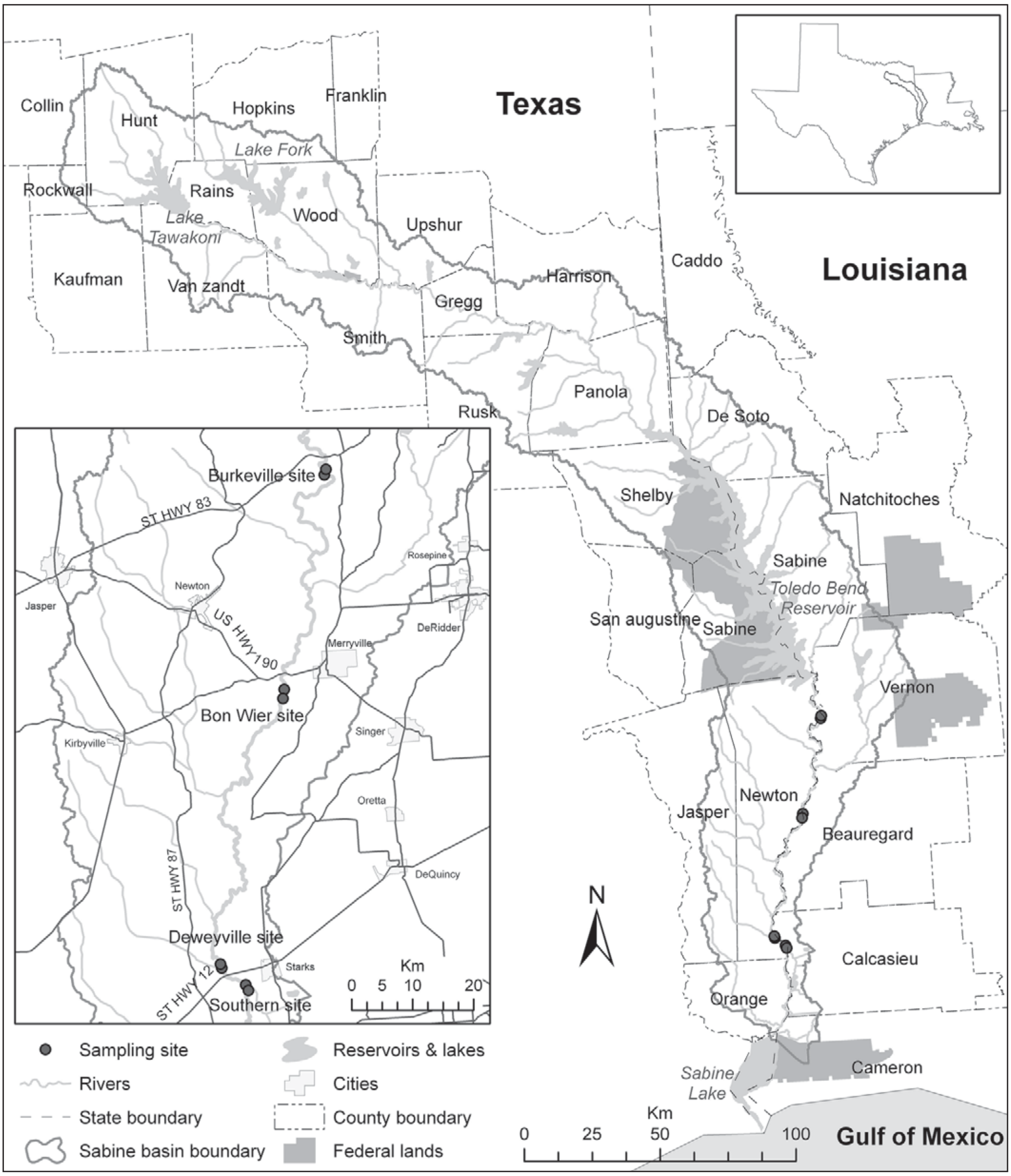

Figure 1. Sampling site locations for large woody debris measurements on the lower Sabine River.

areas of the floodplain are dominated by *Taxodium distichum* L. (Baldcypress), *Salix nigra* Marsh. (Black Willow), *Betula nigra* L. (River Birch), and the invasive exotic *Triadica sebifera* (L.) Small (Chinese Tallow). Much of the surrounding land had previously been cultivated and is now used for pasture or has been reforested, either by natural seeding and resprouting or by planting.

We chose four meander wavelengths as study reaches that represented the upper, middle, lower, and estuarine sections of the river. Three sites were located near USGS river-gauging stations, and discharge data were obtained from these stations. The Burkeville site (USGS 0802600) was northernmost and closest to the dam, followed by Bon Wier (USGS 08028500), and Deweyville (USGS 08030500). We measured sites once—during fall 2007 for Deweyville and summer 2008 for the other three sites. Following Hurricane Rita in 2005, the Sabine River Authority of Texas removed all bankside woody debris for a few river km above the southeast Texas intake canal to prevent possible water supply disruptions to the region. Our fourth site, denoted as the southern site, was located in the de-snagged zone, and we used it to estimate the amount of time required for woody debris to return to pre-snagging densities.

LWD measurement methods

To ensure that we had access to our sample sites, we measured instream LWD during the lowest available river stages. Based on seasonal streamflow patterns and hydropower release schedules from Toledo Bend Reservoir, we chose sample dates when the river stage fell to a level low enough to allow access to a maximum number of stems. Minimum LWD size was 10 cm in diameter and 2 m in length. We measured log length and top butt diameter, and identified the logs to species when possible. We determined relative degree of decay based on methods reported by Hyatt and Naiman (2001) and used a scale from 1 to 5, where 1 meant that no sign of decay was visible and all bark and branches were intact, and 5 indicated that the bark was absent and the wood was irregularly shaped and was darkened.

We determined bank orientation using the following criteria: 0° meant that the root wad was facing upstream and the LWD was parallel to the bank, a bank orientation of 90° indicated that the log was perpendicular to the channel, and a bank orientation of 180° indicated the LWD was facing downstream. In addition, we noted the presence of a root wad and branches with a yes or no. We categorized LWD origin as local riparian or upstream import and noted whether the LWD was an individual piece, jam-associated, or a fallen tree. We defined a debris jam as a discrete grouping of several pieces. Finally, we classified each LWD by stage contact zone: zone 1 indicated that the piece was sitting in a low-flow contact area, zone 2 indicated that it was within the bank-full channel, zone 3 indicated that it extended over the bank-full channel, and zone 4 indicated that LWD was beyond the bank-full channel.

Bankside vegetation data collection

We performed an inventory of the bankside vegetation at all four sites to determine the total volume of standing timber. We established 0.04-ha and 0.004-ha circular plots about 20 m from the bank on both the west and east banks at all four sites. This distance was based on predictions by Robison and Beschta (1990) that at least 50% of woody loading comes from within 15 m of the channel edge. In the 0.004-ha plots, we measured top and bottom diameters, length, and distance from the bank for woody debris on the forest floor. In the 0.04-ha plots, we measured and recorded diameter at breast height (DBH), total tree height, and distance from the bank for all trees ≥10 cm DBH. We followed Clark and Souter (1996) to calculate volumes using Girard Form Class 81 for pines and 79 for hardwoods.

Statistical analysis

For categorical data, we used chi-square tests to determine if a category was uniformly distributed, i.e., the same number of individuals in each category. We chose a uniform distribution because there were no a priori assumptions about expected distributions. We used the chi-square tests ($\alpha = 0.05$) available in the statistical analysis system (SAS) version 9.2 (SAS Institute, Inc. 2008) to examine seven categories within the individual sites: degree of decay, branch presence, origin, bank orientation, root-wad presence, position, and stage contact. The null hypothesis in each case was that there was a uniform LWD distribution in each category. We then developed contingency tables to test these same seven categories between the sites. The null hypothesis was that there was no association between each variable and the four sites. Finally, we used an ANOVA with Tukey's honest significant difference for multiple comparisons to determine if there were significant differences between sites in riparian forest density and instream LWD volumes.

Conceptual models of LWD dynamics

Benda and Sias (2003) developed functions that define wood recruitment into a given study reach (L_i):

$$L_i = I_m + I_f + I_{be} + I_s + I_e, \qquad (1)$$

where I_m is the forest mortality, I_f is the toppling of trees after a fire or during a windstorm, and I_{be} is the recruitment due to bank erosion. They go on to define I_s as the wood brought into the system because of landslides, debris flows, and snow avalanches, and I_e as the exhumation of buried wood. Benda and Sias (2003) further developed a function that defines wood recruitment based on chronic forest mortality only:

$$I_m = [B_L M H P_m]\ N, \qquad (2)$$

where I_m is the annual flux of LWD. They define B_L as the volume of standing live biomass per unit area, M as the rate of mortality, H as the average stand height, P_m as the average fraction of stem length that becomes in-channel LWD, and N as the number of banks contributing LWD.

One of the biggest contributors of LWD is bank erosion. In many regions, the greatest amount of in-channel debris is found on the cutbank side of the river (Wallace and Benke 1984), and that is one reason why the equation developed by Benda and Sias (2003) for bank erosion is appropriate for the Sabine River. The function used for LWD recruitment due to bank erosion is:

$$I_{be} = [B_L E P_{be}]\, N, \quad (3)$$

where B_L is the standing biomass, E is the mean bank erosion rate, and P_{be} is the expected stem length of the debris that falls into the channel.

We applied this model to the lower Sabine River with data collected in the current study. For the four study reaches, we calculated the overall lateral recruitment (Li). We converted the volume of live standing biomass ($m^3\ ha^{-1}$) measured to $m^3\ m^{-2}$, assumed a mortality rate of 1% based on relative mature forest age for the dominant species present, and measured average stand heights. Number of contributing banks was 2 for mortality input calculations, 1 for bank erosion. The proportion of stem becoming biomass was 0.13 for mortality calculations, and 0.75 for bank erosion. We assumed fall direction for mortality to be non-preferential, and we chose a proportion of 0.13 based on long term averages compiled by Van Sickle and Gregory (1990). Fall direction for bank erosion was based on values given in Benda and Sias (2003). We derived estimates for mean bank-erosion rates of 0.1341 $m\ yr^{-1}$for Burkeville, 0.10 $m\ yr^{-1}$ for Bon Wier, and 0.05 $m\ yr^{-1}$ for Deweyville and the southern site based on Heitmuller and Greene (2009).

We then calculated the total woody debris budget from the basic relationship as summarized by Benda and Sias (2003) as follows:

$$\Delta S_c = [L_i - L_o + Q_i / \Delta x - Q_o / \Delta x - D]\, \Delta t, \quad (4)$$

Where:
ΔS_c = change in woody debris storage
Δx = reach length
Δt = time interval
L_i = lateral recruitment of LWD within the reach
L_o = wood loss due to overbank depositions in flood events or the abandonment of jams
Q_i = fluvial transport of wood into the reach
Q_o = transport of wood out of the reach
D = loss of wood due to decay

Results

LWD mass and volume

A total of 374 pieces of LWD were found, with 93, 95, 119, and 67 pieces at the Burkeville, Bon Wier, Deweyville, and southern sites, respectively (Table 1). The total volume of LWD was significantly greater at the Burkeville study site, immediately below Toledo Bend Reservoir. LWD volumes were similar at sites further downstream. Burkeville and the downstream sites had similar LWD counts (number of stems), but because volume was much higher at Burkeville, we inferred that piece size was larger there than at the other sites. Total bankside vegetation volume was not significantly different among the four sites (Table 1).

LWD characteristics by site

Degree of decay was significantly different at each of the 4 sampling sites. Decay class 3 was the most prevalent at Burkeville, Bon Wier, and Deweyville, while significantly more LWD was found in decay class 4 at the southern site than at the other three sites further upstream. Also, jam-associated LWD pieces were more likely to be decayed at Burkeville, Deweyville, and the southern site. There was not a statistically significant relationship between whether a piece was associated with a jam and degree of decay at Bon Wier. In addition, decayed wood was more likely to be in contact with low flows of the river at Burkeville, Deweyville, and the southern site, while there was no relationship between decay and stage contact at Bon Wier. LWD bank-position category was significantly different at the southern site and at Bon Wier. At the southern site, half the LWD was located in jams.

Bank orientation was significantly different among sites. Pieces were more likely to have a 0° orientation (root wad upstream, oriented with the flow) at Burkeville and Bon Wier. However, at Deweyville and the southern site, orientation was more likely to be 180°. Pieces were more likely to have intact root wads at Burkeville, Bon Wier, and Deweyville, while LWD at the southern site was more likely to be without a root wad. Root wads would tend to cause a 0° orientation with the flow, which helps explain why pieces at the southern site have a greater frequency of 180° orientations. However, when contingency tables were analyzed for root wad versus orientation, no significant differences were found at any of the sites. As noted above, pieces at the southern site were more decayed, and pieces with greater decay are less likely to attach to a root wad.

In terms of stage contact, a significantly greater proportion of LWD was in the low-flow contact zone or within the bank-full channel at all four sites, as opposed to being beyond the bank-full channel. Pieces in the low-flow contact zone are subject to greater mechanical battering and decay. In addition, very large floods would be required to float and transport larger pieces (particularly if the root wad is still attached) out of the bank-full channel.

Branches were more likely to be absent at Bon Wier and the southern site, but frequencies were not significantly different at the other two sites. As expected, when analyzing the contingency table for branch presence and degree of decay, significant differences were found among categories, with more decayed pieces lacking branches. We also conducted contingency-table analysis for bank position

Table 1. Total counts, volume, and ANOVA results (using Tukey's honest significant difference) for LWD and bankside vegetation for each study site along the lower Sabine River, TX. Mean values with the same letter are not significantly different at α = 0.05

						Tukey grouping	
	LWD count	LWD volume (m^3)	Reach length (km)	Volume per length (m^3/km)	Bankside volume (m^3 ha^{-1})	for LWD volume	for bankside vegetation
Burkeville	93	98.94	1.16	85.29	349.9	A	A
Bon Wier	95	29.67	1.00	29.67	248.1	B	A
Deweyville	119	49.43	1.06	49.63	407.1	B	A
Southern	67	30.43	2.29	13.29	476.3	B	A

versus branch presence, with frequencies found to be significantly different at all four sites. In general, LWD lacking branches was more likely to be jam-associated, and pieces with branches were typically more likely to occur singly or as bank-fall. This finding is consistent with degree of decay and position as noted above.

The chi square goodness-of-fit test was also run on volume of LWD by origin. In terms of total volume, frequency of origin was significantly different at all four sites, with about 60–90% of the total volume originating from a local source. Larger keystone pieces tended to be less decayed and less mobile, and accounted for more of the overall volume at each site. All four study sites had large amounts of standing vegetation, and most of the overall LWD volume originated from bankside sources.

LWD recruitment rates

The southern site was important to the study because all of the LWD had been removed from the site three years prior to sampling, following Hurricane Rita. This knowledge of a confirmed date at which there was no LWD present, enhanced our ability to estimate the time required for LWD recruitment into the Sabine River. When compared to the LWD counts at the other three sites, the southern site had the least LWD within its reach, with 13.29 m^3 km^{-1}, about half that found at the next lowest site, Bon Wier, with 29.67 m^3 km^{-1}(Table 1).

Based on our sampling, we estimated that about 12–14 years would be required for LWD volume at the southern site to be equal what was observed at the Deweyville site. This figure could change dramatically depending on the number and size of catastrophic events (i.e., hurricanes and mass flooding) that impact the area (Phillips and Park 2009).

Conceptual models of LWD dynamics

Lateral recruitment estimates illustrate differences between the four river segments (Table 2). Burkeville, which has the highest total LWD loading (85.29 m^3 km^{-1}) also had the highest recruitment rate, and bank erosion was the primary source for recruitment. At Deweyville and the southern sites, the riparian forest volume was slightly higher with smaller tree sizes and much lower bank erosion rates; mortality was the dominant recruitment source there.

We then compared these estimates of lateral recruitment with the overall woody debris budget (Equation 4, above). To accomplish this, an estimate of woody debris decay was needed. While specific estimates were not available, Spies et al. (1988) estimated annual decay rates of between 2 and 7% of live biomass in a forest floor

Table 2. Lateral recruitment budget estimates (m^3 km^{-1} yr^{-1}) for the four study reaches on the Lower Sabine River, TX (Benda and Sias 2003).

Site	Mortality recruitment (I_m)	Bank erosion recruitment (I_{be})	Total lateral recruitment (L_i)
Burkeville	1.40	3.52	4.92
Bon Wier	0.95	1.86	2.81
Deweyville	1.80	1.53	3.33
Southern	1.92	1.79	3.71

environment. Due to warm temperatures and high humidity, southeastern Texas has one of the highest wood-decay rates in the continental United States (Harmon et al. 1986), so we used the higher end of this range, 7%, for budget calculations. With a 7% decay rate, the average decay-based residence time for an average piece of LWD is 14.29 years.

For the Burkeville and Deweyville sites, recruitment volume was a net positive, meaning that fluvial transport of wood into the reach was occurring at a greater rate than fluvial outflow. Recruitment volume was highest at Burkeville, which was expected given the higher rates of bank erosion immediately downstream of Toledo Bend Reservoir reported by Phillips (2003). This finding is consistent with measured source data reported above and is also consistent with the lateral recruitment estimates for Burkeville, where recruitment due to erosion is 2.5 times higher than recruitment due to mortality (Table 3). It is unlikely that the Toledo Bend Dam had a significant effect on reducing LWD loadings due to reservoir interruptions of fluvial LWD at the Burkeville site. Additional measurements immediately below the dam in the scour zone described by Phillips (2003) would be necessary to determine if these LWD reservoir storage effects extend upstream of the Burkeville site. At Deweyville, forest mortality recruitment is greater than bank-erosion recruitment, due to the lower gradients at this site. Also, with lower gradients more LWD accumulations from upstream may be occurring. At Bon Wier, we estimated that more wood is being recruited than stored in the channel, so the loss may be due to offsite transport (0.54 m^3 km^{-1} yr^{-1}) as fluvial outflow or floodplain deposition. At the southern site, LWD accumulation had only occurred for about 3 years since the post-Hurricane Rita de-snagging operation, with a lateral recruitment estimate of 10.47 m^3 km^{-1}, meaning that the difference of 2.82 m^3 km^{-1} may have come in as fluvial inflow from further upstream.

Discussion

Total instream LWD volume was found to be significantly higher at Burkeville (immediately below Toledo Bend Reservoir) than the other four sites likely due to greater bankside erosion rates and geomorphologic differences between sites. This result is supported by Phillips' (2003) study of the lower Sabine River in which

Table 3. Estimated woody debris storage, decay, and recruitment by sampling site for the lower Sabine River, TX.

Variable	Burkeville	Bon Wier	Deweyville	Southern
Total recruitment (L_i, m^3 km^{-1} yr^{-1})	4.92	2.81	3.33	3.71
Volume decayed (D, m^3 km^{-1} yr^{-1})	0.34	0.20	0.23	0.22
Net recruitment (m^3 km^{-1} yr^{-1})	4.58	2.61	3.10	3.49
Recruitment in 14.29 Yrs (m^3 km^{-1})	69.29	37.29	44.29	49.86
Volume measured (m^3 km^{-1})	85.29	29.67	49.63	13.29
(Qi - Qo - Lo) Vol. (m^3 km^{-1} yr^{-1})[A]	1.05	-0.54	0.38	N/A[B]

[A] Qi = LWD from fluvial inflow, Qo = LWD from fluvial outflow, Lo = floodplain deposition.
[B] Estimates are not available for the southern site since it was de-snagged 3 years prior to measurement.

he examined the effects of Toledo Bend Reservoir on the river downstream of the dam. In that study, significant bank erosion, sandbar migration, and LWD inputs at the Burkeville site were observed (Phillips 2003). The banks at Burkeville were the steepest of the three study sites, and were heavily eroded, resulting in greater LWD inputs than we observed at the other sites. Phillips (2003) reported that the left bank was characterized by many fallen trees and bank-eroded trees, and that overall, this section of the river was very dynamic, with many migrating sandbars and higher rates of bank erosion. In contrast, lower rates of channel erosion were reported near the Bon Wier section of the river (Phillips 2003). The Deweyville site has a completely different form, with lower banks and fewer sandbars (Phillips 2003). The left bank at Deweyville had large amounts of LWD and numerous tilted trees, and the right bank had former bank scarps with abundant LWD at the bank base and in the channel. The LWD loadings observed in our study were similar to those observed by Phillips (2003) (Table 1). Evaluating local geomorphic features and understanding how river flow was affecting the banks at the local sites were the best ways to explain the LWD loading differences.

The Burkeville site was characterized by active erosion and by larger diameter trees standing closer to the channel, which explained the higher volumes of LWD. Total LWD loading was best explained by the combination of bank erosion rates and riparian forest structure.

In terms of number of pieces, frequency of LWD origin was significantly different at Bon Wier and Deweyville. Wood at these two sites was more likely to be local in origin. Origin frequencies were evenly distributed at the other two sites. Because the Burkeville site is downstream of Toledo Bend Reservoir where banks are steep and erosion is high, it would be expected that a greater number of wood pieces would originate from stream bank erosion, with less relative upstream contribution. This recruited wood would be deposited below the zone of influence immediately below the dam, at the Burkeville site. At the southern site, more decayed wood indicated more pieces being transported in from elsewhere.

The Burkeville and Deweyville sites had a uniform distribution for the position category, meaning that the LWD present had an equal probability of being associated with jams or present as individual pieces. At Bon Wier, a significantly greater portion of LWD occurred as single pieces than as part of debris jams. Jam-entrained pieces were also significantly less likely to have intact branches. Large, infrequent floods would be required to mobilize some of the jams that were found on the Sabine, but as jam-entrained LWD decays and fragments over time, smaller and more mobile decayed pieces move downstream to the southern site, where about half of the LWD was located in jams. However, these smaller pieces represent a lower overall contribution to total LWD volume than a comparable number of larger pieces.

Because we found no significant differences in total bankside volume among sites, we conclude that recent hurricanes have not resulted in significant overall reduction in quantity of riparian forest vegetation at the sites close to the Gulf Coast. This lack of statistical significance can be attributed in part to the large amount of variation observed among individual plots in each stand. Riverside forest vegetation volumes tend to be rather heterogeneous overall, with much higher volumes on the cut-bank side of the meander than on the deposition side. However, there was a great deal of variation within meander wavelengths, and additional vegetation sampling would be needed to make specific determinations about effects on riparian forest structure and composition along the Sabine River. Also, Hurricane Rita, which made landfall at the Sabine estuary on 24 September 2005 resulted in a significant increase in LWD contributions to the river (Phillips and Park 2009).

The northernmost Burkeville site had larger trees overall compared to the more downstream sites. In particular, the invasive exotic Chinese Tallow Tree tended to be much more prevalent at the southern and Deweyville sites than at the two sites further upstream. This would be expected given this tree's ability to dominate the wet conditions characteristic of these two sites. Also, given the high seed production rate, high primary productivity, and extensive colonization of the lower Gulf Coastal Plain of Texas, continued domination of this species in the riparian forest is likely at these two sites (Bruce et al. 1995).

LWD budget estimates are a reasonable approximation of LWD dynamics in the lower Sabine River. One significant conclusion from this budget analysis is that the riparian forest density and volume are the most important factors for LWD recruitment. Fluvial transport into the reach was estimated to be between 11 and 21% of total annual recruitment, with the remainder governed by lateral recruitment, which depends mostly on surrounding forest density and bankside erosion rates. These estimates are consistent with recruitment rates measured upstream. Therefore, the most effective means of enhancing LWD recruitment for the lower Sabine would be to protect and enhance the riparian forest. There does not seem to be much evidence from this analysis that the Toledo Bend Dam had a significant impact on LWD dynamics in the lower Sabine River due to upstream LWD storage in the reservoir. As noted by Phillips (2003), the lower Sabine is transport-limited for sediment, and the same is true for LWD. It is likely that the large volumes of LWD that were historically in the rivers of East Texas were the products of extensive, more contiguous riparian forests composed of relatively decay-resistant species like cypress and oak, and that centuries of riparian forest degradation and spread of less decay-resistant and invasive species like Chinese Tallow has resulted in lower maximum potential LWD loadings.

A majority of LWD research has been conducted in higher-gradient streams, where fluvial export is an important factor controlling LWD dynamics. Very little research has been conducted on low-gradient Coastal Plain streams in the Southeast. One exception to this is a study by Beneke and Wallace (1990) in the Ogeechee River in the Coastal Plain of Georgia, in which they found that decomposition and fragmentation of LWD is the most common fate for LWD rather than direct fluvial export. We reached a similar conclusion for the lower Sabine River, TX in this study. In addition, as concluded by Beneke and Wallace (1990) for the Ogeechee River, as the larger, more stable, and persistent LWD pieces in the lower Sabine break down over decades, they will provide an important source of organic matter and habitat for aquatic organisms. Additional studies are needed to determine the optimal LWD loading for riverine invertebrate and fish populations in the lower Sabine. Additional research is also needed on LWD loading and dynamics on other southeastern lower Coastal Plain rivers.

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