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The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits

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Abstract

We used tree-ring dating and ^{14}C dating to document the temporal distribution and carbon storage of oak (*Quercus* spp.) wood in trees recruited and buried by streams and floodplains in northern Missouri, USA. Frequency distributions indicated that oak wood has been accumulating in Midwest streams continually since at least the late Pleistocene, about 14,000 calibrated radiocarbon years before present (cal. BP). The median residence time of an oak bole in the study streams was 3,515 years (n = 200). More than 30% of sampled oak wood entered the floodplain sediments and stream waters within the last 1,000 years, though very few samples dated to the last 150 years. Temporal variability in the record of oak recruitment to streams suggests a potentially strong influence from shifts in climate and fluvial processes, although other possible influences are addressed. Recent human impacts on streams have altered the dynamics of oak input and sequestered carbon with unknown long-term consequences. The long duration of carbon storage (mean age = 1,960 years) in this waterlogged environment appears to be strongly limited by decreasing wood density resulting from reductions in cell wall thickness. Lack of evidence of biotic degradation may imply that wood loss is largely due to abiotic hydrolyses. These findings document a continuous and long-term form of carbon storage that is sensitive to changes in climate and anthropogenic alteration of fluvial processes.

Key words: carbon; coarse woody debris; dendroecology; Holocene; *Quercus*; riparian.

Introduction

Although many studies have examined carbon (C) storage in forest vegetation and soils (Dixon and others 1994), few studies have documented the temporal distribution of sequestered carbon in dead wood buried in streams and alluvial sediments (Bilby 2003). Woody debris is an important component of temperate stream systems, providing weathered particulate organic carbon (Becker 1993), substrate for invertebrates and plants (O'Conner 1991; Benke and Wallace 2003), and habitat complexity beneficial to wildlife populations (Wondzell and Bisson 2003). The role of wood in streams in terms of carbon sequestration is relatively unknown, although quantitative assessment of carbon pools has been identified as critical to understanding and predicting the human impact on global climate (IPCC 2001). Carbon sequestration in wood is a function of the rate at which C is assimilated by the living tree and the time it is

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stored in the dead components of the tree. Although C storage in forests is typically limited by the relatively rapid decay of wood after the death of a tree, C assimilated in trees that enter aquatic systems as large wood often decays very slowly in submerged or buried environments (Guyette and others 2002; Guyette and Stambaugh 2003).

Quercus is one of the most widespread and abundant tree genera in the world (Barnes and others 1998). Trees of this genus often grow in riparian forests, where they have the potential to be recruited into streams by wind, fire, and fluvial processes (for example, floods) (Benda and others 2003). Oak trees often grow to large sizes, and have wood that is relatively dense and high in moisture content. These characteristics can decrease the mobility of large oak wood (LOW) in streams, thus increasing their potential for incorporation into sediments and the duration of carbon storage. LOW in aquatic environments can remain for thousands of years, making oak potentially one of the most persistent carbon sinks in North America and Europe (Baillie 1982; Becker 1993; Panyushkina and others 2004). In addition, oak wood sequesters carbon for a relatively long period (mean = 1,960 years) compared to wood of other species (~350 years) (Guyette and others 2002). *Quercus* is also one of the most reliable genera for use in tree-ring dating and climatic reconstruction, which can provide additional insight into the dynamics of carbon sequestration in stream and floodplain systems.

Several recent studies have addressed the residence time, accumulation processes, and influence of large wood in rivers. Residence times have been documented for hardwood and conifer wood in rivers in the northwestern United States (Hyatt and Naiman 2001). Some of this wood had residence times as long as 1,400 years. Both landscape geology and forest types affect basin-wide processes that influence the input and accumulation of woody debris in rivers (Abbe and Montgomery 2003). Woody debris input in turn develops feedbacks to fluvial and floodplain characteristics (Montgomery and Abbe 2006). Large woody debris often forms logjams that are resistant to river flow and cause changes in channel and floodplain sediment aggregation.

We examined carbon sequestering, the age distribution, and accumulation of LOW in stream channels flowing through riparian forests and croplands in northern Missouri, USA. The objectives of this study were: (1) to describe ages and residence times of LOW, and (2) to describe the carbon dynamics of a chronosequence of LOW. We hypothesized that carbon may be sequestered for thousands of years by oak wood submerged in freshwater aquatic systems, and that the accumulation and decay of oak wood and carbon in streams are best described by exponential functions.

Methods and Materials

Three study streams in the glaciated till plains of northern Missouri, USA (Table 1) were chosen based on accessibility (for example, landowner permission) and the presence of LOW of variable ages. The alluvial streams flow through agricultural and forested lands (Figure 1) and are low in gradient (~0.4 m km^{-1}). Study stream reaches are relatively shallow (Table 1), often too shallow for canoe navigation even under normal weather conditions. Channels are incised, with peak flows occurring more than 6 m above base flow one to several times per year. Nearly all LOW samples

Table 1. Site and Temporal Characteristics of LOW in Study Streams

Stream system	Medicine Creek	Thompson (Weldon) River	Locust Creek
Latitude	40°22′N	40°30′N	40°29′N
Longitude	93°18′W	94°43′W	93°43′W
Length of stream reaches (km)	15	6	3
Stream order	6	6	7
Mean annual flow (m^3 s^{-1})[1]	44.3	39.3	49.3
Mean channel width (m)[1]	25.1	47.0	22.7
Mean gage height (m)[1]	1.3	1.7	1.9
Floodplain soils[2]	Silty clay loam, silt loam	Silt loam	Loam
Number dated LOW	117	53	30
Mean age (cal. BP)	5,335	3,039	5,045
Range of age (cal. BP)	11–13,818	107–11,500	75–11,960

[1]*Data from nearest USGS gaging station, average of all years available. USGS Surface Water data for USA: Calendar Year Streamflow Statistics.*
[2]*Data from NRCS, Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/.*

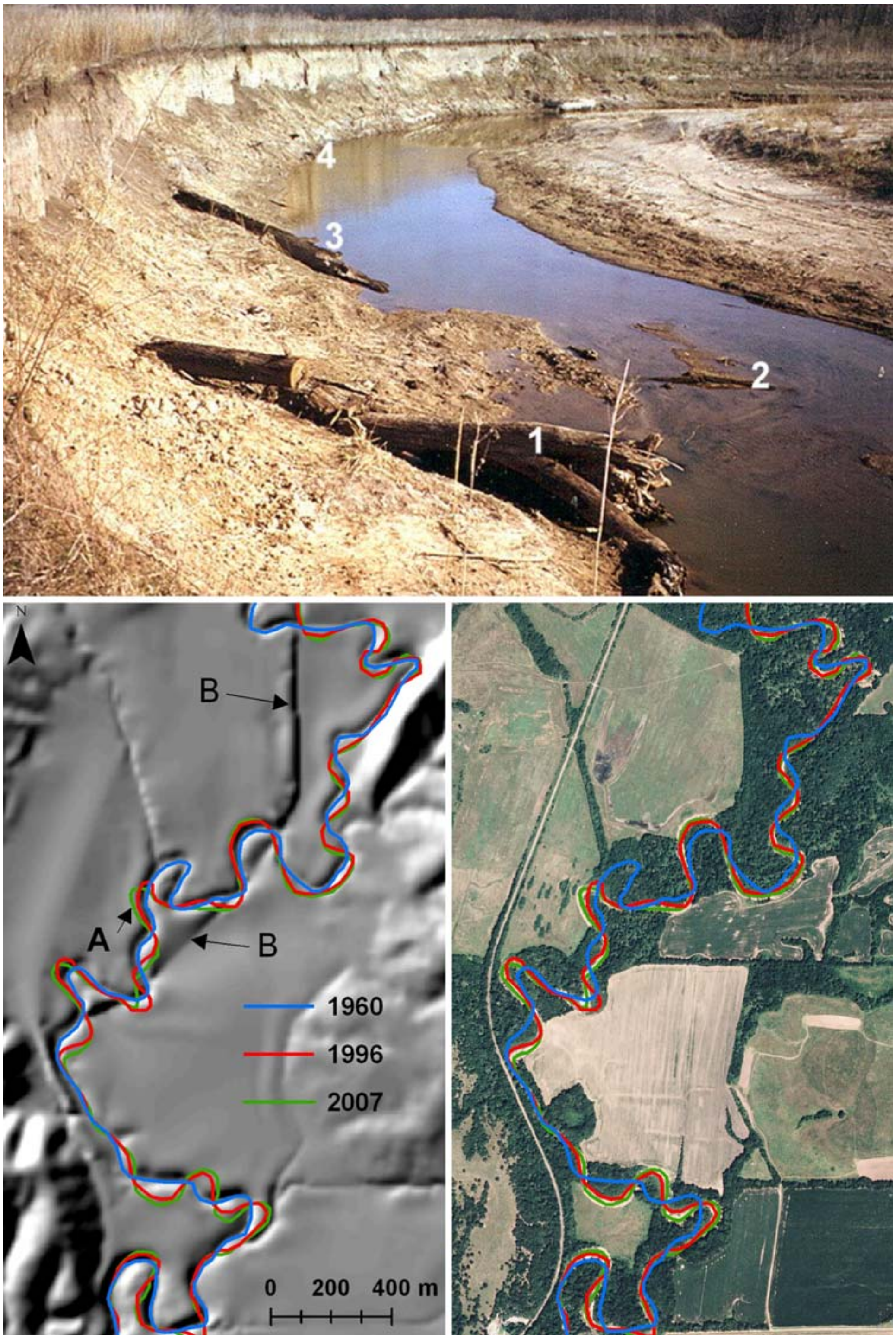

Figure 1. *Top*: Medicine Creek cut bank showing exposed LOW under a former agricultural field. Photograph location and direction corresponds to bottom left figure (letter "*A*" and *arrow*). Calibrated radiocarbon dates [BP = Before Present (ref. AD 1950)] are (1) 2,476 years BP, (2) 9,450 years BP, (3) 2,270 years BP, and (4) 1,540 years BP. *Bottom left*: upper section of Medicine Creek showing changes in channel location since 1960 in relation to land surface features. Land surface is a digital elevation model derived from a 1960 topographic map. *Arrows* are: (**A**) location and direction of perspective of stream photo (below), (**B**) linear land features demarking failed stream channelization efforts. *Bottom right*: aerial photograph taken in 2007 showing changes in channel location in relation to forest land cover and agricultural land uses.

are found 5 to 10 m below the surface of the floodplain in the stream water or washing out of the steep banks (Figure 1). Stream channels meander (Figure 1) in broad floodplains (0.5 to 3 km in width), are composed of sediments with low resistance to hydrologic flow (glacial tills, silts, sands, and clays), and are generally unconstrained by bedrock. Floodplain soils are very deep loams, silt loams, and silty clay loams formed in alluvium (Table 1). Drainage basin areas range from approximately 1,295 to 1,685 km^2 (Vandike 1995).

The surrounding landscape is heavily converted to agricultural production. Historically, the region was a mosaic of tallgrass prairie uplands and wooded lower slopes and bottoms (Nigh and Schroeder 2002). Currently, nearly all former prairie land has been converted to cropland or pasture, often extending to the very edge of streams and rivers. Timber is still present along streams, but in many areas historic species such as oaks have been supplanted by invasive species such as elm and hackberry (Nigh and Schroeder 2002). Euro-American land use began in the 1850s and was dominated by farming and grazing.

Through an exhaustive search by canoe and on foot of 24 km of stream channels, we obtained 180 samples from large (diameter, >25 cm) and mature (>90 annual rings) oak stems that were at least partially exposed (Figure 2). When extrapolated to the floodplain area, this is about 250 pieces of oak wood per km^2 of floodplain. Cross sections and wedges, 10–30 cm in thickness, were cut with a chain saw from the lowest possible location on the bole above the trunk flare. However, because nearly all of the LOW were partially buried and immobile, we often sampled the tree boles at locations above the base of the tree. Samples were collected from newly exposed trees (<10 years ago) in and under the water channel, in the stream banks, and washed up on the channel sediments. Wood sections were bound with tape, labeled, photographed, and locations recorded using a GPS unit.

Visual identification of LOW in the field was based on unique characteristics of waterlogged oak wood, such as distinctive shrinking and cracking along the grain of the wood. In the laboratory, samples were confirmed to be oak through microscopic verification of anatomical traits such as large rays and large earlywood vessels (Panshin and DeZeeuw 1970). Samples were also classified as white oak group (subgenus *Leucobalanus*) or red oak group (subgenus *Erythrobalanus*) based on the abundance of tyloses and latewood vessel shape. The majority of samples belonged to the white oak group, although species within this group cannot be differentiated by their wood alone. Contemporary living white oak species along these streams are bur oak (*Quercus macrocarpa* Michx.) and swamp white oak (*Quercus bicolor* Michx.), and, without the benefit of a more detailed macrofossil analysis we presume that these species probably comprise our sample.

Although wood of several other tree species (for example, maples, ash, elm, spruce) are present in the study streams, we used a single-genus approach to control for differences among species in decay resistance of wood, wood density, and tree size and limb structure. These characteristics influence the behavior and carbon sequestration potential of trees in aquatic systems. Oaks grew throughout the 14,000 years of the study period and are tree-ring datable (most other species are not), and their size and weight make them less likely to migrate out of the study reaches. The broad ecological amplitude of oak increases the potential applicability to more extensive regions. In addition, the cost of radiocarbon dating makes dating of other species prohibitive.

We used density dating, radiocarbon dating, and dendrochronology to determine the age of LOW samples. Wood samples (n = 180) were first placed

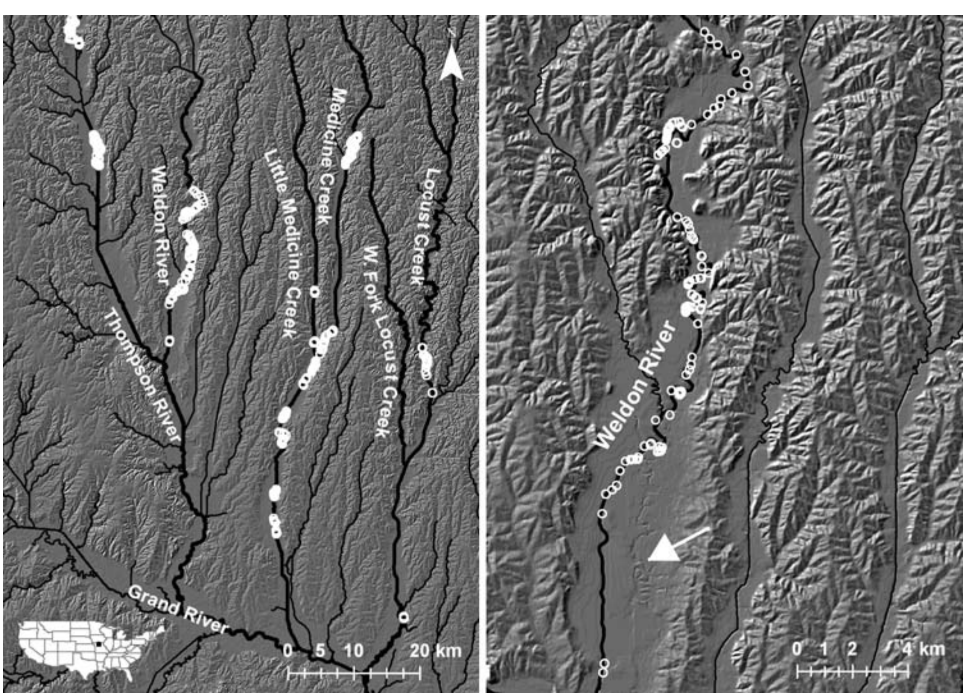

Figure 2. *Left*: region of northern Missouri, USA, showing tributaries of the Grand River and locations of LOW samples (*white circles*) along study streams. *Right*: a section of the Weldon River that was completely searched for LOW (*white circles*). *Arrow* indicates location of old stream channel. Channelized and straightened portion of Weldon River (*left of arrow*) exhibited low frequency of LOW.

into broad age classes using an age-density regression developed by Guyette and Stambaugh (2003). Samples were then evaluated for suitability for radiocarbon dating. Samples that appeared modern (<1,000 years) based on wood color, presence of bark or leaves, and density were not radiocarbon dated but were dated using dendrochronology methods. For radiocarbon dating, 20–30 g samples of wood were chiseled from near (but not including) the outermost edge of the cross section. These samples averaged 26 annual rings in a block approximately 3 × 5 × 8 cm. Sample sections were analyzed by an independent commercial laboratory (Beta Analytic, Inc.), providing radiometric measurements of ^{14}C content and radiocarbon ages. Dates were based upon the Libby half-life (5,570 years) for ^{14}C and were corrected for isotopic ($^{13}C/^{12}C$) fractionation. Conventional radiocarbon ages were calibrated using CALIB Version 4.3 software (Stuiver and Reimer 1993) and the INTCAL98 calibration data set (Stuiver and others 1998). Finally, modern-looking samples and samples ^{14}C dated to within the last 1,000 years were tree-ring cross dated to an absolute date (Baillie 1982; Stokes and Smiley 1996) using a published reference chronology from Iowa (Duvick 1996) and a 1,000-year chronology constructed by the authors using data from northern Missouri (unpublished data). Statistical verification of tree-ring dating was done using correlation analysis in COFECHA (Grissino-Mayer and others 1996) and Student's *t*-tests.

The temporal distribution of LOW abundance in streams was described by its frequency distribution and an interval analysis. We described the temporal distribution of LOW by residence time—the mean age of carbon independent of sample mass (Guyette and others 2002). To increase sample size, these analyses of LOW abundance included 20 additional samples for which only radiocarbon age and genus were obtained. The frequency distribution of LOW abundance was represented by a histogram, with data arbitrarily grouped in 1,000-year bins. The interval analysis involved sorting LOW samples from oldest to youngest and calculating the time span (years) between each sample. Because the absolute interval lengths are influenced by sample size, interval lengths should be considered a relative measure of the age structure of LOW in streams.

Carbon content was approximated for each piece of LOW as 50% of the dry mass, an accepted estimate for oaks (Birdsey 1996; Sampson and Hair 1996). Mass was calculated by multiplying the estimated volume of each piece of LOW by its wood density. Wood density was calculated using the volume and dry weight of a small sample (Guyette and Stambaugh 2003) of each piece of LOW. Because whole trees were generally buried or submerged (actual bole length was not measurable), wood volume was estimated by multiplying diameter by average bole length of oaks (11.6 m), the measurement from the ground to the first large branch. Average bole length was determined from measurements of 43 mature bur and swamp white oak trees growing in northern Missouri floodplains. LOW samples were sorted by age and the C mass summed beginning with the oldest dates. Cumulative values were then divided by the sum of all C to construct a cumulative distribution of percent carbon remaining. A cumulative distribution of LOW abundance through time was constructed in the same manner.

Cumulative distributions of LOW abundance and percent carbon remaining were the basis for the development of density functions, equations describing the accumulation and decay of LOW and assimilated carbon in streams. Mathematically, a density function is the derivative of a cumulative distribution function (Sentilles 1989). Equations were developed using non-linear regression techniques in SAS version 9.1 (SAS 2003) and were evaluated based on goodness-of-fit and preservation of the observed mean.

Results

The frequency distribution of LOW at all study sites spanned about 14,000 years (Figure 3). The median residence time of a piece of LOW was 3,515 years (Table 2). Nearly one-third of sampled LOW (30.5%) was in the most recent age class (1–1,000 cal. BP) (Figure 3). Abundance of LOW in

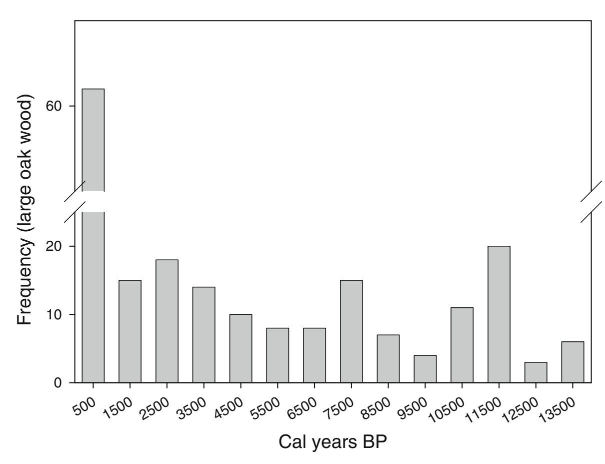

Figure 3. Frequency distribution of LOW sampled in the stream channels.

Table 2. Physical and Temporal Characteristics of LOW Carbon (kg), Dry Mass (kg), and Total Number of Boles from 24 km of Stream and Alluvial Sediment

LOW characteristic	Carbon	Dry mass	Number of boles
Number samples (n)	180	180	200
Mean piece dry weight (kg)	407	815	–
Median age (cal. BP)	1,985	1,985	3,515
Modeled half-life (years)	1,960	1,960	2,618
Decay constants	0.000367	0.000367	0.000221

the next oldest age class (1,001–2,000 cal. BP) was substantially lower, accounting for only 7.5% of all samples. Although the frequency distribution generally conforms to a reverse–J-shape, there were some interesting exceptions in the older age classes. Some of these age classes (for example, 11,001–12,000 cal. BP) comprised more than 10% (n = 20 pieces of LOW) of the total wood sampled, about twice the average of all wood in classes older than 1,000 cal. BP.

Interval lengths between dated LOW samples were influenced by many variables. The recruitment of oaks to stream and sediment storage was relatively continuous, though there was evidence of possibly episodic LOW recruitment. For example, clustering of shorter intervals occurred at about 2,500, 4,000, 7,600, and 11,200 cal. BP (Figure 4).

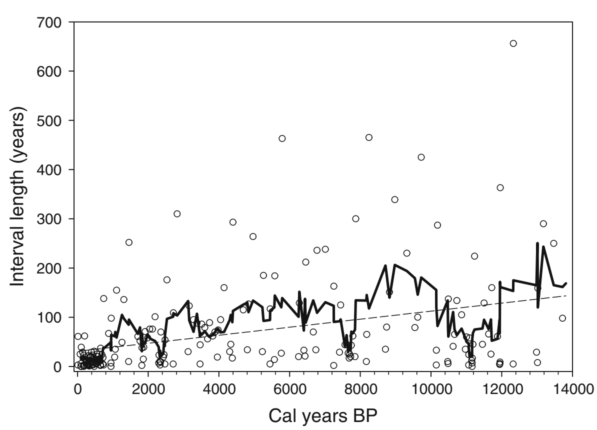

Figure 4. Time intervals between tree boles recruited and preserved in the streams and sediments. The *solid line* is a 7-point moving average and the *dashed line* is the linear regression of age and interval length (r^2 = 0.12, P = 0.01). The 7-point moving average was chosen to emphasize the lower frequency changes in mean interval length. Although interval lengths are influenced by sampling intensity, the regression line shows an increasing trend in interval length with time.

The longest interval between recruitments occurred about 12,300 cal. BP and was 656 years in duration. More than half (57 %) of the intervals were less than 40 years in length, whereas about 3% were longer than 300 years. Intervals between recruitments progressively increased in length with time before present (Figure 4).

The density functions below [equations (1) and (2)] are the equations that best fit the cumulative distribution of the number of boles accumulating through time (Figure 5A). They describe the probabilistic fate of the number of boles of oak trees that are eventually incorporated into stream channels (number of LOW per 24 km of stream):

$$\mathrm{LOW}_n = 200\, e^{-kt} \quad \text{(number of LOW pieces)}, \quad (1)$$

$$\mathrm{LOW}_p = 100\, e^{-kt} \quad \text{(percent of LOW pieces)}, \quad (2)$$

where LOW_n or LOW_p = LOW (n) or the percent of pieces (p), e = 2.718, k = 0.000221, and t = time (cal. BP).

The density functions below [equations (3) and (4)] conformed to a negative exponential curve (Figure 5B) and are the equations that best fit

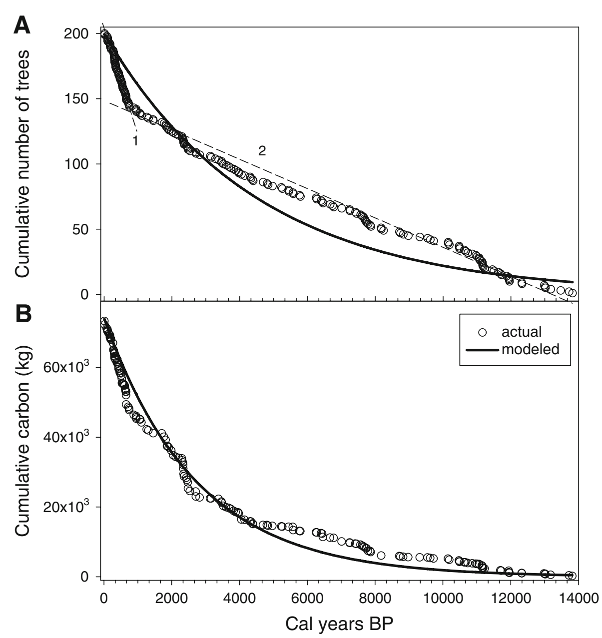

Figure 5. Density functions for the number of large oak trees (**A**) and their percent carbon remaining (**B**) in streams and floodplain sediments. *Solid lines* represent regression models [equations (1) and (4)]. *Dashed lines* in upper graph represent (1) large oak trees hypothesized to be buried and recruited during the time of the most recent (<1,000 years in age) meander belt location and (2) large oak trees buried and recruited from past (>1,000 years in age) meander belt locations.

the cumulative distribution of dated C mass by residence time (cal. BP). They describe the probabilistic fate of C assimilated in the boles of oak trees that are eventually incorporated into stream channels (kg C per 24 km of stream):

$$C_m = 73319\,e^{-kt} \qquad \text{(C mass in kg)} \qquad (3)$$

$$C_p = 100\,e^{-kt} \qquad \text{(percent C)} \qquad (4)$$

where C_m or C_p = C mass (m) or percent (p), $e = 2.718$, $k = 0.000367$, and t = time (cal. BP).

The exponents ($-kt$) describe the temporal release of C from LOW in stream channels. The simple exponential equation describes C storage after the tree dies (Harmon and others 1986), which for trees that are recruited into streams and sediments represents about 95% of C storage duration. Mean residence time for C in LOW in the study streams was 1,960 years (Table 2). The ratio of live-tree storage (~100 years) to stream storage (~1,960 years) of C is about 1:20.

Discussion

Temporal Variability of LOW Abundance

The long-term storage and distribution of oak wood submerged or buried in aquatic systems have been documented elsewhere (for example, Pilcher and others 1984; Becker 1993), and understanding of the temporal dynamics of recruitment and persistence is increasing (Piegay and Gurnell 1997). Based on the frequency distribution (Figure 3) and linear regression (Figure 4), it appears that LOW recruitment to streams generally increased in abundance and frequency over the past 14,000 years, but recruitment may not equal that found in floodplain storage. However, the chronological record of LOW in streams and floodplains is influenced by many factors, including: weathering and decay processes, extended periods of drought, glacial climate events, fire disturbance, and fluvial processes such as channel filling and lateral migration. Recently, human activities related to agriculture, flood control, and bank stabilization have had profound impacts on riparian forests and oak recruitment into stream systems. Although it may not be possible to unravel all of the complexities involved, we propose the following factors driving temporal variability in the record of LOW recruitment to the study streams:

(1) Attrition;
(2) Oak forest abundance;
(3) Fluvial processes (including wood trapping efficiency); and
(4) Sampling limitations.

Attrition. The attrition or depletion of wood in streams is a process that is more or less continuous over millennia. LOW stored for more than 12,000 years in stream sediments that have not been visibly reworked and redeposited (that is, bark and sapwood still intact) has a mass loss of more than 75% (density, <0.15 g cm^{-3}) due to cell wall degradation (Guyette and Stambaugh 2003). The resulting weakness of the wood probably greatly enhances its degradation when it is excavated by the stream channel after more than 5,000 years in floodplain storage. Although subterranean storage in floodplains is the most important process in the long-term preservation and storage of oak wood, heavy waterlogged LOW is constantly being excavated and reburied, causing limited but increased attrition when exposed in the stream channel. Intermittent exposure to flowing water, ice, freezing and thawing, wood boring insects, and moving sediment rapidly erodes the surface of the wood and causes whole tree boles to break into smaller, more mobile sections. These natural processes of attrition may at least partially explain the lower frequency of LOW observed in the oldest age classes.

Oak Forest Abundance. An alternative to attrition is the possibility that oaks have gradually increased in abundance over the last 14,000 years. However, our data and palynological evidence from the Midwest region suggest a more variable pattern of oak abundance (Williams and others 2004). The climate of central North America during the Holocene has generally fluctuated between relatively moist and relatively dry conditions (Arbogast and Johnson 1998; Daniels and Knox 2005). Consequently, oak abundance has fluctuated in response to regional climate changes and resulting variability in fire frequency and other disturbance factors (Abrams 2002). Although the resolution of this study prevents precise correlation of past climate with the temporal distribution of LOW, there were some interesting trends that warrant discussion.

The longest interval (656 years) between tree dates (^{14}C) in the record (Figure 4) occurs around 12,300 cal. BP, during the Younger Dryas stadial. Approximately coinciding with the end of the Younger Dryas cooling event, our distribution of LOW indicates that oak may have been relatively abundant 11,000–12,000 cal. BP (Figure 3). Central United States palynological studies support this idea, indicating a rapid shift in dominating tree species about 12,000 cal. BP, from spruce

(*Picea* spp.) to oak, willow (*Salix* spp.), and elm (*Ulmus* spp.) (Grüger 1973; Van Zant 1979; Laird and others 1996; Arbogast and Johnson 1998). Lower LOW recruitment during the warm and dry mid-Holocene (~4,000–7,000 cal. BP) (Figure 4) corresponds to a reduction in oak pollen concentration in nearby Colo Marsh (Baker and others 1990) and the eastward expansion of prairie in the Midwest (Wright 1968). The conspicuous drop-off in LOW abundance in the 1,001–2,000 cal. BP age group (Figure 3) may correspond to warm and droughty conditions in the late Holocene (~800–1,100 cal. BP) (Daniels and Knox 2005). These synchronicities must be viewed as suggestive, because the effect of climate change on oaks growing in a riparian environment is relatively unclear and perhaps largely determined by landscape position. It is plausible that even during long-term warming or cooling events, floodplain forests better survived prolonged droughts because of their deeper soils, lower rates of runoff than steep uplands, and lower position in the hydrologic landscape (water runs into them).

The temporal extent of the age distribution of LOW (~14,000 cal. BP) was likely constrained by the effects of glacial climate on oak growth and reproduction. Alternatively, older oak wood may be buried deeper in streams and sediments. Because we collected only in natural streambeds, wood buried deep in sediment that has not been excavated by the stream may not have been sampled. Dynamic fluvial processes and their interactions with climate add to the temporal variability of LOW abundance.

Fluvial Processes. Natural changes in hydrology often occur in response to climate change, and the Holocene climate of northern Missouri has been markedly variable (Knox 1983; Arbogast and Johnson 1998; Knox 2003). For example, we found an increase in LOW recruitment about 2,500 cal. BP (Figure 4), possibly due to more rapid channel migration or more oak trees growing in floodplain forests, or both. Knox (1983) postulated that 'active lateral channel migration, cutting, and filling' occurred in the central United States between 2,000 and 3,000 cal. BP, presumably due to wetter climatic conditions. In addition, we found that oaks that grew about 2,200–2,800 cal. BP commonly wash out of stream banks at levels about 2 m above the stream bed, suggesting a rise in the level of base flow and rate of channel accretion during that period. This increase in sediment aggregation could also increase the holding efficiency of the streambed for LOW. In periods of warmer climate with severe drought, it has been hypothesized that precipitation events, though less frequent, were actually more variable and extreme in nature, causing more severe flooding, increased channel incision, and significant disruption of sediment loads (Daniels and Knox 2005). Increased mobility of LOW during droughts due to large floods may be one explanation for the observed lower abundance of LOW during arid time periods.

Although the abundance of LOW was greatest in the most recent 500-year age group, very few samples were recruited to the stream within the last 150 years. Since about AD 1850, human activities have profoundly impacted aquatic wood and riparian forests (Guyette and Cole 1999; Gregory and others 2003). In several sample reaches we found abundant LOW spanning many millennia, but few or no oaks growing along stream banks. Selective logging of oaks in the central United States often favors the regeneration of early successional tree species over oak species. The input of LOW into streams has probably been most severely impacted by conversion of riparian forests to cropland and channel modification. Stream bank stabilization, channelization, and levee construction have inhibited stream meandering and increased stream power. These alterations cause woody debris to be flushed out of stream reaches at higher rates, and reduce burial of wood that would occur with stream meandering. We propose that anthropogenic engineering of stream channels changes streams into '*flushers*' of woody debris as opposed to their previous role as '*accumulators*.' It is currently unknown what long-term effects this fundamental change will have on ecosystem integrity and carbon sequestration in streams.

Sampling Limitations. We sampled only available wood in natural stream channels, and did not randomly excavate wood in floodplains. This sampling method could have resulted in a bias due to long-term fluvial processes, such as the movement of meander belts across the floodplain. Nearly all natural alluvial streams tend to meander, the sinuous shifting and migration of the stream channel over time in response to bank erosion and sediment deposition (Leopold and others 1964). LOW (~1,000 to 2,000+ cal. BP) may be less abundant in stream channels because the meander belt moved away from 'recently' buried wood of this age class. Although the generally diminishing abundance of LOW roughly approximates the decay function of a negative exponential curve (as hypothesized by Harmon and others 1986; MacMillian 1988), the abrupt decline in the rate of the number of boles dated per unit time—as indicated by changing slopes after about 1,000 cal. BP (Figure 5A)—suggests a change affecting the abundance of LOW in the sample. Meander belts are rarely located where they were 1,000 or more years ago (Brown 1997), and this may lead to an underestimation of C stored by LOW in stream and floodplain sediments during recent periods (1,000–2,000 years ago). The slopes of the density function (Figure 5) before and after about 1,000 cal. BP may better approximate two different linear processes affecting wood age in natural streams within a general negative exponential model.

Carbon Sequestration

Carbon sequestration by LOW in the study streams is long (mean 1,960 years) compared to that in terrestrial forest environments (excluding soil) (Nabuurs and Mohren 1995; Spetich and others 1999) due to differences in the rate of wood decomposition. In terrestrial environments, the mean specific gravity of oak wood decaying on forest floors is reduced by half in approximately 40 years (MacMillian 1988), whereas the mean specific gravity of wood buried in floodplain sediments is reduced by half in approximately 6,500 years (Guyette and Stambaugh 2003). Changes in wood density affect the rate of carbon sequestration, and low oxygen levels in streams and sediments likely reduce the effective breakdown of wood by fungi and bacteria. Examination of wood from the study streams using a scanning electron microscope revealed thinner cell walls in riparian LOW (Guyette and Stambaugh 2003), but no evidence of bacterial erosion on cell wall surfaces such as cavitations, longitudinal erosion, or tunneling (Blanchette and others 1990; Eaton and Hale 1993). Abiotic hydrolyses in the solutions of waterlogged environments over thousands of years may be a more significant factor reducing cell wall thickness (that is, density). In waterlogged environments, iron salts are frequently very acidic and may cause hydrolytic degradation that turns wood a dark (Dinwoodie 1981), as is the LOW in this study that has been buried for more than 300 years. Slow hydrolysis from protracted water logging has been suggested by others (Richardson 1978) and may be one of the most important factors controlling the release of carbon stored in oak wood in streams.

The age and temporal distribution of wood in streams is the result of complex interactions among many factors. This study indicates that during at least the last 14,000 years, fluvial processes, climate change, oak forest abundance, and stream alterations have potentially influenced the abundance of LOW and the amount of carbon stored in streams and sediments. However, the nature of sampling LOW from natural streams limits our ability to definitively conclude that these factors have interacted to create the observed temporal variation in LOW and carbon storage. Complete excavation of floodplains could provide more definitive quantification of the temporal distribution of LOW. In order of temporal scale (from short to long), we believe important factors affecting carbon storage of LOW in streams are: agriculture, channel manipulation, channel migration, oak abundance, climate, and attrition.

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