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THE AGE AND DENSITY OF ANCIENT AND MODERN OAK WOOD IN STREAMS AND SEDIMENTS

by

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SUMMARY

Large wood of oak trees (*Quercus* spp.) has resided in the streams and sediments of north Missouri, USA for many thousands of years. This wood affords the opportunity to compare a chronosequence of differences in wood density over a very long period. We analyzed the relationship between the age (residence time) and density of heartwood from oak boles using tree-ring and ^{14}C dating methods and discuss their implications. The residence time of large oak wood (>25 cm diameter) sampled in the streams and sediments ranged from less than 14 years to more than 12,320 years. The oak wood ranged in density from 0.82 g cm^{-3} for a tree that had recently fallen into the stream to 0.14 g cm^{-3} for ancient oak wood. Two regression equations relate age (residence time) and density of oak wood and explain 88 percent of the variance in the dependent variables. Equation 1, heartwood density = age, can be used for studies in carbon cycling, wood as invertebrate habitat, or other questions related to the density and ecology of wood in streams such as wood retention and export. Equation 2, age = heartwood density, can be used for estimating when oak wood was formed on a very coarse scale over many thousands of years.

Key words: *Quercus*, waterlogged, specific gravity, streams, woody debris, wood density.

INTRODUCTION

The properties of wood in aquatic and subterranean environments relate to fisheries habitats (Sickle & Gregory 1990; Christensen et al. 1996; Guyette & Cole 1999), the interpretation and preservation of archaeological remains (Rowell & Barbour 1990; Brown 1997), changes in wood chemistry (Hedges 1990), and riparian dynamics (Maser & Sedell 1994; Raymond & Bauer 2001; Guyette et al. 2002). Oak is known to persist for thousands of years in riparian systems in Europe (Becker 1993). The purpose of this work is to examine the relationship between the age (residence time) and heartwood density of oak trees (*Quercus* spp.) found in the streams and eroding out of riparian sediments in northern Missouri, USA. We developed two regression equations that relate age and density and discuss their implications in light of the ecology and age of wood in streams. Specifically, our objectives were to quantify how the density of oak wood changes with time under aquatic and subterranean conditions and to develop a quantitative relationship for estimating when oak wood was formed based on its density.

MATERIALS AND METHODS

Sites and species

We collected cross sections of oak wood from streams and rivers in north Missouri, USA (Medicine Creek, Locust Creek, and the Fabius River) that meander through glacial sediments of sand, silt, and clay. Oak wood was distinguished from other woods by anatomical characteristics such as large rays and large distinct earlywood vessels (Panshin & DeZeeuw 1970). Native oak species that are common in the present-day riparian forests of north Missouri streams are bur oak (*Quercus macrocarpa* Michx.), swamp white oak (*Quercus bicolor* Michx.), pin oak (*Quercus palustris* Muenchh.), and northern red oak (*Quercus rubra* L.). The majority of the wood samples in our data set are likely bur oak and swamp white oak tree species.

Wood

We collected both modern (wood residing in the stream < 100 years) and ancient oak wood. The only restrictions on our collection were that the wood be large (> 25 cm diameter), have 100 or more annual rings, be of the genus *Quercus*, and not have signs of major and obvious aerobic decay that would inhibit gathering continuous ring-width data. Our sample trees consisted of 40 oaks of the white group (*Leucobalanus* group) and 5 oaks of the red oak group (*Erythrobalanus* group). These were differentiated by the abundance of tyloses in the vessel elements. We measured the density of one sample of heartwood from the large woody remnants collected in the streambeds and banks. The sample wood for density measurement was selected from the outermost section of the trunk that was just inside the exterior weathering rind of the tree. Woods containing sediments, insect galleries, or plant roots were excluded. Color, texture, and growth-ring patterns were used to exclude sapwood, reaction wood, knot wood, and wood with obvious evidence of aerobic decay and weathering. Wood was excluded if it had fungal hyphae at the macroscopic or microscopic level (×40), macroscopic changes in ring structure, internal and external differential patterns of decay, or a brown rot color (Panshin & DeZeeuw 1970).

Density

The density of oak wood for this study was obtained by measuring a wet volume of the wood and its oven-dry weight. We used the water-displacement method to measure volume. A volume of water equal to the volume of wood (at field moisture content) was weighed. Displacement was accomplished by immersing a 10 to 20 g block of wood on the end of a pin in a beaker of water (without touching the sides or bottom of the beaker) on an electronic scale. The weight of the displaced water (1 g per cm^3) was measured to the 100^{th} of a gram. Wood was then oven dried for 24 hours at 60 °C and then reweighed to the 100^{th} of a gram. Basic conventional density (Schniewind 1990) was calculated as oven-dry weight (g) divided by wet volume (cm^3). All references to wood density in this article are to the basic conventional density of wood. Wood density is often a function of the width of annual radial growth increments (ring width) in many ring-porous angiosperms such as *Quercus* spp. (Panshin & DeZeeuw 1970). Although our objective was to focus on the relationship between age (burial and stream residence time) and density, we calculated the mean ring width of wood samples to reduce this possible source of variance in the regression analyses. We used regression and correlation programs (REG and CORR in SAS system software) to model the relationship between age (time since carbon fixation) and density in oak.

Dating

We used dendrochronology to date wood formed within the last 300 years and radiocarbon dating methods to determine the date (age) of oak woody debris that was formed before about 1800 A. D. Annual rings and ring-width plots were visually matched for ring-width signatures and earlywood characteristics (Baillie 1982; Stokes & Smiley 1996). Statistical verification of the ring-width dating was done using COFECHA and Student's t-tests and tree-ring chronologies derived from living, old trees (*Quercus alba* L.) in Iowa (Grissino-Mayer et al. 1996; Duvick 1996). Carbon isotope measurements and radiocarbon age determinations for the samples in this study were done by Geochron Laboratories, Cambridge, MA, USA. The carbon dates are based upon the Libby half life (5,570 years) for ^{14}C and all dates are corrected for ^{13}C. Wood samples of between 20 and 30 grams were treated with hot dilute HCl to remove carbonates; with 0.1N dilute NaOH to remove humic acids and organic contaminants, and a second time with dilute HCl. After washing and drying the samples were combusted to recover carbon dioxide for the analysis. The radiocarbon ages were calibrated using methods by Stuvier et al. (1998).

RESULTS

Description and statistics

A statistical summary of the measured data and variables showed sample wood had a wide variation in age and density (Table 1). The maximum length of oak preservation among our sample trees was 12,320 years at the time this analysis was completed. We carbon dated four oak trees that had ages (residence times) greater than 10,000 years and 25 trees that were greater than 1,000 years. Qualitative features such as exagger-

Table 1. Statistical description of the age and density of oak heartwood found in the streams, stream banks, and stream beds of North Missouri, USA. Correlation coefficients (*r*) and their significance levels are given for the associations between density and age, density and ring width.

Statistic	Age	Density	Ring width
Number of samples	45	45	44
Mean	3453 (years B.P.)	0.50 (g/cm3)	1.74 mm
Range	14–12,320 (years B.P.)	0.13–0.82 (g/cm3)	0.77–3.38 mm
Standard deviation	3990 (years)	0.19 (g/cm3)	0.77 mm
r (age and density)	-0.91 ($p < 0.001$)		
r (density and ring width)		0.36 ($p < 0.02$)	

ated checking, low strength, and decreased hardness compared to modern oak wood were associated with increased age (burial and stream residence time). Deep (5 to 15 cm) fissures were common in old (> 3,000 years B.P.) dried oak wood that has been waterlogged. Longitudinal checking is unlike checking in modern wood. Large 35 cm diameter logs (> 10,000 year B.P.) can be broken with a brash (smooth) break over the knee indicating the extreme structural weakness and the preferential degradation of cellulose. Oak wood more than two or three centuries in age was black. Wood dating over 7,000 years B.P. is soft enough to scratch deeply with a fingernail.

Quantitative relationships

Two equations were developed which relate age and wood density. Transformation of density by a natural log function (ln[density]) produced a linear relationship among the variables. Equation 1 explains variance in the density of wood by the length of time (age) the tree has been involved in the stream channel and sediments. Equation 2 explains the variance in age by the density. The regressions are:

$$\ln[\text{density}] = -0.402 - (0.00011 * \text{age}), \qquad \text{(Equation 1)}$$

$$\text{age} = -2719 - 7818 * \ln[\text{density}], \qquad \text{(Equation 2)}$$

where ln[density] is the natural log of conventional density in grams per cubic centimeter and age is the calibrated ^{14}C date or tree-ring date of the wood in years before present. Both equations explain approximately 88 percent of the variance in the dependent variable. All intercepts, variables, and equations were significant ($p < 0.01$). The 95 percent prediction interval is given in Figure 1 for Equation 2. Despite the high coefficient of variation ($r^2 = 0.88$) for Equation 2 the 95 percent prediction interval is about plus or minus 2,000 years. The exclusion of red oak (versus white oak) wood from the data set made no significant difference in the equations. Also, the inclusion of mean ring width in Equations 1 and 2 did not increase the amount of variance explained in the dependent variables.

DISCUSSION

Ecological implications of age and density

There are several age related ecological effects of the density of oak in streams. When ancient oak dries, large radial and transverse cracks occur due to the loss of wood substance, particularly cellulose (Hedges 1990). The size and abundance of these checks and interstitial spaces are much larger and deeper than those found in modern wood. In North Missouri streams, interstitial spaces (created by transverse cracks) are an important habitat to at least 9 orders of invertebrates such as leeches, crayfish, and chrionomids. The longevity of wood storage provides a continual supply of habitat in a region with no solid aquatic substrate other than wood. The low density of ancient oak wood allows it to be used as food and habitat to animals incapable of eating and colonizing modern, more dense oak. The loss of density weakens the shear and bending strength of the wood. This enables stream currents to erode wood more rapidly as it is uncovered in sediments by the moving channel. In addition, low density increases the probability that large wood as well as particulate wood particles are moved down stream.

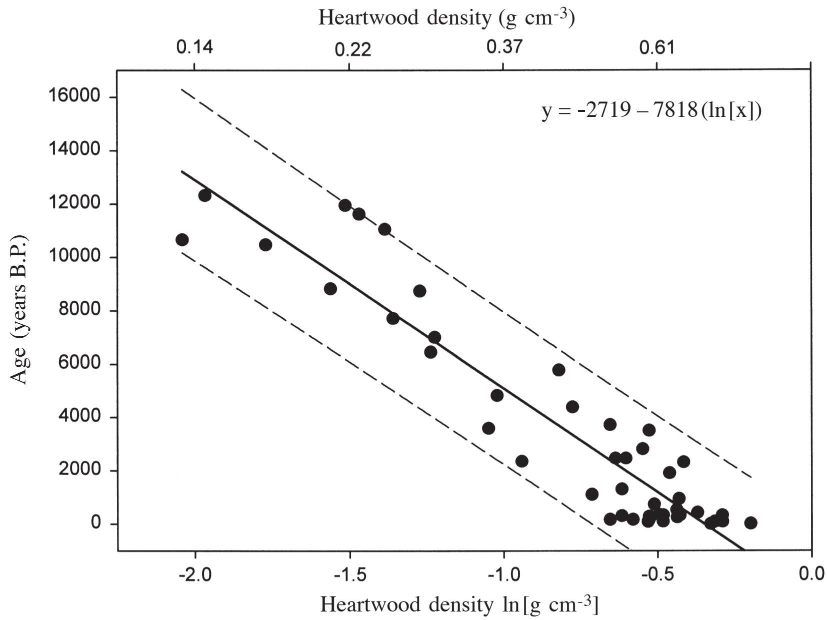

Fig. 1. Scatter plot illustrating the regression of density on the age of oak heartwood collected in streams and riparian sediments of North Missouri. The x axis is logarithmic (natural log). The solid line is the predicted value of age by the given regression equation. The dashed lines are the 95% confidence interval for the prediction of the age of an individual heartwood sample.

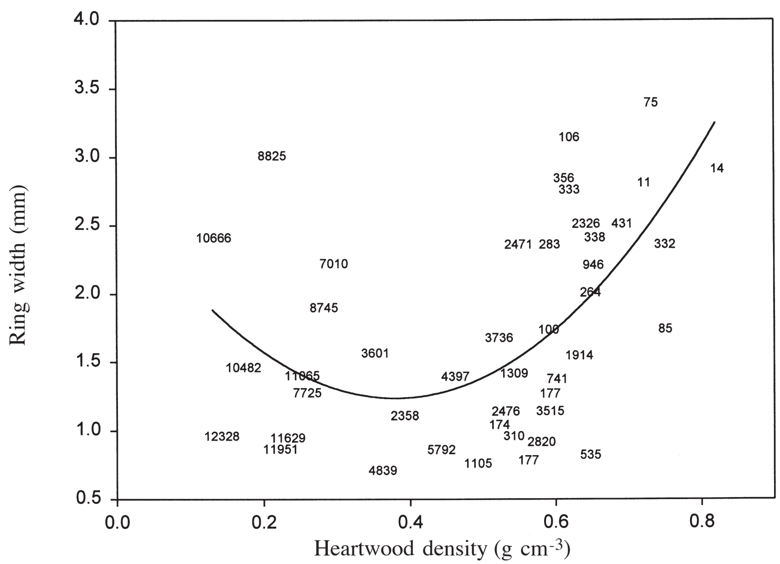

Fig. 2. Scatter plot illustrating the relationship between the conventional density of oak heartwood and radial growth (ring width). Data points are represented by the calibrated ^{14}C age (in years B.P.) of each heartwood sample. The curve presents a hypothetical change in the relationship between heartwood density and ring width that changes after about 4,000 years and at wood densities that are generally less than those of modern oak wood (e.g. < 0.4 g cm^{-3}).

Ring width and density

Ring width affects density in ring-porous woods (Panshin & De Zeeuw 1970) because proportionally more low density earlywood occurs in narrow growth rings. Although this relationship is not the focus of our study, we attempted to incorporate ring width in our equations to reduce the variance in the relationship between density and age that was due to differences in ring width. The relationship between density and ring width was parabolic for all data (Fig. 2). For densities greater than about 0.4 g cm^{-3} (and less than ~ 4,000 years in age) the relationship between density and ring width follows the expected pattern of decreasing density with decreasing ring width ($r = 0.63$, $p < 0.02$). However, for densities lower than about 0.4 g cm^{-3} and samples greater than about 4,000 years in age this relationship does not hold or may be reversed ($r = -0.26$, $p = 0.40$). We hypothesize that differences in heartwood density for samples with densities greater than 0.4 g cm^{-3} are related to both ring width and age. For samples with densities below 0.4 g cm^{-3} differential decay of earlywood and latewood may account for a change in the relationship between density and ring width.

Qualitative observations

Images taken with a scanning electron microscope (Fig. 3) revealed that much of the change in the characteristics and density of oak is associated with reductions in cell wall thickness. These photographs show that tracheid cell walls in ancient oak (Fig. 3d and 3f) are only half or a third as thick as those in modern oak (Fig. 3b). Ancient oak wood also had fewer cell wall layers and weakened and deformed tracheid walls. These characteristics are consistent with a loss in conventional wood density compared to modern wood. The brash breakage of ancient wood at the cellular level (Fig. 3d) is consistent with the smooth and effortless breakage of whole boles of ancient oak. The apparent retention of the middle lamella and degradation of cell wall layers (Fig. 3d) indicates a preferential loss of layers high in cellulose and hemicellulose content (the S_2, S_3 layers) (Panshin & De Zeeuw 1970).

An interesting example of the extraordinarily slow rate of decay of waterlogged trees that are buried in sediments is given by sample MED256 (dated to12,320 years B.P.). This sample was identified as a bur oak and was separated from other species in the white oak group by its thick and deeply furrowed bark which was still present. The sapwood also was intact and light in color compared to the black heartwood. The density of this specimen's heartwood was 0.14 g cm^{-3}, some 20 to 25 percent of that of a living oak tree. Even though this wood has lost more than 75 percent of its mass it still has bark, light colored sapwood, a discernable ring structure, and its original circular shape and a measurable ring structure.

Limitations and potentials

Our analysis does not take into account the known variability in density within the tree that occurs in the radial and axial directions. During field collection, we often have access to only part of a large tree that is buried in sediments. Thus, since we sampled wood just beneath the weathering rind the equations presented here do not represent exact changes in whole tree density, but may be very close to changes in whole tree

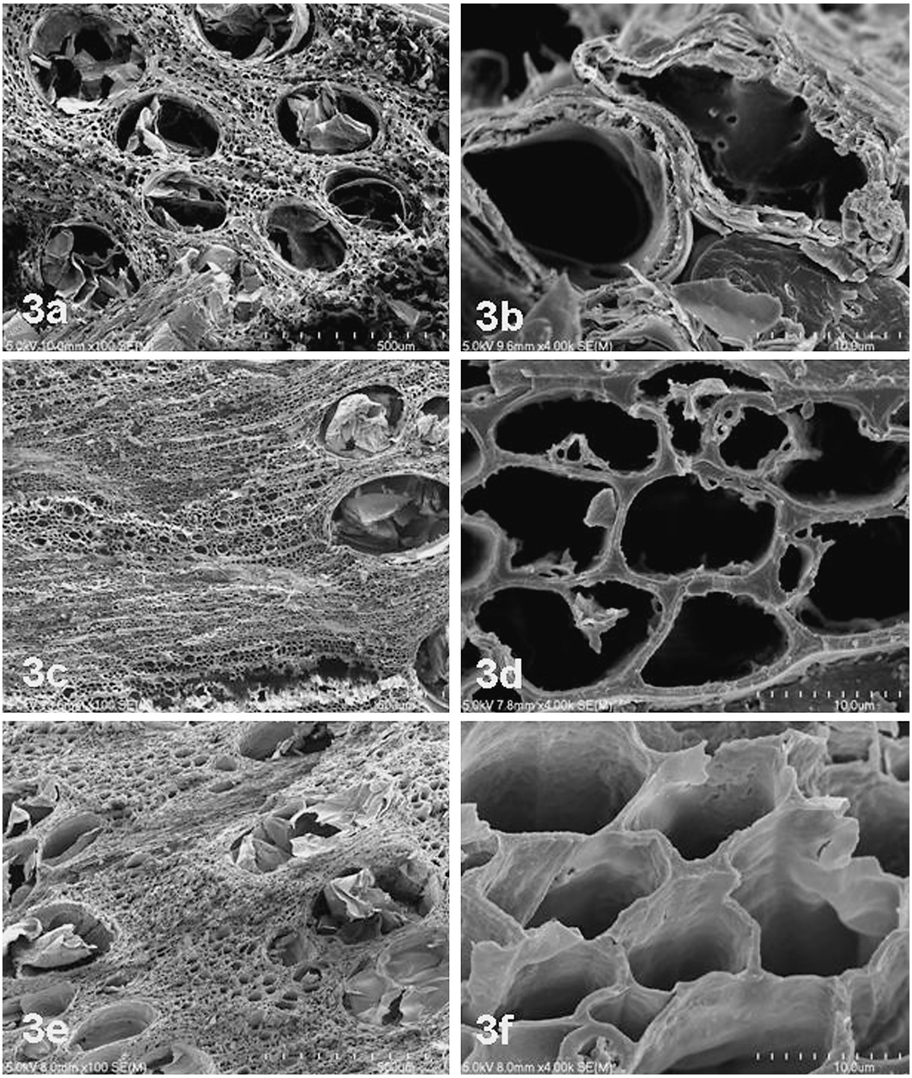

Fig. 3. Photographs (scanning electron microscopy) of transverse surfaces of modern and ancient oak wood. All photos are of air-dried wood with fractured surfaces (modern wood frozen with liquid nitrogen) collected from streams and riparian sediments. Photographs in the left column (3a, 3c, 3e) are taken at ×100 (scale bar 500 μm), those on the right (3b, 3d, 3f) at ×4000 (scale bar 10 μm). The photographs sorted by age and row are: top row (3a, 3b), modern oak (tree-ring dated to1977 A.D.) from a stream; middle row (3c, 3d), ancient buried oak (^{14}C date:11,065 years B.P.) excavated by stream; and bottom row (3e, 3f), ancient buried oak (^{14}C date:13,818 years B.P.) excavated by a stream.

density because the primary loss of wood substance progresses from within the wood. Unlike tree-ring or radiocarbon dating, dating estimates calculated from density assume a constant rate of decay through time. This is probably rarely the case, hence the considerable variability in the confidence intervals for the prediction of age from density (Fig. 1). Also the specific conditions such as temperature, sediment chemistry, and oxygen levels that control the rate of decay may make this approach (Equation 2) to dating wood regionally specific. The large confidence limits (plus or minus about ~2000 years) emphasize that the dating utility of Equation 2 is on a very coarse scale.

There are several possible ways to strengthen the accuracy and precision of the statistical relationship between time and density in oak woody debris. Some minor degree of the error in the relationship between density and time results from the error in carbon dating which has confidence limits in the range of plus or minus 40 to 120 years. High precision carbon dating, although more costly, could be used to reduce the error in the response variable of the regression (Equation 2) and thus reduce the amount of error in the estimates. More research relating ring width and density in bur and swamp white oak might allow the addition of ring-width (i.e. proportion of less dense earlywood to more dense latewood) as a significant variable in the regressions. In addition, as suggested by an anonymous reviewer of this paper, density estimates of coarse woody debris might improve greatly if wood density was measured at several locations within the bole. This could reduce differences in initial wood density caused by reaction wood, unknown injuries, the vertical location of the sample on the stem, and errors in the measurement of wood volume and weight. We expect improvements in prediction confidence intervals to be minor, however, because of the reliance of the method on the variable and unknown conditions of preservation which affect wood density. Time and wood density relationships are unlike carbon dating, for instance, which is based on the very stable rate of a chemical reaction.

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