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Pecan Tree Biomass Estimates

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***Abstract*. Allometric equations were developed for orchard-grown pecan [*Carya illinoinensis* (Wangenh.) C. Koch] trees. Trees, ranging in size from 22 to 33 cm in trunk diameter 1.4 m above the ground, were destructively harvested from two sites. The entire above-ground portion of each tree was harvested and then divided into leaves, current season's shoots, and branches ≥1 year old plus trunk. Roots were sampled by digging a trench beginning beneath the trunk and extending to one-half the distance to an adjacent tree, then separating the roots from the soil. Roots were then divided into those less than 1 cm in diameter and those ≥1 cm in diameter. Equations in the form $Y = e^aX^b$ were developed to estimate dry biomass of most tree components and the whole tree, where Y is the dry weight, e is the base of the natural logarithm, X is the trunk diameter at 1.4 m above the ground, and *a* and *b* are coefficients. A linear equation provided the best fit for estimating the weight of the current season's growth. Power equations were also developed to estimate the weights of inner bark and wood for different size trunks or branches.**

Methods to estimate biomass of either individual trees or tree populations are useful for foresters, ecologists, and scientists. Biomass estimates of tree populations are valuable for such studies as ecosystem productivity, energy and nutrient flows, fire behavior, carbon utilization and sequestering, plus many other applications. Most models for biomass estimation have been developed and used by the forestry or ecology community. These models normally divide above-ground components into bole or main stem, bole bark, and crown (Parresol, 1999). Occasionally a fourth component, below-ground biomass, is estimated.

Biomass equations for southern US hardwood and softwood species have been compiled by Clark (1987). More recently, a review of biomass estimators for tree species in the United States has been published (Jenkins et al., 2003), followed by a comprehensive database of biomass regressions for North America tree species (Jenkins et al., 2004). However, no equations have been developed to estimate pecan biomass. Jenkins and colleagues (2004) developed generic equations to estimate above-ground biomass of selected hardwood and softwood groups. They also developed equations to estimate the component ratios of hardwood and softwood species.

Sampling protocols for individual tree and stand biomass have been reviewed recently (Snowdon et al., 2002). Techniques to estimate tree and stand biomass have also been reviewed (Catchpole and Wheeler, 1992). Below-ground biomass is typically sampled within a fixed distance from the trunk (Parresol, 2001). In many cases, only coarse roots are included in the analysis (Helmisaari et al., 2002). However, fine-root biomass can account for 18% to 45% of the total tree biomass, depending on species, age, and site (Fogel, 1983; Santantonio et al., 1977). In Scots pine (*Pinus sylvestris* L.), below-ground biomass accounted for 13% to 25% of the stand's biomass depending on age, with 2% to 15% consisting of fine roots (Helmisaari et al., 2002). Both coarse- and fine-root biomass increased with tree age. Fine roots accounted for 43% to 60% of the stand's annual biomass production and used 45% to 63% of the tree's nitrogen (N). Needle production accounted for another 27% to 34% of the N utilization, and the other tree components used 9% to 21%.

A study using loblolly pine (*Pinus taeda* L.) reported that biomass was partitioned as 17% crown, 63% stem, and 20% roots (Van Lear and Kapeluck, 1995). Fine roots accounted for 11% of the root mass, but contained 24% to 30% of the nutrients in the root system. Fine roots and foliage made up only 4% of the stand's biomass, but had one-fourth of the stand's N and phosphorus (P).

Biomass estimation of individual trees is also useful in horticultural studies, especially those involving mineral nutrition. Three recently published studies on N nutrition of pecan (Acuña–Maldonado et al., 2003; Kraimer et al., 2001, 2004) used equations developed from destructively harvested forest-grown black oak (*Quercus velutina* Lam.) trees (King and Schnell, 1972) to estimate pecan tree biomass components. Extrapolation of black oak models to pecan trees provides questionable information and their use entails major limitations and substantial error sources. First, and most obvious, is that such equations were not developed to estimate pecan tree biomass, a species exhibiting a different growth form than black oak. One striking difference is that *Carya* spp. produce about three times the leaf weight as black oak trees (Schnell, 1978). Acuña–Maldonado and associates (2003) developed equations from destructively harvested pecan trees to estimate leaf weight because of the discrepancy in leaf production between black oak and pecan.

A second limitation is that equations for relatively shaded forest-grown trees do not accurately estimate the biomass components of relatively nonshaded urban-grown (Nowak, 1994) or open-grown trees. Typically in a commercial pecan orchard, grafted trees are initially trained to a modified leader and are subsequently managed with little or no pruning. These trees obviously exhibit morphological traits considerably different from those of forest-grown, shaded black oaks. The predictive ability of equations to estimate biomass of orchard trees is therefore likely to be most accurate if derived from orchard-grown trees. Another potential limitation of extrapolating existing equations

Fig. 1. Typical growth forms of 'Maramec' and 'Pawnee' trees.

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Table 1. Pecan tree trunk diameters 1.4 m above the ground with their dry weights of selected tree components from harvests at the Madill and Sparks sites.

	Dry weight of tree component, kg							
	Madill site					Sparks site		
	Trunk diameter, cm							
Tree component	21.9	23.1	23.5	24.8	25.8	28.0	32.0	33.0
Roots <1-cm diameter	24.1	20.9	34.2	23.2	37.7	68.7	81.0	64.2
Roots ≥1-cm diameter	58.6	42.4	76.5	63.1	188.6	170.6	192.9	180.2
Bark + wood >3 years old	181.3	177.5	198.3	269.5	300.1	459.7	684.1	924.8
Current season shoots	5.7	6.6	3.7	6.8	6.7	5.9	8.1	8.7
Leaves	29.7	33.5	23.7	36.0	38.3	46.3	75.8	79.5

derived from forest-grown trees to horticultural applications is their inclusion of outer bark. Forestry estimates typically include the dead outer bark, because it is of potential use. However, for nutritional physiology purposes, the outer bark is usually unimportant, whereas the inner bark serves as a storage site, especially for nitrogenous reserves (Coleman et al., 1992; Wetzel et al., 1989). Another limitation is that estimated tree weights can differ substantially for the same hardwood species among geographic regions (Clark, 1982).

Accurate equations are essential for studies such as nutrient absorption efficiency and partitioning, carbon allocation, and other applications. Our objective was to develop allometric equations for orchard-grown pecan trees to estimate the biomass of the whole tree and selected components.

Table 2. Equations for estimating the dry weight, in kilograms, of selected pecan tree parts.

Plant part	Equations[z]	R^2
All roots	$Y = e^{-5.9498}X^{3.3413}$	0.73**
Roots <1 cm in diameter	$Y = e^{-6.6398}X^{3.1537}$	0.79**
Roots ≥1 cm in diameter	$Y = e^{-6.5543}X^{3.4266}$	0.68**
Current season shoots	$Y = -0.9 + 0.2814X$	0.57*
Leaves	$Y = e^{-5.103}X^{2.703}$	0.91***
Above-ground perennial parts, excluding current season shoots	$Y = e^{-7.5899}X^{4.1003}$	0.98***
Above-ground perennial parts	$Y = e^{-7.3917}X^{4.0459}$	0.98***
Above- and below-ground perennial parts	$Y = e^{-6.4051}X^{3.8551}$	0.96***
Above- and below-ground perennial parts plus leaves	$Y = e^{-6.0032}X^{3.7578}$	0.97***

*,**,***Significant at 5%, 1%, or 0.1% respectively.

[z]Y = dry weight in kilograms; e = 2.71828; X = trunk diameter in centimeters.

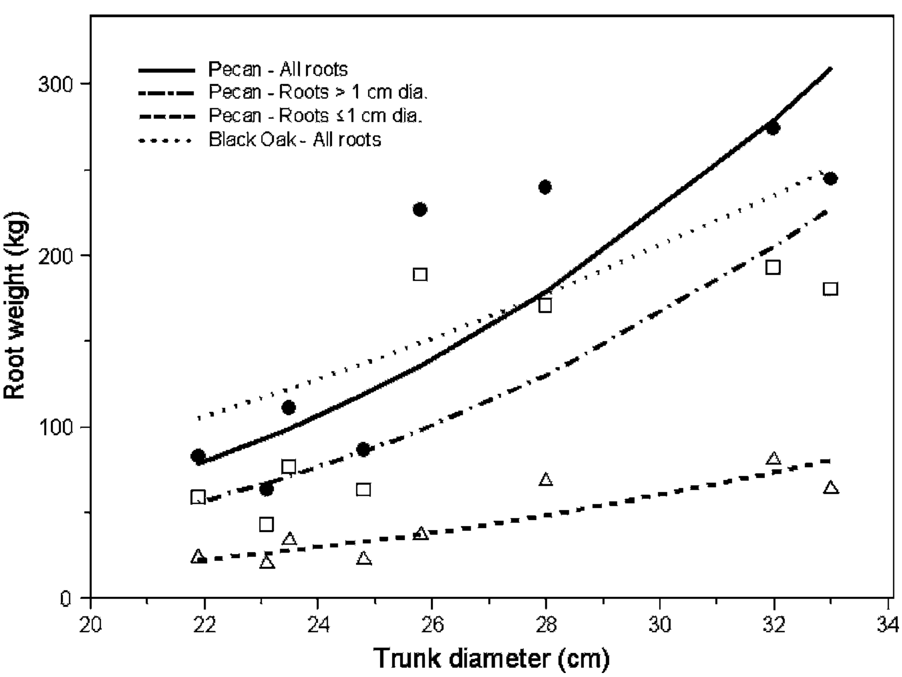

Fig. 2. Estimations of pecan root biomass for trees with different trunk diameters. Estimates are for all roots, roots ≥1 cm in diameter, and roots less than 1 cm in diameter using equations developed for pecan (Table 2), and all roots using equations developed for black oak (King and Schnell, 1972). Open triangles are observed weights for roots less than 1 cm in diameter, open boxes are weights for roots ≥1 cm in diameter, and closed circles represent weights of all roots.

Materials and Methods

Sparks Site

The first site was at the Pecan Research Station in central Oklahoma near Sparks. Fifteen-year-old 'Maramec' trees, spaced 10.7 × 10.7 m apart, were growing in a Port silt loam (fine silty, mixed, superactive, thermic Cumulic Haplustolls). Trees were grafted on open-pollinated seedling rootstocks. After 1 year of scion growth, the trees were transplanted to their orchard location. Trees were not irrigated and rainfall averaged 975 mm annually. Trees were initially trained to a modified leader during years 1 through 6, and then not pruned other than to remove broken branches or limbs that interfered with harvest. Between-tree spacing was sufficient to ensure that canopies had not encroached enough to influence tree morphology markedly.

Madill Site

'Pawnee' trees that were ≈13 years old were harvested from Hauani Creek Ranch in south central Oklahoma near Madill. 'Pawnee' scions had been grafted onto native pecan rootstocks growing in a Madill fine sandy loam (coarse loamy, mixed, active, nonacid, thermic Typic Udifluvents). The native sapling density had been reduced to approximate a 10.7 × 10.7-m spacing before grafting. Trees were not irrigated and rainfall averaged 1053 mm annually. Initial training and subsequent pruning was similar to that at the Sparks site.

Sample Collection and Management

Trees at both sites were harvested and handled in a like manner. Three trees were harvested from the Sparks site during 16 to 23 Oct. 1998. Five trees were harvested from the Madill site during 13 to 15 Sept. (tops) and 20, 22, and 27 Sept. (roots) 2004. Trunk diameters were measured 1.4 m above the soil line before harvest (Table 1). Each tree was cut at the soil line and then the entire tree was divided into leaves, current season's shoots, and branches ≥1 year plus trunk. Roots of each tree at the Sparks site were sampled by excavating two 51-cm wide × 5.3-m long (one-half the distance between trees) trenches ≈2 m deep at a right angle from the crown and centered on the plane of the trunk (Snowdon et al., 2002). The water table was ≈2 m below the soil surface, and no roots were observed below that point. At the Madill site, the excavated area was 81 cm wide, 5.3 m long, and ≈2.5 m deep. The water table was encountered at ≈2.5 m deep.

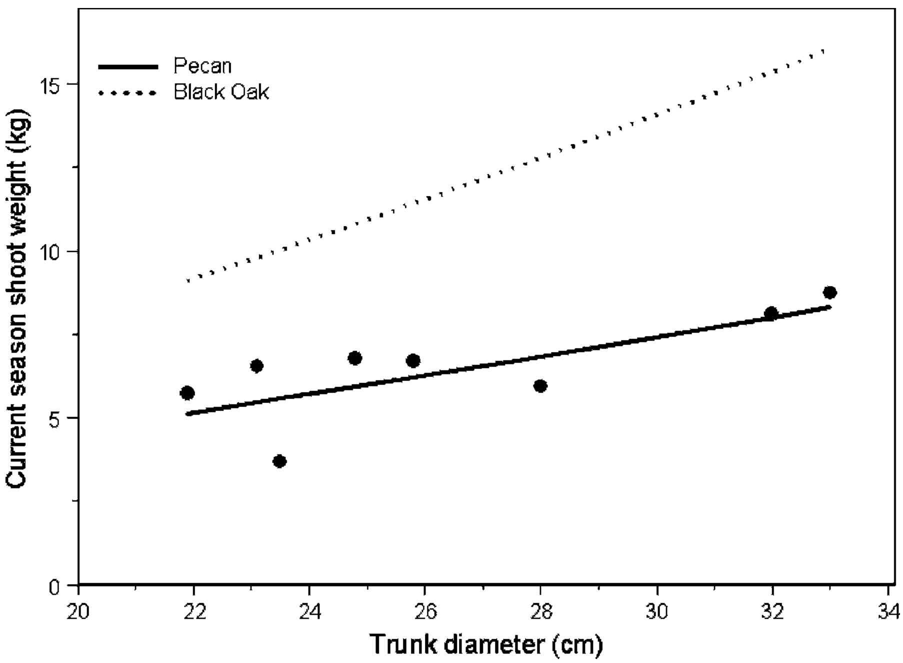

Fig. 3. Estimates of pecan current season shoot biomass using equations developed for pecan (Table 2) and for shoots less than 1.27 cm in diameter using equations developed for black oak (King and Schnell, 1972). Closed circles are observed weights of current season pecan shoots.

Roots were removed from the excavated soil by hand sieving the entire soil volume. The roots were then divided into two size classes: those <1 cm and those ≥1 cm in diameter. Leaves and current season's shoots were dried intact at 70 °C. Branches, roots, and the trunk were cut into sections to fit a walk-in dryer, dried to a constant weight, and then weighed. Root weight per tree was calculated based on the fraction of the root area sampled. Fruit were omitted from analysis because yields vary dramatically among years as a result of alternate bearing; thus, fruit yield predictions based on trunk diameter would be poor.

Six wood disks ≈8 cm thick, and of varying diameter, were collected from the destructively sampled branches and trunk of the trees at the Sparks site. Eighteen wood disks were collected from the Madill site.

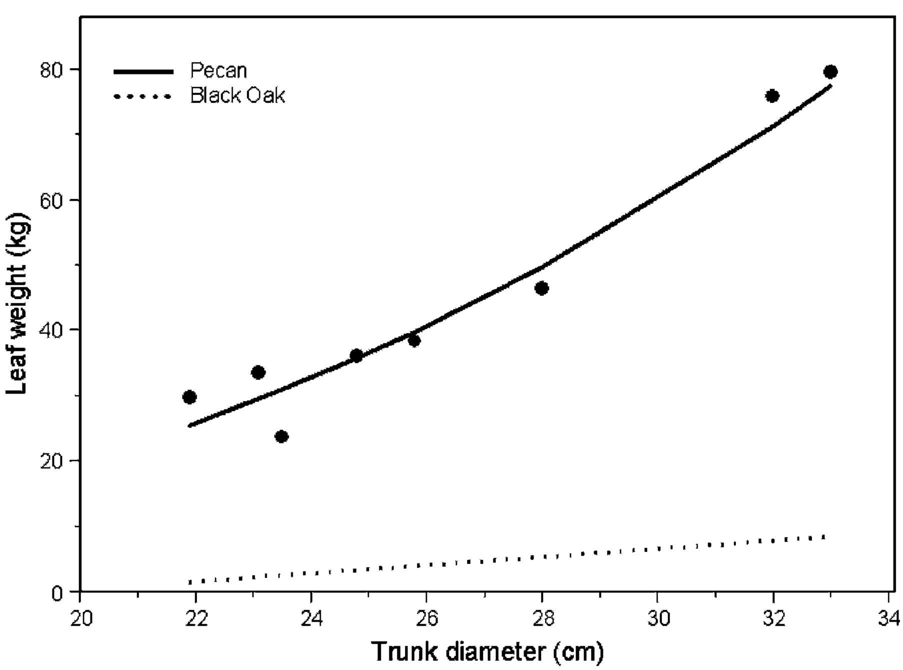

Fig. 4. Estimates of pecan leaf weights using equations developed for pecan (Table 2) and for black oak (King and Schnell, 1972). Closed circles are observed weights of leaves.

Disks ranged in size from 3.1 to 31.7 cm in diameter. The outer bark was removed and discarded, and then the individual disks were separated into inner bark (phloem) and wood (xylem), dried, and weighed.

Statistical Analysis

The most commonly used mathematical model for biomass modeling is the power function:

$$Y = aX^b$$

where Y is the weight, *a* and *b* are coefficients, and X is the trunk diameter at 1.4 m height above the ground (Zianis and Mencuccini, 2004). The trunk diameter and component weights were transformed using natural logarithms, and then regression equations were fit using least squares techniques to estimate the dry weight of each tree component as well as that of the whole tree (Draper and Smith, 1966). These equations take the form

$$\text{Ln}\, Y = \text{Ln}\, a + b\, \text{Ln}\, X$$

and can be rewritten as

$$Y = e^a X^b$$

where Y is the dry weight, e is the natural logarithm base, *a* and *b* are coefficients, and X is the trunk diameter in centimeters. Power function equations were suitable to estimate weights of the whole tree and all components, except current season's shoots. A linear equation, $Y = a + bX$, proved suitable for estimating the weight of current season's shoots.

Power function equations were fit using techniques described earlier to predict weight of bark or wood for various-diameter trunks or branches. In addition, the percentage of inner bark and wood from the disks was calculated for various ages and diameters.

Results and Discussion

'Maramec' tends to have wider crotch angles than 'Pawnee', resulting in a more spreading growth habit (Fig. 1). Branching pattern between the two cultivars was similar. Although differences in growth habit were visible, they were unlikely to have a large effect on component weights. Tree crowding as the trees fill their allotted space is more likely to affect component weight than small differences in growth habit. These trees were harvested before they crowded.

Trees harvested at the Sparks site ranged in trunk diameter from 28 to 33 cm at breast height (Table 1). At the Madill site trees were 21.9 to 25.8 cm in diameter. Equations estimating component or whole tree weights accounted for 57% to 98% of the variation among trees and were significant at the 5% level or greater (Table 2).

Figures include estimated weights using equations for pecan that were developed in this study and those for black oak (King and Schnell, 1972), because they have been used

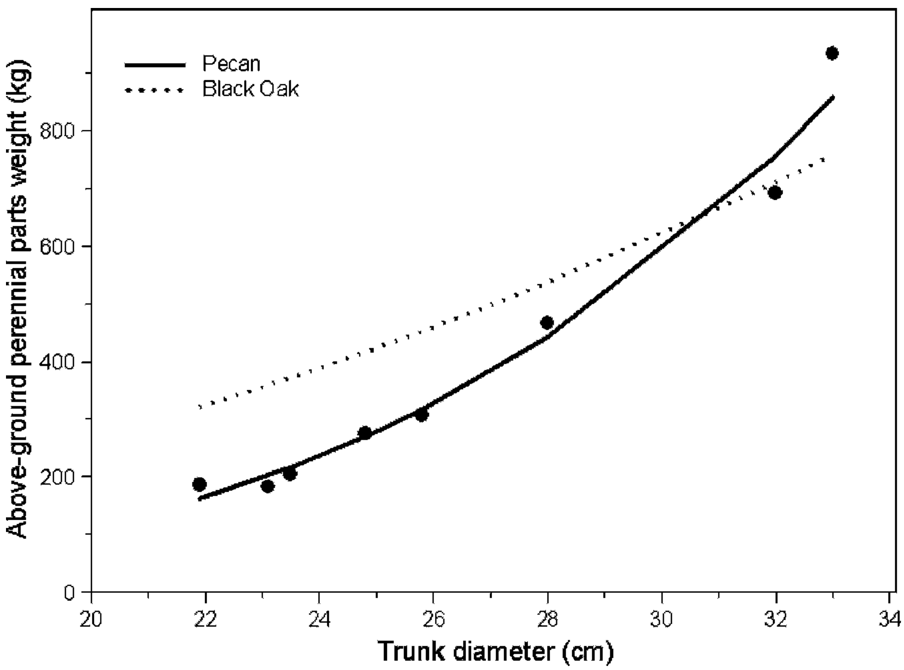

Fig. 5. Estimates of pecan tree above-ground perennial parts using equations developed for pecan (Table 2) and for black oak (King and Schnell, 1972). Closed circles are observed weights.

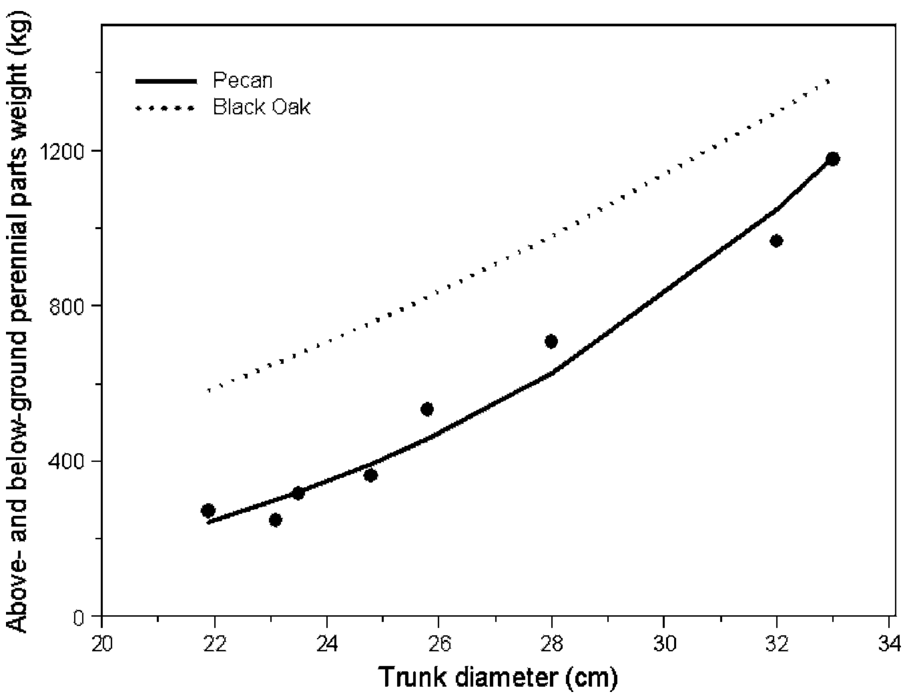

Fig. 6. Estimates of pecan tree above- and below-ground perennial parts using equations developed for pecan (Table 2) and for black oak (King and Schnell, 1972). Closed circles are observed weights.

to estimate pecan tree weights (Acuña–Maldonado et al., 2003; Kraimer et al., 2001, 2004). Total root weight using the black oak equation overestimated weight for small trees and underestimated root weight of larger trees compared with the pecan equation (Fig. 2). The root weight equation for black oak was derived from trunk diameters of the black oaks and the assumption that 25% of the tree's total fresh weight was stump and roots (King and Schnell, 1972). Typically, such an assumption would be used to estimate coarse roots. The equation for pecan was derived from direct measurement data and accounted for 73% of the variation among trees. Pecan root weight was 28% of the complete tree dry weight for 22-cm diameter trees and 19% for 33-cm diameter trees (44% to 26% of the perennial parts for 23-cm and 33-cm diameter trees respectively). Fine roots (<1 cm in diameter) accounted for 29% of the total root mass for 22-cm diameter trees and 26% for 33-cm diameter trees. Root weights as a percent of the complete tree dry weight were estimated to be 15% for black oak (King and Schnell, 1972), 24% for mixed *Carya* spp. (Schnell, 1978), and 16% for the hardwood group containing hickory (Jenkins et al., 2004) for trees in the 22 to 33-cm-diameter size class compared with an average of 23% for pecan. This is similar to the 24% estimated for *Carya* spp. (Schnell, 1978), especially considering the *Carya* spp. were forest grown and the pecans were orchard grown.

Current season shoot weights were substantially overestimated by the black oak equation compared with the equation derived from direct pecan measurements (Fig. 3). Overestimates ranged from 59% for 22-cm-diameter trees to 83% for 33-cm-diameter trees. It should be pointed out that the black oak equation did not directly estimate the weight of current season shoots, but estimated the weight of shoots less than 1.27 cm in diameter. Most current season shoots of pecan would fall within the size range used for black oak, but some vigorous shoots, particularly in the upper canopy, exceed this diameter. Therefore, the overestimate using the black oak equation was even greater than stated here. It is surprising that the less than 1.27-cm-diameter size class for black oak overestimated current season pecan shoots. In a forest situation, much of the lower canopy is lost compared with orchard-grown trees. It therefore seems logical that orchard-grown trees would have many more current season shoots than forest-grown black oak trees. It appears that the equation for shoots less than 1.27 cm in diameter includes many 1- and 2-year-old shoots of black oak in addition to current season shoots to accumulate up to 83% more weight for the same tree size.

Leaf weights were substantially underestimated using black oak equations compared with those derived from direct measurements of pecan (Fig. 4). King and Schnell (1972) obtained leaf data for 8 of the 26 trees in their study. They indicated that data for six of the eight were suspect because they were harvested in the fall after trees began to defoliate or in the spring before the leaves had fully expanded. The black oak equation underestimated 22-cm-diameter pecans 21-fold and 33-cm-diameter trees by 9.5 times. To avoid this problem Acuña–Maldonado and associates (2003) developed an equation to estimate leaf weight from three destructively harvested pecan trees. Their leaf weight estimates were 32% lighter for 22-cm-diameter trees and 2% heavier for 33-cm-diameter trees compared with the pecan equation developed in this study.

The equation estimating of the above-ground perennial parts accounted for 98% of the data variation (Fig. 5, Table 2). Mass estimates using the black oak equation overestimated the weight by 71% for 22-cm-diameter trees and underestimated weight by 19% for 33-cm-diameter trees. The equation to estimate above- and below-ground

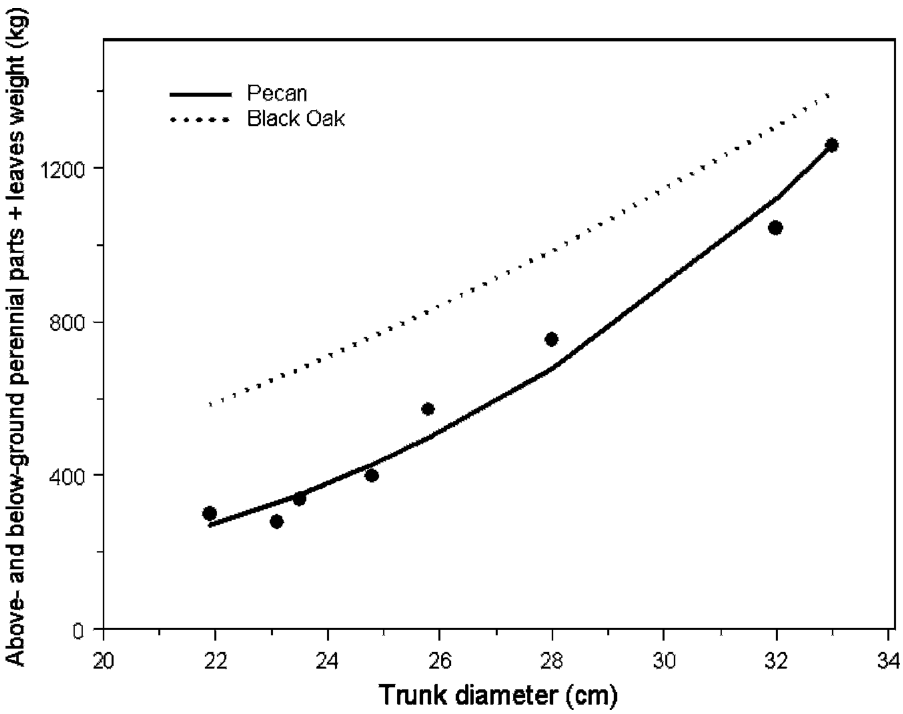

Fig. 7. Estimates of pecan tree above- and below-ground perennial parts plus leaves using equations developed for pecan (Table 2) and for black oak (King and Schnell, 1972). Closed circles are observed weights.

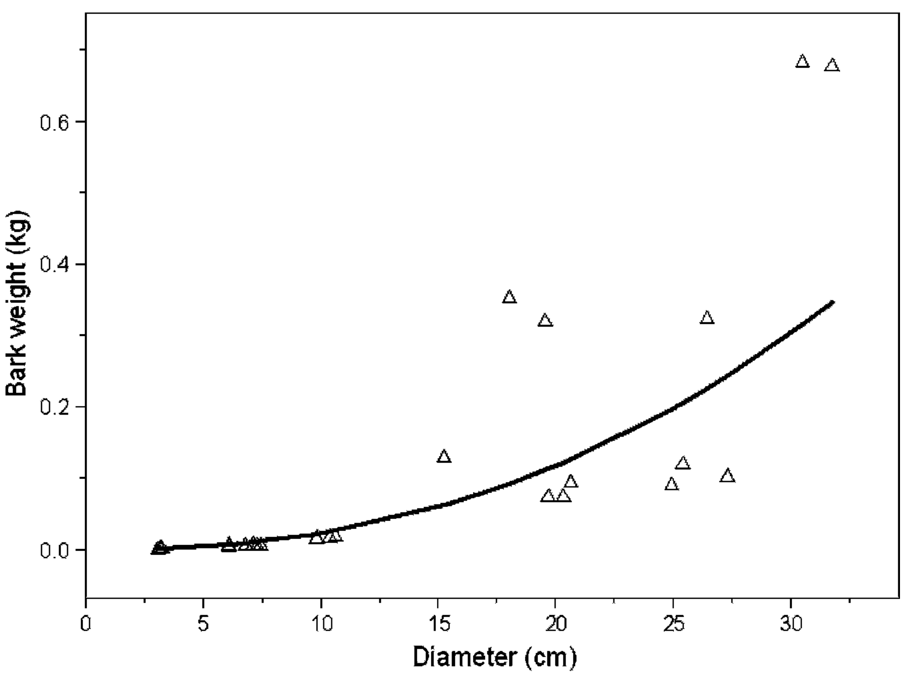

Fig. 8. The relationship between trunk or branch diameter and inner bark weight is $Y = e^{-9.1711}X^{2.3457}$, where Y is the bark weight in kilograms, e is 2.71828, and X is the trunk or branch diameter in centimeters. R^2 = 0.88, F-test <0.001.

perennial parts accounted for 96% of the variation (Fig. 6, Table 2). Black oak equations overestimated weights by 115% for 22-cm-diameter trees and 18% for 33-cm-diameter trees compared with the equation developed for pecan. When the leaves were combined with the above- and below-ground perennial parts, an equation accounting for 97% of the variation was developed (Table 2). The black oak equation overestimated weight for 22-cm-diameter trees by 94% and by 11% for 33-cm-diameter trees compared with equations for pecan (Fig. 7).

Inner bark and wood percentages varied with component age and size (Table 3 and Figs. 8 and 9). Inner bark constituted a smaller fraction of tree component mass as age increased. Equations estimating bark weight for various diameters account for 88% of the variation and were highly significant. Inspection of the graph suggests that weight predictions are very accurate for small diameters, but may underestimate weights for large diameters (Fig. 8). Estimates for wood appear to have the same bias as that for bark (Fig. 9).

Table 3. The percentage of inner bark and wood from wood disks of varying sizes collected from pecan trees at two sites.

	Dry weight ± sd, %	
Tissue age, diameter	Inner bark	Wood
1 and 2 y, 3.1–3.3 cm	14.7 ± 0.9	85.3 ± 0.9
3 y, 6.1–7.5 cm	11.3 ± 1.2	88.7 ± 1.2
>3 y, 9.8–32 cm	11.0 ± 2.1	89.0 ± 2.1

In summary, allometric equations are presented for pecan trees typical to those found in relatively young commercial orchards. These equations are the most accurate to date for estimating the previously described biomass components. The range of tree size covered, 22 to 33 cm in diameter, is typical of diameters exhibited by orchard trees when they first begin severe alternate bearing; thus, the equations are potentially useful in efforts to estimate organic and inorganic resources in trees and their organs. These data provide a foundation on which future studies can build in efforts to produce allometric equations that accurately describe biomass components of pecan trees over a wide range of trunk diameters encountered in orchard situations.

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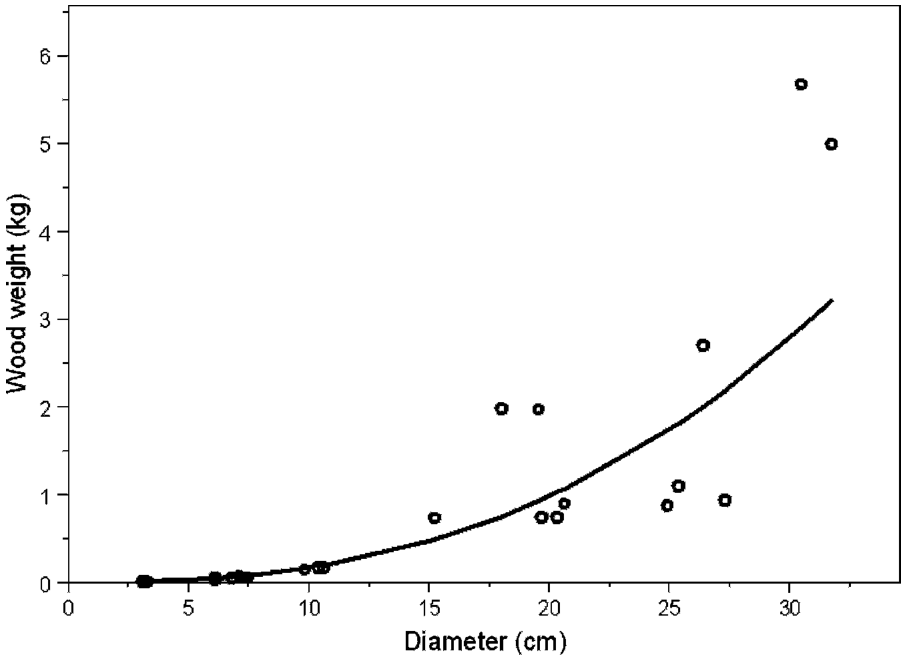

Fig. 9. The relationship between trunk or branch diameter and wood weight is $Y = e^{-7.9886}X^{2.5609}$, where Y is wood weight in kilograms, e is 2.71828, and X is the trunk or branch diameter in centimeters. $R^2 = 0.95$, F-test <0.0001.

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