Leaf Area Index, Leaf Mass Density, and Allometric Relationships Derived From Harvest of Blue Oaks in a California Oak Savanna[1]

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Abstract

Given the key role played by biogenic volatile organic compounds (BVOC) in tropospheric chemistry and regional air quality, it is critical to generate accurate BVOC emission inventories. Because oak species found in California often have high BVOC emission rates, and are often of large stature with corresponding large leaf masses, oaks may be the most important genus of woody plants for BVOC emissions modeling in California airsheds. Accordingly, reference data for leaf mass and leaf area for a stand of native blue oaks were obtained through harvest of 14 trees located in the Sierra Nevada foothills. In addition, leaf mass estimation methods based on a volumetric method and allometric relationships were evaluated for these trees. Leaf mass density (leaf mass per surface area of land) was 310 g m^{-2} for the site, but consideration of the surrounding grassland devoid of trees would result in a value of about 150 g m^{-2}, less than half of reported values for eastern U.S. oak woodlands, but close to a reported value for oaks found in an Italian site, which like California has a Mediterranean climate. The mean value for leaf area index (LAI) for the 14 individual trees at this oak site was 4.4 m^2 m^{-2}. LAI for the site was 1.8 m^2 m^{-2}, but this value was appropriate for the oak grove only; including the surrounding open grassland would result in an overall LAI value of 0.9 m^2 m^{-2} or less. A volumetric method worked well for estimating the leaf mass of the oak trees. Among allometric relationships investigated, trunk circumference, mean crown radius, and crown projection were well correlated with leaf mass. BVOC estimates based on data obtained at the study site indicate blue oaks may be significant contributors of BVOC to California airsheds where this species is plentiful.

Introduction

It is now well known that volatile organic compounds (VOC) are emitted from vegetation, including natural plant communities, urban landscapes, and agricultural crops. An accurate estimate of the magnitude of biogenic VOC (BVOC) emissions relative to anthropogenic VOC emissions may be critical for formulating effective strategies to reduce concentrations of fine particles, ozone, and other secondary air pollutants which affect human health and reduce yields of agricultural crops.

Concern about the possible critical role of BVOC emissions is reinforced by (a) the fact that on average many BVOC are as reactive, or more reactive, in the atmosphere than emissions from mobile or stationary anthropogenic sources (Carter

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1994); and (b) a growing body of research from studies throughout the world suggesting that BVOC can constitute a significant and even dominant contribution to the overall VOC inventory in both regional airsheds and the global atmosphere (Guenther and others 2000, Lenz and others 1997, Seufert and others 1997). For California, modeling studies suggest that development of specific emission control strategies for reducing ambient ozone in certain airsheds is dependent upon estimated emissions of BVOC. These studies showed that emissions of hydrocarbons from vegetation can make the difference between nitrogen oxides vs. VOC emission controls being the most effective in reducing ozone concentrations (Jackson and others 1996). In heavily vegetated airsheds in California, BVOC emissions may limit the effectiveness of VOC control, setting a floor under the reduction in ozone that can be achieved by reducing anthropogenic VOC.

BVOC emission inventories require species-specific data for BVOC emission rates, areal coverage, and leaf mass, and calculated BVOC emissions will be directly proportional to each of these terms. Trees with both high leaf mass and high BVOC emission rates, such as several of the oak species, may be dominant BVOC emitters in California's natural landscapes. For example, in an earlier study in Ventura and Santa Barbara counties (Chinkin and others 1996), a natural oak woodland dominated the biogenic emission inventory, and oaks are the dominant BVOC emitters in the Mediterranean region (Seufert and others 1997).

Considerable attention has been given to determining BVOC emission rates, including proposal of a taxonomic methodology for assigning isoprene and monoterpene emission rates to unmeasured plant species (Benjamin and others 1996), testing of this hypothesis through emission measurements of additional species (Karlik and Winer 2001a, Winer and Karlik 2001), and further emission characterization of oak species (Csiky and Seufert 1999). However, description of areal coverages of plant species and their leaf masses may currently be the weaker links in BVOC inventory development in California. Quantifying oak distribution and leaf mass is of particular interest for such inventories, as is development of methods for leaf mass estimation useful in field surveys.

The principal goals of the present study were to develop data for a stand of native blue oaks for whole-tree leaf mass (g), canopy leaf mass density (LMD) (g m^{-2}), whole-canopy leaf area (LA) (m^{-2}), and leaf area index (LAI) (m^2 m^{-2}), which could subsequently be used as reference values. In addition, leaf mass estimation methods based on a volumetric method and allometric relationships were evaluated for these oak trees.

Experimental Methods

In July 2000, a grove containing 14 blue oak trees (*Quercus douglasii*) was selected on an east-facing slope on private land in the Sierra Nevada foothills near California Hot Springs, approximately 50 miles northeast of Bakersfield. This stand of trees appeared to be representative of blue oaks found in the oak savannas of the foothill areas of the southeastern San Joaquin Valley. The trees had received no cultural attention such as pruning, irrigation, or fertilizer; and had become established from natural acorn dispersion.

A rectangular grid was established in the field by placing 50 m measuring tapes at right angles so as to encompass the crown projections of the 14 trees. The universal transmercator coordinates for the northeast corner of the grid were found with a global positioning system (GPS) receiver (Garmin 12XL) and checked against a second receiver (Magellan GPS 2000), and were 11S 0345696E and 3970295N, with corresponding latitude-longitude coordinates of 35° 51' 53" N and 118° 42' 33" W. The quadrant marked with the measuring tapes opened to the southwest; the compass headings for the baselines were 168° and 258°. Elevation was 975 m measured with a portable altimeter (Pretel Instruments). The trees were numbered, and the position of each tree was noted. Tree dimensions were measured to a precision of 0.1 m. Tree heights were measured with a telescoping pole, and the distance from the ground to the base of the crown was measured with a steel tape. From these measurements vertical crown depth was calculated. Crown radii of trees were measured in the four cardinal directions from the trunk to the average dripline by using a steel tape, and the means were calculated. Trunk circumferences at breast height were also measured with a steel tape, but to a precision of one cm.

Following measurements of standing trees, each specimen was felled with a chain saw approximately five cm above the soil surface, the stump diameter was measured in two directions, and the number of sapwood rings was counted. Each tree was separated in the field into twigs with leaves, branches, and trunk sections. Branches, defined as stems with diameters between two and 10 cm, and trunk sections with diameters greater than 10 cm, were weighed in the field to the nearest gram. The twigs with leaves were transported to the laboratory and all leaves were removed for drying and weighing, and the twigs were also weighed. Leaves were placed in paper bags and dried for approximately two weeks in a vacant greenhouse with daily maximum temperatures of about 65°C and relative humidity less than 20 percent. Bags of leaves were weighed to the nearest even gram on a digital scale and masses summed for each tree. Bags were spot checked to verify complete drying and no decomposition was noticed. To obtain a value for specific leaf area (SLA) (m^2 g^{-1}), area of 50 fresh leaves was measured with a leaf area meter (LiCor), and then these leaves were dried under the same conditions as the rest of the oak leaves and weighed. Samples of trunks, branches, and twigs were also dried to obtain fresh-weight to dry-weight ratios.

Results

Results from Whole-Tree Harvest for Leaf Mass, LMD, LA, and LAI

Blue oak dimensions and leaf masses are given in *table 1.* Total dry leaf mass for the 14 trees was 92.9 kg. Resulting calculated values for tree dimensions such as crown height, crown projection and DBH are seen in *table 2.* Tree no. 1 had extensive dieback and decay resulting in a hollow center; it was excluded from data analysis where trunk diameter was included in allometric equations, but its leafmass and crown dimensions were included in calculations. Based on counts of sapwood rings, the blue oak trees harvested were about 70-180 years old.

Calculated per-tree values for LMD based on crown projection ranged from 410 to 1300 with a mean of 730 g m^{-2} for these blue oak trees *(table 2).* LMD calculated on the basis of total leafmass divided by the sum of areas of crown projection was 720 g m^{-2}, slightly lower than the mean LMD values for the individual trees. The minimum grid dimensions needed to encompass the driplines of all oak crowns were 16.7 x 18.1 m, an area of 302 m^{-2}. The LMD calculated for the site based on total leaf mass divided by this area was 310 g m^{-2}, considered to be the site LMD value. This value may be compared to values (g m^{-2}) for oak woodlands of various locales, including 375 for Atlanta, GA (Geron and others 1995); 375 for the contiguous United States (Lamb and others 1987, 1993); 160 for holm oak (*Q. ilex*) at Castelporziano, Italy (Lenz and others 1997); and 65 and 130 for scrub oak (*Q. dumosa*) in San Diego County (Kummerow and Mangan 1981). However, the oak stand harvested and measured was surrounded by open grassland, and therefore the LMD value of 310 g m^{-2} represents a maximum for that site. If the LMD was calculated on the basis of the area of the grid plus the surrounding grassland, the value would have been approximately half based on observation of tree cover in the vicinity. No quantitative data for oak coverage were available, but a gradation from scattered trees at lower elevations to apparent crown closure on slopes at higher elevations was observed.

Table 1—*Plant dimensions of native blue oak trees selected for harvest and measurement of total dry leafmass.*

Tree (no.)	**Tree height** (m)	**Ground-crown distance** (m)	**Mean crown radius** (m)	**Trunk circum. breast ht.** (cm)	**Stump diameter** (cm)	**Sapwood rings** (no.)	**Dry leaf mass** (g)
1	7.4	3.0	1.1	202	85	N/A	3,750
2	6.7	2.6	2.0	77	30	112	9,750
3	4.7	1.5	1.1	45	29	89	2,210
4	7.8	1.5	1.4	57	22	97	5,230
5	7.5	3.0	1.8	75	30	130	6,790
6	5.9	1.4	1.2	37	14	70	1,950
7	7.2	1.6	1.1	57	22	113	4,420
8	6.7	1.7	1.5	60	23	103	5,380
9	9.9	2.4	3.6	132	49	172	29,300
10	4.2	1.4	1.1	38	25	86	1,830
11	6.8	2.3	1.5	59	22	76	5,230
12	6.3	1.7	1.2	42	17	72	2,200
13	7.5	2.0	1.8	68	29	95	9,040
14	4.4	2.4	2.1	53	21	86	5,930

Leaf areas of individual trees were also calculated by Equation 1 *(table 2):*

$$LA = LM * SLA \qquad \text{(Eq. 1)}$$

where LM was whole-tree leafmass (g) and SLA had a value of 6.03 x 10^{-3} m^2 g^{-1} obtained from the oak leaf sample. The LA for these trees ranged from 11.1-177 m^2, with a mean value of 40.0 m^2. LAI values for individual trees are shown based on LA and the area of crown projection for each tree modeled as a circle *(table 2)*. (LAI was also calculated using measurements of crown radii and the equation for the area of an ellipse to find the area of crown projection, but the resulting values for LAI for each tree differed by only about one percent from those where crown radii were averaged.) The mean per-tree value for LAI was 4.4 m^2 m^{-2}.

Table 2—*Calculated values for tree parameters for native blue oak trees based on crown measurements, whole-tree harvest, and measurement of leafmass and SLA of a 50-leaf sample.*

Tree (no.)	Crown depth (m)	Crown projection (m^2)	DBH (cm)	LMD (g m^{-2})	Leaf area (m^2)	LAI (m^2 m^{-2})
1	4.4	3.6	64	980	21.5	5.9
2	4.1	13	25	780	58.8	4.7
3	3.2	3.6	14	610	13.3	3.7
4	6.3	5.7	18	910	31.5	5.5
5	4.5	10	24	650	40.9	3.9
6	4.5	4.7	12	410	11.8	2.5
7	5.6	3.5	18	1,300	26.6	7.7
8	5.0	6.8	19	790	32.4	4.8
9	7.5	40	42	740	177	4.5
10	2.8	4.0	12	460	11.1	2.8
11	4.5	7.3	19	720	31.5	4.3
12	4.6	4.5	13	490	13.3	2.9
13	5.5	9.6	22	940	54.5	5.7
14	2.0	14	17	440	35.7	2.6

The sum of LA for all 14 trees was 560 m^2. The sum of areas of crown projection for the oak trees was 130 m^2, although overlap of foliage occurred. LAI calculated on the basis of the sum of LA area divided by the sum of areas of crown projection was 4.3 m^2 m^{-2}, with crown projection taken as a circle with mean radius as noted in Table 1. LAI calculated on the basis of total leaf area divided by grid area was 1.8 m^2 m^{-2}, and this value was considered to be the site LAI. This value was appropriate for the grove only; inclusion of surrounding area devoid of trees would result in an overall LAI value of perhaps half, or 0.9 m^2 m^{-2}. Values (m^2 m^{-2}) for LAI for oaks have been reported, including a range of 4.5-8 for a mixed oak forest in Castelporziano, Italy, and 4-6.75 for individual oak species at that Mediterranean site.

A Volumetric Method for Leaf Mass Estimation

A volumetric approach for estimating leaf mass has been used in past studies (Karlik and Winer 1999, Karlik and Winer 2001b, Miller and Winer 1984) because of its relatively simple non-destructive data requirements in field surveys, its potential applicability to the plethora of species found in natural landscapes, and its flexibility in modeling both tree and shrub morphology. Using crown height and radius data for each tree crown, volumes for five geometric solids approximating tree shapes (Karlik and Winer 1999, McPherson and Rowntree 1988) were calculated from the following geometric formulae: $4/3\pi r^3$ (sphere), $\pi r^2 h$ (cylinder), $2/3\pi r^2 h$ (vertical ellipsoid), $1/2\pi r^2 h$ (paraboloid) and $1/3\pi r^2 h$ (cone). These solids are related mathematically and the volumes of a vertical ellipsoid, paraboloid, and cone are respectively 2/3, 1/2 and 1/3 of the volume of a cylinder with the same radius and height. Calculated whole-tree leafmasses were obtained by multiplying the respective volumes by a leaf mass constant (g m^{-3}). A value of 280 g m^{-3} was used for the leaf mass constant, the mean to two significant figures for coast live oak (*Quercus agrifolia)* (Miller and Winer 1984) and interior live oak (*Q. wislizenii)* (Horie and others 1991).

Total measured leaf mass for trees in this study of 92.9 kg may be compared to estimates of total leaf mass derived from the geometric solids, which ranged from 63.4 kg (cone) to 190 kg (cylinder). For the paraboloid, vertical ellipsoid and sphere, total leaf mass estimates were factors of 1.02, 1.36 and 1.15 of the measured, respectively. Therefore, two of the solids gave estimates of total leaf mass within 15 percent of the measured, and the third within approximately 35 percent. As a comparison, for 21 urban trees in the 1999 study of Karlik and Winer (1999), sums of leafmass estimates were within fractions of 0.91, 0.68, or 0.92 of the total measured leafmass when the vertical ellipsoid, paraboloid, or sphere solids were used, respectively. In the present study, the leaf mass constant of 280 g m^{-3} coupled with the paraboloid solid gave the closest estimate to measured leaf mass for the blue oak trees.

As a tree grows the ratio of leaf mass to volume will tend to decrease, because the outer surface of the crown moves up and out as branches grow, and crown volume increases as the cube of the distance from the center of the tree to the outer leaves. However, for small to medium sized trees (< 20 m in height), a leaf mass estimation method based on crown volume may work well in field surveys.

Allometric Relationships for LM

Allometric relationships for leafmass estimation were also obtained by plotting leafmass against crown and trunk dimensions, and also by plotting leafmass against calculated values such as area of crown projection. A second-order polynomial correlation of leafmass vs. circumference at breast height had a coefficient of determination (r^2) of 0.98 *(fig. 1).* A second-order equation was chosen rather than a linear relationship, because the leaf-carrying capacity of a plant is dependent upon vascular transport of water, and the area of the vascular system increases as the cross-sectional area of the stem, proportional to the square of the circumference or diameter. Circumference at breast height is perhaps the easiest tree dimension to measure, so the high value for r^2 is encouraging, and suggests oak circumference may be useful for estimating leaf masses for blue oaks. As expected, the graph of the second-order polynomial correlation for leaf mass vs. trunk DBH was identical in shape to that of leaf mass vs circumference, with the same r^2.

A second-order polynomial equation was also chosen to describe the correlation of leaf mass vs. mean crown radius because leaf mass should increase as the square of the crown radius, and for this correlation an r^2 of 0.96 was obtained *(fig. 2).* Leaf mass vs. area of crown projection modeled with a linear relationship resulted in an r^2 of 0.95. Therefore, leaf mass and either trunk or crown radius measurements appeared to be well-correlated for the trees studied. A second order polynomial correlation for leaf mass vs. stump diameter resulted in an r^2 of 0.92, almost as high as that for trunk DBH.

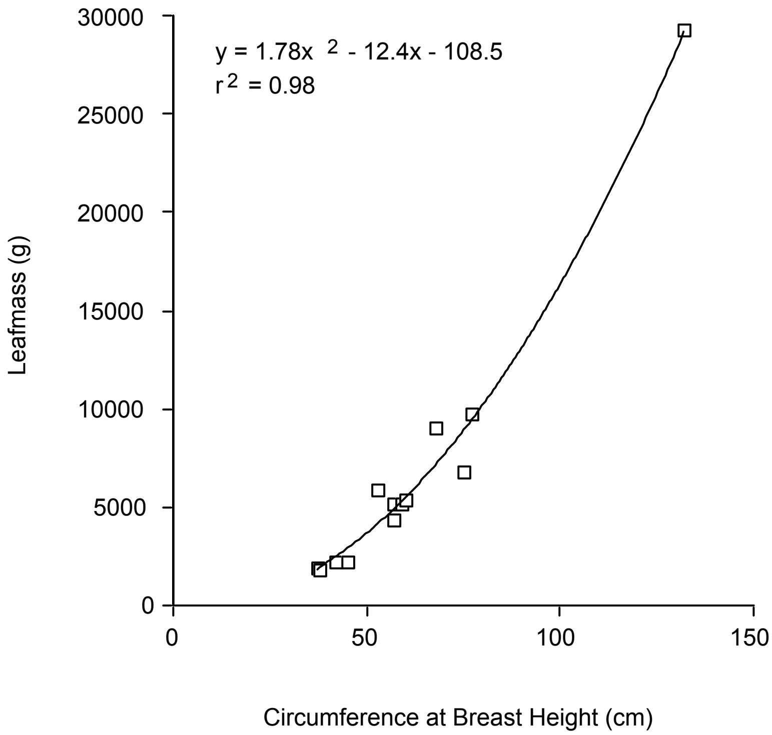

Figure 1—Allometric relationship between measured whole-tree leaf mass and trunk diameter at breast height for 14 blue oak trees harvested from a native stand in the Sierra Nevada foothills.

Several other relationships had lower coefficients of determination than those noted above. The linear relationship of leaf mass vs. rings of sapwood had an r^2 of 0.74, but for leaf mass vs. tree height or crown height r^2 had values of 0.55 and 0.39, respectively.

We are aware that only 14 blue oak trees were harvested in this study, and these trees were limited in ranges of trunk and crown dimensions. Therefore, the specific equations developed may not apply to trees outside this size range or to other species, and should be used with caution even for other blue oaks which fall within the size parameters of the harvested trees.

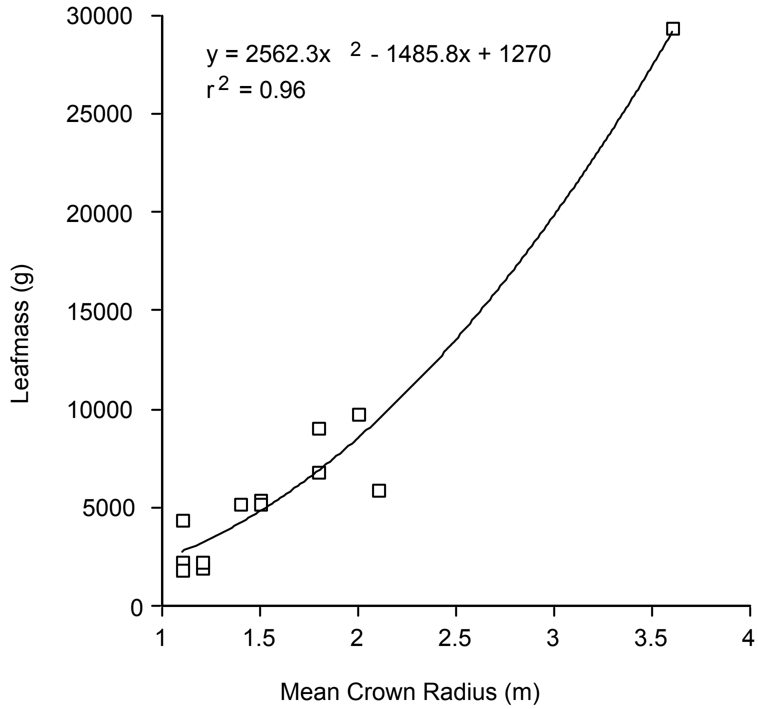

Figure 2—Allometric relationship between measured whole-tree leaf mass and mean crown radius for 14 blue oak trees harvested from a native stand in the Sierra Nevada foothills.

Implications for BVOC Emissions

Blue oaks fall within the Lepidobalanus subgenus of *Quercus*, a group characterized by high isoprene emissions but low or negligible monoterpene emissions (Csiky and Seufert 1999). An estimate of BVOC emissions under standard conditions of light and temperature (30°C and 1,000 µmol m^{-2} s^{-1} for photosynthetically active radiation) was calculated for the study site. (Hourly values for light and temperature and a canopy correction term would be used in a BVOC emission model.) Using a measured branch-level isoprene emission rate for blue oak of 27 µg g^{-1} h^{-1} (Karlik and Winer 2001a) and a value of zero for monoterpene emission rate based on taxonomy (Benjamin and others 1996), the estimate for isoprene flux would be 8.3 mg m^{-2} h^{-1}, equivalent to 7.7 mg C m^{-2} h^{-1}, which could also represent total BVOC emissions from the site since blue oaks are not monoterpene emitters. If we consider the oak stand to comprise 50 percent of the land surface in the vicinity, the emissions would be half, or 3.9 mg C m^{-2} h^{-1}. These values may be compared to estimates of 2.2-11 mg C m^{-2} h^{-1} for mixed deciduous/coniferous woodlands, and 0.8-4.3 mg C m^{-2} h^{-1} for scrub woodlands (Guenther and others 1994). The isoprene flux estimate derived for the stand of blue oaks investigated is at the higher end of the range for mixed deciduous/conifer woodlands, not unexpected considering the high isoprene emission rate for blue oak. The overall value of 3.9 mg C m^{-2} h^{-1} is at the higher end of the range for scrub woodlands. For California oak savannas, estimates of BVOC emissions such as these should be checked against fluxes measured at similar sites.

Conclusions

The LMD for the oak site we studied was calculated as the total leafmass divided by area of the grid needed to encompass the tree crowns. The resulting value of 310 g m^{-2} was considered to be the site LMD value, and may be compared to values for oak woodlands of various locales, and is about 80 percent of LMD values for U.S. woodland sites. However, the oak grove we harvested and measured was surrounded by open grassland, and therefore an LMD value of 310 g m^{-2} represented a maximum for that landcover. If the oak LMD was calculated on the basis of the area of the grove plus the open grassland surrounding it, the value would have no more than half, and the resulting value of approximately 150 g m^{-2} is less than 50% of the value for eastern deciduous forests, but close a reported value for oaks at an Italian site.

The mean value for LAI for the 14 individual trees in this oak site was 4.4 m^2 m^{-2}. LAI calculated on the basis of total leaf area divided by grid area was 1.8 m^2 m^{-2}, and this latter value was considered to be applicable to the site. This value was appropriate for the oak grove only; consideration of the surrounding area which was devoid of trees would result in an overall LAI value of less than 0.9 m^2 m^{-2}, which is lower than reference values for a Mediterranean oak woodland.

For estimating leaf mass, both a volumetric method and an allometric method based on tree dimensions worked well. Modeling tree crowns with a paraboloid gave calculated leaf mass within 2 percent of the total measured leaf mass for these trees. The relationship between leafmass and circumference at breast height had the highest coefficient of determination of the relationships studied, suggesting trunk circumference may be used to estimate leaf masses for blue oaks. Mean crown radius and crown projection were also well-correlated with leaf mass. A volumetric method may be useful in future field studies for leaf mass estimation.

BVOC estimates indicate blue oaks may be significant contributors of isoprene to California airsheds where this species is plentiful. BVOC fluxes should be measured for oak savannas for comparison to estimates.

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