Biomass Equations for *Quercus ilex* L. in the Montseny Massif, Northeastern Spain

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SUMMARY

Biomass estimation equations for individual holm oak (*Quercus ilex* spp. *ilex*) were developed using data from 71 sample trees. Diameter alone was a strong predictor of biomass, but better biomass estimates were obtained when height and crown projection radius were added to the model. In addition to total above-ground dry weight, different biomass components were calculated: stem (greater than 5 cm in diameter), branches 1 to 5 cm in diameter, branches less than 1 cm in diameter, and foliage. Grouping the trees according to height (taller or shorter than 7 m) and aspect (north- and south-facing slopes) resulted in significantly different allometric equations for most of the components considered. Improved estimates were achieved in many cases when D50 (diameter at 0.5 m) was used instead of DBH. Comparison of the results with other published equations developed for *Q. ilex* and other oaks showed differences, probably due to morphological diversity of trees and different DBH class distribution of samples used.

INTRODUCTION

In order to estimate the biomass of the different components of a tree, the dimensional analysis method is often used. This relates certain easily measurable tree parameters (usually stem diameter and total height) with a tree's total weight or with the weight of any component into which the tree can be divided (Whittaker *et al.*, 1971, 1975; Saato and Madgwick, 1982). Relationships between tree dimensions are usually curvilinear; the equations that characterize this type of relationship are often termed 'allometric', and they allow prediction of weight and production through simply measuring diameter or any other tree dimension. This method has been widely used by foresters, and allometric equations are known for the most important species, though in many of them only the commercially exploited component is meaured. For this reason, information concerning total biomass or fractions such as foliage, branches, etc., is more difficult to find, especially for the evergreen oak (*Quercus ilex*). In this context, it is worth noting that in the biomass data of more than 1,200 forest stands of the world compiled by Cannell (1982), only one study on *Quercus ilex* (Rapp and Loissant, 1978) is recorded.

Allometric equations were already available for holm oak at Montseny

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(Ferrés *et al.*, 1980), obtained from 15 trees felled next to an experimental plot set up for monitoring nutrient cycling studies (Terradas *et al.*, 1980; Ferrés *et al.*, 1984). It is accepted that the allometric equations for a species in a given area can be obtained from a detailed study of 15 trees covering the whole range of diameters (Duvigneaud, 1971). Even for a given area of homogeneous characteristics, one allometric equation can be applied to different species (Kira and Shidei, 1977; Whittaker and Woodwell, 1969; Duvigneaud, 1971). But allometric equations used in areas other than those from where they were developed frequently show a notable loss in the accuracy of biomass estimation (Harding and Grigal, 1986).

At present, nutrient cycling studies are being extended to holm oak forested watersheds at La Castanya valley (Montseny massiff) (Avila and Rodà, in press). Holm oak trees found in the valley cover a great variety of morphological types, depending on stand density and topographical factors (trees being shorter on hill tops with shallow soils, and taller in hollows). Due to the special characteristics of the sample trees used by Ferrés *et al.* (1980) to develop their allometric equations (tall trees with narrow crowns, growing in a stand with closed canopy and deep soil), the need was stated for allometric equations applicable to a wide range of tree morphologies and forest stands. These equations are also expected to be an important tool for foresters, contributing to the improvement of the forest management practices at the Montseny massif.

STUDY AREA

The study was carried out in the valley of La Castanya in the Montseny massif, which is part of the pre-coastal Catalonian range (northeastern Spain). The Montseny is located some 40 km NNE of Barcelona at a minimum distance of only 15 km from the sea and experiences a very definite mediterranean influence. Extensive holm oak forests are present throughout the valley, being replaced by beech forests (*Fagus sylvatica* L.) at the highest altitudes (above 900–1,000 m). The holm oak forest under study was exploited extensively for charcoal production until some 25–30 years ago. The sample area is located at an altitude of about 700 m, with slopes ranging from 15 to 30 degrees.

The area selected, like most of the massif, is underlain by metamorphic schists. Soils are dystric lithic xerochrepts, with different degrees of development and leaching. Most of these soils are of a colluvial nature, as is typical of soils found in sloping areas. Average annual air temperature is 9°C and annual rainfall is 870 mm (average over 5 years of observation). Meteorological information corresponds to observations made at the experimental plot located at 665 m above sea level and on the northwestern-facing slope of the valley, so that these data may be subject to changes due to altitude, aspect and topographical location for the different parts of the area sampled.

METHODS

When deciding which trees to fell an attempt was made to span the range of different morphological types existing in the sample area. Thus, holm oaks were cut having diameters at breast height (DBH) of 5 to 24 cm, total heights (H) from 4 to 14 m, and crown projection radius (CPR) from 1.1 to 3.2 m. The sample included trees of low height and wide CPR, common in open stands near ridges, and those of greater height and narrower CPR, usually found in dense stands with deeper soil. Sample trees included stored coppice shoots, from multi-stemmed stools as well as maiden stems (from natural seeding). Two different locations were also taken into account: south- and north-facing slopes of the valley. Average and range of variation of DBH, H, and CPR for sample trees according to aspect are shown in Table 1.

TABLE 1: *Average and range of variation of H, DBH, and CPR for sample trees according to aspect*

	H (m)		DBH (cm)		CPR (m)	
Aspect	Mean	Range	Mean	Range	Mean	Range
North slope	8.0	4.4–12.8	14.1	6.6–24.4	1.76	1.1–3.2
South slope	6.3	4.5– 9.0	12.2	5.3–19.8	2.04	1.4–2.9

H: height; DBH: diameter at breast height; CPR: crown projection radius.

For every sample tree, measurements were taken of: DBH, D50 (stem diameter 50 cm above ground level), H, and CPR. Crown projection radius was calcualted from the quadratic average of two radii, corresponding to half of crown diameter projections taken at right angles. Three fractions were immediately separated in the field as follows: stem (greater than 5 cm in diameter), branches from 1 to 5 cm in diameter, and branches less than 1 cm in diameter. The fresh weight of the three fractions was recorded and a sample per each tree component was oven-dried at 60°C until constant weight in order to determine moisture content. The sample of branches less than 1 cm in diameter was separated into foliage and twigs prior to drying, in order to know the foliage weight. Fifty-six holm oaks were felled (28 from north-facing slopes and 28 from south-facing slopes) which, together with 15 trees from the study carried out by Ferrés *et al.* (1980), make up a total of 71 trees treated in this work.

Univariate and multivariate regression models were used to develop dimensional equations. Statistical significance of the regression coefficients for the independent variables entered to the model were tested by Student's *t* test. The data were also divided into aspect and height groups, and allometric equations were developed separately for each group. The similarity of regression lines across groups was tested by analysis of variance (Dixon, 1981).

RESULTS

Mean moisture content for each biomass fraction is shown in Table 2. Slight differences in moisture content among tree components and between north- and south-facing slopes can be found. Tree sampling was carried out during winter, when differences in insolation between aspects are supposed to be small. Differences in moisture content between aspects are expected to be much larger during the summer, especially for the foliage fraction.

TABLE 2: *Moisture content in tree components of* Quercus ilex, *according to aspect*

	Moisture Content (%)					
	North-facing slope			South-facing slope		
Components	Mean	S.D.	n	Mean	S.D.	n
Stem	38.0	1.81	27	36.9	1.41	12
Branches 1 to 5 cm	38.9	1.97	27	39.0	1.58	11
Branches < 1 cm	43.6	2.08	26	40.9	1.94	11
Foliage	46.6	2.47	26	44.9	2.23	12

S.D.: standard deviation; n: number of samples

When developing allometric equations which would relate one or more variables of the tree to its total dry weight and to any of its biomass components, the best fit was obtained using logarithmic relationships rather than linear and exponential. Logarithmic equations are expressed linearly in the following manner: $\text{Log } Y = A + \text{Log } X$, where Y is the dry weight of the fraction analysed and X is DBH or D50. Rapp (1970, 1978), Susmel *et al.* (1976), Ferrés *et al.* (1980), and Leonardi and Rapp (1982) also used such a relationship in *Q. ilex* studies. For multiple regressions, where in addition to DBH the variables H and CPR were included, the latter were not transformed into logarithms because better fits were obtained without transformation.

Tests were also run substituting DBH for D50, obtaining better fits in many cases. With the same objective, holm oaks were separated and treated independently according to the following height categories: trees from 4 to 7 m in height and those above 7 m. These height classes were arbitrarily selected with the intention of separating two basic morphological types of trees, which would allow us to get better weight estimates. Finally, trees were also grouped according to aspect: those from the north-facing slope of the valley and those from the south-facing slope.

All these results are shown in Table 3 and Fig. 1A for total above-ground dry weight and for each tree fraction: stem, branches, and foliage. In addition, several regressions are also included to obtain separate estimates of the two diameter classes of branches. Separate biomass estimates for branches smaller and greater than 1 cm in diameter are relevant in nutrient cycling studies, since they differ in both wood and bark element concentrations (Ferrés, 1984). Average bark percentages (in relation to total dry weight) were quite different among woody components: 35.7 per cent for branches < 1 cm in basal diameter, 20.5 per cent for branches 1 to 5 cm, and 14.1 per cent for stems.

DISCUSSION

Dry weight estimation by single variable allometric equations on DBH is improved in almost all components if a second variable, total tree height, is also taken into account. This can be made by simply grouping sample trees into two height categories: above and below 7 m. Substantial differences on estimates are obtained when both types of allometric equations are applied to the same DBH (regressions 2 and 3 in Table 3). Thus, for a tree of DBH = 15 cm and above 7 m in height a total biomass of 96 kg is estimated, whereas only 76 kg is obtained for a tree of the same DBH but less than 7 m in height. This significant difference between both allometric equations ($p < 0.05$) (Fig. 1B) is mainly determined by stem length, which is the most important component of total tree weight. Grouping of trees in such a way may be useful when saving effort and time in field work is required, since trees can be easily separated into such broad height categories.

Better fits are also found when height is entered in the allometric model as an additional independent variable using multivariate regression models (regressions 7 and 8 in Table 3). The coefficient of determination (R^2) increases, and the standard error of the estimate diminishes, in all the regressions, changing from 0.90 to 0.94 and from 0.91 to 0.96 for total weight and stem weight, respectively. These are the cases of largest improvements in estimation. Tree height is only significant for total weight and stem weight ($p < 0.05$), which are the fractions influenced to a greater degree by tree height, and does not significantly influence the results for tree fractions such as branches and foliage.

Fitting our data to a regression equation is even better if, together with DBH and height, a new variable containing information about tree-crown development (CPR) is added to the model. This new variable is shown to be significant ($p < 0.05$) for stem, total tree weight, and branches.

Holm oaks were also grouped and treated independently according to site aspect (south- and north-facing slopes of the valley). Aspect was expected to be a factor strong enough to cause differences in tree architecture which, in

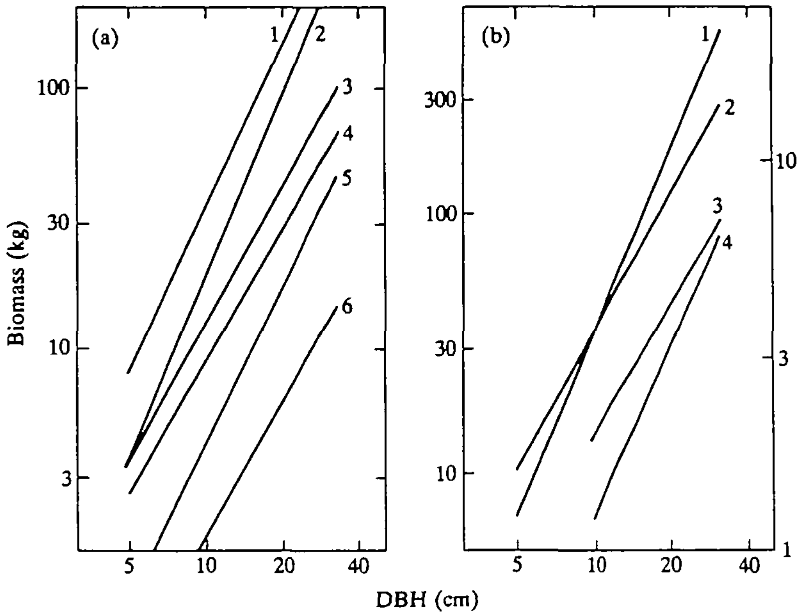

Figure 1. Relationships between DBH and dry weight of *Q.ilex*.

A) For different tree components (equations 1 in Table 3): 1- total biomass; 2- stem; 3- branches > 5 cm in diameter; 4- branches 1 to 5 cm in diameter; 5- branches < 1 cm in diameter; 6- foliage.

B) According to grouping categories: 1- total biomass for trees above 7 m in height (equation 4 in Table 3); 2- total biomass for trees 4 to 7 m in height (equation 5 in Table 3); 3- foliage biomass for trees from south slopes (equation 7 in Table 3); 4- foliage biomass for trees from north slopes (equation 6 in Table 3). (For lines 1 and 2 see left scale; for lines 3 and 4 see right scale.)

TABLE 3: *Allometric equations for all tree components of* Quercus ilex *at Montseny*

NO	FUNCTION	R^2	S.E.E.	N
Total dry weight				
1	LOG DW= −0.656 + 2.217 LOG DBH	0.908	0.097	69
2	LOG DW= −0.275 + 1.831 LOG DBH	0.910	0.074	33
3	LOG DW= −0.854 + 2.413 LOG DBH	0.927	0.071	30
4	LOG DW= −0.902 + 2.433 LOG DBH	0.939	0.085	41
5	LOG DW= −0.313 + 1.900 LOG DBH	0.867	0.101	28
6	LOG DW= −1.047 + 2.461 LOG D50	0.934	0.083	70
7	LOG DW= −0.568 + 1.953 LOG DBH + 0.029 H	0.942	0.076	63
8	LOG DW= −0.581 + 1.808 LOG DBH + 0.020 H + 0.118 CPR	0.953	0.061	33

TABLE 3: (*cont.*)

NO	FUNCTION	R^2	S.E.E.	N
Stem (greater than 5 cm in diameter)				
1	LOG DW= −1.166 + 2.478 LOG DBH	0.918	0.103	71
2	LOG DW= −0.747 + 2.044 LOG DBH	0.929	0.073	33
3	LOG DW= −1.355 + 2.674 LOG DBH	0.958	0.061	32
4	LOG DW= −1.336 + 2.640 LOG DBH	0.941	0.091	43
5	LOG DW= −0.839 + 2.156 LOG DBH	0.882	0.107	28
6	LOG DW= −1.610 + 2.756 LOG D50	0.946	0.083	71
7	LOG DW= −1.088 + 2.157 LOG DBH + 0.039 H	0.963	0.069	65
8	LOG DW= −1.095 + 2.075 LOG DBH + 0.034 H + 0.065 CPR	0.963	0.061	35
Branches (less than 5 cm in diameter)				
1	LOG DW= −0.704 + 1.833 LOG DBH	0.803	0.125	69
2	LOG DW= −0.411 + 1.546 LOG DBH	0.784	0.105	33
3	LOG DW= −0.825 + 1.953 LOG DBH	0.697	0.134	30
4	LOG DW= −0.996 + 2.077 LOG DBH	0.840	0.125	41
5	LOG DW= −0.370 + 1.544 LOG DBH	0.775	0.113	28
6	LOG DW= −1.009 + 2.019 LOG D50	0.810	0.123	69
7	LOG DW= −0.617 + 1.672 LOG DBH + 0.014 H	0.807	0.121	63
8	LOG DW= −0.540 + 1.345 LOG DBH + 0.005 H + 0.204 CPR	0.817	0.108	33
Branches (1 to 5 cm in diameter)				
1	LOG DW= −0.825 + 1.789 LOG DBH	0.781	0.129	56
8	LOG DW= −0.897 + 1.517 LOG DBH − 0.005 H + 0.210 CPR	0.859	0.105	35
Branches (greater than 5 cm in diameter)				
1	LOG DW= −1.429 + 2.089 LOG DBH	0.443	0.324	69
8	LOG DW= −0.727 + 1.048 LOG DBH − 0.013 H + 0.215 CPR	0.538	0.180	33
Foliage				
1	LOG DW= −1.624 + 1.891 LOG DBH	0.615	0.207	69
2	LOG DW= −1.347 + 1.654 LOG DBH	0.467	0.229	33
3	LOG DW= −2.128 + 2.309 LOG DBH	0.650	0.177	30
4	LOG DW= −2.142 + 2.269 LOG DBH	0.735	0.188	41
5	LOG DW= −1.366 + 1.774 LOG DBH	0.740	0.143	28
6	LOG DW= −1.951 + 2.093 LOG D50	0.626	0.204	69
7	LOG DW= −1.533 + 1.808 LOG DBH + 0.002 H	0.593	0.208	63
8	LOG DW= −1.669 + 1.538 LOG DBH + 0.001 H + 0.220 CPR	0.550	0.236	33

NO=sample type code number; DW=dry weight (kg); DBH=diameter at breast height (cm); D50=diameter at height of 0.50 m (cm); H=height (m); CPR=crown projection radius (m); R^2= coefficient of determination; S.E.E.=standard error of estimate; N=number of trees in sample. Code numbers on the left refer to groups used in developing regressions. Groups are coded as follows: 1,6,7 and 8-all trees; 2-trees 4 to 7 m in height; 3-trees above 7 m in height; 4-trees north slopes; 5-trees from south slopes.

turn, would result in weight differences for some fractions. On the south-facing slope we found holm oaks to have less biomass for the same DBH (except in the case of foliage biomass), due to the highest proportion of trees with heights ranging from 4 to 7 m. The differences between allometric equations for south and north slopes are significant for all tree components ($p < 0.05$). On the other hand, the greater foliage biomasses are found on the south side (Fig. 1B). A tree of DBH 15 cm located on the south slope of the valley has a foliage biomass estimate of 5.2 kg, whereas a tree of the same DBH from the north-facing slope has a foliage biomass estimate of 3.4 kg. This significant difference between regression lines ($p < 0.001$) may be due to the development of particular growth form in response to a greater amount of sunlight. It should be pointed out, however, that other stand characteristics are also different between both aspects, such as tree density, rotation length, and soil depth.

Some stocky holm oaks show stem forking or lateral branching at 1.30 m, which makes it difficult to measure a meaningful DBH and subsequently appropriate correlations with weight. The use of D50 instead of DBH to fit allometric equations provides substantial improvements, especially for those fractions directly related to the stem, such as total and stem weight. In both cases there is a substantial decrease in the estandard error of the estimate: 0.014 in the first case and 0.020 in the second (both expressed in logarithms) (see Table 3). This improvement is due to greater stem uniformity at this height (50 cm) compared with measures of diameter taken at 1.30 m above ground level.

The values obtained from our allometric equations for total biomass (regression 1) have been compared with the scant data found in literature for evergreen oaks and deciduous *Quercus* especies (Table 4). Some authors give biomass estimates for the same DBH which are higher than those presented in our study. This is the case of Susmel *et al.* (1976) for the holm oak forest of Supramonte di Orgosolo (Sardinia); they used a sample of trees of great size, all of them with DBH ranging from 20 to 90 cm. Ferrés *et al.* (1980) also get higher biomass estimates; in this case, regression equations were developed from a sample of 15 very tall trees (average height = 9.0 m) with average DBH of 15 cm, situated at the bottom of La Castanya valley (Montseny massif) with deep and moist soil. If we compare their regressions with those presented in our study for holm oaks on north facing slopes (regression 4 instead of regression 1) the differences in biomass estimates are lower although the allometric equations are still statistically different ($p < 0.05$). If we make the comparison with the regressions for holm oaks above 7 m in height (regression 3), the difference is no longer significant ($p > 0.005$).

In contrast, our study used a sample containing a wide variety of morphological types, ranging from large trees to smaller ones (in some cases stocky and growing in shallower soils). We also included shoots from both multi-stemmed coppice trees and maiden trees. In addition to such morphological diversity, there is the fact that this holm oak forest is young

TABLE 4: *Above-ground biomass predicted from diameter from other published work for various species*

	DBH (cm)					
	5	10	15	20	25	30
Species	Above-ground dry weight (kg)					
Q.ilex, Italy. (Susmel *et al.*, 1976)	9	44	111	213	353	535
Q.ilex, Spain, (Ferrés *et al.*, 1980)	9	42	106	205	342	520
Q.ilex, Italy. (Leonardi & Rapp, 1982)	6	24	56	102	161	235
Q.ilex, Spain. (This study)	8	36	89	169	277	415
Q.hypoleucoides, Arizona. (Whittaker & Niering, 1975)	8	28	58	96	143	198
*Q.alba**, New York. (Whittaker & Woodwell, 1968)	7	30	71	133	261	321
*Q.coccinea**, New York. (Whittaker & Woodwell, 1968)	8	38	93	175	286	426

	D50 (cm)					
	5	10	15	20	25	30
Species	Above-ground dry weight (kg)					
Q.ilex, Spain. (This study)	5	26	70	142	247	387
Q.ilex, Spain. (Sánchez *et al.*, unpubl.)	4	21	64	150	300	540

DBH: Diameter at breast height.
D50: Diameter at 50 cm above ground level.
*: Deciduous.

and that none of its trees exceeded 30 cm DBH. All these features distinguish this holm oak forest from the others mentioned above, at least as far as the sample used for developing equations is concerned.

On the other hand, Leonardi and Rapp (1982) and Sánchez (data unpublished) for *Q. ilex* and Whittaker and Niering (1975) for the evergreen oak *Q. hypoleucoides* obtained biomass estimates lower than those reported here. Leonardi and Rapp (1982) studied an intensively exploited holm oak forest in the Monte Minardo (Etna massif, Sicily), formed almost exclusively by coppice trees: 860 stools ha^{-1} with a total of 9,634 stems ha^{-1}. The allometric equations were developed from 12 trees, none exceeding 20 cm DBH. Holm oaks of greater size and weight are thus not represented in the sample. With regard to the estimates presented by Sánchez (unpublished data) for the holm oak forest in l'Avic (Prades, Tarragona, Spain), it should be stated that this forest contains short, stocky trees. Due to this fact, the diameter could not be measured at breast height, and so the weights are correlated with diameter at 0.5 m above ground level (D50). These trees logically show lower weights due to the lower stem length, in comparison with trees having an equal diameter but greater size, as in our case. Above a D50 of 25 cm, and contrary to what was expected, the estimates are greater in the l'Avic forest. This tendency, not explicable by the morphology of the trees, must be due to the sample used, which is made up only of trees with D50 ranging from 5 to 15 cm. For this reason, the weights obtained from DBH above 20 cm are unreliable. This might be also true for the *Q. hypoleucoides* data, calculated from allometric equations reported by Whittaker and Niering (1975). In this case, mean DBH of sample trees was 7.65 cm and they grew in a small tree stratum beneath a pine canopy.

As it has been shown through all this work, dimensional relationships vary substantially for a given species in a limited area. However, interest should also be paid to allometric patterns that link different species with one other (Whittaker and Marks, 1975). Table 4 shows close similarities in the basal diameter – above ground dry weight relationship between temperate deciduous *Quercus* species (*Q. alba* and *Q. coccinea*) and some of the data reported for the evergreen *Q. ilex*. This similarity may be due to their close phyllogenetic relationship, which gives them a common growth pattern. On the other hand, the lower biomass estimates obtained from the regressions reported for the evergreen oak *Q. hypoleucoides* by Whittaker and Niering (1975) and for *Q. ilex* by Leonardi and Rapp (1982) seem to point to the fact that more care should be devoted to growing conditions of the stand and the range of diameters used to calculate dimension relationships, if more accurate estimates of biomass or any other growth measure are required.

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