Using basal area to estimate aboveground carbon stocks in forests: La Primavera Biosphere’s Reserve, Mexico

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Increasing use of woody plants for greenhouse gas mitigation has led to demand for rapid, cost-effective estimation of forest carbon stocks. Bole diameter is readily measured and basal area can be correlated to biomass and carbon through application of allometric equations. We explore different forms of allometric equations and analyse the potential to use of equations for individual trees to derive stand-level equations, where the basal area and the average diameter are used as explanatory variables. To test the relationships derived from published allometric equations, we used data from a forest inventory in the oak–pine forests in La Primavera (Mexico). Results show that in two forests with the same species and basal area, there will be more carbon where trees are larger. Allometric equations for individual trees can be transformed into stand-level equations. The values of average diameter weighted by the basal area for these equations can be based on a small sample of large trees once the local relationship between tree size and tree density per hectare is known. This approach could considerably reduce field data requirements in comparison with inventory methods based on enumeration of all trees for estimation of biomass and carbon.

Introduction

Basal area, the sum of cross-sectional area measured at breast height (1.3 m) of all trees in a stand, expressed as m² ha⁻¹, has frequently been used as a surrogate for biomass and carbon in tropical moist and dry forests.¹⁻¹² The basal area is a good predictor for biomass and carbon since it integrates the effect of both the number and size of trees.¹³ A correlation between these variables is to be expected since the basal area and biomass are both related to the trunk diameter.¹⁴

Previous studies have used the basal area for different purposes, for example, to identify the ratio of biomass to basal area⁶,¹³⁻¹⁷ to estimate biomass expansion factors;¹⁴ to predict biomass of trees;¹⁸ to predict biomass at the stand level in combination with the mean tree height⁹⁻¹¹ and to obtain estimates of biomass of fine roots.²² The basal area has been found to be the best predictor of biomass in open dry forests, giving better results than canopy cover or leaf area index.²³

As Burrows et al.¹³ point out, the relationship between the biomass and basal area could be used to facilitate the estimation of biomass since the basal area can rapidly be measured on the ground through different methods, e.g. Bitterlich stick,²⁴ prism sweep method,²⁵ relascopes or dendrometers,²⁶ which do not require individual tree measurements, thus speeding up the process considerably. Moreover, in some sites, there is information available for the basal area over large areas for long periods,⁹ which would allow historical estimates of biomass to be made; these are necessary, for example, in setting baselines for stock increases/decreases. The relationship between these variables could also be used in combination with remote sensing to scale up biomass and carbon figures over extensive tracts of forest,²⁷ since high-resolution images can be used to derive the basal area and other stand-level variables once the model is calibrated for a given site.²⁸,²⁹⁻³²

Mitigation of climate change through forestry-based strategies to reduce emissions from deforestation and forest degradation and to enhance carbon sequestration by forests, such as those contained in the REDD+ policies,³³,³⁴ requires the measurement and monitoring of carbon stocks and stock changes in forests.³¹ However, if the basal area is to be used in estimating biomass, it is essential that the nature of the relation between these two variables is well understood. Based on pipe model theory, Chiba⁴ suggested a linear relationship between the basal area and biomass. Linear and near-linear relationships between these two variables have been reported and used in the literature for a wide range of forest types from tropical dry open forests in Australia and India to rainforests in the Amazon.⁵,⁷,⁹,¹¹,¹³,¹⁵⁻¹⁷ The relationships at the plot-level correlating the biomass and basal area have been called ‘stand
allometric equations. Stand-level equations for different species have been developed from equations for individual trees to estimate the volume of timber in a stand while minimizing the number of measurements and calculations required.

The objective of this work is to assess the potential use of the basal area to predict aboveground biomass and carbon at the plot level. For this, we discuss whether the relationship between the basal area and carbon is expected to be linear or not and the implications of applying different models derived from allometric equations. Based on these results, we explore the potential to modify allometric equations for individual trees into stand-level allometric equations where the basal area is an independent variable. Field data from a standard forest inventory in which individual trees in sampling plots were measured in La Primavera Biosphere Reserve in Mexico was used to explore the accuracy of this approach. We discuss the potential of transforming allometric equations for individual trees into stand allometric equations to estimate aboveground biomass and carbon, and the possibility of reducing effort in collection of fieldwork data for estimation of carbon stocks. First, the relationship between carbon and basal area in allometric equations with different specifications is discussed. This is followed by a description of the forest inventory data. Results, discussion and conclusions are then presented.

**Basal area and carbon from allometric equations**

Allometry, as initially proposed by Huxley and Tessier, studies how the characteristics of organisms change with size. In forestry, allometric equations usually describe the change in biomass stocks in a tree as a function of readily measurable characteristics, typically bole diameter, tree height, species and wood density. The most important predictor of biomass in trees is bole diameter at breast height (DBH). Allometric equations are used to estimate carbon and biomass from individual trees and inventory plots; and these are then scaled up to stand and landscape levels. The equations follow a variety of mathematical specifications (e.g. log-linear, non-linear) and are obtained for specific ranges of tree size. We analyse the relationship between carbon and basal area for three types of equations generating values for carbon (equations 1–3). Allometric equations usually estimate the amount of dry biomass; this can be converted to carbon by multiplying the results by the percentage of carbon in dry biomass; we use a default factor of 0.5 to convert biomass to carbon figures in equations (1)–(3). Equation (1) depicts the general form of the most common specification used, the log-linear model. Equation (2) corresponds to the form used in default equations for hardwoods and conifers in IPCC Guidelines; equation (3) represents a quadratic polynomial regression form, such as those presented by Brown.

In equations (1)–(3), represents the amount of carbon in individual trees (tC tree⁻¹), is the diameter at breast height in cm and are constants obtained from the regressions made for the development of the allometric equations.

In order to obtain the expression for the relationship between carbon and basal area, we first consider the model presented in equation (1) (the log-linear model). The expression for the basal area of an individual tree is the equation for a circle, presented in equation (4) (expressed in m² tree⁻¹). Since is the value of the trunk diameter in cm, a factor of 40,000 is used to obtain the area in m², assuming the tree base has a circular form, in equation (4).

\[ G = \frac{\pi}{40,000} \times D^2 \]  

Equation (5) is proposed to analyse the relationship between carbon and basal area, in a manner similar to that used by Chiba. Here indicates the proportionality between these variables; if the relationship between these variables is linear then will be a constant; is in units of carbon per square meter of the basal area (tC m⁻²).

\[ C = m \times G \]  

By substituting equations (1) and (4) into (5), the expression for can be obtained for this allometric specification.

\[ m = \frac{C}{G} = \frac{40,000 \times D^x}{\pi \times D^2} = K' \times D^{x-2} \]  

where

\[ K' = \frac{40,000 \times K}{\pi} \]  

It can be seen in equation (6) that would be constant, thus implying a linear relationship between the basal area and carbon only when the exponent in the log-linear model is equal to 2; in this case, the slope will be equal to . When is a value other than 2, the ratio between the basal area and carbon will depend on the tree size, being a function of to the power of . For , will decrease as the size of the trees increases. Conversely, for , there will be more carbon per unit of basal area for larger trees; this might be the most common case since the theoretical and empirical values of are in fact 2.67 and 2.37, respectively. In their review of 277 allometric studies, Zianis and Mencuccini show that the value of was above 2 in 94% of the cases reviewed; only in rare cases did the allometric equation imply a strict linearity between the basal area and carbon or a diminishing value for with increased tree size.

The expression for aboveground arboreal carbon as function of the basal area for an individual tree can be obtained by solving for in equation (6).

\[ C = K' \times D^{x-2} \times G \]  

The process described above can also be developed for the non-linear models represented in equations (2) and (3). This will give us equations expressing carbon as function of the basal area in
equations (9) and (10), which are comparable with equation (8).

\[
C = m \times G = \left( \frac{a \times k + b \times k \times D^x}{D^{x+1} + c \times D^y} \right) \times G \tag{9}
\]

\[
C = m \times G = k \times \left( \frac{d}{D^2} + \frac{e}{D^x} + f \right) \times G. \tag{10}
\]

where \( k = 40,000 \, \text{m}^{-1} \).

Equations (9) and (10) represent more complex non-linear relationships between the basal area and carbon. The mathematical expression in equation (9) implies that for large trees as \( D \) increases, the value of \( m \) decreases, in fact for very large \( D \) values, which might be outside the valid range for the equation, the expression implies that the value of \( m \) tends to zero. It is important to recall that allometric equations are prepared for a specific range of \( D \) values; hence, equations should be used only within these ranges of validity. On the other hand, the expression for \( m \) in equation (10) implies that when \( D \) increases it will reach an asymptotic value equal to \( 40,000 \, \text{m}^{-1} \), where \( f \) is the coefficient of the quadratic term in equation (3). Equations (8)–(10) show that none of the three allometric models considered supports the assertion that the relationship between the basal area and carbon is strictly linear when the data from individual trees are considered for a wide range of \( D \).

Equation (8) can be converted into a stand allometric equation if values of the basal area per hectare and the average diameter (\( D \)) are available [equation (11)]; in this case, \( C \) represents the carbon (t ha\(^{-1}\)) and \( G \) is basal area (m\(^2\) ha\(^{-1}\)) obtained at the inventory plot level.

\[
\tilde{C} = K \times \tilde{D}^{x-2} \times \tilde{G} \tag{11}
\]

Most studies relating biomass and basal area have followed an approach based on the use of allometric equations for individual trees. Typically a forest inventory is carried out and biomass/carbon figures for individual trees are obtained using local or published allometric equations to derive aggregated values per site or per hectare; then the relationship between the basal area and biomass/carbon is analysed with the aggregated information per hectare. An alternative approach is that followed by Martinez-Yrizar et al.,\(^{35}\) in which they directly compared biomass figures in a dry tropical forest to the basal area of the plots where trees were cut. However, this latter approach depends on destructive sampling and would require that instead of cutting down, measuring and weighing individual trees, entire sites (with different values of \( D \) and basal area) would need to be cut down, thus increasing the cost of developing these allometric relationships.

There is one issue to be addressed in equation (11): while figures for the basal area can be obtained in the field without taking physical measurements from each tree (e.g. by using a relascope), it is necessary to find a method to obtain the average diameter without having to measure all the trees in a site (otherwise, the sampling effort would be no less than that for the establishment of inventory plots and complete enumeration of trees). In the simplest case that can be depicted, all the trees in a site could have the same diameter. In this special case, equation (8) can be rearranged to give the obvious result that carbon is simply the product of the carbon per tree multiplied by the density \( n \) (trees ha\(^{-1}\)) and \( D \) in equation (8) will be equal to the average \( D \) in the inventory plot in equation (9) (Appendix A).

However, in reality not all the trees in a forest and in a plot will have the same \( D \). The simple mean \( D \) in the site could be used in equation (11), however by reference to equation (8) we can argue that since trees with larger diameters might contribute more to the carbon stock per unit of basal area, then the diameter of the larger trees should also contribute more to the average diameter to be used in equation (9). One option to account for this effect would be to use the diameter weighted by the basal area (\( D_G \)) instead of the simple average; however, for this, all trees in a site would have to be measured individually to obtain the weighted average. The objective of our analysis is to reduce the measurement effort and generate consistent values for the diameter to be used in the stand allometric equation. For this, we select only a portion of the trees in an inventory site to obtain a weighted average for the sub-sample (\( D_G \)). If we consider a sub-sample of size 1, including only the largest tree in the plot (\( D_{\text{max}} = D_G \)), we know that \( D_G > D_c \) and thus \( D_G / D_G > 1 \). For every tree, we include in this sub-sample, by the order of descending \( D \), the value of \( D_G \) will decrease. Naturally, as the number of trees in the sub-sample gets closer to that of the trees in the site, \( D_G \) will converge to \( D_G \), thus \( D_G / D_G \) will decrease and reach the value of 1 only when all, including the last (smallest) tree, is included in the sub-sample. It is important to note however that the weight of each additional tree that is included in the sub-sample will be diminishing since its relative contribution to the basal area will be steadily smaller in comparison with the accumulated basal area of the largest trees already included.

In order to derive the value of \( D_G \) as function of \( D_G \) of a sub-sample of large trees, we use the inverse relationship between tree size and tree density. Reineke\(^{47}\) showed a negative relationship between the logarithms of the mean quadratic diameter and stand density consistent for different tree species in natural forests and plantations.\(^{48}\) At higher tree densities, the area available for each tree to grow is reduced.\(^{49-50}\) Thus the growing space, and potential growth of the trees, would be inversely related to tree density.\(^{49}\) Considering this, the following equation is proposed to relate tree density to \( D_G \):

\[
\bar{D} = \frac{A}{n^2} \tag{12}
\]

where \( A \) and \( n \) are constants and \( n \) is the tree density per hectare. If for a sub-sample taken, the value of \( D_G \) is also found to be inversely correlated with tree density, then the following equation could be used:

\[
\bar{D}_G = \frac{A'}{n'^2} \tag{13}
\]

By dividing equation (13) by equation (12), the equality holds [equation (14)], and from this the expression to find \( D_G \) as function of \( D_G \) of a sub-sample and tree density can be found [equation (15)].
Equation (15) can be obtained for a specific forest type or region and so can be used to correct the diameter figures obtained on the ground measuring a sub-sample of large trees ($\bar{D}_{G*}$) [equation (16)]; this corrected value can be used in the stand allometric equation.

$$\bar{D}_{G*} = \frac{A}{A'} \times n^{-2} \times \bar{D}_G$$  \hspace{1cm} (16)

Based on this analysis, we use the data from a forest inventory to calculate $\bar{D}$ and $\bar{D}_G$ and use them in stand allometric equations together with the plot-level values of the basal area to estimate carbon figures and compare the results with those based on the enumeration of trees. To assess the potential to reduce sampling effort to obtain an appropriate value of diameter, we estimate $\bar{D}_{G*}$ in each inventory plot for different sub-samples of large trees. For this we first ordered the data of all the trees in each plot from largest to smallest $D$. Then for each plot we took eight sub-samples considering the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th and 10th largest trees. We calculated the ratio $\bar{D}_{G*}/\bar{D}_G$ for each site and sub-sample and plotted it against tree density; we obtain a power regression between the ratio and tree density consistent with equation (14) from which functions following equation (16) are derived. These equations are used to estimate a value of $\bar{D}_G$ in each site based on $\bar{D}_G$ from each sub-sample of large trees. This estimated $\bar{D}_{G*}$ is used to obtain carbon using the stand allometric equations; the results generated following this approach are compared with those obtained through the enumeration of trees [i.e. carbon content is estimated using the stand allometric equations and the $D$ from as few as one tree in each plot, which is corrected by equation (16)].

### Table 1. Allometric equations used in the analysis of the carbon to basal area relationship.

<table>
<thead>
<tr>
<th>Equation for individual trees</th>
<th>Stand allometric equations (carbon in t ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allometric equation (carbon in kg tree$^{-1}$)</td>
<td>$D$ range, species (Source)</td>
</tr>
<tr>
<td>1 0.50 × 0.0752 × $D^{2.4448} \times 2.0331$</td>
<td>7.3–62.5 cm, oaks</td>
</tr>
<tr>
<td>2 0.50 × exp$(-1.966) \times D^{2.32}$</td>
<td>5–40 cm, broadleaves</td>
</tr>
<tr>
<td>3 0.50 × exp$(-1.170) \times D^{2.19}$</td>
<td>2–52 cm, conifers</td>
</tr>
<tr>
<td>4 0.50 × (42.69 – 12.800 × $D + 1.242 \times D^2$)</td>
<td>5–148 cm, broadleaves (large trees)</td>
</tr>
<tr>
<td>5 0.50 × (21.297 – 6.953 × $D + 0.740 \times D^2$)</td>
<td>4–112 cm (tropical trees)</td>
</tr>
<tr>
<td>6 0.50 × $\left(0.50 + \frac{25 000 \times D^{2.5}}{D^{1.5} + 24.6872}\right)$</td>
<td>1.3–82.2 cm, Temperate US Eastern hardwoods</td>
</tr>
<tr>
<td>7 0.50 × $\left(\frac{0.887 + 10 486 \times D^{2.84}}{D^{2.84} + 376 907}\right)$</td>
<td>0.5–56 cm, temperate/tropical pines</td>
</tr>
</tbody>
</table>

$\bar{D}$ is the average $D$ in the plot in cm, $\bar{G}$ is the basal area in m$^2$ ha$^{-1}$ and $k$ is 40 000 π$^{-1}$; quantities are divided by 1000 to convert from kg to ton.

1Wood specific density $\rho$, oak $= 0.63$; pine $= 0.55$.

2Broad leaves, precipitation range 800–1500 mm.

3Moist climatic zone.

4Wet climatic zone.
to an asymptotic value resembling a horizontal line. As expected
given the equations reported by Penman et al. [following the
specifications of equation (2)], after D reaches about 60 cm m starts
to decrease; however, these equations were prepared for D
ranges <82.2 for hardwoods and 56 cm for pines and thus
they should not be used for trees of larger size. Brown42 suggests
equation (4) in Table 1 for the largest trees, showing an increas-
ing content of carbon per unit of the basal area. The equations of
Navar51 include the effect of wood-specific gravity and produce
similar values to those obtained through the IPCC’s default equa-
tions44 for small D values. Navar’s equations also produce similar
values to those derived from the equation suggested by Brown42
for large trees. Thus the equations of Navar51 may provide a
good fit for oaks and pines for a wide range of D values. The
equations of Navar do not present an asymptotic trend.

For purposes of comparison, we included in Figure 1 the equa-
tion for the wet climatic zone corresponding to rainforests.42 It
can be seen that for diameters above 30–40 cm the value of m,
while it still is increasing, does so at a very low rate, thus it
may resemble a horizontal line in Figure 1. This may explain
why a linear relationship between carbon and basal area has
been used for rainforests5,7 since in the permanent measure-
ment plots used in intact tracts of forests in the cited studies,
D values may be large, the values would be relatively homogen-
ous and would not include stands with small average D values.
However, this apparent linearity might not apply to stands and
forests with smaller trees. The linear relationship between
carbon and basal area obtained from stands with trees of
large D will overestimate carbon figures if used to estimate
carbon during the first years in plantations, in reforested areas
or in areas with trees with smaller D.

**Forest inventory**

Data from a forest inventory carried out in La Primavera Bio-
sphere Reserve in Jalisco, Mexico, were used to compute
carbon estimates using two sets of allometric equations and fol-
lowing the standard IPCC methodologies.44 Here we explore the
potential and pitfalls of using the basal area as a predictor for
carbon in the inventory data. The allometric equations used
were those developed by Navar51 and those published by
Brown42 [equations (1)–(3) in Table 1]. The inconvenience of per-
forming destructive sampling to obtain local allometric equa-
tions, as opposed to using published relationships, needs to be
carefully evaluated. It may be only justified if the forest will con-
tinue to be monitored with a large number of measurement
plots (more than 40), otherwise uncertainty associated with a
small number of plots will be higher than that of the allometric
model53; moreover, a large number of trees would need to be cut
down since regional or pantropical equations should generate
the results of higher quality than those from equations based
on small samples (less than 100 trees) and with a small range
of D values.43 Thus we used published allometric equations as
a first approximation. If future activities such as sub-national
REDD+ projects are to be undertaken in the region, it is recom-
ended to sample a few trees and evaluate if published equa-
tions are suitable and if not develop local equations.

La Primavera forest is a Biosphere Reserve encompassing
30 500 ha located in the State of Jalisco in Mexico.55,56 It consists
mainly of oak–pine mixes but tropical deciduous forests, natural
grasslands and agricultural areas are also present. The altitude
ranges from 1400 to 2200 m asl. Annual mean temperature is
20.6°C and annual precipitation ranges from 800 to 1000 mm,
which defines it as a montane tropical forest.46,55 Regosols and
lithosols are the principal types of soils present; in general, soil
is poor and affected by erosion and recurrent fires.

The inventory focused on the measurement of trees in oak–
pine mixed forests; 103 measurement plots of 30 × 30 m were
begun during June and July 2009. Variables measured
included D, total height, height to the base of living crown and
crown diameter. All trees with D >7.5 cm were measured,
sprouts bifurcating <1.3 m height were considered to be individ-
ual trees. The length of the plot sides was corrected for slope.
The basal area was obtained by summing cross-sectional area
at breast height for all trees in the measurement plots. The aim
of the forest inventory was to create 95% confidence intervals
for the expected aboveground carbon content per hectare (in
hectare) with a margin of error of <10%. Pre-stratification was
initially made by canopy cover classes based on aerial photog-
raphs for the location of the measurement plots including the different
conditions present in the forest (low < 30%, 15 sites; medium 30–
60%, 48 sites; and high canopy cover > 60%, 40 sites). Sites were
located randomly over areas with slopes of <65%; the average
slope of the sites sampled was 12% (range 1–60%). The mean
altitude was 1713 m asl (range 1410–2180).

The equations of Navar51 are considered to be the best avail-
able published equations to derive aboveground carbon esti-
mates in La Primavera as they were obtained in oak–pine
forests in northwestern Mexico with similar soil types and precipi-
tation ranges to those in La Primavera; they produce similar
values to those of the default IPCC equations and those for
larger trees. As part of the third national communication to the
UNFCCC, de Jong et al.52 used the equations of Brown42 to esti-
mate emissions from deforestation because they provided the
lowest figures for biomass52; here we include the equations of
Brown,42 since we did not perform local truthing of the allometric

![Figure 1 Relationship between the basal area to carbon ratio (m) as a function of diameter at breast height (D) for the allometric equations shown in Table 1.](https://academic.oup.com/forestry/article-abstract/86/2/267/548410/271)
equations, in order to be consistent with the national inventory and to evaluate the effect of using different allometric equations when using basal area as predictor of carbon.

Results

Forest inventory

In the forest inventory, 3412 living trees of 14 different species were measured (nine species of Oaks, \( n = 2291 \); two of Pines, \( n = 1102 \); and three from other genera \( n = 16 \)); the dominating species were Quercus resinosa Liebm. and Pinus oocarpa Schiede ex Schltdl. The largest \( D \) registered corresponded to a Quercus castanea Née (158 cm) whose crown (36 m) covered more than the area of one plot. Table 2 presents the general results of the inventory at plot level. The ranges for \( D \), density, canopy cover and basal area indicate the heterogeneity of the sites measured.

The inventory data allowed generation of 95% confidence intervals for the basal area, carbon and other variables of interest within this forest. The equations used in the national inventory generate conservative estimates as indicated by de Jong et al.\(^52\) and are 21.4% lower in comparison with the results from the equations of Návar.\(^51\)

Carbon and basal area

Both the basal area and carbon estimates obtained through the complete enumeration of trees were plotted for the two sets of equations to test the fit with linear regressions (Figure 2a and b). Table 3 presents the information of the equations relating carbon to basal area as shown in Figures 2a and b.

When the data from the 103 sites are regressed together as one sample the relationship between carbon and basal area fits well to a straight line passing through the origin (Table 3, ‘All Sites’). However, when the sites of the inventory were classified by the weighted diameter \( (\bar{D}_G) \) the adjusted \( R^2 \) and the standard error of the estimates improved considerably (Table 3). For the two sets of equations, the slopes of the straight lines increase as tree size increases and are statistically different (Table 3). This increase in the slope with the tree size was expected based on the analytical discussion presented in the previous section and implies that at constant basal area values, there is more carbon in those areas with larger trees. Only the slope of the equation for the last diameter class, which includes the largest trees, is not statistically different; however, the subsample for this size range was very small. The dispersion of the data in Figure 2a and b resembles that presented by Chiba,\(^4\) Bi et al.\(^57\) and Burrows et al.,\(^13\) showing a heteroskedastic pattern for larger values of the basal area. This dispersion of the data for larger values of the basal area is explained by the variation in the tree size. The carbon-to-basal area ratio (value of \( m \)) for all the inventory plots was estimated and plotted against the corresponding weighed diameter area \( \bar{D}_G \) in each site (Figure 3).

In Figure 3 the solid curves correspond to the value of \( m \) for pure oak or pine stands from the allometric equations. Most of

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**Table 2. General characteristics of the forest inventory at measurement plot level.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal area (m² ha⁻¹)</td>
<td>17.0₁</td>
<td>7.5</td>
<td>1.9–37.0</td>
</tr>
<tr>
<td>Canopy cover (%)</td>
<td>54%₁</td>
<td>22%</td>
<td>10–96%</td>
</tr>
<tr>
<td>Density (trees ha⁻¹)</td>
<td>368</td>
<td>280</td>
<td>11–1,144</td>
</tr>
<tr>
<td>Mean ( D ) in site (cm)</td>
<td>27.3</td>
<td>15.8</td>
<td>14.7–158.0</td>
</tr>
<tr>
<td>Mean crown diameter in site (m)</td>
<td>6.3</td>
<td>4.4</td>
<td>1.9–36.3</td>
</tr>
<tr>
<td>Mean height in site (m)</td>
<td>12.2₁</td>
<td>4.3</td>
<td>3.6–35.9</td>
</tr>
<tr>
<td>% of Oaks</td>
<td>62%₁</td>
<td>30%</td>
<td>0–100%</td>
</tr>
<tr>
<td>Carbon (tC ha⁻¹)</td>
<td>58.5₁</td>
<td>28.8</td>
<td>5.3–155.0</td>
</tr>
<tr>
<td>Carbon (tC ha⁻¹)</td>
<td>46.9₁</td>
<td>21.5</td>
<td>4.2–109.0</td>
</tr>
</tbody>
</table>

₁The sample size is sufficient to generate 95% C.I. with an error of 10% for this variable.

²Canopy cover maps were drawn in 90 sites.

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**Figure 2** Relationship between carbon and basal area for the two sets of equations, trees in the plots are classified by different size class according to the weighted diameter \( (\bar{D}_G) \). (a) Carbon estimates using the equations published by Navar;\(^51\); (b) Carbon estimates using the equations published by Brown.\(^42\)
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Table 3. Statistical information for the linear regressions between carbon and basal area stratified by $D_{GB}$ presented in Figure 3a and b.

<table>
<thead>
<tr>
<th>Model (classes by $D_{GB}$)</th>
<th>n</th>
<th>Set 1 (^{51})</th>
<th>Set 2 (^{22})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m (t C m(^{-2}) G)</td>
<td>95% CI for m</td>
</tr>
<tr>
<td>All sites</td>
<td>103</td>
<td>3.438</td>
<td>3.299–3.576</td>
</tr>
<tr>
<td>C1 ($D_{GB} &lt; 25$ cm)</td>
<td>22</td>
<td>2.839</td>
<td>2.796–2.882</td>
</tr>
<tr>
<td>C2 ($D_{GB} 25–30$ cm)</td>
<td>28</td>
<td>3.130</td>
<td>3.096–3.165</td>
</tr>
<tr>
<td>C3 ($D_{GB} 30–40$ cm)</td>
<td>29</td>
<td>3.424</td>
<td>3.376–3.472</td>
</tr>
<tr>
<td>C4 ($D_{GB} 40–55$ cm)</td>
<td>21</td>
<td>4.065</td>
<td>3.982–4.148</td>
</tr>
<tr>
<td>C5 ($D_{GB} &gt; 55$ cm)</td>
<td>3</td>
<td>5.906*</td>
<td>3.218–8.594</td>
</tr>
</tbody>
</table>

$D_{GB}$ denotes $D$ average weighted by contribution to the basal area in each inventory plot.
*Significance of the regression 0.011, significance of the slope (m) 0.011; for all the other regressions the significance of the regression and the slope are higher than 0.001.

Figure 3 Comparison of the carbon-to-basal area ratios from the inventory measurement plots (dashed lines) and allometric equations (solid lines). The two sets of curves for pines and oaks are presented for the estimates obtained using the equations published by Návar\(^{51}\) and those using the equations published by Brown.\(^{22}\)

<60 cm, conifers show higher values of biomass per unit of the basal area, but >60 cm $m$ for broadleaves will be higher; this change should be reviewed in more detail in further allometric research.

The stand allometric equations presented in Table 1 were used to predict the value of carbon per hectare following four different approaches (Table 4): (i) using the stand allometric equations, the basal area and weighted average $D_{GB}$; (ii) using the stand allometric equation, the basal area and simple average $D_{GB}$; (iii) by obtaining the carbon content for a tree of size equal to the simple $D$ average and multiplying it by tree density in the plot; (iv) the same as previously, but using $D_{GB}$ instead. When the plot was oak dominated (>70% of living trees were oak), the value of the equations for oaks was used; the same approach was followed for pine-dominated plots (>70% of living trees were pines). For mixed stands, half of the values for oaks and pines were summed. The basal area figures were obtained from the aggregation of the basal areas of all the trees in the plots.

Table 4 shows that the best results are obtained when the basal area and weighted diameter $D_{GB}$ are used with the stand-level equation since this approach produces the closest estimates to those based on enumeration of individual trees (within 0.8 and 1.4% depending on the allometric model selected). The results obtained using this approach are very similar to those based on the complete enumeration of trees; variations appear due to differences in the composition of the plots (relative percentage composition of oaks or pines) and the simple rules to assign the value for pure or mixed plots as described above. Results also show that when the simple average $D$ is used, then the carbon estimates are underestimated. Results from Table 4 and Figure 3 indicate that the use of average diameter weighted by the basal area in the stand allometric equation generates accurate results in comparison with the enumeration of trees. Figure 4a and b shows the values obtained through the enumeration of trees (horizontal axis), and those obtained using the stand allometric equation (vertical axis) for the equations of Návar and Brown. Results fit well to a straight line and the slope is very close to 1, the standard errors of the estimates of a linear regression were 1.59 and 3.58 t Ch\(^{-1}\), respectively (Figure 4a and b).

In order to assess the potential to estimate an unbiased value of $D_{GB}$ and reduce the measurement effort, the relationship between the ratio $D_{GB}/D_{GB}$ and tree density is obtained for three

\[DG\]
different sub-samples of large trees (Figure 5). The data of the
inventory were used to generate the equations similar to those
presented in equation (14), which are shown in Figure 5.

In Figure 5 it can be seen that when the sub-sample of large
trees is larger, the standard error of the estimate will be smaller
and $R^2_{adj}$ will be higher. As expected, the additional inclusion of
trees in the sub-sample reduces the overestimation of the
weighted diameter; this can be seen in the fact that the power
relationships for each sub-sample are displaced downwards
closer to the 100% line.

The power regressions obtained following this approach are
used to calculate $D_{av}$ based on the value of $D_C$ for each
sub-sample in each plot and the local density values from the
inventory plot; this value is used jointly with the basal area to
calculate carbon through the stand allometric equations.
Figure 6 shows the fit between the data for carbon per hectare
based on the enumeration of trees from the inventory data (hor-
izontal axis) and that obtained using the corrected $D_{av}$ and the
basal area using the stand allometric equations of Návar for
a sub-sample of 1, 5 and 10 largest trees (vertical axis).

In Figure 6 it can be seen that even when only the largest tree
in each plot is considered for the estimation of $D_{av}$ this procedure
provides values similar to those obtained through the full en-
umeration of trees. The slope of the straight lines in Figure 6
indicates that on average the values will be between 1 and 2%
higher depending on the sub-sample size; the standard error of
the estimate in comparison with the inventory decreases as the
size of the sub-sample increases; measuring the five
largest trees reduces the standard error by about 40% in com-
parison with the measurement of the largest tree only. Table 5
shows the variation in the errors of these values in comparison
with the results based on the full enumeration of trees using
the equations of Návar; the results are presented for the
poled sites and stratified by tree density.

Table 5 shows that on average this method generates results
that are from 0.8 to 2.8% higher than those based on the
enumeration of all trees, depending on tree density and the
size of the sub-samples. The width of the 95% ranges for the
errors decreases as the sub-sample of large trees increases; for
the whole inventory (Column ‘All inventory plots’), it goes from
approximately ±10% when only the largest tree is measured,
±6.2% when the sub-sample includes 5 trees and ±5.5%
for 10 trees. The columns showing the values for different tree
density values can help to determine how many large trees
should be measured to reduce sampling effort and keep the
error low: e.g. for areas with <200 trees ha$^{-1}$ measuring three
trees per site would produce estimates within ±5–7% of error
while reducing the measurement effort by 70–85%; for areas
with higher densities (>450 trees ha$^{-1}$) measuring the largest
five trees generates estimates with error margins around ±6%
error, but effort would be reduced by 87–95%.

The method to obtain $D_{av}$ adds the tree density as a new
variable to obtain the carbon estimates (i.e. to correct $D_C$ and
obtain $D_{av}$ using the equations shown in Figure 5). However,
the sensitivity of the results to errors in tree density is low
(Appendix B). Appendix C presents the comparison of results
based on $D_{av}$ against those based on $D_C$ (from the forest inven-
tory) using the stand allometric equation; in this way, it is
possible to isolate the effect introduced by using the method
based on the sub-sample of large trees to determine $D_{av}$. The
mean differences in the carbon estimates are close to zero, indi-
cating that the results based on this alternative method target-
ing large trees are unbiased; the 95% range of the errors go
below ±5% symmetrically distributed around the mean for
sub-samples of two or more large trees.

### Discussion

The results show that the relationship between the basal area
and carbon in most cases is not linear, as in the vast majority
of published allometric equations the exponent $x$ in the log-linear

<table>
<thead>
<tr>
<th>Allometric equation/method based on plot-level data</th>
<th>Carbon tC ha$^{-1}$</th>
<th>Error (%)$^1$</th>
<th>95% Range$^2$</th>
<th>95% Range$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Návar$^{51}$ Complete enumeration of trees</td>
<td>58.5</td>
<td>28.8</td>
<td>(19.4, 124.2)</td>
<td>—</td>
</tr>
<tr>
<td>(1) Stand allometric equation ($G_0$, $D_0$)</td>
<td>59.3</td>
<td>29.2</td>
<td>(19.6, 127.2)</td>
<td>1.4%</td>
</tr>
<tr>
<td>(2) Stand allometric equation ($G_0$, $D$)</td>
<td>53.1</td>
<td>26.0</td>
<td>(16.5, 112.1)</td>
<td>–8.7%</td>
</tr>
<tr>
<td>(3) Tree density × carbon in tree of $D$</td>
<td>46.9</td>
<td>23.4</td>
<td>(11.5, 102.1)</td>
<td>–19.0%</td>
</tr>
<tr>
<td>(4) Tree density × carbon in tree of $D_0$</td>
<td>67.5</td>
<td>46.8</td>
<td>(11.5, 182.4)</td>
<td>13.9%</td>
</tr>
<tr>
<td>Brown$^{42}$ Complete enumeration of trees</td>
<td>46.9</td>
<td>21.5</td>
<td>(15.9, 98.2)</td>
<td>—</td>
</tr>
<tr>
<td>(1) Stand allometric equation ($G_0$, $D_0$)</td>
<td>47.3</td>
<td>21.8</td>
<td>(15.5, 96.5)</td>
<td>0.8%</td>
</tr>
<tr>
<td>(2) Stand allometric equation ($G$, $D$)</td>
<td>44.6</td>
<td>20.5</td>
<td>(14.8, 93.4)</td>
<td>–4.8%</td>
</tr>
<tr>
<td>3) Tree density × carbon in tree of $D$</td>
<td>39.3</td>
<td>18.2</td>
<td>(11.7, 81.0)</td>
<td>–15.8%</td>
</tr>
<tr>
<td>(4) Tree density × carbon in tree of $D_0$</td>
<td>69.9</td>
<td>37.9</td>
<td>(19.5, 162.9)</td>
<td>47.3%</td>
</tr>
</tbody>
</table>

---

$^1$ Error = (Inventoryi – Stand allometric Eq.) × (Inventoryi)$^{-1}$.
$^2$ 95% Range given by the 2.5% and 97.5% percentiles.
$G_0$ denotes simple $D$ average weighted by contribution to basal area in each inventory plot.
$D_0$ denotes $D$ average weighted by contribution to basal area in each inventory plot.
model is >2, and that allometric equations for individual trees can be modified to produce stand-level equations in which the basal area is an additional independent variable; these equations are similar to those used in the forestry trade to estimate timber volume and biomass as a function of the basal area and height. Given the well-known relationship between D and height, this is not surprising. These stand-level equations allow the estimation of carbon to be made which are very close to those derived from tree by tree methods. Moreover, the stand allometric equations including the effect of D can be used to parameterize models and to refine estimates that previously assumed a linear relationship between the basal area and carbon.

Although our basal area data were obtained through enumeration of trees in fixed area plots, generating information for the basal area and tree density through these alternative methods will be faster, cheaper and easier than using full forest inventories in which the dimensions of all the trees in sampling plots are measured individually.

It is necessary to define which value of D will be used in the stand allometric equation. As expected from analysis of the allometric equations, the best results were obtained when the average diameter weighted by the basal area was used. Results also show that it is possible to generate accurate values for the weighted average diameter to be used in these equations, based on a very small sample of large trees once the local relationship between tree size and density is known. In cases when cannot be obtained, use of the simple D average, or a conservative value for D, will systematically underestimate the figures of carbon. This is because overestimation of carbon in trees with D smaller than the average will be less than the underestimation corresponding to trees with D larger than the average. However, in fact it will be easier to estimate the weighted diameter average based on a sub-sample of large trees than the simple diameter average. If a consistent figure for the simple average of the diameter is needed, it will be necessary to sample around 30% of the trees to have average values with an error ±20%, or up to 90% of the trees in the site to reduce the error to ±10% with 95% confidence (Appendix D); for the weighted average as shown above it will suffice to sample as few as 5% of the trees in an inventory site.

The relationship between the ratio \( \overline{D}_G / \overline{D}_E \) and tree density obtained here describes the conditions of the oak–pine forests in La Primavera and can be used to adjust diameter figures if new measurement plots are to be established in this site. In order to extend the approach to other locations, it will be necessary to know how these relationships change for different species and site conditions. In the analysis of the stand density index, indicated that the slope of the linear relationship between the logged quadratic mean diameter and density seemed to be consistent for different species, the parameter that seemed to vary across species was the intercept of this equation. Thus, it is likely that equations similar to those presented in Figure 5 can be obtained for other vegetation types to follow the approach described here.

The system to monitor forests as part of REDD+ should include the use of both remotely acquired and ground-level data. Reducing the effort to gather the field data could be particularly important in this context since data generated at lower cost could represent a considerable improvement where no previous data exist and estimates are based on default values. It has been shown elsewhere that members of rural communities with only a few years of formal education can rapidly learn and develop basic forest inventories. Local communities might be able to participate in the systems to monitor, report and verify information for the national REDD+ programs. If relascope measurements are included as part of community monitoring, it may help reducing the effort to acquire ground-level data; this might help reducing the uncertainty of estimates as it will be easier to increase sample size. Based on the approach here presented, it will be possible to develop field tables where the basal area and D are the variables to estimate the value of carbon; this will emulate the existing tables to estimate timber volume as function of basal area and height.
In Appendix E we present one example of a basal area-D-carbon table for oaks using the equation of Na'var.

An important issue to keep in mind is that trees with a large $D$ usually are not included in studies to generate allometric equations. This is a very important point to consider when using allometric equations given the importance of large trees as carbon stocks. It is critical to generate allometric equations by non-destructive methods that include valid ranges for trees with large $D$.

**Conclusions**

We explored the potential of using the basal area as predictor of aboveground carbon in trees as determined by different types of allometric equations. The configurations of the allometric equations show that the relationship between the basal area and biomass and carbon is, in most cases, non-linear. This implies that in forests and stands with larger trees there will be more biomass and carbon than others with similar basal area but trees of smaller size. Previous carbon estimates using linear basal area to carbon equations may produce biased results if applied to stands with different $D$ distributions. If there is not much variation in $D$ across stands, the linear relationship between the basal area and carbon will represent whether there are more or fewer trees of the same size. Stand allometric equations using the basal area and weighted diameter as independent variables can be used to derive carbon figures per hectare; consistent figures for the weighted diameter can be obtained by measuring a few of the largest trees in site once the relationship between tree size and density is known. We consider that the use of these stand allometric equations is promising since basal area, tree density and the diametric distribution in a site can be quickly measured in the field. The uncertainty associated with use of non-local allometric equations and hence any systematic error between the true and estimated values should be assessed since this might be the highest contribution to the uncertainty of the results; however, the development of local equations should be carefully considered.
Table 5. Differences in carbon estimates obtained through the largest trees method and the stand level allometric equation, in comparison with carbon estimate based on the full enumeration of trees per plot (mean values, in parenthesis the 95% range considering the percentiles 2.5 and 97.5%).

<table>
<thead>
<tr>
<th>Sub-sample (size)</th>
<th>All inventory plots</th>
<th>Inventory plots classified by tree density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;10 trees per site</td>
<td>10–20 trees per site</td>
</tr>
<tr>
<td></td>
<td>(&lt;111 trees ha⁻¹)</td>
<td>(111–222 trees ha⁻¹)</td>
</tr>
<tr>
<td>1</td>
<td>1.5% (−7.9, 12.5)</td>
<td>1.2% (−4.8, 9.0)</td>
</tr>
<tr>
<td>2</td>
<td>1.4% (−6.5, 9.9)</td>
<td>0.8% (−4.1, 7.0)</td>
</tr>
<tr>
<td>3</td>
<td>1.4% (−5.2, 8.9)</td>
<td>0.8% (−3.5, 6.7)</td>
</tr>
<tr>
<td>4</td>
<td>1.4% (−4.8, 8.3)</td>
<td>0.8% (−3.3, 6.5)</td>
</tr>
<tr>
<td>5</td>
<td>1.4% (−4.7, 7.7)</td>
<td>0.9% (−3.1, 6.4)</td>
</tr>
<tr>
<td>6</td>
<td>1.4% (−4.6, 7.2)</td>
<td>0.9% (−3.0, 6.2)</td>
</tr>
<tr>
<td>7</td>
<td>1.4% (−4.7, 6.8)</td>
<td>1.6% (−5.2, 6.6)</td>
</tr>
<tr>
<td>10</td>
<td>1.6% (−4.7, 6.5)</td>
<td>1.7% (−5.0, 5.9)</td>
</tr>
</tbody>
</table>

Acknowledgements
We thank A.L.S., A.G., A.R. R., R.V., A.A.M., M.B. and personnel from ITESO and La Primavera Executive Office for their contribution in the fieldwork of the forest inventory and to the Helen McKay and to two anonymous reviewers for their comments that helped to improve the manuscript. We thank to Margaret Skutsch for valuable input and comments to earlier versions of the manuscript.

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Appendix A

When all the trees in a site have the same diameter, then the basal area will be given by equation (A1) which is the basal area of a single tree times the density n in trees ha\(^{-1}\). When equation (A1) is substituted into equation (11), it can be seen that carbon will be equal to the amount of carbon in an individual tree times the tree density in the site [equation (A2)]. Definitions of the variables used here correspond to those defined in Basal Area and Carbon from Allometric Equations section.

\[
\bar{G} = n \times \frac{\pi}{40\,000} \times D^2 \quad \text{(A1)}
\]

\[
\bar{C} = K' \times D^{1-2} \times \bar{G} = K' \times D^{1-2} \times n \times \frac{\pi}{40\,000} \times D^2 \quad \text{(A2)}
\]

Appendix B

In order to assess the effect of introducing an error in the measurement of tree density, we estimated the variation in results, with density values rounded to the closest 100 level in each site instead of the density-value obtained from the forest inventory (e.g. if density in one site was 85, a value of 100 is used; if density was 255, a value of 300 is used). These changes produce a mean variation (error) of 8% for the density values (95% range, from −80% to +21%). The \(\bar{D}_{n1}\) are corrected using the rounded tree densities in the formulas presented in Figure 5; then carbon content and the errors in comparison with the forest inventory are re-calculated. It can be seen that the 95% ranges for the errors widen slightly but there are no meaningful changes in the means. The effect would be relatively higher for areas with lower tree density and when the sub-sample of large trees is smaller. (Table B1)

Appendix C

Tables C1 and C2 present the errors in the estimation of carbon, based on the use of the estimated \(\bar{D}_{n1}\) derived from local tree density and the sub-samples of large trees using the stand-level equations in comparison with the values obtained using the stand-level equation with the weighted diameter from the forest inventory. The objective is to identify the error introduced by the use of large trees to generate figures of the weighted diameter. Table C2 shows the effect of introducing an error in tree density. Tables C1 and C2 show that the differences between the two methods are small and unbiased with a symmetrical dispersion of errors; results also show a small sensitivity to errors in the measurement of tree density (Table C2).

Appendix D

In order to identify the effort required to obtain a consistent value for the simple mean diameter (\(\bar{D}\)) in a measurement plot, we analysed the error in \(\bar{D}\) depending on the percentage of trees considered for this estimation in comparison with the mean value obtained in the inventory. Trees were sampled systematically by sub-quadrats in each inventory plot; Figure D1 shows the variation in simple D average in each measurement plot and how it changes and converges to the value of the inventory as more trees are considered; the 95% range of the errors is included. The values converge to the mean; however, the variation (i.e. potential error) is larger when fewer trees are considered. As mentioned in the manuscript if 30% of the trees were sampled in the plots to obtain the simple average, the mean will be close to the real value however the error would be ±20%; in order to reduce error to ±10% with 95% confidence the sampling effort required would be 90% of the trees in the site. If stand-level equations were to use mean D instead of \(\bar{D}\) weighted by the basal area, the sampling intensity would have to be high.
Table B1. Variation in the error of the estimates when an error in tree density is introduced for the estimation of the weighted diameter ($\overline{D_{w}}$). The values indicate the error in comparison with carbon estimates based on the full enumeration of trees in the inventory plot (mean values, in parenthesis the 95% range considering the percentiles 2.5 and 97.5%).

<table>
<thead>
<tr>
<th>Sub-sample (size)</th>
<th>All inventory plots</th>
<th>Inventory plots classified by tree density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;10 trees per site</td>
<td>10–20 trees per site</td>
</tr>
<tr>
<td></td>
<td>(&lt;111 trees ha$^{-1}$)</td>
<td>(111–222 trees ha$^{-1}$)</td>
</tr>
<tr>
<td>1.2% (–8.0, 12.6)</td>
<td>0.5% (–7.0, 9.4)</td>
<td>2.3% (–5.1, 11.8)</td>
</tr>
<tr>
<td>0.1% (–6.6, 7.6)</td>
<td>0.6% (–3.0, 6.4)</td>
<td>1.0% (–3.8, 6.8)</td>
</tr>
<tr>
<td>0.2% (–2.0, 3.8)</td>
<td>0.9% (–2.5, 4.6)</td>
<td>−1.3% (–6.4, 4.6)</td>
</tr>
<tr>
<td>0.3% (–1.3, 2.6)</td>
<td>0.7% (–1.9, 3.7)</td>
<td>−1.1% (–5.1, 3.8)</td>
</tr>
<tr>
<td>0.2% (–1.1, 1.9)</td>
<td>0.5% (–1.4, 3.0)</td>
<td>−0.8% (–4.2, 3.0)</td>
</tr>
<tr>
<td>0.3% (–0.8, 1.4)</td>
<td>0.4% (–1.5, 2.4)</td>
<td>−0.7% (–3.6, 2.5)</td>
</tr>
</tbody>
</table>

Table C1. Differences in carbon estimates obtained through the largest trees method, in comparison with carbon estimate based on the stand allometric equation using the data from the forest inventory (mean values, in parenthesis the 95% range considering the percentiles 2.5 and 97.5%).

<table>
<thead>
<tr>
<th>Sub-sample (size)</th>
<th>All inventory plots</th>
<th>Inventory plots classified by tree density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;10 trees per site</td>
<td>10–20 trees per site</td>
</tr>
<tr>
<td></td>
<td>(&lt;111 trees ha$^{-1}$)</td>
<td>(111–222 trees ha$^{-1}$)</td>
</tr>
<tr>
<td>−0.2% (–6.8, 7.8)</td>
<td>−1.1% (–6.9, 6.7)</td>
<td>0.9% (–3.7, 6.4)</td>
</tr>
<tr>
<td>−0.3% (–5.9, 5.5)</td>
<td>−1.5% (–6.4, 4.1)</td>
<td>0.7% (–2.9, 4.4)</td>
</tr>
<tr>
<td>−0.2% (–4.4, 4.6)</td>
<td>−0.8% (–4.0, 3.1)</td>
<td>0.5% (–2.2, 3.5)</td>
</tr>
<tr>
<td>−0.2% (–3.7, 3.9)</td>
<td>−0.8% (–3.6, 2.3)</td>
<td>0.3% (−2.4, 2.9)</td>
</tr>
<tr>
<td>−0.1% (–3.3, 3.4)</td>
<td>−0.4% (–2.1, 1.9)</td>
<td>0.2% (−2.7, 2.5)</td>
</tr>
<tr>
<td>−0.1% (–3.0, 3.0)</td>
<td>−0.4% (–2.0, 1.6)</td>
<td>0.1% (−2.9, 2.4)</td>
</tr>
<tr>
<td>0.0% (–2.6, 2.7)</td>
<td>0.0% (−2.8, 2.4)</td>
<td>−0.4% (−2.3, 1.8)</td>
</tr>
<tr>
<td>0.0% (–2.2, 2.7)</td>
<td>0.0% (−2.3, 2.5)</td>
<td>−0.2% (−1.5, 1.6)</td>
</tr>
</tbody>
</table>

Table C2. Differences in carbon estimates obtained through the largest trees method in comparison with carbon estimate based on the stand allometric equation, basal area and weighted diameter obtained for each plot of the forest inventory. Tree density is rounded to the closest 100 density. (Mean values, in parenthesis the 95% range considering the percentiles 2.5 and 97.5%).

<table>
<thead>
<tr>
<th>Sub-sample (size)</th>
<th>All inventory plots</th>
<th>Inventory Plots Classified by Tree Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;10 trees per site</td>
<td>10–20 trees per site</td>
</tr>
<tr>
<td></td>
<td>(&lt;111 trees ha$^{-1}$)</td>
<td>(111–222 trees ha$^{-1}$)</td>
</tr>
<tr>
<td>−7.9% (–80.0, 21.4)</td>
<td>−41.1% (–200, 10.0)</td>
<td>−4.7% (–28.6, 25.0)</td>
</tr>
</tbody>
</table>
Appendix E

Table E1 shows the implications of the non-linear relationship between the basal area and carbon as discussed in Basal area and carbon from allometric equations section. As the slope or ratio \( m \) in equation (6) is a function of the diameter, it can be seen that for a given basal area, there will be a considerable variation in the aboveground carbon content depending on the tree size.

Table E1. Basal area-D-carbon table for oaks using the equation published by Naár\(^{51}\) presented in Table 1 in the text (values in tC ha\(^{-1}\)).

<table>
<thead>
<tr>
<th>Basal area (m(^2) ha(^{-1}))</th>
<th>Diameter at breast height (cm) (weighted by basal area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>7.3</td>
</tr>
<tr>
<td>5</td>
<td>9.2</td>
</tr>
<tr>
<td>6</td>
<td>11.0</td>
</tr>
<tr>
<td>7</td>
<td>12.8</td>
</tr>
<tr>
<td>8</td>
<td>14.7</td>
</tr>
<tr>
<td>9</td>
<td>16.5</td>
</tr>
<tr>
<td>10</td>
<td>18.3</td>
</tr>
<tr>
<td>12</td>
<td>22.0</td>
</tr>
<tr>
<td>14</td>
<td>25.7</td>
</tr>
<tr>
<td>16</td>
<td>29.3</td>
</tr>
<tr>
<td>18</td>
<td>33.0</td>
</tr>
<tr>
<td>20</td>
<td>36.7</td>
</tr>
<tr>
<td>22</td>
<td>40.4</td>
</tr>
<tr>
<td>24</td>
<td>44.0</td>
</tr>
<tr>
<td>26</td>
<td>47.7</td>
</tr>
<tr>
<td>28</td>
<td>51.4</td>
</tr>
<tr>
<td>30</td>
<td>55.0</td>
</tr>
<tr>
<td>32</td>
<td>58.7</td>
</tr>
<tr>
<td>34</td>
<td>62.4</td>
</tr>
<tr>
<td>36</td>
<td>66.0</td>
</tr>
<tr>
<td>38</td>
<td>69.7</td>
</tr>
<tr>
<td>40</td>
<td>73.4</td>
</tr>
</tbody>
</table>

When all the trees have the same diameter, the weighted diameter and simple mean will be equal (e.g. in plantations).