OPINION PAPER

Guidelines for documenting and reporting tree allometric equations

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1 Introduction

Given the pressing need to quantify carbon fluxes associated with terrestrial vegetation dynamics, an increasing number of researchers have sought to improve estimates of tree volume, biomass, and carbon stocks. Tree allometric equations are critical tools for such purpose and have the potential to improve our understanding about carbon sequestration in woody vegetation, to support the implementation of policies and mechanisms designed to mitigate climate change (e.g. CDM and REDD+; Agrawal et al. 2011), to calculate costs and benefits associated with forest carbon projects, and to improve bioenergy systems and sustainable forest management (Henry et al. 2013).

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Many methods, ranging from the most generic (i.e. IPCC Tier 1) to site- and species-specific (i.e. Tiers 2 and 3) are available for estimating tree biomass. The most widely used approach is the use of generic equations based on trees harvested in several sites (Brown 1997; Jenkins et al. 2003; Chave et al. 2005; Chave et al. 2014; Chojnacky et al. 2014). However, such generic equations may lead to systematic errors of up to 400 % at the site level (Alvarez et al. 2012; Ngomanda et al. 2014; Chave et al. 2014). Well-implemented, locally developed models may be a better alternative and are expected to provide less uncertainty than generic equations (Chave et al. 2014). However, the lack of proper documentation describing the methods used to develop equations is a major obstacle to choosing the most appropriate model.

Until recently, there was no harmonized global repository of allometric equations that could aid in choosing the tree biomass or volume model most adapted to a given study site. The GlobAllomeTree platform (http://www.globallometree.org/; Henry et al. 2013) is a first step towards this goal but also has raised the issue of the lack of consistency in how allometric equations and their associated metadata are reported. A large number of the publications reviewed for inclusion into GlobAllomeTree did not comply with basic IPCC "good practice" guidelines (IPCC 2003) in terms of completeness, documentation, transparency, or comparability. Although a few authors have proposed general guidelines to describe and evaluate allometric equations (Baldasso et al. 2012; Bombelli et al. 2009; IPCC 2003, 2006; Jenkins et al. 2003; Picard et al. 2012; Ponce-Hernandez 2004; Pretzsch et al. 2002), no document gives practical recommendations on the necessary information that should be provided with published allometric models. Authors are left to their own initiative to decide the breadth and depth of information they publish about the allometric equations they develop, leading to the abovementioned inconsistencies between studies. For instance, many published equations lack basic descriptions of the study location, sampling design, the statistics associated with the equation, or even the allometric model construction. This missing information limits the harmonization and use of allometric equations in a transparent and comparable way and the estimation of associated uncertainties and, ultimately, prevents scientific progress towards sustainable forestry practices.

We address that need by providing standard guidelines for publishing allometric equations worldwide. These recommendations are the result of expert discussions held during the "Regional Technical Workshop on Tree Volume and Biomass Allometric Equations in South and Central America" in Costa Rica, on May 21–24, 2014. The workshop brought together

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30 scientists from throughout Latin America, the USA, and Europe to discuss the state of the art on allometric equations, identify knowledge gaps, and offer potential ways forward. We expect the widespread adoption of these guidelines will lead to a more complete and harmonized reporting of information on tree allometric equations worldwide, which will increase their value and robustness for predicting biomass and carbon stocks.

2 Recommended guidelines for documenting allometric equations

The following recommendations should apply to all situations and circumstances where an allometric equation is published in the scientific or technical literature. We focus on six areas: definitions and concepts, description of the target population and environmental conditions where the study was carried out, sampling details and scope of the study, methods for data analysis and calculations, model fitting and uncertainty, and metadata (Table 1). All this information should be included within the main document or in its associated appendices and may be organized in tables when dealing with multiple equations.

2.1 Definitions and concepts

Authors should describe the variables and units used in field measurements or in data processing and of the output estimates from allometric equations. Units need to be stated using the International System of Units (SI). Clearly defined variables aid in understanding which tree components were considered in developing the allometric equations. For example, it is not always obvious if a basic variable such as "tree height" refers to total tree height or to commercial tree height (e.g. Feldpausch et al. 2010 or Ribeiro et al. 2011). Information about the height where the diameter measurement was taken is needed. For example, if trees were buttressed or were irregular at the standard point of measurement (1.3 m), how were diameters measured? Similar details on volume and tree components included in the model need to be clearly stated.

2.2 Description of the target population and environmental conditions

A proper environmental description of the sites where equations were constructed allows researchers to determine whether allometric models constructed elsewhere would be valid in their study areas. The location (latitude, longitude, and altitude data) and environmental conditions of all sampling areas are mandatory. If coordinates are projected, reporting the projection system is needed.

Information on climate variables should include at least mean annual temperature, mean annual precipitation, and the length of the dry season (<100 mm/month), if any. Including additional variables such as seasonality, water deficit, and maximum and minimum values is advisable. It is recommended to also provide information from the country's specific or an international preferred ecological zone classification system such as FAO (2001), Olson et al. (2001), Holdridge (1967), Udvardy (1975), or Bailey (1989).

Known or approximate stand age should be indicated, together with a description of the forest community (dominant species, tree abundance or stand density, basal area, disturbance regime, and phenology) and management system. Whenever possible, it is also recommended to provide information on soils (e.g. texture and depth) and landscape characteristics (elevation, slope, aspect) of the sampling sites. It would also be advisable to include some mention of the geographic representativeness of any sample set.

2.3 Sampling and scope of the study

It is essential that much thought and precise documentation exist for the sample design and actual sampling needed to construct robust allometric equations. This includes information on the number of trees considered, the range of diameter, the tree components measured (e.g. were the belowground components measured?), the area investigated (e.g. trees were harvested in a single plot or in several randomly located within a landscape), and whether trees were chosen randomly, based on diameter classes, vertical stratification, or floristic composition. Such information helps potential users to gauge the robustness of models and determine the limits of their application.

We recommend that the tree partitioning proposed by Henry et al. (2011) be adopted as a minimum standard for partitioning tree components during biomass harvests and data processing: stump, trunk, bark, small roots ($D<5$ mm), medium roots ($5<D<10$ mm), big roots ($D>10$ mm), thin branches ($D<7$ cm), large branches ($D>7$ cm), dead branches, leaves, and fruits. With small roots, it may be necessary to choose a cutoff diameter and clearly state that the biomass equation only accounts for roots larger than that, as other more detailed methods are available to account for this highly dynamic component (Vogt et al. 1998).

Since common names vary considerably among locations, and taxonomy is being updated constantly, it is desirable to have both lists made available to users. Efforts should be made to have taxonomists identify the harvested tree species in the field and to collect voucher specimens and deposit them in an institutional herbarium.

2.4 Methods used for data and laboratory analyses

Reporting measurement methods, tools, and calculation procedures also helps to evaluate the model robustness and allows to replicate measures and model construction with expanded

Table 1 Checklist of recommended guidelines for documenting allometric equations in scientific or technical publications

Guideline category	Information to include
Definitions and concepts	*Mandatory*
	☐ Tree components measured (e.g. bole, crown, roots)
	☐ Type of height measurements (total, commercial)
	☐ Type of diameter measurements (point of measurement)
	☐ Units of measures
	☐ Definitions of variables used
Target population and environmental conditions	*Mandatory*
	☐ Geographic coordinates (latitude and longitude) and projection system
	☐ Elevation (in m above sea level)
	☐ Climate variables: mean annual temperature (°C), mean annual precipitation (mm/year), length of dry season (in month with rainfall <100 mm)
	☐ Estimated age or successional status
	Highly recommended
	☐ Biographic or ecological classification system used (e.g. Holdridge Life Zone System)
	☐ Additional climate variables (: e.g. maximum climatological water deficit, seasonality in precipitation and in temperature.)
	☐ Dominant species
	☐ Stand structure (e.g. basal area, stand density–number of individuals per unit of area)
	☐ Phenology (e.g. deciduous, evergreen)
	☐ Landscape characteristics (slope, aspect)
	☐ Soil information (texture, depth)
Sampling and laboratory analysis	*Mandatory*
	☐ Sampling criteria (e.g. diameter classes, species composition or guild, plot-based sampling)
	☐ Sample size
	☐ Range of values for diameter, height, wood specific gravity, tree components, etc.
	☐ Scientific and vernacular (if used) names
	☐ Methods used in the field or in the laboratory (e.g. method used to measure wood specific gravity)
	Highly recommended
	☐ Number of replicates
	☐ Instruments used in the field or in the laboratory (e.g. laser model for tree height measurement)
	☐ Precision of instruments used
	☐ Calculation procedures
Model fitting, prediction and uncertainty	*Mandatory*
	☐ Functional form of the model(s) (e.g. power, non-linear, log-log)
	☐ Model mathematical formula, including form of the error term (multiplicative versus additive)
	☐ Data transformations (if any, e.g. log transformation)
	☐ Statistical parameters (R^2, RSE, mean bias, at a minimum)
	☐ Parameter values and confidence intervals of the parameters
	☐ Comparative statistics (e.g. *F*-value, AIC, BIC, Furnival index)
	☐ Software (and version)
	Highly recommended
	☐ Analysis scripts
	☐ Correlation matrix between parameters
	☐ Correlation between compartments in the case of SUR regressions
Meta data	*Highly recommended*
	☐ Purpose of the data
	☐ Dates of project
	☐ Data owner (contact information)
	☐ Storage and rights of use

or additional datasets. Several instruments are used to measure forest variables, and it is important to mention them so the reader can gauge their accuracy. For example, different biases can be associated with tree height measurement according to the instrument used (Hunter et al. 2013; Larjavaara and Muller-Landau 2013). The manuals developed by Anderson and Ingram (1993) and Picard et al. (2012) provide lengthy descriptions regarding laboratory techniques. In addition, forest mensuration manuals (e.g. Husch et al. 2002; Laar and Akça 2007) are sources of basic formulas and procedures for calculating volume, wood density, biomass expansion factors, and other variables, as well as procedures for dealing with outlier data, which should all be clearly described.

2.5 Model fitting, prediction, and uncertainty

Statistical parameters are needed to evaluate the robustness and the accuracy of any given model and to aid comparisons among them. The mathematical form of the models (e.g. power, log-transformed, and non-linear), distinguishing between additive and multiplicative error terms, and any transformations performed on the data (e.g. log and back transformation) must be clearly described with the associated formula, as they have important implications for interpreting and using allometric models (Zell et al. 2014).

Details about the software (name and version, at least) and processes used to fit the models are necessary to replicate model fits or run diagnostic tests. The best solution is to provide the scripts of the analyses as an appendix of the main document. Although the R^2 associated with the model is often provided, a description of other statistical parameters used to fully assess the goodness of the fit is advisable. Among them, the residual standard error (RSE) of the model and the mean bias should be provided for all models included in the document. Whenever multiple models are derived, we recommend that the statistical parameters used for model comparison and selection be described too (e.g. sum of squared estimated residuals (SSE), F-test, Akaike or Bayesian information criterion (AIC, BIC), Furnival index). Statistics on the data used for validation (sample size, relative average error, etc.) should also be indicated.

Finally, users are encouraged to present graphics illustrating the relationship between tree diameter versus tree height, diameter versus biomass, crown diameter versus biomass (if available), and predicted values versus observed values, at least in the appendices. Figures showing model fit must have complete descriptions of units used on the axes and in the figure captions.

2.6 Metadata on raw data

Raw data and its accompanying metadata help understand the scope and limitations of available datasets, calculate uncertainties, validate models, and construct new improved allometries. Properly documented volume data, for example, are very useful to develop biomass expansion factors, which are used by most countries to assess national forest biomass (FAO 2010). In contrast, poorly documented raw data or missing metadata preclude validation or further development equations based on expanded datasets.

Authors are encouraged to share their raw data to facilitate future efforts and to build collaborations within the scientific community. Data repositories such as Dryad (http://datadryad.org/), DataONE (http://www.dataone.org/), and others are now available for storing ecological and biological data. They offer the possibility of standardizing metadata and data formats and assigning a citable DOI number to the dataset.

3 Conclusions

The necessary criteria and information that scientists should use to develop allometric models and provide adequate information on them had not been considered before in a systematic manner. The recommendations we offer are meant to serve scientists and data users as a reference framework to improve biomass and volume allometric equation construction and reporting. These rules should be applied systematically and be part of a shared responsibility among authors, journal editors and reviewers, and users to improve reporting and use of allometric equations. Baldasso et al. (2012) and Picard et al. (2012) are good examples of how these guidelines can be incorporated into electronic formats and technical writing. We expect that the adoption of these guidelines will lead to a more complete, transparent, documented, and harmonized reporting of information on tree allometric equations worldwide, which will increase their value and robustness in predicting biomass and carbon.

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