AMAËL LE SQUIN, FLORENCE GOHON,
HENRI CUNY

TECHNICAL NOTE ON TOTAL AND BOLE VOLUMES, AND ON WOOD DENSITY TO THE CONSEIL SCIENTIFIQUE ET TECHNIQUE DE L'IGN

Technical note on total and bole volumes, and on wood density to the Conseil Scientifique et Technique de l'IGN

Technical note on total and bole volumes, and on wood density to the Conseil Scientifique et Technique de l'IGN

Amaël Le Squin, Florence Gohon, Henri Cuny

Contents

Context

The French National Forest Inventory (NFI) publishes statistics annually, such as basal area or wood resources, on both private and public forest. These statistics are derived from a sampling scheme in which about 6000 new plots are surveyed each year, along with 6000 plots that were first visited five years earlier. The published statistics are calculated using a moving five-year average; for instance, the published results for 2024 are based on campaigns spanning from 2020 to 2024.

Initially designed to assess forest area and produce estimates of standing timber stock, the French NFI is gradually evolving into more comprehensive tools for forest monitoring, incorporating a variety of indicators. Among this new information, the estimation of forest biomass and carbon is crucial, as it makes it possible to monitor biomass production and its use by different sectors, to estimate the contribution of forests to mitigating the effects of climate change as part of climate commitments monitoring (Citepa), and to develop forest strategies adapted to contemporary environmental and societal challenges (Commission Européenne 2018).

The European Union developed a New EU Forest Strategy for 2030 as part of the plan to adapt to and fight against climate change and make Europe a climate neutral continent by 2050. This strategy relies on improved monitoring of European forests to better understand their condition and respond accordingly. Specifically, it calls for assessing carbon sequestration in forests to evaluate whether or not Europe reached carbon neutrality. One bottleneck is the harmonisation of the forest monitoring methods between European member states, if not within them. The PathFinder project supports member states in implementing a European Forest Monitoring System in order to standardise or harmonise forest data collection and reporting across the EU. This prompted the French NFI to update its methods for assessing forest carbon storage.

Three steps are necessary to estimate carbon storage from field data (see Fig. 1): (*i*) the total aerial volume is estimated from diameter at breast height (dbh) and height (Vallet et al. 2006), (*ii*) biomass is then derived by using a coefficient for wood density, and (*iii*) a factor is applied to convert the biomass into carbon content.

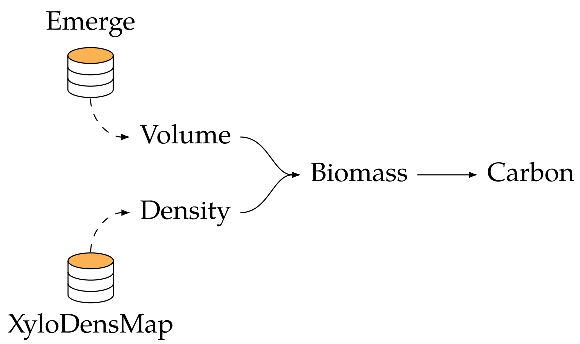

Figure 1: Computation chain for biomass and carbon content.

In this technical note, we explain the whole computation chain we foresee to estimate carbon content. We focus mostly on the base of the chain, *i.e.,* the two volumes computed at the French NFI for each tree (bole and total volumes), and the wood density. In the section Definitions and datasets, we define the different tree components and explain the origins of the data. Then, in the sections Bole volume and Total aerial volume, we expose the models to compute the individual bole and total volumes, respectively. Lastly, we present the undergoing work on wood density and potential path to convert total aerial volume into biomass and carbon content in the sections XyloDensMap and Root volume and wood carbon content.

Definitions and datasets

Trees are partitioned into hierarchical elements with definitions that may vary between Forest Inventories and datasets (*e.g.*, Fig. 2).

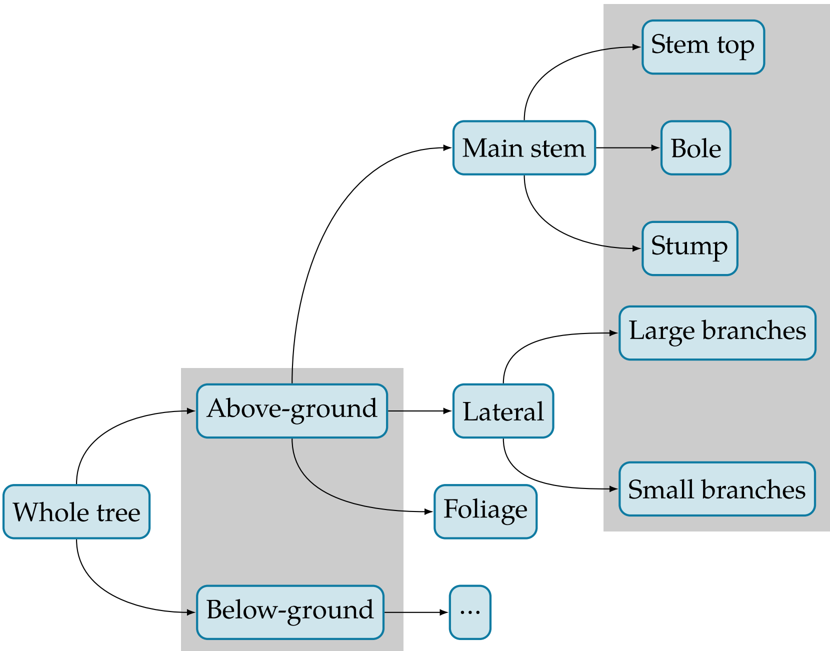

Figure 2: Hierarchical elements of trees, figure inspired by Gschwantner et al. 2009

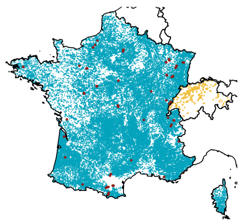

Figure 3: Plot location for French NFI, Emerge, and Swiss dataset.

In our case, the tree data come from different institutes, different periods of time, and do not all have the same tree components recorded:

1. 'Protocole Oudin', dataset preserved by INRAE, ranging from 1930 to 1980 (in red on Fig. 3). Recorded the bole volume, and the large and small branches. Hereafter, we name this dataset 'Emerge', which was the name of the

project that digitalised this dataset in 2008 (Deleuze et al. 2013).

2. The French NFI(in blue on the Fig. 3). Data range from 1988 to 2007 (data before 1988 record diameter rather than circumference). Recorded the bole volume.

3. Experimental Forest Management project dataset (Didion et al. 2024, in yello on Fig. 3). Data range from 1888 to 1974, and bole volume, large branches, and small branches were recorded.

4. The 'Office National des Forêts (ONF)', with protocols from 1972 and from 1983 (not used as there is no coordinates)

5. Institut Technologique Forêt, Cellulose, Bois-construction, Ameublement (FCBA), not used so far for the aerial volume

6. L'Institut pour le développement forestier (IDF) which is the R&D of the Centre National de la Propriété Forestière and the Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (IRSTEA, currently INRAE)

We decided to use the definitions from Gschwantner et al. 2009 (see Figs. 2 and 4):

- Main stem: The stem of a tree is the above-ground part of the main (off) shoot with apical dominance
  - Stem top: topmost part of the stem from an over-bark base-diameter of 7 cm (French NFI) to the stem tip
  - Bole: above-ground part of the stem between stump and the stem top
  - Stump: above-ground base part of the stem which would remain after a tree was cut under normal felling practices
- Lateral parts:
  - Large branches: portion of the above-ground lateral parts with a diameter of more than or equal to 7 cm (French NFI)
  - Large branches: portion of the above-ground lateral parts with a diameter of less than 7 cm (French NFI)

A total of 594 616 individuals were measured, with 98% coming from the NFI (bole volume only), 6% from the Swiss dataset

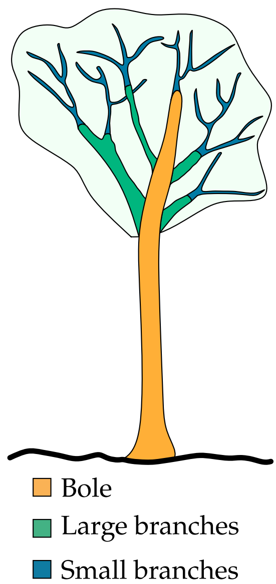

Figure 4: Scheme of tree components.

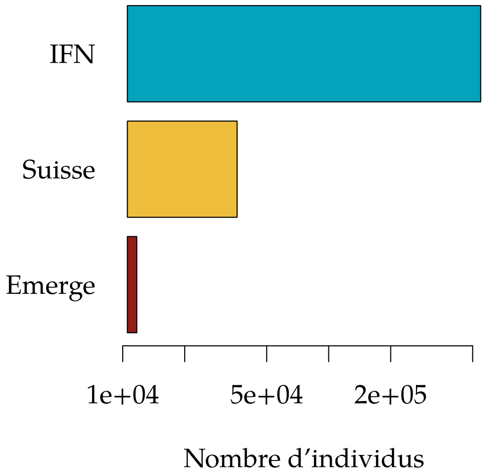

Figure 5: Composition of the used dataset for the bole volume and total aerial volume.

(bole, large and small branches), and 2% from Emerge (same components as the Swiss dataset; see Fig. 5). The difficulties in fitting the data are twofold: first, the data show high heteroskedasticity (see Fig 6), and second, the datasets are unbalanced.

Bole volume (volume bois-fort tige)

The bole volume is the 'reference' volume since the creation of the French NFI (1958). Its definition is largely driven by the requirements of the wood industry, for which the estimation of standing timber volume is an essential tool for resource management and planning.

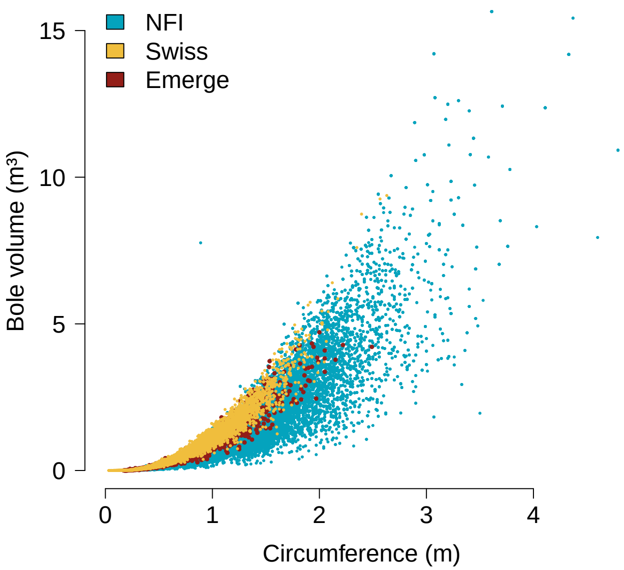

Figure 6: Typical response of bole volume to circumference (here displayed for *Fagus sylvatica*). We can see that both the Emerge and Swiss datasets (Deleuze et al. 2013; Didion et al. 2024) are quite similar and covers elongated trees, while the French NFI covers less regular trees.

Bole volume

Total aerial volume

In this section, I explore two possible paths to estimate the total aerial volume, V_{tot}. The first option, based on Longuetaud et al. 2013, uses the ratio:

$$r = \frac{V_{\text{bole}}}{V_{\text{tot}}} \tag{1}$$

and is comprised between 0 and 1 by construction. Therefore, a Beta-distribution is a good fit. The second option is to fit a multivariate normal distribution, MVN, to the *transformed* ratio, $\text{logit}(r)$, jointly with the log-transformed total volume, $\log(V_{\text{tot}})$:

$$\begin{pmatrix} \text{logit}(r) \\ \log(V_{\text{tot}}) \end{pmatrix} \sim \text{MVN}\left\{ \begin{pmatrix} f(c, h; \boldsymbol{\theta}) \\ g(c, h; \boldsymbol{\theta}) \end{pmatrix}, \boldsymbol{\Sigma} \right\}, \tag{2}$$

where f and g are functions tailored to our specific needs, c is circumference at breast height, h, is tree height, and θ is a vector of parameters to estimate.

Ratio approach

Multivariate approach

Multivariate models allow pulling information across components, *i.e.*, they describe the variation within and covariation among tree components. I chose to model jointly r and V_{tot} but the alternative modelling bole and crown could also be considered.

Intractability

Note that whatever I try to model, there will always be intractability somewhere. If I model both components – trunk and crown – with a multivariate lognormal, the distribution of the total volume becomes untractable (sum of two lognormals has no closed form distribution). Alternatively, if I model the total volume and the ratio r, then V_{bole} becomes untractable. Indeed:

$$\mathbb{E}[V_{\text{bole}}] = \mathbb{E}[rV_{\text{tot}}]$$
$$\mathbb{E}[V_{\text{bole}}] = \mathbb{E}[r]\,\mathbb{E}[V_{\text{tot}}] + \text{Cov}[r, V_{\text{tot}}]$$

and similarly for the variance. In any case, I do not have a closed-form distribution.

Simulated data

In order to demonstrate the relevance of multivariate methods, I simulate two correlated random variables and then recover the generating parameters.

Perspectives

Use copulas?

XyloDensMap

In France, national estimates of forest biomass and carbon stocks have so far relied on wood density values derived from an unpublished dataset, compiled from a literature review conducted by Jean-Luc Dupouey (INRAE) as part of the CARBOFOR project (Loustau 2004). Some of these values originate from a 170-year-old source (Mathieu 1855), updated to provide a single average value per species, covering around 50 species. However, these estimates are based on small and unbalanced samples—typically fewer than 10 mature trees per species and do not reflect the diversity of conditions found in French forests, particularly in terms of species, tree size, and growth conditions.

To address the lack of precise and comprehensive data on wood density for forest species in mainland France, the XyloDensMap project was launched in 2015 through a collaboration between INRAE and IGN. The resulting open dataset, XyloDensMap, includes individual wood density measurements from 110 763 wood cores taken at breast height across metropolitan France. These data were obtained by combining the spatially systematic sampling design of the French National Forest Inventory (NFI) with a high-throughput method for measuring wood density using X-ray computed tomography (Freyburger et al. 2009; Jacquin et al. 2019). Due to the systematic nature of the IFN's annual sampling framework (Bontemps and Bouriaud 2024; Bouriaud et al. 2023), the XyloDensMap dataset is representative of French forests, particularly in terms of species diversity and tree size.

All details regarding the sampling design, sample processing, and wood density measurement in XyloDensMap are provided in the corresponding data paper (Cuny, Leban et al. 2025). A second publication on wood density modeling in France using the XyloDensMap dataset is currently under review at Biogeosciences, with the article already available as a preprint (Cuny, Bontemps et al. 2025). This work compares the application of different methods (average species coefficients, more detailed linear models incorporating tree size and climatic conditions, random forest) to simulate wood density in IFN data, and discusses the influence of the chosen method on estimating total aboveground biomass stocks at multiple scales in France. The publication thus already includes simulations of wood density across the entire NFI framework (see Fig. 7)—a necessary step for calculating biomass and carbon stocks and fluxes at different scales in France—and may serve as a basis for discussion to define the method to be used for simulating wood density in the NFI dataset.

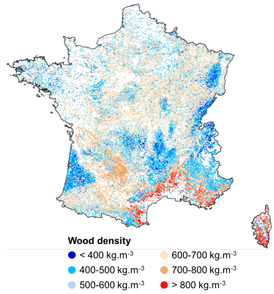

Figure 7: Map of community-wide mean wood density in mainland France on each forest plot inventoried by the French NFI between2005 and 2022.

Root volume and wood carbon content

While actions regarding aboveground volumes (stem wood and total aerial biomass) and wood density are already underway, aspects related to root volume and carbon content in wood remain less explored at this stage. Unlike the evaluation of or wood density, the IGN does not currently have datasets that allow for the analysis of root volumes or wood carbon content. For these aspects, a different approach will be implemented, involving a literature review to assess the current state of knowledge.

The objective will be to determine whether the current assumptions used in the IGN method—namely, a root expansion coefficient by botanical class (1.28 for broadleaves and 1.30 for conifers) and a single carbon content coefficient (0.475)—are still relevant in light of current knowledge, or whether they could be improved to better reflect natural variability. The literature review will be complemented by discussions with expert researchers in these fields, such as those at the INRAE center in Champenoux.

An internship was already conducted during the summer of 2025 on this topic. It helped identify a number of bibliographic references for each aspect. Regarding wood carbon content, many articles have recently been published, and a global database was even compiled through a literature review (Doraisami et al. 2022). This database includes carbon content values for several species found in French forests. As for root volume, an interview was conducted with Frédéric Danjon, a root specialist at INRAE, which provided access to numerous relevant references on root volume. A synthesis of the various identified references for each aspect now needs to be carried out.

Should the assumptions regarding root volume and carbon content be revised, an analysis and documentation of the impact of these revisions on carbon estimates will be undertaken.

Bibliography

Bontemps, Jean-Daniel and Olivier Bouriaud (2024), ‘Take five: about the beat and the bar of annual and 5-year periodic national forest inventories’, *Annals of Forest Science*, 81, 1, p. 53, DOI: 10.1186/s13595-024-01268-1.

Bouriaud, Olivier, François Morneau and Jean-Daniel Bontemps (2023), ‘Square-grid sampling support to reconcile systematicity and adaptivity in periodic spatial surveys of natural populations’, *Journal of Vegetation Science*, 34, 3, ISSN: 1100-9233, DOI: 10.1111/jvs.13195.

Commission Européenne (2018), *Règlement (ue) 2018/841 du parlement européen et du conseil*, tech. rep., JO L 156 du 19.6.2018 p. 1, Commission Européenne, http://data.europa.eu/eli/reg/2018/841/2023-05-11.

Cuny, Henri, Jean-Daniel Bontemps, Nikola Besic, Antoine Colin, Lionel Hertzog, Amaël Le Squin, William Marchand, Cédric Vega and Jean-Michel Leban (2025), ‘Wood density variation in European forest species: drivers and implications for multiscale biomass and carbon assessment in France’, *EGUsphere*, 2025, pp. 1–34, DOI: 10.5194/egusphere-2025-4152.

Cuny, Henri, Jean-Michel Leban, Jean-Christophe Hervé, Jean-Daniel Bontemps, Baptiste Kerfriden, Philippe Jacquin, Maxime Lacarin, Vincent Dauffy, Cédric Duprez and Stéphanie Wurpillot (2025), ‘XyloDensMap: a georeferenced dataset for the wood density of 110,000 trees from 156 European species in France’, *Scientific Data*, 12, 1, p. 380, DOI: 10.1038/s41597-025-04645-1.

Deleuze, Christine, François Morneau, Fleur Longuetaud, Laurent Saint-André, Nina Ognouabi and Alain Bouvet (2013), ‘La force de la mise en commun des données des partenaires: inventaire national, gestion et recherche’, *Rendez-vous techniques de l’ONF*, 39–40, pp. 37–47.

Didion, Markus, Anne Herold, Esther Thürig, Serra Topuz, Zeljka Vulovic, Meinrad Abegg, Jens Nitzsche, Jonas Stillhard and

Jonas Glatthorn (2024), ‘A dataset of 40’000 trees with section-wise measured stem diameter and branch volume from across Switzerland’, *Scientific Data*, 11, 1, p. 476, DOI: 10.1038/s41597-024-03336-7.

Doraisami, Mahendra, Rosalyn Kish, Nicholas J. Paroshy, Grant M. Domke, Sean C. Thomas and Adam R. Martin (2022), ‘A global database of woody tissue carbon concentrations’, *Scientific Data*, 9, 1, p. 284, DOI: 10.1038/s41597-022-01396-1.

Freyburger, Charline, Fleur Longuetaud, Frédéric Mothe, Thiéry Constant and Jean-Michel Leban (2009), ‘Measuring wood density by means of X-ray computer tomography’, *Annals of Forest Science*, 66, 8, pp. 804–804, ISSN: 1286-4560, DOI: 10.1051/forest/2009071.

Gschwantner, Thomas, Klemens Schadauer, Claude Vidal, Adrian Lanz, Erkki Tomppo, Lucio di Cosmo, Nicolas Robert, Daisy Englert Duursma and Mark Lawrence (2009), ‘Common tree definitions for national forest inventories in Europe’, *Silva Fennica*, 43, 2, DOI: 10.14214/sf.463.

Jacquin, Philippe, Frédéric Mothe, Fleur Longuetaud, Antoine Billard, Baptiste Kerfriden and Jean-Michel Leban (2019), ‘CarDen: A software for fast measurement of wood density on increment cores by CT scanning’, *Computers and Electronics in Agriculture*, 156, pp. 606–617, ISSN: 0168-1699, DOI: 10.1016/j.compag.2018.12.008.

Longuetaud, Fleur, Philippe Santenoise, Frédéric Mothe, Tristan Senga Kiessé, Michaël Rivoire, Laurent Saint-André, Nina Ognouabi and Christine Deleuze (2013), ‘Modeling volume expansion factors for temperate tree species in France’, *Forest Ecology and Management*, 292, pp. 111–121, ISSN: 0378-1127, DOI: 10.1016/j.foreco.2012.12.023.

Loustau, Denis (2004), *Rapport final du projet Carbofor. Séquestration de Carbone dans les grands écosystèmes forestiers en France. Quantification, spatialisation, vulnérabilité et impacts de différents scénarios climatiques et sylvicoles.* P. 138, http://www.gip-ecofor.org/gicc/wp-content/uploads/2021/12/Projet3_rapport_final_Lousteau.pdf.

Mathieu, Auguste (1855), *Description des bois des essences forestières les plus importantes*, Grimblot et veuve Raybois, Nancy, https://books.google.fr/books?id=1xBiAAAAcAAJ.

Vallet, Patrick, Jean-François Dhôte, Gilles Le Moguédec, Michel Ravart and Gérôme Pignard (2006), ‘Development of total aboveground volume equations for seven important forest tree species in France', *Forest Ecology and Management*, 229, 1-3, pp. 98–110, ISSN: 0378-1127, DOI: 10.1016/j.foreco.2006.03.013.