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Data Article

Data and non-linear models for the estimation of biomass growth and carbon fixation in managed forests

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Abstract

The data and analyses presented support the research article entitled “Coupling partial-equilibrium and dynamic biogenic carbon models to assess future transport scenarios in France” (Albers et al., 2019). Carbon sequestration and storage in forestry products (e.g. transport fuels) is sought as a climate change mitigation option. The data presented support and inform dynamic modelling approaches to predict biomass growth and carbon fixation dynamics, of a tree or forest stand, over specific rotation lengths. Data consists of species-specific yield tables, parameters for non-linear growth models and allometric equations. Non-linear growth models and allometric equations are listed and described. National statistics and surveys of the wood supply chain serve to identify main tree species, standing wood volumes and distributions within specific geographies; here corresponding to managed forests in France. All necessary data and methods for the computation of the annual fixation flows are presented.

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1. Data

The data presented provides the basis for a non-linear forestry biomass growth model, whose outputs were used for modelling time-dependent carbon fixation in forest biomass [1]. This data article aggregates data from various datasets, including national statistics and surveys, yield tables, non-linear growth parameters and allometric relations (Table 1). The wood supply chain in France is represented by 12 main forest tree species (Table 2). National surveys and statistical results describe the distribution per tree species, used for weighted mean estimates (Table 3). Yield tables tabulate the age-dependent mean tree development and productivity of fully stocked managed stands, measured largely from long-standing experimental forest stand surveys. Yield table data is used to estimate i) initial parameters to fit non-self-starting non-linear regression growth parameters included). ii) age-dependent growth variables, and iii) site-dependent management practices (e.g. thinning periods, rotation cycles). Allometric models are used for volume estimation. All data sources primary originate from French studies,
### Table 3
National inventory (2012–2016) and distribution of living standing volume per forest tree species in France.

| Common name          | Species botanical name | Distribution standing volume [Bm³] | Distribution standing volume [%] |
|----------------------|------------------------|-----------------------------------|----------------------------------|
| Douglas fir          | Pseudotsuga menziesii  | 106                               | 4                                |
| Norway spruce        | Picea abies            | 213                               | 8                                |
| Maritime pine        | Pinus pinaster         | 133                               | 5                                |
| Silver fir           | Abies alba             | 213                               | 8                                |
| Scots pine           | Pinus sylvestri        | 160                               | 6                                |
| Sweet chestnut       | Castanea sativa        | 146                               | 6                                |
| Hornbeam             | Carpinus betulus       | 135                               | 5                                |
| Ash                  | Fraxinus excelsior     | 108                               | 4                                |
| European beech       | Fagus sylvatica        | 108                               | 4                                |
| Sessile oak          | Quercus petraea        | 297                               | 11                               |
| English oak          | Quercus robur          | 297                               | 11                               |
| White oak            | Quercus pubescens      | 108                               | 4                                |
| Other broadleaved    | Fagaceae spp           | 365                               | 14                               |

Source: Global TRY Plant Trait Database [3].

### Table 4
Specifications on analysed yield tables per forest tree species.

| Common name          | Species botanical name | Country     | Eco-region               | Geographical specifications | Yield class | Source | Page in source document |
|----------------------|------------------------|-------------|--------------------------|-----------------------------|-------------|--------|-------------------------|
| Douglas fir          | P. menziesii           | France      | West Massif Central      | Creuse, Corrèze et Haute-Vienne 2 [9] | 2           | [9]     | 50                      |
| Norway spruce        | P. abies               | France      | South Massif Central     | Montagne Noire, Monts de Lacune-Sommall-Espinouse, Levezou and Aigoual 16 [9] | 16          | [9]     | 134                     |
| Maritime pine        | P. pinaster            | France      | South-West Jura          | Landes de Gascogne 3 [9] | 3           | [9]     | 54                      |
| Silver fir           | A. alba                | France      | Sologne                  | N/A 12 [9] | 12          | [9]     | 112                     |
| Scots pine           | P. sylvestri           | France      | North Spain              | N/A 3 [9] | 3           | [9]     | 20                      |
| Other conifers       | C. sativa              | Spain       | European part            | N/A 4 [10] | 4           | [10]    | 131                     |
| Sweet chestnut       | C. betulus             | N/A         | European part            | N/A 2 [11] | 2           | [11]    | 375                     |
| Hornbeam             | F. excelsior           | N/A         | Northern Eurasia         | N/A 2 [11] | 2           | [11]    | 108                     |
| Ash                  | F. sylvatica           | France      | North-West Loire         | N/A 6 [9] | 6           | [9]     | 84                      |
| European beech       | Q. petraea             | France      | European part            | N/A 1a [11] | 1a         | [11]    | 294                     |
| Sessile oak          | Q. robur               | N/A         | European part            | N/A 2 [11] | 2           | [11]    | 295                     |
| English oak          | Q. pubescens           | N/A         | European part            | N/A 1a [11] | 1a         | [11]    | 294                     |

Source: [4].
for geographical coherence. However, adequate European studies were retained when French data was unavailable (Table 4). Biomass yield and carbon content were obtained by applying specific conversion factors (Table 5). The Supplementary Material provides technical guidance and data for all assessed tree species concerning selected yield tables, regression analysis and parameters, biomass yield calculations, and annual carbon stocking factors. It includes a R [2] script to compute the regression parameters for running the growth model, applicable to future studies.

2. Experimental design, materials, and methods

The presented data is used to inform the models described in the following sub-sections.

2.1. Modelling non-linear growth

The cumulative tree growth is represented by the non-linear Chapman-Richards (CR) curve. The CR equation (Eq. (1)) is based on species- and site-dependent parameters and one independent variable, with the following notation [13]:

| Common name | Species     | Wood density [t·m⁻³] | Carbon content [C·t⁻¹] |
|-------------|-------------|-----------------------|------------------------|
| Douglas fir | *P. menziesii* | 0.4533 | 0.5280 |
| Norway spruce | *P. abies* | 0.3700 | 0.4980 |
| Maritime pine | *P. pinaster* | 0.4140 | 0.5212 |
| Silver fir | *A. alba* | 0.3530 | 0.4750 |
| Scots pine | *P. sylvestri* | 0.4219 | 0.5036 |
| Other conifers | *Pinaceae spp* | 0.4024 | 0.5052 |
| Sweet chestnut | *C. sativa* | 0.4400 | 0.5010 |
| Hornbeam | *C. betulus* | 0.7060 | 0.4899 |
| Ash | *F. excelsior* | 0.5597 | 0.4918 |
| European beech | *F. sylvestri* | 0.5855 | 0.4709 |
| Sessile oak | *Q. petraea* | 0.5597 | 0.4970 |
| English oak | *Q. robur* | 0.5597 | 0.5016 |
| White oak | *Q. pubescens* | 0.5997 | 0.4948 |
| Other broadleaved | *Fagacea spp* | 0.5672 | 0.4942 |

Note: General recommended factors are 0.5 t·m⁻³ for conifers/evergreen and 0.6–0.7 t·m⁻³ for broadleaves/deciduous. The carbon content for all tree organs (different tree compartments), can be estimated with a factor of 0.5, by neglecting the lower carbon concentration in the needles/leaves [12].

Table 6

| Common name | Species     | Initial parameters | A | k | p |
|-------------|-------------|--------------------|---|---|---|
| Douglas fir | *P. menziesii* | 140 | 0.03 | 2 |
| Norway spruce | *P. abies* | 172 | 0.03 | 2 |
| Maritime pine | *P. pinaster* | 140 | 0.03 | 2 |
| Silver fir | *A. alba* | 326 | 0.03 | 2 |
| Scots pine | *P. sylvestri* | 180 | 0.03 | 2 |
| Other conifers | *Pinaceae spp* | 172 | 0.03 | 2 |
| (Sweet) Chestnut | *C. sativa* | 120 | 0.03 | 2 |
| Hornbeam | *C. betulus* | 200 | 0.02 | 2 |
| Ash | *F. excelsior* | 320 | 0.03 | 2 |
| European Beech | *F. sylvestri* | 300 | 0.02 | 2 |
| White oak | *Q. petraea* | 240 | 0.04 | 2 |
| English oak | *Q. robur* | 320 | 0.02 | 2 |
| Sessile oak | *Q. pubescens* | 400 | 0.04 | 2 |
| Other broadleaves | *Fagacea spp* | 300 | 0.04 | 2 |

Sources: A. Pommerening, pers. comm.; H. Pretzsch, pers. comm.
### Table 7
Overview of retained allometric equations for volume estimations.

| Species                  | Allometric equation                                                                 | Coefficients | Volume | Location | Creator | Source       |
|--------------------------|-------------------------------------------------------------------------------------|--------------|--------|----------|---------|--------------|
|                          |                                                                                     | $\alpha$     | $\beta$ | $\gamma$ | $\delta$ | $\epsilon$  |
| $P.$ menziesii           | $V_{\text{above}} = (a + \beta \times Ci) \times (1 + \delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 5.3E-1       | -5.3E-4 | -        | 5.7E+1  | -            |
| $P.$ abies               | $V_{\text{above}} = (a + \beta \times Ci) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$                                  | 6.3E-1       | -9.5E-4 | -        | -       | -            |
| $P.$ pinaster            | $V_{\text{above}} = (a + \beta \times Ci) + \gamma \times Ci^2 / H \times (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4E + 04^4 \times \pi)$ | 2.4E-1       | 9.7E-4  | 4.0E-1  | 2E+2    | -            |
| A. alba                  | $V_{\text{stem}} = (a + \beta \times (Ci / \pi)^2) \times H + \frac{1}{\gamma} \times (Ci^2 / \pi^2)$                      | -2.8E+0      | 3.4E-2  | 8.4E-2  | -       | -            |
| $P.$ sylvestri           | $V_{\text{above}} = (a + \beta \times Ci) + \gamma \times Ci^2 / H \times (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 3.0E-1       | 3.2E-4  | 3.8E-1  | 2E+2    | -            |
| Pinaceae spp             | $V_{\text{above}} = (a + \beta \times Ci) \times Ci^2 + \gamma \times H / (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 3.0E-1       | 3.2E-4  | 3.8E-1  | 2E+2    | -            |
| C. sativa                | $V_{\text{stem}} = \alpha \times (Ci / \pi)^2 \times H + \beta$                      | 3.8E-2       | 8.5E-1  | -       | -       | -            |
| $C.$ betulus             | $V_{\text{stem}} = \alpha \times (Ci / \pi)^2 \times H + \beta$                      | 3.8E-2       | 3.0E+0  | -       | -       | -            |
| F. excelsior             | $V_{\text{stem}} = (Ci / \pi)^2 \times H^0 \times e^{-\gamma} 1$                     | 2.0E+0       | 7.7E-1  | 2.5E+0  | -       | -            |
| F. sylvatica             | $V_{\text{above}} = (a + \beta \times Ci) + \gamma \times Ci^2 / H \times (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 4.0E-1       | 2.7E-4  | 4.2E-1  | 4.5E+1  | -            |
| Q. petraea               | $V_{\text{above}} = (a + \beta \times Ci) + \gamma \times Ci^2 / H \times (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 4.7E-1       | -3.5E-4 | 3.8E-1  | -       | -            |
| Q. robur                 | $V_{\text{stem}} = (Ci / \pi)^2 \times H^0 \times e^{-\gamma}$                       | 2.0E+0       | 8.6E-1  | 2.9E+0  | -       | -            |
| Q. pubescens             | $V_{\text{stem}} = \alpha \times 10^0 \times \log(Ci / \pi) \times \gamma \times \log(Ci / \pi)^2 \times \delta \times \log(H) + \epsilon \times \log(H)^2$ | 3.5E-4       | 1.1E+0  | 3.1E-1  | 5.4E-1  | 2.1E-1      |
| Fagaceae spp             | $V_{\text{above}} = (a + \beta \times Ci) + \gamma \times Ci^2 / H \times (1 + (\delta / (Ci^2)) \times Ci^2 \times H / (4 \times 10^4 \times \pi)$ | 4.7E-1       | 3.5E-4  | 3.8E-1  | -       | -            |

Acronyms: H: top height; DBH: Diameter breast height; Ci: Circumference; Total AG: total aboveground; Stem UB: stem under bark; FRA: France; ITA: Italy; NDL: Netherlands; ROU: Romania.

Note: Equations are all expressed in Ci and the given units needed respective conversions to be expressed in common units. The volume is expressed in stem under bark (i.e. bark and wood) or total aboveground tree volume. The total aboveground volume includes stem under bark, needles/leaves and branches. The group "other conifers" (Pinaceae spp) and "other broadleaved" (Fagaceae spp) use the same volume relations as Scots pine and sessile oak respectively, due to their representativeness.

Source: Allometric equations analysed and selected from Ref. [6]; and respective references in the table.
where $\omega$ expresses the potential growth of a tree species $i$ in height and circumference (response growth variables) at age $t$ (independent variable), $A$, $\beta$, $k$, $p$ are parameters, exp is the basis of natural logarithm and $\epsilon$ the term for random error; with $\beta$ is fixed to 1 [14], and the allometric constant $m$ fixed to 0.5 ($0 < m < 1$) [13]. CR forms a sigmoid and asymptotic curve with a point of inflection determined by the allometric constant $p$, approaching a maximum threshold of the response variable, the asymptote $A$. The empirical growth parameter $k$ scales the absolute growth, governing the rate at which $A$ approaches its potential maximum.

2.2. Initial parameters to fit non-self-starting non-linear regression model

The statistical model using the CR curve $[\omega \sim f(t_i, \theta) + \epsilon]$ fits the vector of parameters $\theta$ to the growth variable $\omega_i$, whereby the function $f$ represents a non-linear combination of the parameters. Initial parameters to fit the non-self-starting non-linear regression model (Table 6) were developed for $k$ and $p$. Values for $k$ lie between 0.02 and 0.04, depending on the studied species and for $p$ 2. The acceptable values for $k$ range between 0.2 and 2.5. $A$ is estimated as twice the maximum value given for age in the species-specific yield tables.

2.3. Allometric equations and specifications

Allometric models presented in Table 7 are used for tree volume estimation.

2.4. Mean biomass growth development of all species

Fig. 1 shows the non-linear mean biomass growth per tree species. For the computation of annual $C_{bio}$ fixation flows [t $C_{bio}$·yr$^{-1}$] in biomass (as presented with the stocking factors in the Supplementary material) see section 2.3.1. in the companion research article [1]. Data from Table 3 to Table 7 are used for these calculations.
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Transparency document

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Appendix A. Supplementary data

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