

# **SUPPLEMENTARY MATERIAL. Energy, water and carbon exchanges in managed forest ecosystems: description and evaluation of the INRAE GO+ model, version 3.0.**

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## **1 introduction**

This supplementary material is including details of the equations and algorithms cited in the main article. It is organised in different sections corresponding to specific processes included in the GO+ model. Some additional illustrations of the sensitivity analysis, uncertainty analysis and model evaluation are also provided in the last section number 9. The tables and figures are presented at the end of the document for readability. The main table,Table S1, shows the complete list of the model parameters. Each parameter refers to one or several entities that are denoted in the third column, namely:

5 – entire vegetation layers, either the trees, T, or understorey, U;

– individual tree, t;

– soil, S;

10 – "air" or "water" for the parameters related to the air or water physical constants or thermodynamic properties.

The Table S1 is organised in subsections corresponding to the physical constants, radiative transfer, latent and sensible heat transfer, physiological parameters, canopy structure, phenology, soil hydraulics and soil carbon. Further details on variables and parameters as well as the GO+V3 version code are available at [https://github.com/DenisLOUSTAU/GOplus\\_model\\_INRAE](https://github.com/DenisLOUSTAU/GOplus_model_INRAE).

## 2 Radiative transfer

### 15 2.1 Canopy foliage

We have assumed that, providing adequate values of the parameters are used, the de Pury and Farquhar (1997, further abbreviated as dPF) model for the 400–700 nm domain may be extended to the entire shortwave domain (300–1200 nm). The calculations are identical for both canopy layers and all values are expressed on a ground area basis. As the first step, the sunlit leaf area index of the layer  $c$  is given by :

$$20 \quad LAI_{sun,c} = 1 - LAI_{shade,c} = \frac{1 - \exp(-k_{b,c} \times LAI_c)}{k_{b,c}} \quad (S1)$$

where  $LAI_c$  is the leaf area index and  $k_{b,c}$  the canopy extinction coefficient for direct beam radiation that is:

$$k_{b,c} = \frac{k_{bh,c}}{\sin\beta} \quad (S2)$$

$k_{bh,c}$  being the extinction coefficient for a beam normal to the canopy (dPF, Eq.18). The canopy reflection coefficients for direct radiation and a uniform leaf distribution are given by :

$$25 \quad \rho_{b,c}(\beta) = 1 - \exp\left[\frac{-2 \times \rho_{h,c} \times k_{b,c}}{(1 + k_{b,c})}\right]$$

$$\rho_{h,c} = \frac{1 - (1 - \sigma_l)^{1/2}}{1 + (1 - \sigma_l)^{1/2}} \quad (S3)$$

where  $\rho_{h,c}$  is the reflection coefficient from the horizontal surface and  $\sigma_l$  is the leaf scattering coefficient that is  $\rho_l + \tau_l$  (dPF eq. A19 to A20). For sake of simplicity, the diffuse radiation reflection coefficient for the canopy is fixed at a constant value  $\rho_{d,c} = 0.036$  rather than calculated as the  $\rho_{b,c}$  integral over  $\pi/2$ . For accounting for the scattering of radiation, extinction 30 coefficients including scattered radiations are introduced (dPF Eq. A4):

$$k'_{b,c} = k_{b,c}(1 - \sigma_l)^{0.5}$$

$$k'_{d,c} = k_{d,c}(1 - \sigma_l)^{0.5} \quad (S4)$$

The irradiance absorbed by the sunlit fraction of each canopy layer is given as the sum of direct, diffuse and scattered-beam components:

35  $SW_a(sun) =$

$$\begin{aligned}
 & SW_{dir} \times (1 - \sigma_c) \times [1 - \exp(-k_{b,c} \times LAI_c)] \\
 & + (SW_{dif} \downarrow + SW_{dif} \uparrow) \times (1 - \rho_{d,c}) \times [1 - \exp(-(k'_{d,c} + k_{b,c}) \times LAI_c)] \times \frac{k'_{d,c}}{(k'_{d,c} + k_{b,c})} \\
 & + SW_{dir} \times (1 - \rho_{b,c}) \times [1 - \exp(-(k'_{b,c} + k_{b,c}) \times LAI_c)] \times \frac{k'_{b,c}}{(k'_{b,c} + k_{b,c})} \\
 & - (1 - \sigma_c) \times \frac{[1 - \exp(-2 \times k_{b,c} \times LAI_c)]}{2}
 \end{aligned} \tag{S5}$$

40 where  $\alpha$ ,  $\rho_{cd}$  and  $\rho_{cb}$  are the leaf absorbance and diffuse and direct beam canopy reflectance respectively (Eq. 20-b, to 20-d dPF). The total amount of SW radiation absorbed is :

$$SW_a = (1 - \rho_b) \times SW_b \times [1 - \exp(-k'_b \times LAI)] + (1 - \rho_d) \times SW_d \times [1 - \exp(-k'_d \times LAI)] \tag{S6}$$

The amount of shortwave radiation that is absorbed by the shaded canopy fraction is then :

$$SW_a(shade) = SW_a - SW_a(sun) \tag{S7}$$

45 The longwave radiation absorbed by a canopy layer is given by:

$$LW_{a,c} = (LW \downarrow_{I,c} + LW \uparrow_{I,c}) - (LW \downarrow_{S,c} + LW \uparrow_{S,c}) \tag{S8}$$

where the subscripts  $I$  and  $S$  stand for intercepted and scattered radiation. These are calculated following Berbigier and Bonnefond (1995) assuming a fixed partitioning of the scattering of intercepted radiation between reflection (0.75) and transmission (0.25) :

50  $LW \downarrow_{I,c} = LW \downarrow_{c-1} \times (1 - \exp[(k_{LW1} + k_{LW2} \times LAI_c) \times LAI_c]$

$$LW \uparrow_{I,c} = LW \uparrow_{c+1} \times (1 - \exp[(k_{LW1} + k_{LW2} \times LAI_c) \times LAI_c]$$

$$LW \uparrow_{S,c} = (1 - \epsilon) \times (LW \downarrow_{I,c} \times 0.75 + LW \uparrow_{I,c} \times 0.25)$$

$$LW \downarrow_{S,c} = (1 - \epsilon) \times (LW \downarrow_{I,c} \times 0.25 + LW \uparrow_{I,c} \times 0.75) \tag{S9}$$

The subscript  $c$  refers to the layer number increasing from the top to the bottom of the canopy.

## 55 2.2 Canopy Woody parts

The wood area index ( $WAI$ ) intercepting radiation and rainfall accounts for the interception by the tree trunks and branches.  $WAI$  is function of the stem standing stock,  $SD$ , mean trunk diameter ( $D_{130}$ , cm) and height ( $H_c$ ) and a tree stand shape

factor,  $f$ , that is the ratio of stand tree stem volume over the product  $BA \times H_c$  ( $m^3$ ), and branches biomass (kg dry matter  $m^{-2}$ ) :

$$60 \quad WAI = \frac{f \times SD \times H_c \times D_{130} \times \cos(75)}{100 \times area} + \frac{4 \times W_{T,branches} \times \cos(45)}{d_{wood} \times 1000 \times \Pi \times D_{130}/100/5} \quad (S10)$$

The first part of the left member refers to the stem and the second part to the branches, where the mean angle between beam radiation –or rainfall– is here 75 and 45 degrees for trunks and branches respectively and the mean branch diameter is 1/5 of the stem diameter. These values are species specific. The interception of throughfall by the understorey woody parts is neglected.

### 3 Rainfall interception model

65 The wet and dry fractions of each canopy and soil layer are calculated dynamically using Gash's (1979) canopy water balance model resolved at an hourly time step,  $S_{W,c,h}$ . The rainfall amounts intercepted by the canopy,  $Rain_{I,c}$ , and the throughfall and stemflow dripping from the canopy layer,  $Rain_{TS,c}$  are calculated :

$$Rain_{I,c} = Rain \times [1 - \exp(k_{R,f} \cdot LAI + k_{R,w} \cdot WAI)] \quad (S11)$$

$$Rain_{TS,c} = [S_{w,c,h-1} + Rain_{I,c} - E_{wet,c}] - S_{Wmax,c} \quad (S12)$$

$$70 \quad S_{W,c,h} = S_{w,c,h-1} + Rain_{I,c} - E_{wet,c} - Rain_{TS,c} \quad (S13)$$

$$f_{dry,c,h} = 1 - \frac{S_{W,c,h}}{S_{Wmax,c}} \quad (S14)$$

where  $k_R$  are rainfall extinction coefficients for the canopy and  $S_{Wmax,c}$  the canopy storage capacity that is  $(LAI_c \times S_{Wmax,f} + WAI_c \times S_{Wmax,w})$  with  $S_{Wmax}$  the storage capacity per unit area of  $LAI$  or  $WAI$  area.

### 75 4 Water transfer model

- The mean tree water capacitance,  $C_T$  (kg H<sub>2</sub>O m<sup>-2</sup> leaf area MPa<sup>-1</sup>, Eq. 21) is taken from Loustau et al. (2000).

$$C_T = \frac{0.07 \times W_T}{13} \quad (S15)$$

where  $W_T$  is the tree biomass (kg d.m. m<sup>-2</sup>soil area).

- The calculation of soil water potential in the soil rooted zone comes from Van Genuchten (1980):

$$80 \quad \psi_{soil} = \frac{-1}{\alpha_{VG}} \times \left[ \left( \frac{\theta_{rootlayer} - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \right)^{\frac{-1}{m_{VG}}} - 1 \right]^{1-m_{VG}} \times 10^{-3} \quad (S16)$$

where  $10^{-3}$  converts unit from kPa to MPa.

## 5 Photosynthesis

The photosynthetic carbon uptake by each canopy layer is formalised in GO+ following de Pury and Farquhar (1998) and Farquhar et al. (1980) as :

$$85 \quad A_{net,c} = \left(1 - \frac{\Gamma^*}{c_c}\right) \times \min(W_{c,c}, W_{c,j}) - R_d \quad (\text{S17})$$

The net carbon assimilation is calculated separately for shaded and sunlit fractions of the foliage but apart from the amount of light absorbed per unit leaf area, the calculations are identical and are not duplicated here. The two terms  $W_{c,c}$  and  $W_{c,j}$  are the Ribulose biPhosphate carboxylation rate limited by the RubisCO activity and the rate of regeneration of Ribulose -biPhosphate limited by electron transport respectively.

$$90 \quad W_{c,c} = \frac{c_c \times V_{cmax,c}}{c_c + K_c \times (1 + O_2/K_o)} \quad W_{c,j} = \frac{J_{c,c}}{4 + 8 \times \Gamma^*/c_c} \quad (\text{S18})$$

The electron transport rate,  $J_c$  ( $\mu\text{mol e- m}^{-2} \text{ s}^{-1}$ ), with  $Q_{c,a}$  being the amount of light absorbed by unit leaf area ( $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ) and  $\alpha$  the quantum efficiency of electron transport ( $\text{mol e- mol photons}^{-1}$ ), is:

$$J_c = \frac{\alpha \times Q_{c,a} + J_{max,c} - \sqrt{(\alpha \times Q_{c,a} + J_{max,c})^2 - 4 \times \theta \times \alpha \times Q_{c,a} \times J_{max,c}}}{2 \times \theta} \quad (\text{S19})$$

The conversion of the amount of SW radiation absorbed by a vegetation layer and exposure class — sunlit or shaded —, 95  $SW_{a,c,s}$ , into moles of photons in the band 400-700 nm absorbed by a unit area of leaf,  $Q_{a,c,s}$ , is:

$$Q_{a,c,s} = \frac{SW_{a,c,s}}{LAI_{c,s}} \times 4.6 \times 10^{-6} \quad (\text{S20})$$

For tree species, the internal leaf conductance to the CO<sub>2</sub> transport,  $g_{m,c}$  ( $\text{mol m}^{-2} \text{ s}^{-1}$ ) is taken from Ellsworth et al. (2015):

$$g_{m,c} = r_{m,c}^{-1} = -0.04 \times 10^{-6} + 1.34 \times g_{s,c,t} \quad (\text{S21})$$

For understorey species, no internal resistance is included. In Eq. S18 to S21, parameters are the mean value for the entire layer 100 and may differ from values obtained using e.g. gas exchange measurements calculations at leaf level. Following Bernacchi et al. (2001) and Medlyn et al. (2002) and with  $k_{T,c}$  a temperature factor used for describing the temperature dependency of metabolic parameters, the following temperature response functions are used:

$$k_{T,c} = \frac{T_{K,c} - T_{K,ref}}{R \times T_{K,c} \times T_{K,ref}} \quad (\text{S22})$$

$$V_{cmax,c} = V_{cmax25,c} \times \exp(Ea(Vc) \times k_{T,c}) \quad (\text{S23})$$

$$105 \quad J_{max,c} = J_{opt,c} \times \frac{H_d \times \exp(H_a \times k_{Top,c})}{H_d - H_a \times (1 - \exp(H_d \times k_{Top,c}))} \quad (\text{S24})$$

$$K_{c,c} = K_{c25,c} \times \exp(Ea(Kc) \times k_{T,c}) \quad (\text{S25})$$

$$K_{o,c} = K_{o25,c} \times \exp(Ea(Ko) \times k_{T,c}) \quad (\text{S26})$$

$$K_{m,c} = K_{c,c} \times (1 + O_2/K_{o,c}) \quad (\text{S27})$$

$$\Gamma_c^* = \Gamma_{25}^* \times \exp(Ea(\Gamma^*) \times k_{T,c}) \quad (\text{S28})$$

110 where  $T_{K,c}$  is the mean temperature of foliage layer (in  $K$ ), and other parameters are detailed in the Table S1.

## 6 Calculation of the total amount of nitrogen in the tree living biomass

The living fraction of the stem biomass in a tree,  $W_{stem,t}^*$ , is estimated for each individual tree  $t$  as follows:

$$W_{stem,t}^* = W_{stem,t} \times (1 - W_{stem,t}^+) \quad (S29)$$

where the heartwood biomass,  $W_{stem,t}^+$ , is:

$$115 \quad W_{stem,t}^+ = d_{wood} \times [(\pi \times (\frac{D_{130,t}}{4})^2 - SA_t)] \times \frac{h_t}{3} \quad (S30)$$

and the living wood — or sapwood — cross sectional area,  $SA_t$ , is derived from McDowell et al. (2002), assuming the ratio between the canopy leaf area and the cross sectional sapwood area at 1.3m height,  $A_l:A_s$ , is related to the tree height.

$$SA_t = \frac{A_{l,t}}{A_l:A_s}$$

and

$$120 \quad A_l:A_s = k_{H,1} + k_{H,2} \times h_t^{k_H,3} \quad (S31)$$

The amount of nitrogen in the living stem biomass,  $N_{stem}^*$ , is :

$$N_{stem}^* = kN_{stem} \times W_{stem}^* \quad (S32)$$

where  $kN_{stem}$  is the nitrogen content of living stem part and  $W_{stem}^*$  the living stem biomass ( $\text{kg d.m. m}^{-2}$ ). Whereas the live fraction of the foliage and fine roots is assumed constant to 0.8 for coniferous and 1.0 for broadleaf species, the live fraction of 125 the other tree parts (the branches and root parts),  $W_x^*$ , is assumed to be linearly depending on the tree age:

$$W_x^* = k_{mx,x} - (k_{mx,x} - k_{mn,x}) \times \frac{\text{Age}}{100} \quad \text{if Age}<100, \\ W_x^* = k_{mn,x} \quad \text{otherwise.} \quad (S33)$$

The Table S1 lists the  $kN_x$  and  $k_{mn,mx,x}$  default values used of the maritime Pine species.

## 7 Carbon allocation and growth

130 This section details the allocation equations used for different tree species in the GO+ model. The parameter values for tree biomass,  $D_{130}$  and height computations are summarised in Table S2. This section details the equations used for three species. The following equations continue the main text Eq. (31). The stem diameter, tree height and biomass values are in cm, m and kg dry matter tree $^{-1}$  respectively.

The allocation algorithm was derived from allometric equations (Shaiek et al. 2011, Achat et al. 2018). For clarity, we keep the same parameter name ( $k_1$  to  $k_4$ ) throughout the equations, their default values being listed in Table S2.

Step 3.1. Calculation of stem diameter,  $D_{130}$  and height,  $h$ , from the tree aboveground biomass,  $W_{a,i}$ .

$$140 \quad D_{130,i} = k_1 \times W_{a,i}^{k_2} \times Age^{k_3}, \quad (\text{S34})$$

$$h_i = k_1 \times W_{a,i}^{k_2} \times Age^{k_3} \quad (\text{S35})$$

Step 3.2. Calculation of the biomass of each tree parts (subscript  $i$  is not repeated for clarity).

$$W_{leaf, cohort=1} = k_1 \times W_a^{k_2} \times Age^{k_3} \quad (\text{S36})$$

$$W_{stem} = k_1 \times W_a^{k_2} \times Age^{k_3} \quad (\text{S37})$$

$$145 \quad W_{leaftotal} = k_1 \times W_a^{k_2} \times Age^{k_3} \quad (\text{S38})$$

$$W_{branches} = W_a - W_s - W_l \quad (\text{S39})$$

$$W_{tr} = W_r \times \min(k_1, k_2 \times D_{130}^{-k_3}), \quad (\text{S40})$$

$$W_{cr} = W_r \times \max(k_1, k_2 \times \log(D_{130}) - k_3), \quad (\text{S41})$$

$$W_{sr} = W_r \times \min(k_1, k_2 \times D_{130}^{-k_3}), \quad (\text{S42})$$

$$150 \quad W_{fr} = W_r - W_{tr} - W_{cr} - W_{sr} \quad (\text{S43})$$

where  $W_{tr}$ ,  $W_{cr}$ ,  $W_{sr}$  and  $W_{fr}$  are biomass variables of taproot, coarse roots (> 20 mm), small roots (2-20 mm) and fine roots (< 2 mm), respectively.

## 2. Douglas fir (*Pseudotsuga menziesii*)

Allometric equations of aboveground compartments were derived from Gholz et al. (1979). The relationship between height and aboveground biomass was computed using the GIS coop database (Seynave et al., 2018).

$$D_{130} = k_1 \times W_a^{k_2} \quad (\text{S44})$$

$$h = k_1 \times W_a^{k_2} \quad (\text{S45})$$

$$160 \quad W_{stem} = k_1 \times W_a^{k_2} \quad (\text{S46})$$

$$W_{leaf, cohort=1} = k_1 \times W_a^{k_2} \times Age^{k_3} \quad (\text{S47})$$

$$W_{leaftotal} = k_1 \times W_a^{k_2} \quad (\text{S48})$$

$$W_{branches} = W_a - W_{stem} - W_{leaftotal} \quad (\text{S49})$$

165 The biomass of different root classes are simulated as follows (Achat et al. 2018):

$$W_{cr} = W_r \times \max(k_1, k_2 \times \log(D_{130}) - k_3), \quad (\text{S50})$$

$$W_{fr} = W_r \times \min(k_1, k_2 \times D_{130}^{-k_3}), \quad (\text{S51})$$

$$W_{tr} = (W_r - W_{cr} - W_{fr}) \times \frac{(-k_1 \times D_{130} + k_2)}{(-k_1 \times D_{130} + k_2) + (-k_3 \times D_{130} + k_4)}, \quad (\text{S52})$$

$$W_{sr} = (W_r - W_{cr} - W_{fr}) \times \frac{(-k_3 \times D_{130} + k_4)}{(-k_1 \times D_{130} + k_2) + (-k_3 \times D_{130} + k_4)}, \quad (\text{S53})$$

170 where  $W_{tr}$ ,  $W_{cr}$ ,  $W_{sr}$  and  $W_{fr}$  are biomasses of stump plus taproot, coarse roots (> 40 mm), small roots (2–40 mm) and fine roots (< 2 mm), respectively.

### 3. European beech (*Fagus sylvatica*)

175 Equations for the stem, branches and foliage biomass are taken from Wutzler et al. (2008) and include covariates (altitude (m), tree age (yr) or site index(m)). Biomass of root parts are simulated following Achat et al. (2018).

$$D_{130} = k_1 \times W_a^{k_2} \times h^{k_3} \quad (\text{S54})$$

$$W_l = k_1 \times D_{130}^{k_2} \times h^{k_3} \quad (\text{S55})$$

$$W_{stem} = k_1 \times D_{130}^{k_2} \times h^{k_3} \quad (\text{S56})$$

$$W_{branches} = k_1 \times D_{130}^{k_2} \times h^{k_3} \quad (\text{S57})$$

$$180 \quad W_{cr} = W_r \times \begin{cases} k_1 & \text{for } D_{130} < 4 \text{ cm} \\ k_2 - k_3 \times e^{-k_4 \times D_{130}} & \text{otherwise} \end{cases} \quad (\text{S58})$$

$$W_{fr} = W_r \times \min(k_1, k_2 \times D_{130}^{-k_3}) \quad (\text{S59})$$

$$W_{tr} = (W_r - W_{cr} - W_{fr}) \times \frac{(k_1 \times D_{130} + k_2)}{(k_1 \times D_{130} + k_2) + (-k_3 \times D_{130} + k_4)} \quad (\text{S60})$$

$$W_{sr} = (W_r - W_{cr} - W_{fr}) \times \frac{(-k_3 \times D_{130} + k_4)}{(k_1 \times D_{130} + k_2) + (-k_3 \times D_{130} + k_4)} \quad (\text{S61})$$

The algorithm for the calculation of individual tree height (Le Mogedec and Dhôte, 2012) reads:

$$185 \quad m = 1.218, \quad K = 55$$

$$Cm = \exp(1+m) \times (1 - \log 10(1+m))$$

$$H0 = K \times \exp[-((\log 10(K/1.3))^{-m} + \frac{(0.4 \times m \times Cm)}{K} \times (Age - 5))^{-1/m}]$$

$$alpha = H0 - 1.3 + \pi \times 0.412 \times D_{130,i}$$

$$h_i = 1.3 + \frac{alpha - \sqrt{alpha^2 - 4 \times \pi \times 0.412 \times 0.98764 \times (h0 - 1.3) \times D_{130,i}}}{2 \times 0.98764} \quad (\text{S62})$$

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where  $W_{tr}$ ,  $W_{cr}$ ,  $W_{sr}$  and  $W_{fr}$  are the biomass of stump, coarse roots ( $> 40$  mm), small roots (2-40 mm) and fine roots ( $< 2$  mm), respectively.

## 8 Vegetation phenology and growth

### 8.1 Tree species

195 Table S3 details the references used for simulating the lifecycle of the foliage for three European tree species and Table S4 lists the equations and parameters used for modelling the senescence of living organs of the individual trees. They include a temperature dependent budburst date and a fixed foliage lifecycle for the coniferous needles. The onset of senescence of beech leaves depends on the amount of incident shortwave radiation accumulated from budburst until DOY 258.

### 8.2 Understorey

200 The phenology of the understorey vegetation is shown in Table S5. It includes a simple thermal time model for leaf unfolding and a mechanistic model of foliage growth, as described in the main text, that is sensitive to temperature and soil moisture. The maximal foliage life duration is fixed and is shortened by high water deficit of the soil or low air temperature.

## 9 Sensitivity and uncertainty analysis

### 9.1 Sensitivity assessment

205 Figures S1 to S3 show the values of the sensitivity value index (Eq. 38 of the main text) of 14 output variables related to the main energy, water and CO<sub>2</sub> fluxes to 28 model parameters and for the years 1994 (wet), 2005 (wet) and the full rotation cycle 1970–2010 in a coniferous stand at Le Bray . The following figures S4 and S5 illustrate the long-term sensitivity of "fluxes" and "stocks" variables to meteorological forcing variables over a forest rotation (1970-2010).

### 9.2 Uncertainty assessment

210 The normalized uncertainty values of key model variables calculated for the Le Bray site are shown Figs. S6–S8. The variables are split by canopy layers whereas the overall ecosystem values are given in Figs. 10–11 of the main text. The uncertainty is calculated from the uncertainty of the 14 most influential parameters of the model (Table 3 of the main text) using the MonteCarlo method with 2500 runs for the year 1994 at the Le Bray site.

### 9.3 Model evaluation

215 Table S7 presents the variance fraction accounted for by model predictions at different time spans of the latent heat, net radiation  $Rn$ , latent heat flux,  $\lambda E$  and net ecosystem exchange,  $NEE$ . It continues the table 7 of the main article.

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Table S1: List of the model parameters. Default values are for Pine species unless specified. Additional values of other tree species are downloadable with the GO+ software package.

Symbol	Definition and entity concerned	Unit	Default value	Ref
Physical constants				
$\gamma$	Psychrometric constant	air	Pa K <sup>-1</sup>	66.1 at 293 K
$\lambda$	Latent heat of vaporisation	water MJ Kg <sup>-1</sup>		2.45 at 293 K
$\rho_a$	dry air density	air	kg m <sup>-3</sup>	1.20 at 293 K
$\sigma$	Stefan-Boltzmann constant	all	W m <sup>-2</sup> K <sup>-4</sup>	5.6703 E-8
$c_p$	Specific heat capacity	air	J kg <sup>-1</sup> K <sup>-1</sup>	1010
$D_{CO_2}$	CO <sub>2</sub> diffusivity	air	m <sup>2</sup> s <sup>-1</sup>	1.47 E-7
$D_{H_2O}$	H <sub>2</sub> O diffusivity	air	m <sup>2</sup> s <sup>-1</sup>	2.42 E-7
$g$	Acceleration due to gravity	air	m <sup>2</sup> s <sup>-1</sup>	9.8067
$k$	Von Karman constant	air	-	0.41
$R$	Gas constant	air	J K <sup>-1</sup> mol <sup>-1</sup>	8.3144
$s$	Slope of temperature - saturation water vapour pressure relationship	air	Pa K <sup>-1</sup>	145 at 293 K
Radiation transfer				
$\alpha$	Leaf absorptance of SW	T,U		1 - $\sigma_l$
$\epsilon$	Long wave emissivity	T,U,S		0.98
$\tau_l$	Leaf transmittance (SW)	T,U		0.014
$\rho_l$	Leaf reflectance (SW)	T,U		0.09
$\sigma_l$	Leaf scattering coefficient (SW)	T,U		0.104
$\rho_{b,c}$	Canopy reflection coefficient in direct SW	T,U		
$\rho_{d,c}$	Canopy reflection coefficient in diffuse SW	T,U		0.036
$\rho_{h,c}$	Canopy reflection coefficient for a beam normal to the surface	T,U		0.0274
$a$	Soil albedo	S		0.25
$k_{bh,c}$	Canopy extinction coefficient for beam normal to the surface	T,U		0.33
$k_{b,c}$	Canopy extinction coefficient for SW beam radiation	T,U	$= k_{bh,c} \times \sin \beta^{-1}$	2

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned	Unit	Default value	Ref	
$k'_{b,c}$	Canopy extinction coefficient for direct SW including scattering	T,U	$= k_{b,c} \times (1 - \sigma_l)^{0.5}$		
$k_{d,c}$	Canopy extinction coefficient for diffuse SW radiation	T,U	0.467	2	
$k'_{d,c}$	Canopy extinction coefficient for diffuse SW including scattering	T,U	$= k_{d,c} \times (1 - \sigma_l)^{0.5}$		
$k_{b,w}$	Woody parts extinction coefficient for direct SW radiation	T,U	1.0		
$k_{d,w}$	Woody parts extinction coefficient for diffuse SW radiation	T,U	1.0		
$k_{LW1-2}$	Extinction coefficient of LW radiation	T,U	-0.548, 0.0177	2	
<b>Latent and sensible Heat transfer</b>					
$g_{smax,c}$	Maximal stomatal conductance	T,U	$\text{m s}^{-1}$	0.004	
$k_{SW,c}$	parameter for $g_s$ response to incident SW radiation	T,U	$\text{W m}^{-2}, -$	50	
$k_{c,1-2}$	parameters for displacement height $d_c$	T,U	0.000724 / 0.273	3	
$k_{CO2,c}$	parameters for $g_s$ response to the air CO <sub>2</sub> concentration	T,U	-	0.9	
$k_{e,c,1-2}$	parameters for $g_s$ response to the air water vapor saturation deficit	T,U	$\text{Pa}^{-1}, -$	750 / 1.0	
$k_{\psi,c,1-2}$	parameters for $g_s$ response to the leaf water potential	T,U	$\text{MPa}^{-1}, -$	-1.45 / 15	
$\tau$	Time constant for stomatal response	T,U	mn	12	
<b>Physiological parameters - Photosynthesis</b>					
$\alpha_c$	Quantum efficiency of electron transport	T,U	$\mu\text{mol e } \mu\text{mol phot.}^{-1}$	0.138 / 0.187	8
$\Gamma_c^*$	Photosynthetic compensation point for CO <sub>2</sub> at 25°C	T,U	$\mu\text{mol CO}_2 \text{mol air}^{-1}$	42.75	4
$Ea(\Gamma^*)$	Activation energy for $\Gamma^*$	T,U,	$\text{J mol}^{-1}$	37 830	9
$Ea(K_c)$	Activation energy for $K_c$	T,U,	$\text{J mol}^{-1}$	79 430	10

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned		Unit	Default value	Ref
$Ea(K_o)$	Activation energy for $K_o$	T,U,	J mol <sup>-1</sup>	36 380	10
$Ea(V_c)$	Activation energy for $V_{cmax}$	T,U,	J mol <sup>-1</sup>	62 220	10
$H_{a,c}$	Activation energy for $J_{max}$	T,U	J mol <sup>-1</sup>	34 830	10
$H_{d,c}$	Deactivation energy for $J_{max}$	T,U	J mol <sup>-1</sup>	2.0E5	10
$J_{max25,c}$	Maximal electron transport rate at T=25°C	T,U	μmol e <sup>-</sup> m <sup>-2</sup> s <sup>-1</sup>	77.37	10
$V_{cmax25,c}$	Maximal carboxylation rate	T,U	μmol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup>	45.0	10
$K_{c25,c}$	RubisCO Michaelis constant for CO <sub>2</sub>	T,U,	μmol CO <sub>2</sub> mol air <sup>-1</sup>	404.9	10
$K_{o25,c}$	RubisCO Michaelis constant for O <sub>2</sub>	T,U,	mmol CO <sub>2</sub> mol air <sup>-1</sup>	278.4	10
$K_m$	RubisCO Michaelis constant	T,U,	μmol CO <sub>2</sub> mol air <sup>-1</sup>		
$T_{opt}(J_{max})$	Optimal temperature for $J_{max}$	T,U	K	310.02	10
 Physiological parameters - Respiration					
$Q_{10}$	Respiration multiplier for a 10°C increase	T,U	1.7 -2.0 according to organs		11
$R_{d,T15,c}$	Foliage respiration at T=25°C	T,U	μmol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup>	0.80	10
$Ea(R_d)$	Activation energy for $R_d$	T,U,	J mol <sup>-1</sup>	46 390	10
$R_{N,T15}$	Woody parts respiration at T=15°C	T,U	gC gN <sup>-1</sup> hr <sup>-1</sup>	0.0064	12
-	Min. and max. fractions of tissues alive in a given organ	T		0.01 -1.0 (organs)	
$R_g$	Respiration associated with growth	T,U	gC gC <sup>-1</sup>	0.28	13
-	Photoinhibition of leaf mitochondrial respiration	T,U,	0.51 /0.65		
$kN_{leaf}$	Nitrogen content of foliage	T	gN kg <sup>-1</sup> d.m	10	15
$kN_{stem}$	Nitrogen content of stem	T	gN kg <sup>-1</sup> d.m	0.05	15
$kN_{branch}$	Nitrogen content of branches	T	gN kg <sup>-1</sup> d.m	2.5	15
$kN_{tr}$	Nitrogen content of tap root	T	gN kg <sup>-1</sup> d.m	1.2	15
$kN_{cr}$	Nitrogen content of coarse roots	T	gN kg <sup>-1</sup> d.m	1.4	15
$kN_{sr}$	Nitrogen content of small roots	T	gN kg <sup>-1</sup> d.m	2.9	15
$kN_{fr}$	Nitrogen content of fine roots	T	gN kg <sup>-1</sup> d.m	8.2	15
$k_{mn,mx,br}$	parameters of the live fraction of branches	T	-, year <sup>-1</sup>	0.10, 0.50	
$k_{mn,mx,tr}$	same for taproot	T	-, year <sup>-1</sup>	0.05, 0.10	
$k_{mn,mx,cr}$	same for coarse roots	T	-, year <sup>-1</sup>	0.05, 0.20	
$k_{mn,mx,sr}$	same for small roots	T	-, year <sup>-1</sup>	0.10, 0.25	

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned	Unit	Default value	Ref
Physiological parameters - Plant water relations				
$C_T$	Global capacitance of the root-to-leaf water pathway	T	$\text{kg H}_2\text{O m}^{-2} \text{leaf area Mpa}^{-1}$	$0.05 \times \frac{W}{15}$
$k_{H,1-3}$	Leaf area to sapwood area ratio	t	$\text{m}^2 \text{cm}^{-2}$	0.20/-0.07/0.8
$k_{x,0-2}$	Root-to-Leaf hydraulic resistance parameters	T,U	$\text{MPa m}^2 \text{LAI s kg H}_2\text{O}^{-1} \text{m}^{-1}$	5000/7500/0.7
Canopy structure 1. Generic				
$SLA$	Specific leaf area (area to mass ratio)	T,U	$\text{m}^2 \text{area kg}^{-1} \text{d.m.}$	6.5
-	Biomass carbon content	T,U	$\text{gC kg d.m.}^{-1}$	480
$\lambda_i$	Coefficient of distribution of $GPP_T$ among tree parts	t	-	-
$d_{wood}$	Wood basic density	t	$10^3 \text{ kg d.m. m}^{-3}$	0.45
$k_{\lambda,1-3}$	Root-shoot partitioning coefficient $\Lambda$	T	-	0.2/1.0/3.0
$k_{N,c}$	Nitrogen content of living parts of biomass	T, U	$\text{mg N g d.m.}^{-1}$	0.5
$k_{R,f}$	Extinction coefficient of precipitations by foliage	T,U	-	0.3
$k_{R,w}$	Extinction coefficient of precipitations by stem and branches	T, U	-	0.5
$S_{wmax,c}$	Canopy water storage capacity	T,U	$\text{kg H}_2\text{O m}^{-2} \text{LAI or WAI}$	0.2
$\xi$	Leaf or needle area to LAI ratio	T,t	-	0.5
	Decomposable over Resistant plant	T,U	-	0.15-5.0
$DPM/RPM$	material ratios (organs)			
	Age of plant material input into the soil	T,U	yr	1-30
Canopy structure 2. Understorey				
$\lambda_f, \lambda_p, \lambda_r,$	Allocation of $NPP_U$ to understorey biomass parts	U	-	0.45/0.10/0.45
$W_{max,f,p,r}$	Peak value of the biomass of understorey parts	U	$\text{kg d.m. m}^{-2}$	0.25

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned	Unit	Default value	Ref	
$h_{max}$	Maximal height of understorey canopy	U	m	0.8	
Phenology- 1.Tree species					
$BB_T$	Heat sum for Pine needles bud burst	T	$^{\circ}\text{C day}$	1400	18
-	Life duration of leaf cohort	T	days	1002	17
-	fractions of needle cohort lifecycle - (fixed)	T		0.42/0.55/0.80	17
-	parameter Tmin of the equation of chilling rate	T		-17.02	19
-	parameter Tmax of the equation of chilling rate	T		92.15	19
-	parameter Topt of the equation of chilling rate	T		-1.34	19
-	base temperature of the sequential phenology model	T	degC	0.0	19
-	chilling rate threshold (fitted)	T	degC day	102.83	19
-	forcing rate threshold (fitted)	T	deg daysC	7.05	19
-	$k$ parameters of the forcing rate equation	T		1.0/-0.12/-20.54	19
$-k_{1-2}$	parameters 1-2 of the broadleaf leaf life duration	T	days ( $\text{W m}^{-2}$ ) $^{-1}$	0.0023/110	
-	parameter a/b/c of secondary growth model (-)	T		105.5/2.084/62.8	
$k_{S1,S2,S3}$	Parameters of branch turn-over rate	t	$\text{yr}^{-1}$ , -, -	0.3678/1.097/-1.256	
$k_{S1,S2,S3}$	Parameters of root turn-over rate	t	$\text{yr}^{-1}$ , -, -	0.8/0.5/0.0	
Phenology- 2.Understorey					
$BB_U$	Heat sum for understorey foliage bud burst	T	$^{\circ}\text{C day}$	600	
$GD$	Maximal duration of understorey growth	U	day	130	
$k_{S1,S2}$	Parameters setting up understorey leaf senescence	T	$\text{day m}^{-2} \text{ W}^{-1}$	7.5E-3, -63.4	
$k_p$	Sigmoid function parameter	U	-	calculated	

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned	Unit	Default value	Ref
$k_s$	Flattening coefficient of the derivative of the sigmoid growth function	U	-	0.01
$SMD_{G,U}$	Soil moisture deficit limiting growth	U	-	0.85
$T_{G,U}$	Temperature threshold of growth	U	$^{\circ}\text{C}$	0.85
$T_{MU}$	Temperature threshold for mortality	U	K	273, 265, 273
$DOY_{MU}$	day of the year triggering mortality	U	-	315
$SMD_{MU}$	Soil moisture deficit threshold of mortality	U	-	0.85
$M_{rate}$	Rate of mortality (Date/air T/Soil moisture)	U	$\text{day}^{-1}$	0.05/0.025/0.005
<b>Soil hydraulics</b>				
$c/si/s$	soil clay/silt/sand contents	S	pct	
-	Basic density	S	$\text{t m}^{-3}$	
$\alpha_{VG}$	Van Genuchten $\alpha$	S	$\text{cm}^{-1}$	0.0003
$m_{VG}$	Van Genuchten $m$	S	$\text{cm}^{-1}$	0.75
$\theta_{FC}$	Water content at Field capacity	S	$\text{kg H}_2\text{O m}^{-3}$	150
$\theta_{SAT}$	Water content at saturation	S	$\text{kg H}_2\text{O m}^{-3}$	275
$\theta_{WP}$	Water content at wilting point	S	$\text{kg H}_2\text{O m}^{-3}$	65
$T_{ref,S}$	Reference temperature of the soil	S	$^{\circ}\text{C}$	13.5
$D_{max}$	Maximal drainage rate	S	$\text{kg H}_2\text{O m}^{-2} \text{d}^{-1}$	2.5
$z_{min}$	Depth at which groundwater discharge = 0	S	m	2.5
$k_w$	Power of the discharge curve equation	S		2.0
$h$	Thermal conductivity	S	$\text{J m}^{-2} \text{s}^{-1}$	1.7
$z_{root}$	Rooting depth	S	m	0.8
<b>Soil carbon</b>				
$k_{Ta}$	parameters of the force-restore model of the soil temperature for respiration	S	-	0.005
$k_{T_{ref}}$	parameters of the force-restore model of the soil temperature for respiration	S	-	0.005
$k_{HUM}$	decomposition rate of the HUM fraction	S	$\text{yr}^{-1}$	0.02
$k_{BIO}$	decomposition rate of the BIO fraction	S	$\text{yr}^{-1}$	0.66

Table S1: (continued) List of the model parameters.

Symbol	Definition and entity concerned		Unit	Default value	Ref
$k_{DPM}$	decomposition rate of the DPM fraction	S	$\text{yr}^{-1}$	10	6
$k_{RPM}$	decomposition rate of the RPM fraction	S	$\text{yr}^{-1}$	0.16	6
$k_{plow}$	amplification factor of decomposition rate by plowing	S	-	3.0	7
$\tau_{plow}$	half time duration of the plowing effect	S	day	182	7

(1) Chen et al. (1991), (2) Berbigier and Bonnefond (1995), (3) Nakai et al. (2008), (4) Medlyn et al. (2001)

(5) Van Genuchten (1980),(6) Coleman and Jenkinson (1996), (7) Moreaux (2012), (8) Porte and Loustau (1998)

(9) Loustau et al. (1998), (10) Medlyn et al. (2002),(11) Bosc et al.(2003), (12) Ryan (1991), (13) Penning de Vries et al. (1974)

(14) McDowell et al. (2002), (15) Achat et al. (2018), (16) Roman-Dobarco et al. (2019)

(17) Granier and Loustau. (1994), (18) Desprez-Loustau and Dupuis (1994),(19) Kramer (1994)

**Table S2.** Allometric coefficient values used for *Pinus pinaster*, *Pseudotsuga menziesii* and *Fagus sylvatica*.

Tree species	Tree part	$k_1$	$k_2$	$k_3$	$k_4$	Eq.	Reference
<i>Pinus pinaster</i>	$D_{130}$	3.221	0.0403	0.0	-	S34	Shaiek et al. (2011)
	$h$	1.60	0.381	0.12	-	S35	Shaiek et al. (2011)
	$W_{stem}$	0.344	1.063	0.131	-	S37	Shaiek et al. (2011)
		1.010	0.796	-0.694	-	S36	Shaiek et al. (2011)
	$W_{leafcohort=1}$						
	$W_{leafftotal}$	1.563	0.835	-0.67	-	S38	Shaiek et al. (2011)
	$W_{tr}$	0.285	0.499	0.21	-	S40	Achat et al. (2017)
	$W_{cr}$	0	0.206	0.2218	-	S41	Achat et al. (2017)
	$W_{sr}$	0.159	0.262	0.259	-	S42	Achat et al. (2017)
	$D_{130}$	2.574	0.403	0	-	S44	Gholz et al. (1979)
<i>Pseudotsuga menziesii</i>	$h$	2.10	0.41	0	-	S45	GIS Coop data set
	$W_{stem}$	0.686	1.037	0	-	S46	Gholz et al. (1979)
		0.401	0.796	-0.602	-	S47	
	$W_{leafcohort=1}$						
	$W_{leafftotal}$	0.290	0.686	0	-	S48	Gholz et al. (1979)
	$W_{tr}$	0.002	0.400	0.003	0.315	S52	Achat et al. (2017)
	$W_{cr}$	0	0.212	0.335	-	S50	Achat et al. (2017)
	$W_{sr}$	0.002	0.400	0.003	-	S53	Achat et al. (2017)
	$W_{fr}$	0.606	0.512	0.603	-	S51	Achat et al. (2017)
	$D_{130}$	$k_1 = 0.0551 + 30 \times 2.39 \cdot 10^{-4} - 4.68 \cdot 10^{-6} \times Altitude$			S54	(site index=30)	
<i>Fagus sylvatica</i>		$k_2 = 2.11$				Wutzler et al. (2008)	
		$k_3 = 0.589 + 4.06 \cdot 10^{-4} \times Age$					
	$h$	cf. Eq. S62		Le Moguedec and Dhote (2012)			
	$W_l$	0.038	2.43	-0.913	-	S55	Wutzler et al. (2008)
	$W_{stem}$	$k_1 = 0.00347 + 30 \times 6.72 \cdot 10^{-4} + 8.11 \cdot 10^{-6} \times Altitude$				Wutzler et al. (2008)	
		1.84		1.04	-	S56	(site index=30)
	$W_{branch}$	0.122	3.09		-	S57	Wutzler et al. (2008)
		$k_3 = -0.151 - 0.0309 \times 30 - 9.87 \cdot 10^{-4} \times Altitude + 3.06 \cdot 10^{-5} \times 30 \times Altitude$					
	$W_{tr}$	0.0023	0.082	0.001	0.234	S60	Achat et al. (2017)
	$W_{cr}$	0	0.542	0.757	0.115	S58	Achat et al. (2017)
	$W_{sr}$	0.002	0.082	0.001	0.234	S61	Achat et al. (2017)
	$W_{fr}$	0.489	4.670	1.106	-	S59	Achat et al. (2017)

**Table S3.** Models of phenology and life cycle of leaf cohorts implemented in the GO+ v3.0

Model type (species)	Budburst	Lifecycle	End of senescence
Thermal time (Maritime Pine)	$\sum_{DOY=1}^n T_{a,mean}(DOY) = 1400^\circ C$ Desprez-Loustau and Dupuy (1994)	Beadle et al. (1982) Granier and Loustau (1994)	$age = 1002$ days
Parallel (Douglas Fir)	Harrington et al. (2010)	Mohren and Bartelink (1990)	$age = 2555$ days
Alternate (European Beech)	Kramer (1994)		$BB + [k_1 \cdot \sum_{BB}^{258} SW \downarrow] - k_2$

$SW \downarrow$  is the daily mean incident shortwave radiation,  $k_1$  and  $k_2$  are parameters listed in Table S1.

**Table S4.** Equations and parameters used for modelling the senescence of living organs of the individual trees.

Tree part	Senescence model	Reference
Branch	$S_{br}(\text{kg dmyear}^{-1}) = k_{S,1} \times W_{br}^{k_{S,2}} \times Age^{k_{S,3}}$	unpublished
Roots	$S_r(\text{kg dmyear}^{-1}) = k_{S,1} \times \frac{W_r}{1+W_r^{1-k_{S,2}}} \times Age^{k_{S,3}}$	unpublished

**Table S5.** Models of phenology and life cycle of the understorey vegetation parts implemented in the GO+ v3.0

Phase	Model	Reference
Budburst	$\sum_{DOY=1}^n T_{a,mean} = 600^\circ C$	unpublished
Growth	Soil moisture and Temperature threshold : $SMD_{GU}, T_{GU}$ $dW_{l,p,r} = \min(\text{Max. Growth rate, C available})$	Moreaux (2012)
Senescence	Temperature: $T_{MU,l,p,r}$ Soil moisture : $SMD_{MU,l,p,r}$ Date: $DOY_{MU,l,p,r}$	$\Rightarrow M_{rate} = 0.05, 0.001, 0.05 day^{-1}$ Moreaux (2012) $\Rightarrow M_{rate} = 0.025, 0.003, 0.025 day^{-1}$ $\Rightarrow M_{rate} = 0.05, 0.001, 0.05 day^{-1}$

**Table S6.** Characteristics of the sites selected for long term series of tree ( $\Delta D_{130}$ ) and stand growth ( $\Delta BA$ )

Site name (code)	Lat / Lon (°)	Annual temperature (°C) / rainfall( $\text{mm yr}^{-1}$ )	Main species	Tree age (yr)	Period	Reference
St Pardoux	45.44 / 1.45	11.5/1020	Douglas fir	28-42	1997-2011	1
Ecouves	48.50 / 0.10	11.0/750	Douglas fir	21-62	1969-2010	1
Quartier	45.80 / 3.60	11.5/720	Douglas fir	12-21	2004-2013	1
La Houve	49.35 / 5.99	10.7/760	Douglas fir	11-22	2000-2011	1
Soroe (DK-Sor)	55.49 / 11.6	8.2 / 660	European beech	88-97	2000-2009	2
Collelongo (IT-Col)	41.85 / 13.59	6.3 / 1180	European beech	130-140	2002-2012	3
Hesse	48.67 / 7.07	9.2 / 820	European beech	33-44	1999-2010	4
Solling	51.47 / 9.37	6.5/1090	European beech	148	1996-2014	European database
Le Bray (FR-LBr)	44.72 / -0.77	13.5 / 930	Maritime pine	26-37	1987-2008	5
Vielle	44.03 / -0.18	9.2 / 820	Maritime pine	33-46	1991-2014	1
Pompogne	44.25 / 0.04	9.2 / 820	Maritime pine	33-43	1993-2009	1

(1) <https://www6.inra.fr/giscoop>, Seynave et al. (2018); (2) European database, Pilegaard et al. (2011);(3) European database, Scartazza et al. (2013); (4) European database, Granier et al. (2008); (5) European database, Berbigier et al. (2001)

**Table S7.** Variance fraction ( $R^2$ ) of latent heat, net radiation and net ecosystem exchange accounted for by the model predictions at different time spans in five sites. The number of data values used is given in the bottom section.

Time span: (day)	1/24	1	5	10	30	90	180	365
<i>Rn</i>								
BC Campbell 49		0.97	0.97	0.98	0.98	0.98	0.40	0.00
BC Campbell 88		0.95	0.97	0.97	0.97	0.97	0.95	0.33
Collelongo	0.71	0.56	0.75	0.76	0.66	0.73	0.00	0.00
Hesse		0.75	0.90	0.92	0.95	0.96	0.44	0.42
Soroe	0.71	0.63	0.86	0.90	0.92	0.85	0.07	0.35
Le Bray		0.68	0.87	0.91	0.84	0.96	0.39	0.05
<i><math>\lambda E</math></i>								
BC Campbell 49		0.76	0.86	0.89	0.93	.94	0.00	0.10
BC Campbell 88		0.68	0.75	0.77	0.81	0.84	0.20	0.77
Collelongo	0.30	0.22	0.27	0.24	0.23	0.19	0.31	0.44
Hesse		0.70	0.72	0.85	0.87	0.88	0.10	0.28
Soroe	0.28	0.44	0.63	0.69	0.78	0.87	0.09	0.10
Le Bray		0.18	0.24	0.29	0.31	0.57	0.51	0.30
<i>NEE</i>								
BC Campbell 49		0.67	0.70	0.70	0.72	0.85	0.81	0.14
BC Campbell 88		0.25	0.19	0.16	0.15	0.34	0.38	0.76
Collelongo	0.29	0.23	0.30	0.29	0.31	0.28	0.01	0.03
Hesse		0.57	.070	0.75	0.80	0.80	0.05	0.18
Soroe	0.32	0.34	0.44	0.47	0.50	0.47	0.08	0.14
Le Bray		0.15	0.19	0.20	0.27	0.50	0.30	0.57
<b>Data values</b>								
BC Campbell 49	4002	797	394	130	42	20	9	
BC Campbell 88	2110	415	208	69	22	10	4	
Collelongo	53601	2654	653	358	145	56	29	14
Hesse		4414	878	433	146	50	23	12
Soroe	105178	4381	886	430	145	46	22	10
Le Bray		3559	704	349	120	40	20	9

**Figure S1.** Values of the sensitivity index  $I_k$  of 14 model variables for the year 1994 (wet year). Variables are grouped into three processes, energy balance, water balance and carbon balance. Within each group, the heading are the variable symbol, nominal value (annual sum) and unit. The numbers in boxes are the highest  $I_k$  value per variable whereas bold numbers show  $I_k$  values that are greater than half the maximum value,  $0.5 \times I_{kmax}$ , e.g.  $2.2 \text{ MJ m}^{-2} \text{ yr}^{-1}$  for  $I_{Rn}$  (1994). The numbers in normal font show values between  $0.1 \times I_{kmax}$  and  $0.5 \times I_{kmax}$ , that are within  $[0.22, 2.2] \text{ MJ m}^{-2} \text{ yr}^{-1}$  for  $I_{Rn}$  (1994). Empty cells denotes  $I_k$  values less than  $0.1 \times I_{kmax}$ .

		Energy balance			Water balance			Carbon Balance							
		$R_{net}$	$H$	$LE$	$E$	$E_{dry, T}$	$\theta_{soil}$	$D$	$NEE$	$GPP$	$Reco$	$R_a$	$NPP$	$R_b$	$W$
Allometry	Root -shoot allocation coefficient	$k_{x1}$													
	Tree LMA	$LMA_T$	<b>2.5</b>	<b>22.9</b>	<b>2199</b>	<b>892</b>	<b>298</b>	<b>203</b>	<b>472</b>	<b>568</b>	<b>2363</b>	<b>1795</b>	<b>1045</b>	<b>1318</b>	<b>750</b>
	Understorey LMA	$LMA_U$	<b>2.7</b>												
Pheno-logy	Heat sum for tree foliage bud burst	$BB$													
	Growth duration of understorey foliage	$GD_{Uf}$	<b>2.3</b>	6.4											
	Mt. Foliage biomass of understorey	$W_{max,f}$													
Radiative transfer	Soil albedo	$\alpha$	<b>4.3</b>												
	Direct beam extinction coefficient	$k_{h,T}$													
	Diffuse light extinction coefficient	$k_{d,T}$	<b>4.4</b>												
	Leaf reflectance	$\rho_{Tf}$	<b>2.3</b>												
Soil	Rooting Depth	$z_{root}$	2.1	<b>28.0</b>	<b>30.0</b>	<b>12.3</b>	<b>9.7</b>	<b>8.2</b>	<b>13.3</b>	<b>41.2</b>	<b>57.1</b>	15.9	<b>55.4</b>	<b>14.2</b>	<b>56.5</b>
	Max. drainage rate	$D_{max}$		21.1	21.8	8.8	2.1	<b>12.1</b>					11.3		<b>10.4</b>
	Van Genuchten - $\alpha$	$\alpha_{VG}$													
	Van Genuchten $m$	$m_{VG}$													
	Water content at field capacity	$\theta_{FC}$	2.2	<b>44.0</b>	<b>46.0</b>	<b>18.7</b>	4.4	5.1	3.1	30.7	24.3	6.4	24.1	6.7	24.8
	Water content at wilting point	$\theta_{WP}$	2.9	17.3	20.0	8.2	<b>16.1</b>	2.9	-	<b>81.6</b>	<b>81.9</b>		<b>82.3</b>		<b>85.5</b>
Tree canopy layer	Quantum efficiency	$\alpha_T$								<b>82.7</b>	<b>82.7</b>		<b>82.7</b>		<b>86.1</b>
	Foliage mitochondrial respiration at 25 °C	$R_{425,U}$								36.1	14.4	<b>50.5</b>	<b>50.5</b>	36.1	37.6
	Max. carboxylation rate $V_{max}$	$V_{max,U}$								<b>45.3</b>	<b>45.3</b>		<b>45.3</b>		<b>47.2</b>
	Canopy water storage capacity	$S_{w,T}$	8.5	8.6		3.5	3.4	2.4	6.1						2.3
	Max. stomatal conductance	$g_{s,max,T}$	21.8	22.3		9.0	<b>11.1</b>	3.7	0.3	18.1	25.0	7.8	23.6	6.4	24.2
	Stomatal conductance response to leaf water potential	$k_{q2}$								13.1	12.8				12.8
	Root-to-leaf hydraulic resistance	$k_{x1}$													13.2
	Respiration multiplier for a 10°C increase	$Q_{10}$													
Understorey canopy layer	Quantum efficiency	$\alpha_T$													
	Foliage mitochondrial respiration at 25 °C	$R_{425,U}$													
	Max. carboxylation rate $V_{max}$	$V_{max,T}$													
	Max. stomatal conductance	$g_{s,max,U}$													
	DPM / RPM ratio of foliage									11.5	13.9				

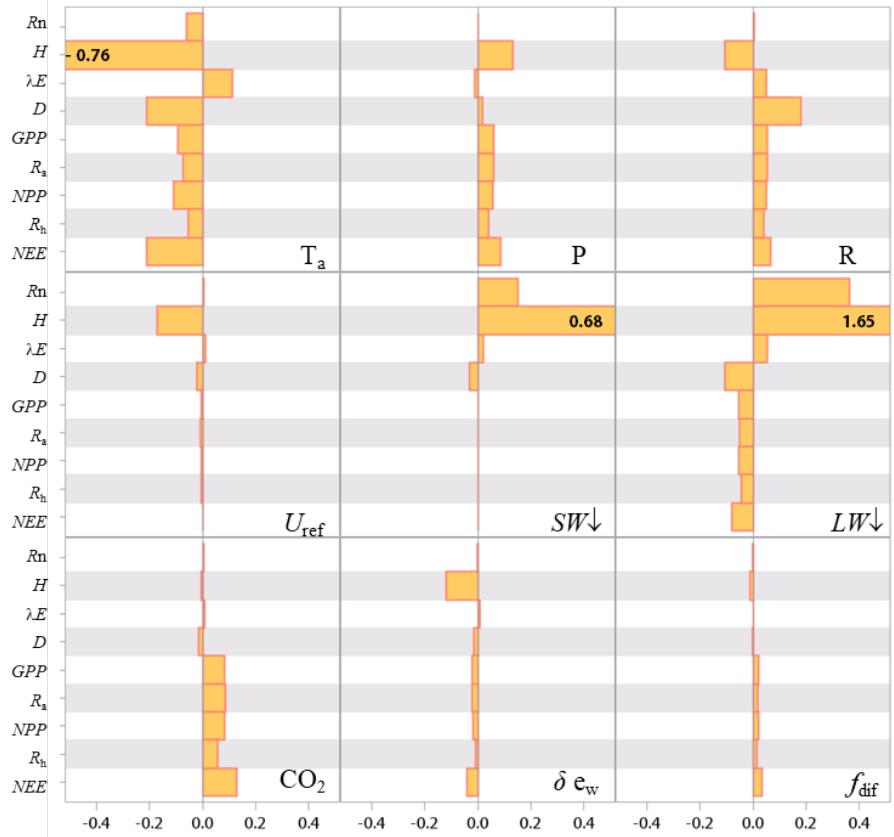
**Figure S2.** Values of the sensitivity index  $I_k$  of 14 model variables for the year 2005 (dry year).

		Energy balance			Water balance			Carbon Balance								
		$R_{net}$	$H$	$LE$	$E$	$E_{dry, T}$	$\theta_{soil}$	$D$	$NEE$	$GPP$	$Reco$	$R_a$	$NPP$	$R_b$	$W$	
Allometry	Root -shoot allocation coefficient	$k_{x1}$														
	Tree LMA	$LMA_T$	<b>19.2</b>	8.0	11.2		4.5	4.5	3.4	<b>244</b>	<b>1413</b>	<b>1169</b>	<b>557</b>	<b>856</b>	<b>611</b>	
	Understorey LMA	$LMA_U$	8.6	9.1			2.3			28.0	<b>44.3</b>	<b>16.3</b>	<b>21.2</b>	23.1	<b>4.8</b>	28.0
Pheno-logy	Heat sum for tree foliage bud burst	$BB$		2.2						27.9	37.1	9.1	7.6	29.4	1.5	21.7
	Growth duration of understorey foliage	$GD_{Uf}$	8.2	9.2			2.7			28.7	39.3	10.6	8.4	30.9	2.2	20.1
	Maximum of foliage biomass of understorey	$W_{max,f}$	5.0	5.8						16.2	22.7	6.5	4.8	17.9	1.7	
Radiative transfer	Soil albedo	$\alpha$	<b>17.4</b>	<b>16.1</b>												
	Direct beam extinction coefficient	$k_{h,T}$	4.1	3.9												
	Diffuse light extinction coefficient	$k_{d,T}$	<b>17.0</b>	<b>15.9</b>												
	Leaf reflectance	$\rho_{Tf}$	3.1	-											11.9	
Soil	Rooting Depth	$z_{root}$	5.3	16.3	<b>22.1</b>		<b>9.0</b>	<b>5.2</b>	3.3	30.6	44.8	<b>14.3</b>	6.3	38.5	<b>7.9</b>	29.7
	Max. drainage rate	$D_{max}$							7.3						2.8	
	Van Genuchten - $\alpha$	$\alpha_{VG}$														
	Van Genuchten $m$	$m_{VG}$														
	Water content at field capacity	$\theta_{FC}$	4.4	<b>39.3</b>	<b>43.9</b>	<b>17.8</b>	4.1	<b>13.8</b>	<b>25.3</b>	27.0	33.3	6.4	29.4	2.5	24.1	
	Water content at wilting point	$\theta_{WP}$	4.4	13.6	18.3	7.5	<b>19.3</b>			<b>11.1</b>	<b>122.1</b>	11.0	4.9	<b>117.2</b>	<b>6.1</b>	<b>115.5</b>
Tree canopy layer	Quantum efficiency	$\alpha_T$								30.8	30.8					
	Foliage mitochondrial respiration at 25 °C	$R_{425,U}$								15.0		<b>24.0</b>	<b>24.0</b>	15.0		15.6
	Max. carboxylation rate $V_{max}$	$V_{max,U}$								28.5	28.5					29.7
	Canopy water storage capacity	$S_{w,T}$														
	Max. stomatal conductance	$g_{s,max,T}$														
	Stomatal conductance response to leaf water potential	$k_{q2}$														
	Root-to-leaf hydraulic resistance	$k_{x1}$														
	Respiration multiplier for a 10°C increase	$Q_{10}$														
Understorey canopy layer	Quantum efficiency	$\alpha_T$														
	Foliage mitochondrial respiration at 25 °C	$R_{425,U}$														
	Max. carboxylation rate $V_{max}$	$V_{max,T}$														
	Max. stomatal conductance	$g_{s,max,U}$														
	DPM / RPM ratio of foliage															

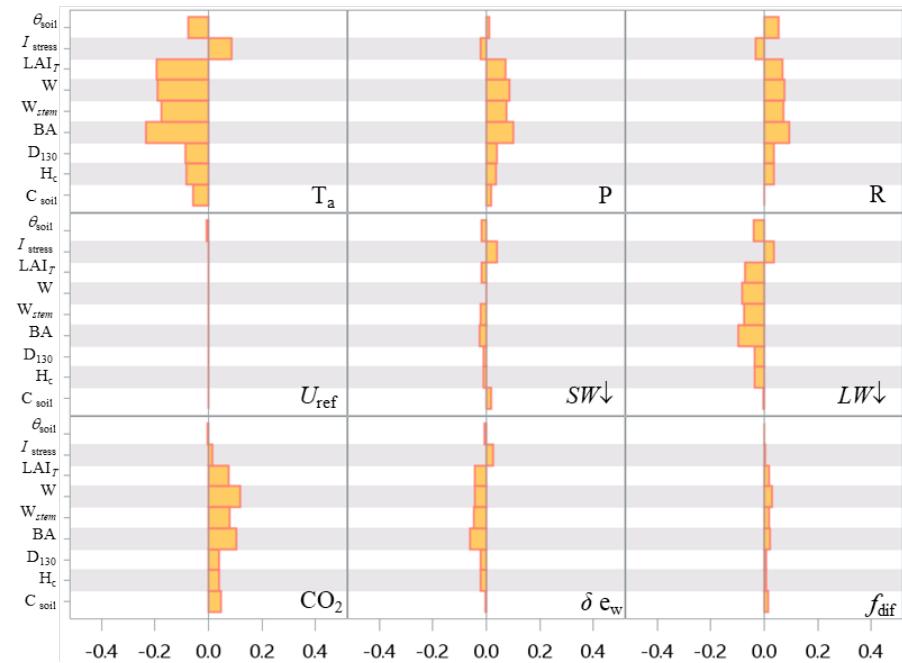
**Figure S3.** Values of the sensitivity index  $I_k$  of 14 model variables over a complete forest rotation from 1970 (plantation) to 2010 (clearcut).

Albedo	Energy balance				Water balance				Carbon Balance						Tree canopy				Understorey			
	Rnet	H	AE	E	$E_{40,T}$	$\theta_{\text{sat}}$	D	NEE	GPP	Reco	$R_s$	NPP	$R_b$	W	C <sub>soil</sub>	$H_t$	$D_{100}$	$LAf$	$W_{\text{tree}}$	$LAf$	$I_{\text{stress}}$	
	2047	697	1350	mm.y <sup>-1</sup>	728	387	115	275	482	2463	1981	1314	1149	667	8504	9150	25.3	37.7	2.8	10	2.2	0.6
parameter for DBH - Wa eq.	$k_{DBH,1}$	15	7	8	3	5	4	4	29	37	10	8	43	13	444	553	1.2	1.2	0.10	1.6	0.09	0.011
parameter for Height - Wa eq.	$k_{H,1}$	30	12	20	8	8	6	10	26	64	38	24	40	14	238	624	2.1	0.9	1.3	0.20	1.3	0.025
parameter of Leaf current cohort to aboveground b $k_{w,1}$		5			5				15	26	12	11	16	151	92	0.9	1.4	0.08	1.2	0.03	0.010	
parameter of stem to aboveground biomass	$k_{w,1}$	12	5	8	3	3	3	4	33	75	42	29	46	13	334	704	1.3	1.9	0.23	1.8	0.11	0.031
Root-shoot allocation coefficient	$k_{x,1}$	36	15	24	10	10	7	12	24	25	29	29	4	74	0.2	0.3	0.02	0.3	0.30			
Tree SLA	$LM_{A_T}$																					
Understorey SLA	$LM_{A_U}$																					
parameter for tree foliage bud burst	$BB$																					
Growth fraction of understorey foliage	$GD_{U_T}$	4																				
Mt. Foliage biomass of understorey	$W_{\text{mt},U}$																					
Photo- logy																						
Soil albedo	$\alpha$	19	18																			
Radiative transfer																						
Direct beam extinction coefficient	$k_{d,T}$	4	5																			
Diffuse light extinction coefficient	$k_{d,U}$	19	16																			
Leaf reflectance	$\rho_{Tf}$																					
Soil																						
Rooting Depth	$d_{\text{root}}$	14	16	29	12	10	6	13	13	74	61	49	25	12	292	106	0.5	0.7	0.04	0.6	0.08	0.008
Max. drainage rate	$D_{\text{max}}$	5	5	10	4	4	7	5	29	27	20	9	7	73								0.05
Van Genuchten - $\alpha$	$\alpha_{VG}$																					
Van Genuchten $n$	$n_{VG}$																					
Water content at field capacity	$\theta_{FC}$	9	43	53	22	4	11	22	10	29	20	16	13	3	138	185	0.4	0.5	0.03	0.4	0.03	0.004
Water content at wilting point	$\theta_{WP}$	28	6	26	11	19	6	10	15	38	23	17	21	6	236	268	1.6	2.4	0.14	2.1	0.20	0.006
Tree canopy layer																						
Quantum efficiency	$\alpha_T$	8																				
Foliage mitochondrial respiration at 25 °C	$R_{act,T}$																					
Max. carboxylation rate $V_{Cmax}$	$V_{act,T}$	15	7	9	4	4	3	5	20	55	35	24	31	11	245	367	0.7	1.1	0.09	1.1	0.04	0.012
Canopy water storage capacity	$S_{w,T}$																					
Max. stomatal conductance	$g_{con,T}$	9	7		3	5		3	15	13	97	76	59	20	626	571						0.04
Stomatal conductance response to leaf water potential $k_{g,1}$																						
Root-to-leaf hydraulic resistance	$k_{rl}$																					
Respiration multiplier for a 10°C increase	$Q_{10}$																					
Understorey																						
Quantum efficiency	$\alpha_U$																					
Foliage mitochondrial respiration at 25 °C	$R_{act,U}$																					
Max. carboxylation rate $V_{Cmax}$	$V_{act,U}$																					
Max. stomatal conductance	$g_{con,U}$																					

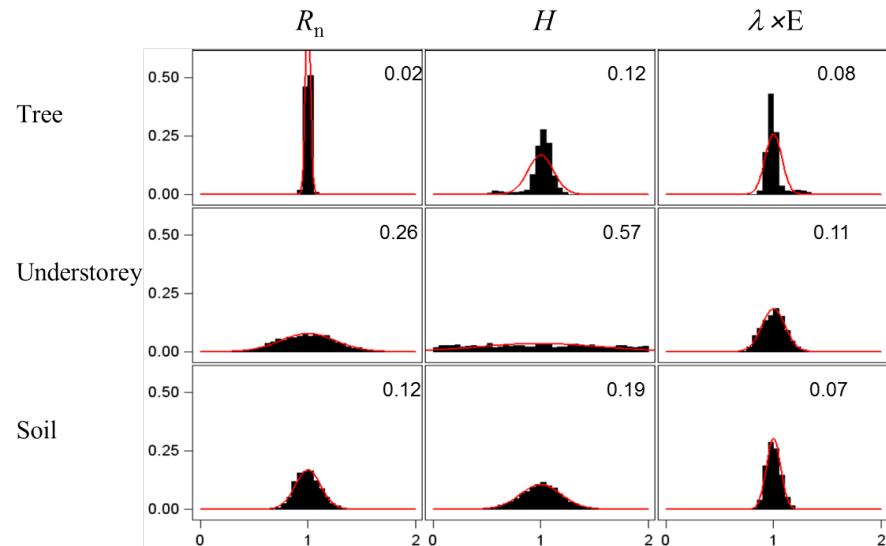
**Figure S4.** Values of the relative sensitivity index  $I_k$  of "fluxes" variables to meteorological variables over a complete forest rotation from 1970 (planting) to 2010 (clear-cut). Each box shows the relative sensitivity value of nine output variables to one of the six forcing input variables.



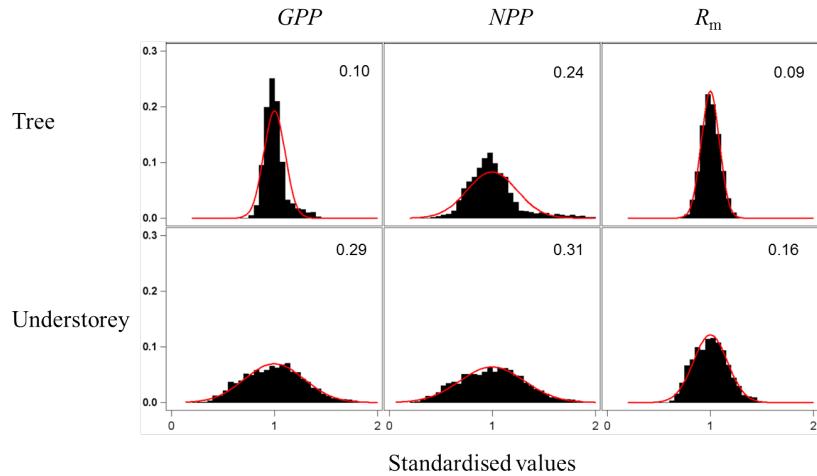
**Figure S5.** Relative sensitivity of soil water, stress index, tree stand variables and soil carbon stock to meteorological variables over a complete forest rotation from 1970 (planting) to 2010 (clear-cut).



**Figure S6.** Normalized uncertainty of the annual mean values of the energy balance components calculated for the year 1994 at Le Bray. Red curve is the normal distribution fitted and inset numbers are the standard deviation.



**Figure S7.** Normalized uncertainty of the annual mean values of the carbon balance components calculated for the year 1994 at Le Bray. The red curve is the normal distribution fitted and inset numbers are the standard deviation.



**Figure S8.** Normalized uncertainty of the annual mean values of the biomass components calculated for the year 1994 at Le Bray. The red curve is the normal distribution fitted and inset numbers are the standard deviation.

