Supplementary information

1. Description of ORCHIDEE in function of the aggregation model

1.1. Dependency of tree growth on climate

For deciduous trees, when the phenological thresholds are exceeded in ORCHIDEE r5698, leaves emerge using carbon from the reserve pool and as such an essential condition for carbon assimilation is fulfilled. Carbon assimilation is calculated following the analytical solution of the Farquhar and Ball and berry model, defined by Yin and Struik (Yin and Struik, 2009):

\[
C_i = C_a - F_A \times (1/g_b + 1/g_s) ,
\]

\[
C_c = C_i - F_A / g_m ,
\]

\[
F_A = (C_c - \Gamma^*) \times x1 / (C_c + x2) - F_{Rd} ,
\]

where \(C_i\), \(C_a\), and \(C_c\) are intercellular, inside of the canopy, and chloroplast CO\(_2\) partial pressure, respectively (\(\mu\)bar), \(F_A\) is the rate of assimilation (\(\mu\)mol \(\text{CO}_2\) \(\cdot m^{-2} \cdot s^{-1}\)), \(g_b\), \(g_s\), and \(g_m\) are the boundary layer, stomatal, and mesophyll diffusion conductance (\(mol \cdot m^{-2} \cdot s^{-1} \cdot \text{bar}^{-1}\)), \(\Gamma^*\) is the CO\(_2\) compensation point (\(\mu\)bar), \(x1\) and \(x2\) are the variables differ by the limitation for the assimilation (Rubisco-limited or electron-transport-limited), and \(F_{Rd}\) is the day respiration (\(\mu\)mol \(\text{CO}_2\) \(\cdot m^{-2} \cdot s^{-1}\)). The assimilation is co-limited by stomatal conductance which accounts for plant hydraulic architecture (Sperry et al., 1994). Subsequently the newly assimilated carbon is stored in the labile pool. After satisfying the carbon cost of maintenance respiration (Amthor, 1984), the fraction of the labile pool that will be allocated to total biomass production (\(\Delta M_{tot}\)) and the associated growth respiration are calculated as a function of temperature. The temperature dependency of plant growth (Fatichi et al., 2014) was accounted for as follows:
\[
\Delta M_{\text{labile,c}} = M_{\text{labile,c}} + \Delta F_{\text{gpp}} \tag{4}
\]

\[
\Delta M_{\text{tot,c}} = \hat{f}_{\text{gtemp}} \times M_{\text{labile,c}} \tag{5}
\]

\[
g_{\text{temp}} = f(T). \tag{6}
\]

where \( M_{\text{labile}} \) is carbon mass of labile pool \((gC \cdot m^{-2})\), \( \text{GPP} \) is gross primary production \((gC \cdot m^{-2} \cdot dt^{-1})\), \( M_{\text{tot}} \) is total allocatable carbon \((gC \cdot m^{-2})\), \( \hat{f}_{\text{gtemp}} \) is the turnover coefficient for the labile carbon pool (unitless), and \( T \) is the air temperature \((K)\). \( \hat{f}_{\text{gtemp}} \) increases with increasing long term annual mean temperature, but was set to never exceed 0.75.

As such photosynthesis \((\Delta F_{\text{gpp}})\) and biomass production \((M_{\text{tot,c}})\) are no longer strictly coupled.

This approach thus partly addresses the criticism that growth in most vegetation models is too strongly driven by photosynthesis (Fatichi et al., 2014). The dependency of tree-ring width on climate thus emerges primarily from the control of radiation, temperature, and soil humidity on gross primary production (GPP), autotropcity respiration, and biomass production.

### 1.2. Dependency of tree growth on tree age or size

The allocation scheme is based on the pipe model theory (Shinozaki et al., 1964) and its implementation by Sitch et al., (2003) and Magnani et al., (2000). The scheme allocates carbon to different biomass pools, e.g., leaves, fine roots, and sapwood, while respecting the differences in longevity and hydraulic conductivity between the pools (Naudts et al., 2015).

According to the pipe model theory, each unit of branch and stem, a so-called pipe, supports a specific amount of leaves providing both mechanical and functional support. From this
assumption, leaf mass \( (M_{L,c}, gC \cdot tree^{-1}) \), sapwood mass \( (M_{S,c}, gC \cdot tree^{-1}) \) and height \((d_h, m)\) relate as follows:

\[
\frac{M_{S,c}}{M_{L,c}} = \frac{d_h}{f_{KF}}. \tag{7}
\]

Where \( f_{KF} (m) \) is defined as,

\[
f_{KF} = \frac{k_{ls}}{(k_{sla} \times k_{ps} \times k_{ff})}, \tag{8}
\]

where \( k_{sla} \) is the specific leaf area \((m^2 gC^{-1})\), \( k_{ps} \) is the sapwood density \((gC \cdot m^{-3})\), \( k_{ff} \) is the tree form factor indicating how the stem differs from a cylinder, and \( k_{ls} \) is the target leaf area to sapwood area ratio, which is calculated as:

\[
k_{ls} = k_{ls\text{min}} + f_{pgap} \times (k_{ls\text{max}} - k_{ls\text{min}}), \tag{9}
\]

where \( k_{ls\text{min}} \) is the parameter from minimum observed leaf area to sapwood area ratio, \( f_{pgap} \) is a light stress factor based on the transmitted light (Haverd et al., 2012), and \( k_{ls\text{max}} \) is the parameter from maximum observed leaf area to sapwood area ratio. Root mass and sapwood mass are proportional to tree height to account for hydraulic constraints on, optimal growth (Magnani et al., 2000):

\[
\frac{M_{S,c}}{M_{r,c}} = k_{sar} \times d_h, \tag{10}
\]

where the variable \( k_{sar} (m^{-1}) \) represents the carbon cost to connect a root pipe to a sapwood pipe (Magnani et al., 2000):

\[
k_{sar} = \sqrt{(k_{Cr}/k_{Cs}) \times (k_{ts}/k_{tr}) \times 2 \times k_{ps}/1000}, \tag{11}
\]

where \( k_{Cr} \) is the conductivity of root \((m^2 g^{-1} s^{-1} MPa^{-1})\), \( k_{Cs} \) is the conductivity of sapwood \((m^2 s^{-1} MPa^{-1})\), \( k_{ts} \) is the sapwood longevity (days), and \( k_{tr} \) is the root
longevity (days). The multiplication by 2 converts carbon density into wood density and the division by 1000 converts g to kg. Following substitution of Eq. (10) in (7), a linear relationship of leaf mass and root mass is obtained:

\[ \frac{M_{l,c}}{M_{r,c}} = f_{LF}, \]  

(12)

where,

\[ f_{LF} = k_{sat} \times k_{KF}. \]  

(13)

Tree height is calculated using a relationship between tree height and basal area \(d_{ba}\) (Pretzsch, 2009):

\[ d_h = k_{pipe2} \times \left(\frac{4}{\pi} \times d_{ba}\right)^{\frac{k_{pipe3}}{2}}, \]  

(14)

where \(pipe_2 (m^{-1})\) and \(pipe_3\) (unitless) are parameters relating tree height and basal area. At the start of the allocation module, it is checked whether the current biomass pools satisfy the allometric relationships. Biomass pools are expected to be out of balance after carbon losses through leaf, sapwood and root-specific turnover have been accounted for. If compared to the allometric relations there are imbalances in the biomass pools, newly assimilated carbon is used for restoring the allometric relationships. If some of the carbon is left from restoring, it will be allocated for growth while accounting for intra-stand competition. Tree-ring growth thus accounts for the pipe-model theory, allometric relationships and within-stand competition between diameter classes (Deleuze et al., 2004):

\[ \Delta d_{ba(i)} = f_Y \times \left( d_{cir(i)} - k_m \cdot f_\sigma + \left( (k_m \times f_\sigma + d_{cir(i)})^2 - 4 \times \sigma \times d_{cir(i)} \right)^{1/f_{\text{power}}} \right)/2. \]  

(15)
Where, $f_y$ is the variable that relates the $d_{ba}$ increment of a tree to its $d_{ba}$. ORCHIDEE r5698 is not an individual-based model, and instead the model simulates stand structure by using a prescribed number of size classes ($i$ index in equation 15). Therefore, $d_{cir(i)}$ denotes the circumference of size class $i$, and $\Delta d_{ba(i)}$ is a basal area increment of size class $i$ which can be converted in tree-ring width increment if the diameter of the tree is known. In ORCHIDEE r5698, each diameter class represents trees with a different mean diameter and height and therefore informs the user about the social position of trees within the canopy. The difference in social position within a stand is the basis of intra-stand competition, which accounts for the fact that trees with a dominant position in the canopy are more likely to intercept light than suppressed trees and therefore contribute more to the stand-level photosynthesis and biomass growth (Deleuze et al., 2004). In Eq. 15, $m$ is a smoothing parameter, $\sigma$ is a circumference threshold for allocating carbon, and $f_{power}$ is the denominator of power for deleuze-dhote simulation.

In the original equation, $f_{power}$ is 2, which results in a linear increase in $\Delta d_{ba(i)}$ with $d_{cir(i)}$ (see Fig. 3 in Bellassen et al., (2010)). Following the observation that ecological properties such as crown length and tree height first increase but then saturate with an increasing diameter (Hemery et al., 2005; Peper et al., 2001), we introduced such a saturation point in the relationship between $\Delta d_{ba}$ and $d_{cir}$ by making $f_{power}$ a function of the tree diameter:

$$f_{power} = 1.8 + k_{power} \times d_{dia}. \quad (16)$$

Where $k_{power}$ is the slope for the $f_{power}$ increment by $d_{dia}$. Following empirical testing, $k_{power}$ was set such that $f_{power}$ ranged between 2 and 3.5 as higher values further increase the similarity between the diameter classes, making their use meaningless.
According to Eq. 15, biomass is allocated to all size classes but more biomass will be allocated to the larger than to smaller size classes (see Fig. 3 in Bellassen et al., (2010)). Furthermore, the calculation of tree growth needs to conserve mass:

$$\Delta M_{tot,c} = \sum_i (\Delta M_{c(i)} \times d_{ind(i)})$$

(17)

$$\Delta M_{s,c(i)} + \Delta M_{l,c(i)} + \Delta M_{r,c(i)} = \Delta M_{c(i)}$$

(18)

Where $$\Delta M_{c(i)}$$, $$d_{ind(i)}$$, $$\Delta M_{s,c(i)}$$, $$\Delta M_{l,c(i)}$$, and $$\Delta M_{r,c(i)}$$ are respectively, the total allocated carbon ($$gC \cdot tree^{-1}$$), the number of trees per meter square, and the increase of sapwood mass, leaf mass, root mass, in size class. $$\Delta M_{s,c(i)}$$, $$\Delta M_{l,c(i)}$$, $$\Delta M_{r,c(i)}$$. The height increment can be re-written using Eqs. (7), (10), and (14):

$$\frac{(M_{s,c(i)} + \Delta M_{s,c(i)})}{(M_{l,c(i)} + \Delta M_{l,c(i)})} = k_{KF} \times d_{h(i)}$$

(19)

$$\frac{(M_{s,c(i)} + \Delta M_{s,c(i)})}{(M_{r,c(i)} + \Delta M_{r,c(i)})} = k_{sar} \times d_{h(i)}$$

(20)

$$d_{h(i)} + \Delta d_{h(i)} = k_{pipe2} \times \left(4/\pi \times d_{ba(i)} + \Delta d_{ba(i)} \right)^{k_{pipe3}/2}$$

(21)

Subsequently, Eqs. (17) to (21) need to be solved simultaneously to obtain a value for $$k_{\gamma}$$ to determine $$\Delta M_{s,c(i)}$$, $$\Delta M_{l,c(i)}$$, $$\Delta M_{r,c(i)}$$, $$\Delta d_{h(i)}$$, and $$\Delta d_{ba(i)}$$. In other words, a value for $$f_{\gamma}$$ needs to be found that both satisfies the allometric relationships and also conserves mass. Such the system of equations cannot be solved analytically and would require an iterative scheme. ORCHIDEE r5698, however, overcomes the need for iterations by assuming a locally linear relationship of height and basal area (linearization of Eq. (14)). The fact that the calculation is performed at daily time steps makes this a fair assumption because the height increment during a single day is small:
\[ \Delta d_h(i) = \Delta d_{ba(i)}/f_s(i), \quad (22) \]

where, \( f_s(i) \) is the slope of the linear relationship between a small increment in height and basal area. Eq. (15) can therefore be re-written as:

\[ f_s(i) = \frac{\Delta d_{ba(i)}}{k_{pipe2} \times \left( \frac{4}{\pi} \times (d_{ba(i)} + \Delta d_{ba(i)}) \right)^{k_{pipe3}/2} - k_{pipe2} \times \left( \frac{4}{\pi} \times d_{ba(i)} \right)^{k_{pipe3}/2}} \]

where \( \Delta d_{ba(i)} \) is a small increment of basal area of size class \( i \).

\[ \Delta M_{s,c(i)}, \Delta M_{l,c(i)}, \text{ and } \Delta M_{r,c(i)} \text{ are then calculated by making use of } f_s : \]

\[ \Delta M_{s,c(i)} = k_{ff} \times k_{\rho} \times (d_{ba(i)} + f_{l(i)} \times f_Y) \times \left( \frac{d_h + f_{l(i)}}{f_s \times f_Y} \right) - M_{s,c(i)} - M_{h,c(i)}, \quad (24) \]

\[ \Delta M_{l,c(i)} = f_{KF} \times k_{ff} \times k_{\rho} \times (d_{ba(i)} + f_{l(i)} \times f_Y) \times \left( \frac{f_{l(i)}}{f_s \times f_Y} \right) - f_{KF} \times M_{h,c(i)} \times (d_h + \frac{f_{l(i)}}{f_s} \times f_Y) - M_{l,c(i)}, \quad (25) \]

\[ \Delta M_{r,c(i)} = f_{KF} \times f_{LF} \times k_{ff} \times k_{\rho} \times (d_{ba(i)} + f_{l(i)} \times f_Y) - \left( \frac{f_{KF}}{f_{LF}} \times M_{h,c(i)} \right) \times (d_h + \frac{f_{l(i)}}{f_s \times f_Y}) - M_{r,c(i)}, \quad (26) \]

Where \( k_{\rho} \) is wood density \((gC \cdot m^{-3})\) and \( f_{l(i)} \) is part of Eq. 15.
\[
\left( d_{\text{cir}(i)} - k_m \cdot f_{\sigma} + \left( (k_m \times f_{\sigma} + d_{\text{cir}(i)})^2 - 4 \times \sigma \times d_{\text{cir}(i)} \right)^{1/f_{\text{power}}} \right) / 2.
\]  

(27)

\(k_{ff}\) was added to incorporate the form of the tree when relying on the relationship between tree mass and dimension. When substituting Eq. (24), (25) and (26) in Eq. (17), a quadratic equation for \(f_y\) is obtained. Subsequently the increase in tree-ring width for each diameter class is calculated by using the positive root of \(f_y\) in Eq. (15). The size-related decrease in tree-ring width, which could be as much as one order of magnitude, thus emerges from simulating wood growth following allometric relationships under the assumption that a certain mass of sap wood is required to support root and leaves for mechanical and functional support (Magnani et al., 2000; Shinozaki et al., 1964).

1.3. **Dependency of tree growth on endogenous disturbances**

The endogenous disturbances that are accounted for correspond to self-thinning, recruitment and background mortality. Self-thinning takes place in an overcrowded stand due to resource competition such as light, soil water, and nutrient. When the resource supply is insufficient, the density of a stand starts to decrease, a process known as self-thinning. In ORCHIDEE we thus use a pre-defined self-thinning relationship that reflects the maximum possible density of a stand at a given tree size. Tree size has been quantified by biomass, diameter, volume, and height (Reineke, 1933; Zeide, 2010) as described in the previous section. In ORCHIDEE r5698, a relationship between number of individuals and the quadratic mean diameter is used to define the self-thinning relationship:

\[
d_{\text{ind, max}} = \frac{d_{\text{dia}}}{k_\alpha, s}^{1/k_\beta, s},
\]

(28)

where \(d_{\text{ind, max}}\) is the number of individual per hectare from the self-thinning relationship \((\text{trees} \cdot \text{m}^{-2})\), \(d_{\text{dia}}\) is the quadratic mean diameter \((m)\) across all size classes, \(k_\alpha, s\) is the
intercept for the self-thinning relationship, and $k_{\beta,s}$ is the slope for the self-thinning relationship. At the start of a simulation, the initial number of individuals is prescribed to overcome numerical issues from the self-thinning relationship stemming from the fact that this relationship is ill-defined for very small trees. The loss of trees by self-thinning starts when $d_{\text{ind, max}}$ calculated from the self-thinning relationship is smaller than the actual number of individuals in the model ($d_{\text{ind}}$). If this is the case $d_{\text{ind}}$ is set to $d_{\text{ind, max}}$ and $d_{\text{ind}} - d_{\text{ind, max}}$ trees are killed.

Recruitment occurs when resources are underused. In ORCHIDEE r5698, the number of recruits is calculated as a function of the light availability at the forest floor (Rüger et al., 2009):

$$\log_{10} d_{\text{ind, new}} = k_{\alpha,r} + k_{\beta,r} \times (\log_{10}(f_L + \epsilon) - k_L), \quad (29)$$

Where $d_{\text{ind, new}}$ is the number of recruits added per $m^2$ area (trees $\cdot$ m$^{-2}$), $k_{\alpha,r}$ is the intercept, $k_{\beta,r}$ is the slope for the relationship that links the number of recruits to the available light, $f_L$ is the seasonal average of the transmitted light that reaches to the floor, $\epsilon$ is a small offset added to avoid taking the log of zero (10E-8), and $k_L$ is an average of the $\log_{10}$ light that ensures that recruitment only occurs if the seasonal mean transmittance exceeds the average transmittance. The calculation is done at the end of each year and only for PFTs where recruitment is expected to be substantial and therefore accounted for. The calculated recruits are added to the smallest size class.

Background mortality represents the loss of individuals in stands in the absence of self-thinning when the stand is young. It, thus, represents individual tree mortality that is unexplained from the endogenous and exogenous disturbances accounted for in ORCHIDEE. Background
mortality is calculated using a concept of residence time for a tree and it is a constant-low rate of tree mortality that is applied to the living biomass.

\[ k_{\text{death}} = \frac{1}{k_{\tau,\text{res}}}, \]  

(30)

where \( k_{\text{death}} \) is the mortality \((\text{day}^{-1})\), and \( k_{\tau,\text{res}} \) is the residence time \((\text{days})\). If mortality from self-thinning occurs, background mortality is not accounted for because self-thinning and background mortality would not be independent when the stand is matured. This implies that only the population dynamics of young stands are governed by background rather than self-thinning mortality. The within-stand population dynamics described above control the contribution of endogenous disturbances to tree growth.

1.4. Dependency of tree growth on exogenous disturbances

The main exogenous disturbances in forests are fire, pests, droughts, windthrow (Seidl et al., 2017), management (Pichler et al., 2010), N-deposition (Vitousek et al., 1997), and CO\(_2\) fertilization (Schimel, 1995). Except for pests, all is included in ORCHIDEE r5698, but only the latter three were implemented such that they affect the simulated tree-ring width.

One of the biggest exogenous disturbances, affecting 98% of the European forest and over 50% of the global forests, is forest management (Pichler et al., 2010). ORCHIDEE r5698 simulates four management strategies: (1) unmanaged stands of which mortality is driven solely by self-thinning, (2) regular thinning and harvesting of wood, (3) coppicing, and (4) short rotation coppicing of willow and poplar for biomass production (Naudts et al., 2015). Under all three management systems a harvest is triggered when a PFT and management-specific maximum diameter or minimum stand densities is exceeded. Under thin and fell management thinning
makes use of the concept of relative density index \( f_{RDI} \) (Bellassen et al., 2010) and aims at reducing resource competition for the remaining individuals:

\[
 f_{RDI} = \frac{d_{ind}}{d_{ind,\text{max}}} ,
\]

(31)

where \( d_{ind,\text{max}} \) is the maximum number of individuals from self-thinning relationship \((trees \cdot m^{-2})\).

The global nitrogen cycle has been strongly perturbed by anthropogenic activities (Vitousek et al., 1997); biologically reactive nitrogen is emitted to the atmosphere (Durka et al., 1994) and has caused an increase in the biological carbon sequestration following wet and dry deposition especially in the context of increasing atmospheric CO2 concentration given that nitrogen availability may become a limiting factor (Bowman & Steltzer, 1998; Janssens et al., 2010; Magnani et al., 2007). When the soil becomes nitrogen saturated negative effects on plant growth, soil fertility, and water quality have been observed (Aber et al., 1998). ORCHIDEE r5698 includes a dynamic nitrogen cycle and thus accounts for plant responses and tree ring growth to nitrogen deposition and nitrogen limitation.

The nitrogen cycle in ORCHIDEE r5698 follows the approach implemented in an earlier version of ORCHIDEE (Zaehle and Friend, 2010) and the enhancements proposed in ORCHIDEE r4999 (Vuichard et al., 2019). At every time step, ORCHIDEE r5698 reads the total nitrogen deposition from a nitrogen input file which prescribes four nitrogen sources: deposition of ammonium, deposition of nitrate, fertilization and biological nitrogen fixation. Nitrogen losses through leaching resulting from drainage and gaseous emission resulting from nitrification and denitrification are accounted for. Furthermore, the plant-available nitrogen pool in the soil distinguishes an ammonium and nitrate pool which in turn depend on the
 above-mentioned nitrogen inputs and outputs, as well as on the decomposition of litter and
nitrogen immobilization. Nitrogen uptake by the plant depends on the plant-available nitrogen
in the soil along with fine root mass \(M_r\), temperature and the actual plant nitrogen status. The
nitrogen status of the plant is quantified through the dynamic C/N ratio of the leaves, roots,
fruits, and the sapwood.

The nitrogen uptake is added to the labile pool before it is used in support of plant growth and
it is allocated to the different biomass pools. In ORCHIDEE, nitrogen allocation follows carbon
allocation:

\[
\Delta M_{\text{tot,n}} = f_{\text{cost}} \times f_{\text{dnc}} \times f_{\text{nc,l}} \times f_{f,R} \times \Delta M_{\text{tot,c}},
\]  

(32)

where \(\Delta M_{\text{tot,n}}\) (\(gN \cdot m^{-2}\)) is nitrogen allocated to leaf, wood, root and fruits, \(f_{\text{cost}}\) is the
nitrogen cost per unit carbon allocation and accounts for the differences in carbon-nitrogen
ratio between leaves, wood, root, and fruit, \(f_{\text{dnc}}\) is an elasticity parameter (Eq. (21) in Text S1
from (Zaehle and Friend, 2010)), \(f_{\text{nc,l}}\) is nitrogen-carbon ratio of leaf, and \(f_{f,R}\) is the fraction
of the total allocatable carbon used for growth respiration. \(f_{\text{cost}}\) is calculated using the fraction
of carbon allocated to leaves, wood, roots, and fruits on the basis of the carbon-nitrogen ratio
of each compartment (Eq. (20) in Text S1 from (Zaehle and Friend, 2010)). \(f_{\text{nc,l}}\) dynamically
dampens the nitrogen cost in accordance with the nitrogen available in the labile pool and the
required nitrogen (\(\Delta M_{\text{tot,n}}\)). In extreme cases where the nitrogen in the labile pool is not
sufficient to sustain the growth in Eq. 32 and the maximum C/N ratio is reached, the nitrogen
concentration of newly grown leaf is adjusted. The nitrogen concentrations in the leaves affect
carbon dynamics through nitrogen-dependencies of maximum carboxylation capacity, electron
transport capacity and maintenance respiration. Nitrogen availability will thus leave an imprint
on the simulated tree-ring width.
Increased atmospheric CO₂ concentrations may now be among the most dominant anthropogenic disturbance. CO₂ fertilization stems from the fact that CO₂ may be a limiting factor for growth and thus increasing it could enhance plant growth. The effect has been examined through experiments (Ainsworth and Long, 2004) and tree-ring width observations (Cienciala et al., 2018; Koutavas, 2008), but the evidence from tree-ring records has been questioned (Brienen et al., 2012; Groenendijk et al., 2015). Assessing the response of trees to increasing atmospheric CO₂ concentrations is important for understanding changes in the global carbon cycle, consequently, numerous modelling approaches have been developed to simulate the CO₂ fertilization effect on net primary productions (Rathgeber et al., 2000; Su et al., 2007) or tree-ring widths (Gaucherel et al., 2008; Li et al., 2014). ORCHIDEE-CN-CAN prescribes atmospheric CO₂ concentrations based on reconstructions and observations. This input enables the model to simulate responses of plant growth to increasing CO₂ concentrations following Eq. 1 to 3. Increased partial pressure of ambient CO₂ strengthens the cellular gradient in CO₂ which in turn results in greater assimilation in the model.

Current ORCHIDEE r5698 simulates the growth response to windthrow and drought. Critical wind speeds above which uprooting and stem breakage occurs are calculated as a function of tree dimensions and stand characteristics (Chen et al., 2018; Hale et al., 2015). Following wind damage, individual trees are killed. Following mortality from windthrow, ORCHIDEE r5698 grows new cohorts for the same PFT as before windthrow. This implies that ORCHIDEE does not simulate resource competition with existing cohorts, and therefore only represents stand-replacing disturbances from windthrow. Windthrow of a few individual trees within a stand would stimulate recruitment and therefore impact tree-ring with in real forests, but this chain of events is not simulated in ORCHIDEE r5698. In addition, windthrow which does not
completely destroy a tree can impact tree ring growth; this process is also neglected in ORCHIDEE. The effect of windthrow on tree ring widths is therefore not accounted for at the moment.

Drought is defined by the ‘absence of rainfall for a long enough period of time to result in depletion of soil water and injury to plants’ (Kramer and Boyer, 1995). In ORCHIDEE r5698, based on aforementioned definition, drought is induced by the climate forcing. A hydraulic-based framework based on stomatal regulation (McDowell et al., 2008) has been implemented (Naudts et al., 2015) to simulate survival and mortality of plants from droughts. Drought-induced growth reduction is triggered by reduction in carbon assimilation and reflected in the tree-ring widths in the model. Referring to the hydraulic-based framework, there are two causes of mortality following a long and/or intense drought: carbon starvation which is caused by carbon deficiency from stomata closure and hydraulic failure which comes from cavitation of xylem by the reduced water supply (Sevanto et al., 2014). ORCHIDEE r5698 can simulate carbon starvation. Although ORCHIDEE r5698 simulates cavitation, it does not yet result in plant mortality.

2. Tree-ring data and simulation set-up of the test case

We selected 10 sites from the International Tree Ring Data Bank (ITRDB) for comparison with simulations, based on following criteria: (1) forest located in Europe; (2) forest composed of Pinus sylvestris L.; (3) forests between 100 to 150 years old; and (4) forest sites cover the entire range of P. sylvestris within Europe. The location of the selected forests is detailed in Table S2.
ORCHIDEE was run for 10 individual pixels, each containing one of the selected sites. The start year and the length of each simulation is set to match the site observations. The model run was repeated four times for every site to obtain simulated tree ring widths for four different model configurations. The first configuration, is the simplest configuration in this test (hence its label ‘simple’): sapling recruitment is not accounted for, the nitrogen cycle is open and the parameter quantifying resource competition within a stand \( f_{\text{power}} \) was fixed at 2. The second configuration was a copy of the first but the modified expression for resource competition (Eq. 16 in Text S1) was used (named ‘power’). The third configuration was building on the second but also accounted for recruitment (named ‘recru’) by setting \( k_{\alpha,r} \) and \( k_{\beta,r} \) to -3 and 6, respectively (Eq. 29 in Text S1). Finally, the fourth configuration uses a closed and dynamic nitrogen cycle (Eq. 32 in Text S1), recruitment, and the modified within-stand competition \( f_{\text{power}} \) (named ‘Ndyn’).

The configuration with an open nitrogen cycle prescribed the leaf carbon-to-nitrogen-ratios with the average leaf carbon-to-nitrogen-ratio obtained from the ‘Ndyn’ simulation following the method proposed by Vuichard et al. (2019). This ensured that the differences came from the C-N feedbacks rather than from differences in leaf nitrogen. For the years prior to 1901, the simulations cycled through the climate forcing from 1901 to 1910. From 1901 onwards, climate forcing matching the simulation years were used. An observed time series of atmospheric CO\(_2\) concentrations was used (Keeling et al., 1996) and all forest were considered to be unmanaged. Every simulation started from a 300 yearlong spinup that is needed to draw an equilibrium of the slow carbon and nitrogen pools in the soil.
Supplementary tables

Table S1. Description of the variables used in the description of the ORCHIDEE model

<table>
<thead>
<tr>
<th>Name</th>
<th>Name in ORCHIDEE</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_a$</td>
<td>Ca</td>
<td>$\mu$bar</td>
<td>Inside canopy CO$_2$ partial pressure</td>
</tr>
<tr>
<td>$C_c$</td>
<td>Cc</td>
<td>$\mu$bar</td>
<td>Cholorplast CO$_2$ partial pressure</td>
</tr>
<tr>
<td>$C_i$</td>
<td>leaf_ci</td>
<td>$\mu$bar</td>
<td>Intercellular CO$_2$ partial pressure</td>
</tr>
<tr>
<td>$d_{ba}$</td>
<td>ba</td>
<td>$m^2 \cdot$ tree$^{-1}$</td>
<td>Plant basal area</td>
</tr>
<tr>
<td>$d_{cir}$</td>
<td>circ_class_circ_eff</td>
<td>$m$</td>
<td>Effective circumference of individual trees</td>
</tr>
<tr>
<td>$d_{dia}$</td>
<td>Dg</td>
<td>$m$</td>
<td>Quadratic mean of diameter</td>
</tr>
<tr>
<td>$d_h$</td>
<td>height</td>
<td>$m$</td>
<td>Plant height</td>
</tr>
<tr>
<td>$d_{ind}$</td>
<td>circ_class_n</td>
<td>trees $\cdot m^{-2}$</td>
<td>Number of individuals in stand</td>
</tr>
<tr>
<td>$d_{ind,new}$</td>
<td>new_ind</td>
<td>trees $\cdot m^{-2}$</td>
<td>number of recruitments added</td>
</tr>
<tr>
<td>$d_{ind,max}$</td>
<td>Nmax</td>
<td>trees</td>
<td>Maximum number of trees according to the self-thinning relationship</td>
</tr>
<tr>
<td>$F_A$</td>
<td>assimtot</td>
<td>$\mu$mol $\cdot m^{-2}$</td>
<td>Carbon assimilation rate</td>
</tr>
<tr>
<td>$F_{gpp}$</td>
<td>gpp</td>
<td>$gC \cdot m^{-2}$</td>
<td>Gross primary production</td>
</tr>
<tr>
<td>$F_{Rd}$</td>
<td>Rd</td>
<td>$\mu$mol $\cdot m^{-2}$</td>
<td>Respiratory CO$_2$ release other than by photorespiration</td>
</tr>
<tr>
<td>$f_{cost}$</td>
<td>costf</td>
<td>-</td>
<td>Nitrogen cost per unit gram carbon</td>
</tr>
<tr>
<td>$f_{dnc}$</td>
<td>1/deltacn</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Symbol</td>
<td>Equation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>Fraction of growth respiration usage</td>
<td>$f_{f.R}$</td>
<td>$1 -$</td>
<td>Fraction of growth respiration usage from gross primary production</td>
</tr>
<tr>
<td>Turnover coefficient of labile carbon pool</td>
<td>$f_{frac_growthresp_dyn}$</td>
<td>$gtemp$</td>
<td>Turnover coefficient of labile carbon pool</td>
</tr>
<tr>
<td>Slope for size competition</td>
<td>$f_{\gamma}$</td>
<td>$gammas$</td>
<td>Slope for size competition</td>
</tr>
<tr>
<td>Scaling factor to convert plant sap wood mass to plant leaf mass</td>
<td>$f_{KFW}$</td>
<td>$KF$</td>
<td>Scaling factor to convert plant sap wood mass to plant leaf mass</td>
</tr>
<tr>
<td>Fraction of light transmitted to the forest floor</td>
<td>$f_{L}$</td>
<td>$lstress_fac$</td>
<td>Fraction of light transmitted to the forest floor</td>
</tr>
<tr>
<td>Nitrogen to carbon ration of leaf</td>
<td>$f_{nc.L}$</td>
<td>$1/cn_leaf$</td>
<td>Nitrogen to carbon ration of leaf</td>
</tr>
<tr>
<td>Scaling factor to convert plant root mass to plant leaf mass</td>
<td>$f_{LF}$</td>
<td>$LF$</td>
<td>Scaling factor to convert plant root mass to plant leaf mass</td>
</tr>
<tr>
<td>Transmission probability of light through to forest floor</td>
<td>$f_{Pgap}$</td>
<td>$Pgap$</td>
<td>Transmission probability of light through to forest floor</td>
</tr>
<tr>
<td>Relative density index</td>
<td>$f_{RDI}$</td>
<td>$rdi$</td>
<td>Relative density index</td>
</tr>
<tr>
<td>Slope of relationship between small increase of height and basal area</td>
<td>$f_{s}$</td>
<td>$s$</td>
<td>Slope of relationship between small increase of height and basal area</td>
</tr>
<tr>
<td>Size threshold of plants for carbon allocation in size competition</td>
<td>$f_{\sigma}$</td>
<td>$sigma$</td>
<td>Size threshold of plants for carbon allocation in size competition</td>
</tr>
<tr>
<td>Boundary-layer conductance</td>
<td>$g_{b}$</td>
<td>$gb_co2$</td>
<td>Boundary-layer conductance</td>
</tr>
</tbody>
</table>

Units: $\mu mol \cdot m^{-2} \cdot s^{-1} \cdot bar^{-1}$
<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesophyll diffusion conductance</td>
<td>$g_m$</td>
<td>$\mu\text{mol} \cdot \text{m}^{-2}$</td>
<td>$\cdot \text{s}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$g_s$</td>
<td>$\mu\text{mol} \cdot \text{m}^{-2}$</td>
<td>Stomatal conductance to CO2</td>
</tr>
<tr>
<td></td>
<td>$k_{\alpha,r}$</td>
<td>-</td>
<td>Intercept for calculating new individuals from recruitments</td>
</tr>
<tr>
<td></td>
<td>$k_{\alpha,s}$</td>
<td>-</td>
<td>Intercept for the self-thinning relationship</td>
</tr>
<tr>
<td></td>
<td>$k_{\beta,r}$</td>
<td>-</td>
<td>Slope for calculating new individuals from recruitments</td>
</tr>
<tr>
<td></td>
<td>$k_{\beta,s}$</td>
<td>-</td>
<td>Slope for the self-thinning relationship</td>
</tr>
<tr>
<td></td>
<td>$k_{CR}$</td>
<td>$m^3 \cdot \text{kg}^{-1}$</td>
<td>Root specific conductivity $\cdot \text{s}^{-1}$ $\cdot \text{MPa}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$k_{CS}$</td>
<td>$m^2 \cdot \text{s}^{-1}$</td>
<td>Sapwood specific conductivity $\cdot \text{MPa}^{-1}$</td>
</tr>
<tr>
<td>Background mortality</td>
<td>$k_{f\text{death}}$</td>
<td>-</td>
<td>Background mortality $\text{year}^{-1}$</td>
</tr>
<tr>
<td>Tree form factor</td>
<td>$k_{ff}$</td>
<td>-</td>
<td>Tree form factor</td>
</tr>
<tr>
<td>Average log light</td>
<td>$k_{L}$</td>
<td>$\log_{10} 0.02$</td>
<td>-</td>
</tr>
<tr>
<td>Leaf area to sapwood area ratio</td>
<td>$k_{ls}$</td>
<td>-</td>
<td>Leaf area to sapwood area ratio</td>
</tr>
<tr>
<td>Maximum leaf area to sapwood area ratio</td>
<td>$k_{ls\text{max}}$</td>
<td>-</td>
<td>Maximum leaf area to sapwood area ratio</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>$k_{lsmin}$</td>
<td>Minimum leaf area to sapwood area ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_m$</td>
<td>Smoothing parameter for competition-allocation scheme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{pipe2}$</td>
<td>Allometric parameter relating tree height and basal area</td>
<td>$m^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$k_{pipe3}$</td>
<td>Allometric parameter relating tree height and basal area</td>
<td>$m$</td>
<td></td>
</tr>
<tr>
<td>$k_{power}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_p$</td>
<td>Wood density</td>
<td>$gC \cdot m^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$k_{ps}$</td>
<td>Sapwood density</td>
<td>$mgC \cdot m^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$k_{sar}$</td>
<td>Scaling factor to convert root mass to sapwood mass</td>
<td>$m^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$k_{sla}$</td>
<td>Specific leaf area</td>
<td>$m^2 \cdot gC^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$k_{tau_root}$</td>
<td>Root longevity</td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>$k_{tau_sap}$</td>
<td>Sapwood longevity</td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>$k_{r_res}$</td>
<td>Residence time of plants</td>
<td>years</td>
<td></td>
</tr>
<tr>
<td>$M_{l_c}$</td>
<td>Plant leaf mass</td>
<td>$gC \cdot tree^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$M_{labile_c}$</td>
<td>Carbon mass of labile pool</td>
<td>$gC \cdot m^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$M_{r_c}$</td>
<td>Plant root mass</td>
<td>$gC \cdot tree^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$M_{s_c}$</td>
<td>Plant sap wood mass</td>
<td>$gC \cdot tree^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta M_{tot_n}$</td>
<td>Nitrogen growth</td>
<td>$gN \cdot m^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$M_{tot_c}$</td>
<td>Plant total biomass</td>
<td>$gC \cdot tree^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$T_{2m}$</td>
<td>Air temperature at 2m</td>
<td>$K$</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Unit</td>
<td>Notes</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------</td>
<td>-----------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>$x_1$</td>
<td>$x_1$</td>
<td>$\mu mol \cdot m^{-2}$</td>
<td>The variable to solve analytic equation for assimilation.</td>
</tr>
<tr>
<td>$x_2$</td>
<td>$x_2$</td>
<td>$\mu bar$</td>
<td>The variable to solve analytic equation for assimilation.</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>min_ stomate</td>
<td>-</td>
<td>Small value to avoid numerical problems</td>
</tr>
<tr>
<td>$\Gamma^*$</td>
<td>gamma_star</td>
<td>$\mu bar$</td>
<td>CO2 compensation point</td>
</tr>
</tbody>
</table>
Table S2. Information of the sites used in the test case.

<table>
<thead>
<tr>
<th>Site name</th>
<th>Number in ITRDB</th>
<th>Number in Fig. 9</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Length of longest individual record (years)</th>
<th>Number of cores</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>birt019</td>
<td>1</td>
<td>1</td>
<td>52.23</td>
<td>5.92</td>
<td>134</td>
<td>24</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/4418">https://www.ncdc.noaa.gov/paleo/study/4418</a></td>
</tr>
<tr>
<td>brit021</td>
<td>2</td>
<td>2</td>
<td>63.10</td>
<td>29.63</td>
<td>120</td>
<td>22</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/4399">https://www.ncdc.noaa.gov/paleo/study/4399</a></td>
</tr>
<tr>
<td>finl039</td>
<td>3</td>
<td>3</td>
<td>61.85</td>
<td>28.90</td>
<td>130</td>
<td>55</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/3999">https://www.ncdc.noaa.gov/paleo/study/3999</a></td>
</tr>
<tr>
<td>finl052</td>
<td>4</td>
<td>4</td>
<td>56.63</td>
<td>-3.35</td>
<td>149</td>
<td>33</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/3998">https://www.ncdc.noaa.gov/paleo/study/3998</a></td>
</tr>
<tr>
<td>fran6</td>
<td>5</td>
<td>5</td>
<td>42.03</td>
<td>-2.70</td>
<td>136</td>
<td>51</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/5113">https://www.ncdc.noaa.gov/paleo/study/5113</a></td>
</tr>
<tr>
<td>germ153</td>
<td>6</td>
<td>6</td>
<td>50.95</td>
<td>-1.68</td>
<td>134</td>
<td>13</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/16663">https://www.ncdc.noaa.gov/paleo/study/16663</a></td>
</tr>
<tr>
<td>germ214</td>
<td>7</td>
<td>7</td>
<td>43.32</td>
<td>5.73</td>
<td>147</td>
<td>11</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/16747">https://www.ncdc.noaa.gov/paleo/study/16747</a></td>
</tr>
<tr>
<td>neth034</td>
<td>8</td>
<td>8</td>
<td>46.30</td>
<td>7.57</td>
<td>142</td>
<td>304</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/3919">https://www.ncdc.noaa.gov/paleo/study/3919</a></td>
</tr>
<tr>
<td>spai006</td>
<td>9</td>
<td>9</td>
<td>51.15</td>
<td>9.08</td>
<td>144</td>
<td>22</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/4405">https://www.ncdc.noaa.gov/paleo/study/4405</a></td>
</tr>
<tr>
<td>swit188</td>
<td>10</td>
<td>10</td>
<td>50.78</td>
<td>7.57</td>
<td>116</td>
<td>48</td>
<td><a href="https://www.ncdc.noaa.gov/paleo/study/6121">https://www.ncdc.noaa.gov/paleo/study/6121</a></td>
</tr>
</tbody>
</table>
References


Janssens, I. A., Dieleman, W., Luyssaert, S., Subke, J.-A., Reichstein, M., Ceulemans, R.,
Ciais, P., Dolman, A. J., Grace, J., Matteucci, G., Papale, D., Piao, S. L., Schulze, E.-D.,
Tang, J. and Law, B. E.: Reduction of forest soil respiration in response to nitrogen
inferred from atmospheric CO2 measurements, Nature, 382(6587), 146–149,
doi:10.1038/382146a0, 1996.
Koutavas, A.: Late 20th century growth acceleration in greek firs (Abies cephalonica) from
Cephalonia Island, Greece: A CO2 fertilization effect?, Dendrochronologia, 26(1), 13–19,
Marketing Department, San Diego, US., 1995.
Li, G., Harrison, S. P., Prentice, I. C. and Falster, D.: Simulation of tree-ring widths with a
model for primary production, carbon allocation, and growth, Biogeosciences, 11(23), 6711–
Magnani, F., Mencuccini, M. and Grace, J.: Age-related decline in stand productivity: the
role of structural acclimation under hydraulic constraints, Plant. Cell Environ., 23(3), 251–
Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle,
A., Hari, P., Jarvis, P. G., Kolari, P., Kowalski, A. S., Lankreijer, H., Law, B. E., Lindroth,
A., Loustau, D., Manca, G., Moncrieff, J. B., Rayment, M., Tedeschi, V., Valentini, R. and
Grace, J.: The human footprint in the carbon cycle of temperate and boreal forests, Nature,
McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J.,
Sperry, J., West, A., Williams, D. G. and Yepez, E. A.: Mechanisms of plant survival and
mortality during drought: why do some plants survive while others succumb to drought,


Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J.,
Ascoli, D., Petr, M., Honkaniami, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M.,
Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O.,
Sperry, J. S., Nichols, K. L., Sullivan, J. E. M. and Eastlack, S. E.: Xylem Embolism in Ring-Porous, Diffuse-Porous, and Coniferous Trees of Northern Utah and Interior Alaska,
Su, H., Sang, W., Wang, Y. and Ma, K.: Simulating Picea schrenkiana forest productivity under climatic changes and atmospheric CO2 increase in Tianshan Mountains, Xinjiang Autonomous Region, China, For. Ecol. Manage., 246(2), 273–284,
Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W.,


