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):

$$C_i = C_a - \mathrm{F}_A \times (1/g_b + 1/g_s)\,, \tag{1}$$

$$C_c = C_i - F_A/g_m\,, \tag{2}$$

$$F_A = {}^{(C_c - \Gamma^*) \times x1}\!\big/_{(C_c + x2)} - F_{Rd}\,, \tag{3}$$

where C_i, C_a, and C_c are intercellular, inside of the canopy, and chloroplast CO_2 partial pressure, respectively (μbar), F_A is the rate of assimilation ($\mu mol\, CO_2 \cdot m^{-2} \cdot s^{-1}$), g_b, g_s, and $g_m$are the boundary layer, stomatal, and mesophyll diffusion conductance ($mol \cdot m^{-2} \cdot s^{-1} \cdot bar^{-1}$), Γ^* is the CO_2 compensation point (μbar), $x1$ 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 ($\mu mol\, CO_2 \cdot m^{-2} \cdot s^{-1}$). 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 (ΔM_{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:

$$\Delta M_{labile\_c} = M_{labile\_c} + \Delta \mathrm{F}_{gpp} \tag{4}$$

$$\Delta M_{tot\_c} = f_{gtemp} \times M_{labile\_c} \tag{5}$$

$$g_{temp} = f(T), \tag{6}$$

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

As such photosynthesis (ΔF_{gpp}) and biomass production (M_{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), autotropic 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:

$$M_{s\_c}/M_{l\_c} = d_h/f_{KF}. \tag{7}$$

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

$$f_{KF} = k_{ls}/(k_{sla} \times k_{\rho s} \times k_{ff}), \tag{8}$$

where k_{sla} is the specific leaf area($m^2 gC^{-1}$), $k_{\rho s}$ 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:

$$k_{ls} = k_{lsmin} + f_{P_{gap}} \times (k_{lsmax} - k_{lsmin}), \tag{9}$$

where k_{lsmin} is the parameter from minimum observed leaf area to sapwood area ratio, $f_{P_{gap}}$ is a light stress factor based on the transmitted light (Haverd et al., 2012), and k_{lsmax} 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):

$$M_{s\_c}/M_{r\_c} = k_{sar} \times d_h, \tag{10}$$

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

$$k_{sar} = \sqrt{(k_{Cr}/k_{Cs}) \times (k_{\tau s}/k_{\tau r}) \times 2 \times k_{\rho s}/1000}, \tag{11}$$

where $k_{Cr}$is the conductivity of root ($m^3 \cdot kg^{-1} \cdot s^{-1} \cdot MPa^{-1}$), k_{Cs} is the conductivity of sapwood ($m^2 \cdot s^{-1} \cdot MPa^{-1}$), $k_{\tau s}$ is the sapwood longevity (days), and $k_{\tau r}$ 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:

$$M_{l\_c}/M_{r\_c} = f_{LF} \, , \tag{12}$$

where,

$$f_{LF} = k_{sar} \times k_{KF} \, . \tag{13}$$

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

$$d_h = k_{pipe2} \times \left({}^{4}\!/_{\pi} \times d_{ba}\right)^{\frac{k_{pipe3}}{2}} \, , \tag{14}$$

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):

$$\Delta d_{ba(i)} = f_{\gamma} \times \left(d_{cir(i)} - k_m \cdot f_{\sigma} + \left(\left(k_m \times f_{\sigma} + d_{cir(i)}\right)^2 - 4 \times \sigma \times d_{cir(i)}\right)^{1/f_{power}}\right)/2 \, . \tag{15}$$

Where, f_{γ} 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, σ 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 Δd_{ba} and d_{cir} by making f_{power} a function of the tree diameter:

$$f_{power} = 1.8 + k_{power} \times d_{dia}. \tag{16}$$

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:

$$\Delta M_{tot\_c} = \sum_i (\Delta M_{c(i)} \times d_{ind(i)}), \tag{17}$$

$$\Delta M_{s\_c(i)} + \Delta M_{l\_c(i)} + \Delta M_{r\_c(i)} = \Delta M_{c(i)} \ . \tag{18}$$

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):

$$(M_{s\_c(i)} + \Delta M_{s\_c(i)}) \Big/ (M_{l\_c(i)} + \Delta M_{l\_c(i)}) = k_{KF} \times d_{h(i)} \ , \tag{19}$$

$$(M_{s\_c(i)} + \Delta M_{s\_c(i)}) \Big/ (M_{r\_c(i)} + \Delta M_{r\_c(i)}) = k_{sar} \times d_{h(i)} \ , \tag{20}$$

$$d_{h(i)} + \Delta d_{h(i)} = k_{pipe2} \times \left({}^{4}\!/_{\pi} \times d_{ba(i)} + \Delta d_{ba(i)} \right)^{\frac{k_{pipe3}}{2}} \ . \tag{21}$$

Subsequently, Eqs. (17) to (21) need to be solved simultaneously to obtain a value for k_{γ} to deteremine $\Delta M_{s\_c(i)}$, $\Delta M_{l\_c(i)}$, $\Delta M_{r\_c(i)}$, $\Delta d_{h(i)}$, and $\Delta d_{ba(i)}$. In other words, a value for f_{γ} 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:

$$\Delta d_{h(i)} = \Delta d_{ba(i)} / f_{s(i)} \,, \tag{22}$$

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-rewritten as:

$$f_{s(i)} = \frac{\Delta d_{ba(i)}}{\mathrm{k}_{\mathrm{pipe2}} \times \left({}^{4}\!/_{\pi} \times \left(\mathrm{d}_{ba(i)} + \Delta d_{ba(i)}\right)\right)^{k_{pipe3}/2} - k_{\mathrm{pipe2}} \times \left({}^{4}\!/_{\pi} \times \mathrm{d}_{ba(i)}\right)^{k_{pipe3}/2}} \tag{23}$$

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

$\Delta M_{s\_c(i)}$, $\Delta M_{l\_c(i)}$, and $\Delta M_{r\_c(i)}$ are then calculated by making use of f_s :

$$\Delta M_{s\_c(i)} = k_{ff} \times k_{\rho} \times \left(d_{ba(i)} + f_{I(i)} \times f_{\gamma}\right) \times \left(d_h + {}^{f_{I(i)}}\!/_{f_s} \times f_{\gamma}\right) - M_{s\_c(i)} - M_{h\_c(i)}, \tag{24}$$

$$\Delta M_{l\_c(i)} = f_{KF} \times k_{ff} \times k_{\rho} \times \left(d_{ba(i)} + f_{I(i)} \times f_{\gamma}\right) - (f_{KF} \times M_{h_{c(i)}})/(d_h + {}^{f_{I(i)}}\!/_{f_{s(i)}} \times f_{\gamma}) - M_{l\_c(i)}, \tag{25}$$

$$\Delta M_{r\_c(i)} = {}^{f_{KF}}\!/_{f_{LF}} \times k_{ff} \times k_{\rho} \times \left(d_{ba(i)} + f_{I(i)} \times f_{\gamma}\right) - ({}^{f_{KF}}\!/_{f_{LF}} \times M_{h\_c(i)}) / (d_{h(i)} + {}^{f_{I(i)}}\!/_{f_{s(i)}} \times f_{\gamma}) - M_{r\_c(i)}, \tag{26}$$

Where k_{ρ} is wood density $(gC \cdot m^{-3})$ and $f_{I(i)}$ is part of Eq. 15

$$\left(d_{cir(i)} - k_m \cdot f_\sigma + \left(\left(k_m \times f_\sigma + d_{cir(i)}\right)^2 - 4 \times \sigma \times d_{cir(i)}\right)^{1/f_{power}}\right)/2. \tag{27}$$

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_γ is obtained. Subsequently the increase in tree-ring width for each diameter class is calculated by using the positive root of f_γ 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:

$$d_{ind\_max} = {d_{dia}/k_{\alpha\_s}}^{1/k_{\beta\_s}}, \tag{28}$$

where d_{ind_max} is the number of individual per hectare from the self-thinning relationship $(trees \cdot m^{-2})$, d_{dia} is the quadratic mean diameter (m) across all size classes, k_{α_s} is the intercept for the self-thinning relationship, and k_{β_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_{ind_max} calculated from the self-thinning relationship is smaller than the actual number of individuals in the model (d_{ind}). If this is the case d_{ind} is set to d_{ind_max} and $d_{ind} - d_{ind\_max}$ 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):

$$\log_{10} d_{ind\_new} = k_{\alpha\_r} + k_{\beta\_r} \times (\log_{10}(f_L + \epsilon) - k_{\bar{L}}), \tag{29}$$

Where d_{ind_new} is the number of recruits added per m^2 area $(trees \cdot m^{-2})$, k_{α_r} is the intercept, k_{β_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, ϵ is a small offset added to avoid taking the log of zero (10E-8), and $k_{\bar{L}}$ 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.

$$k_{fdeath} = 1/k_{\tau\_res}, \tag{30}$$

where k_{fdeath} is the mortality (day^{-1}), and k_{τ_res} is the residence time $(days)$. 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:

$$f_{RDI} = {d_{ind}}\Big/{d_{ind\_max}} , \tag{31}$$

where d_{ind_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 abovementioned 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:

$$\Delta M_{tot\_n} = f_{cost} \times f_{dnc} \times f_{nc\_l} \times f_{f\_R} \times \Delta M_{tot\_c}, \tag{32}$$

where ΔM_{tot_n} $(gN \cdot m^{-2})$ is nitrogen allocated to leaf, wood, root and fruits, f_{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_{dnc} is an elasticity parameter (Eq. (21) in Text S1 from (Zaehle and Friend, 2010)), f_{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_{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_{nc_l} dynamically dampens the nitrogen cost in accordance with the nitrogen available in the labile pool and the required nitrogen (ΔM_{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 CO_2 concentrations may now be among the most dominant anthropogenic disturbance. CO_2 fertilization stems from the fact that CO_2 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 CO_2 concentrations is important for understanding changes in the global carbon cycle, consequently, numerous modelling approaches have been developed to simulate the CO_2 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 CO_2 concentrations based on reconstructions and observations. This input enables the model to simulate responses of plant growth to increasing CO_2 concentrations following Eq. 1 to 3. Increased partial pressure of ambient CO_2 strengthens the cellular gradient in CO_2 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). ORCDHIEE 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 sylvestri*s 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_{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_{α_r} and k_{β_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_{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

Name	Name in ORCHIDEE	Unit	Description
C_a	Ca	μbar	Inside canopy CO_2 partial pressure
C_c	Cc	μbar	Cholorplast CO2 partial pressure
C_i	$leaf\_ci$	μbar	Intercellular CO2 partial pressure
d_{ba}	ba	$m^2 \cdot tree^{-1}$	Plant basal area
d_{cir}	$circ\_class\_circ\_eff$	m	Effective circumference of individual trees
d_{dia}	Dg	m	Quadratic mean of diameter
d_h	$height$	m	Plant height
d_{ind}	$circ\_class\_n$	$trees \cdot m^{-2}$	Number of individuals in stand
d_{ind_new}	new_ind	$trees \cdot m^{-2}$	number of recruitments added
d_{ind_max}	$Nmax$	$trees \cdot hactare^{-1}$	Maximum number of trees according to the self-thinning relationship
F_A	$assimtot$	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Carbon assimilation rate
F_{gpp}	gpp	$gC \cdot m^{-2} \cdot dt^{-1}$	Gross primary production
F_{Rd}	Rd	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Respiratory CO2 release other than by photorespiration
f_{cost}	$costf$	-	Nitrogen cost per unit gram carbon
f_{dnc}	$1/deltacn$	-	

f_{f_R}	$1 - frac\_growthresp\_dyn$	-	Fraction of growth respiration usage from gross primary production
f_{gtemp}	$gtemp$	-	Turnover coefficient of labile carbon pool
f_{γ}	$gammas$	-	Slope for size competition
f_{KF}	KF	m	Scaling factor to convert plant sap wood mass to plant leaf mass
f_{L}	$lstress\_fac$	-	Fraction of light transmitted to the forest floor
f_{nc_l}	$1/cn\_leaf$	-	Nitrogen to carbon ration of leaf
f_{LF}	LF	-	Scaling factor to convert plant root mass to plant leaf mass
f_{Pgap}	$Pgap$	-	Transmission probability of light through to forest floor
f_{power}	$deleuze\_power$	-	
f_{RDI}	rdi	-	Relative density index
f_{s}	s	-	Slope of relationship between small increase of height and basal area
f_{σ}	$sigma$	-	Size threshold of plants for carbon allocation in size competition
g_{b}	gb_co2	$\mu mol \cdot m^{-2} \cdot s^{-1} \cdot bar^{-1}$	Boundary-layer conductance

g_m	gm	$\mu mol \cdot m^{-2} \cdot s^{-1} \cdot bar^{-1}$	Mesophyll diffusion conductance
g_s	gs	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Stomatal conductance to CO2
k_{α_r}	$alpha\_recruitment$	-	Intercept for calculating new individuals from recruitments
k_{α_s}	$alpha\_selfthinning$	-	Intercept for the self-thinning relationship
k_{β_r}	$beta\_recruitment$	-	Slope for calculating new individuals from recruitments
k_{β_s}	$beta\_selfthinning$	-	Slope for the self-thinning relationship
k_{Cr}	k_root	$m^3 \cdot kg^{-1} \cdot s^{-1} \cdot MPa^{-1}$	Root specific conductivity
k_{Cs}	k_sap	$m^2 \cdot s^{-1} \cdot MPa^{-1}$	Sapwood specific conductivity
k_{fdeath}	$mortality$	$year^{-1}$	Background mortality
k_{ff}	$tree\_ff$	-	Tree form factor
$k_{\bar{L}}$	$\log_{10} 0.02$	-	Average log light
k_{ls}	k_latosa	-	Leaf area to sapwood area ratio
k_{lsmax}	k_latosa_max	-	Maximum leaf area to sapwood area ratio

k_{lsmin}	k_latosa_min	-	Minimum leaf area to sapwood area ratio
k_{m}	m_dv	-	Smoothing parameter for competition-allocation scheme
k_{pipe2}	$pipe\_tune2$	m^{-1}	Allometric parameter relating tree height and basal area
k_{pipe3}	$pipe\_tune3$	m	Allometric parameter relating tree height and basal area
k_{power}			
k_{ρ}	$pipe\_density$	$gC \cdot m^{-3}$	Wood density
$k_{\rho s}$	$sapwood\_density$	$mgC \cdot m^{-3}$	Sapwood density
k_{sar}	$c0\_alloc$	m^{-1}	Scaling factor to convert root mass to sapwood mass
k_{sla}	sla	$m^{2} \cdot gC^{-1}$	Specific leaf area
$k_{\tau r}$	tau_root	$days$	Root longevity
$k_{\tau s}$	tau_sap	$days$	Sapwood longevity
k_{τ_res}	$residence\_time$	$years$	Residence time of plants
M_{l_c}	Cl	$gC \cdot tree^{-1}$	Plant leaf mass
M_{labile_c}	$labile\_pool$	$gC \cdot m^{-2}$	Carbon mass of labile pool
M_{r_c}	Cr	$gC \cdot tree^{-1}$	Plant root mass
M_{s_c}	Cs	$gC \cdot tree^{-1}$	Plant sap wood mass
ΔM_{tot_n}	n_alloc_tot	$gN \cdot m^{-2}$	Nitrogen growth
M_{tot_c}	$circ\_class\_biomass$	$gC \cdot tree^{-1}$	Plant total biomass
T_{2m}	$t2m$	K	Air temperature at 2m

$x1$	$x1$	$\mu mol \cdot m^{-2} \cdot s^{-1}$	The variable to solve analytic equation for assimilation.
$x2$	$x2$	μbar	The variable to solve analytic equation for assimilation.
ϵ	$\min\ \_stomate$	-	Small value to avoid numerical problems
Γ^*	$gamma\_star$	μbar	CO2 compensation point

Table S2. Information of the sites used in the test case.

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

References

Aber, J., McDowell, W., Nadelhoffer, K., Magill, A., Berntson, G., Kamakea, M., McNulty, S., Currie, W., Rustad, L. and Fernandez, I.: Nitrogen saturation in temperate forest ecosystems, Bioscience, 48(11), 921–934, doi:10.2307/1313296, 1998.

Ainsworth, E. A. and Long, S. P.: What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2, New Phytol., 165(2), 351–372, doi:10.1111/j.1469-8137.2004.01224.x, 2004.

Amthor, J. S.: The role of maintenance respiration in plant growth., Plant, Cell Environ., 7(8), 561–569, doi:10.1111/1365-3040.ep11591833, 1984.

Bellassen, V., Le Maire, G., Dhôte, J. F., Ciais, P. and Viovy, N.: Modelling forest management within a global vegetation model—Part 1: Model structure and general behaviour, Ecol. Modell., 221(20), 2458–2474, doi:10.1016/j.ecolmodel.2010.07.008, 2010.

Bowman, W. D. and Steltzer, H.: Positive feedbacks to anthropogenic nitrogen deposition in Rocky Mountain alpine tundra, Ambio, 514–517, 1998.

Brienen, R. J. W., Gloor, E. and Zuidema, P. A.: Detecting evidence for CO 2 fertilization from tree ring studies: The potential role of sampling biases, Global Biogeochem. Cycles, 26(1), n/a-n/a, doi:10.1029/2011GB004143, 2012.

Chen, Y.-Y., Gardiner, B., Pasztor, F., Blennow, K., Ryder, J., Valade, A., Naudts, K., Otto, J., McGrath, M. J., Planque, C. and Luyssaert, S.: Simulating damage for wind storms in the land surface model ORCHIDEE-CAN (revision 4262), Geosci. Model Dev., 11(2), 771–791, doi:10.5194/gmd-11-771-2018, 2018.

Cienciala, E., Altman, J., Doležal, J., Kopáček, J., Štěpánek, P., Ståhl, G. and Tumajer, J.: Increased spruce tree growth in Central Europe since 1960s, Sci. Total Environ., 619–620, 1637–1647, doi:https://doi.org/10.1016/j.scitotenv.2017.10.138, 2018.

Deleuze, C., Pain, O., Dhôte, J.-F. and Hervé, J.-C.: A flexible radial increment model for individual trees in pure even-aged stands, Ann. For. Sci., 61(4), 327–335, doi:10.1051/forest:2004026, 2004.

Durka, W., Schulze, E.-D., Gebauer, G. and Voerkeliust, S.: Effects of forest decline on uptake and leaching of deposited nitrate determined from 15N and 18O measurements, Nature, 372(6508), 765–767, doi:10.1038/372765a0, 1994.

Fatichi, S., Leuzinger, S. and Körner, C.: Moving beyond photosynthesis: from carbon source to sink-driven vegetation modeling, New Phytol., 201(4), 1086–1095, doi:10.1111/nph.12614, 2014.

Gaucherel, C., Guiot, J. and Misson, L.: Changes of the potential distribution area of French Mediterranean forests under global warming, Biogeosciences, 5(6), 1493–1504, doi:10.5194/bg-5-1493-2008, 2008.

Groenendijk, P., van der Sleen, P., Vlam, M., Bunyavejchewin, S., Bongers, F. and Zuidema, P. A.: No evidence for consistent long-term growth stimulation of 13 tropical tree species: Results from tree-ring analysis, Glob. Chang. Biol., doi:10.1111/gcb.12955, 2015.

Hale, S. E., Gardiner, B., Peace, A., Nicoll, B., Taylor, P. and Pizzirani, S.: Comparison and validation of three versions of a forest wind risk model, Environ. Model. Softw., 68, 27–41, doi:10.1016/j.envsoft.2015.01.016, 2015.

Haverd, V., Lovell, J. L., Cuntz, M., Jupp, D. L. B., Newnham, G. J. and Sea, W.: The Canopy Semi-analytic Pgap And Radiative Transfer (CanSPART) model: Formulation and application, Agric. For. Meteorol., 160, 14–35, doi:10.1016/j.agrformet.2012.01.018, 2012.

Hemery, G. E., Savill, P. S. and Pryor, S. N.: Applications of the crown diameter–stem diameter relationship for different species of broadleaved trees, For. Ecol. Manage., 215(1–3), 285–294, doi:10.1016/j.foreco.2005.05.016, 2005.

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 deposition, Nat. Geosci., 3(5), 315–322, doi:10.1038/ngeo844, 2010.

Keeling, C. D., Chin, J. F. S. and Whorf, T. P.: Increased activity of northern vegetation 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, doi:10.1016/j.dendro.2007.06.001, 2008.

Kramer, P. J. and Boyer, J. S.: Water relations of plants and soils., Academic Press, Book 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), 6711–6724, doi:10.5194/bg-11-6711-2014, 2014.

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), 251–263, doi:10.1046/j.1365-3040.2000.00537.x, 2000.

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, 447(7146), 849–851, doi:10.1038/nature05847, 2007.

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?, New Phytol., 178(4), 719–739, doi:10.1111/j.1469-8137.2008.02436.x, 2008.

Naudts, K., Ryder, J., McGrath, M. J., Otto, J., Chen, Y., Valade, A., Bellasen, V., Berhongaray, G., Bönisch, G., Campioli, M., Ghattas, J., De Groote, T., Haverd, V., Kattge, J., MacBean, N., Maignan, F., Merilä, P., Penuelas, J., Peylin, P., Pinty, B., Pretzsch, H., Schulze, E. D., Solyga, D., Vuichard, N., Yan, Y. and Luyssaert, S.: A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes, Geosci. Model Dev., 8(7), 2035–2065, doi:10.5194/gmd-8-2035-2015, 2015.

Peper, P. J., McPherson, E. G. and Mori, S. M.: Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees, J. Arboric., 27(6), 306–317, 2001.

Pichler, V., Godinho-Ferreira, P., Zlatanov, T., Pichlerová, M. and Gregor, J.: Changes in forest cover and its diversity, in Forest Management and the Water Cycle, pp. 209–224, Springer., 2010.

Pretzsch, H.: Forest dynamics, growth, and yield, in Forest Dynamics, Growth and Yield, pp. 1–39, Springer., 2009.

Rathgeber, C., Nicault, A., Guiot, J., Keller, T., Guibal, F. and Roche, P.: Simulated responses of Pinus halepensis forest productivity to climatic change and CO2 increase using a statistical model, Glob. Planet. Change, 26(4), 405–421, doi:https://doi.org/10.1016/S0921-8181(00)00053-9, 2000.

Reineke, L. H.: Perfecting a stand-density index for even-aged forests, , 627–638, 1933.

Rüger, N., Huth, A., Hubbell, S. P. and Condit, R.: Response of recruitment to light availability across a tropical lowland rain forest community, J. Ecol., 97(6), 1360–1368, doi:10.1111/j.1365-2745.2009.01552.x, 2009.

SCHIMEL, D. S.: Terrestrial ecosystems and the carbon cycle, Glob. Chang. Biol., 1(1), 77–

91, doi:10.1111/j.1365-2486.1995.tb00008.x, 1995.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A. and Reyer, C. P. O.: Forest disturbances under climate change, Nat. Clim. Chang., 7(6), 395–402, doi:10.1038/nclimate3303, 2017.

Sevanto, S., McDowell, N. G., Dickman, L. T., Pangle, R. and Pockman, W. T.: How do trees die? A test of the hydraulic failure and carbon starvation hypotheses, Plant. Cell Environ., 37(1), 153–161, doi:10.1111/pce.12141, 2014.

Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T.: A quantitative analysis of plant form-the pipe model theory: I. Basic analyses, Japanese J. Ecol., 14(3), 97–105, doi:10.18960/seitai.14.3_97, 1964.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Chang. Biol., 9(2), 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

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, Ecology, 75(6), 1736–1752, doi:10.2307/1939633, 1994.

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, doi:https://doi.org/10.1016/j.foreco.2007.04.010, 2007.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H. and Tilman, D. G.: Human alteration of the global nitrogen cycle: sources and consequences, Ecol. Appl., 7(3), 737–750, doi:10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2, 1997.

Vuichard, N., Messina, P., Luyssaert, S., Guenet, B., Zaehle, S., Ghattas, J., Bastrikov, V. and Peylin, P.: Accounting for carbon and nitrogen interactions in the global terrestrial ecosystem model ORCHIDEE (trunk version, rev 4999): multi-scale evaluation of gross primary production, Geosci. Model Dev., 12(11), 4751–4779, doi:10.5194/gmd-12-4751-2019, 2019.

Yin, X. and Struik, P. C.: C3 and C4 photosynthesis models: an overview from the perspective of crop modelling, NJAS-Wageningen J. Life Sci., 57(1), 27–38, doi:10.1016/j.njas.2009.07.001, 2009.

Zaehle, S. and Friend, A. D.: Carbon and nitrogen cycle dynamics in the O-CN land surface model: 1. Model description, site-scale evaluation, and sensitivity to parameter estimates, Global Biogeochem. Cycles, 24(1), doi:doi:10.1029/2009GB003521, 2010.

Zeide, B.: Comparison of self-thinning models: an exercise in reasoning, Trees, 24(6), 1117–1126, doi:10.1007/s00468-010-0484-z, 2010.