

Appendix A: Description of the model ForCEEPS

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Beyond forest succession: a gap model to study ecosystem functioning and tree community composition under climate change

Model overview

ForCEEPS is a forest gap model (or forest dynamics model) following the scheme of JABOWA (Botkin *et al.* 1972) and ForCLIM (Bugmann 1996, Didion *et al.* 2009), with notable exceptions. It simulates forest dynamics and succession by considering the effects of abiotic (climate and soil properties) and biotic constraints (tree-tree competition for light) on tree establishment, growth, and survival in small parcels of land (“patches”) (Fig. A).

Simulated patches are independent from each other, and properties at the forest level are obtained by aggregating the properties over all patches. Within each patch, environmental conditions are assumed to be horizontally homogeneous, and patches are usually do not exceed 1000 m² to ensure this assumption. The spatial location of trees is therefore implicit. This allows for several simplifications in the representation of tree-tree interactions, but imposes that the patch size cannot be larger than 1000 m², which is considered as the maximum area influenced by a tree (Shugart 1984). Gap models are often cohort-based, assuming that all trees of the same species and age behave similarly, for the sake of simulation efficiency, but ForCEEPS is completely individual-based, which notably allows to take inter-individual variability into account. ForCEEPS also allows imposing a feedback between the actual forest composition and the identity of the colonizing seedlings each year. The main development of ForCEEPS in comparison with the classic scheme of gap model is the implementation of a new module for light competition where the individual crown lengths are explicitly represented in the vertical canopy space.

The main processes of the model are described in the next sections, according to Figure B illustrating how the input variables and species parameters operate in ForCEEPS.

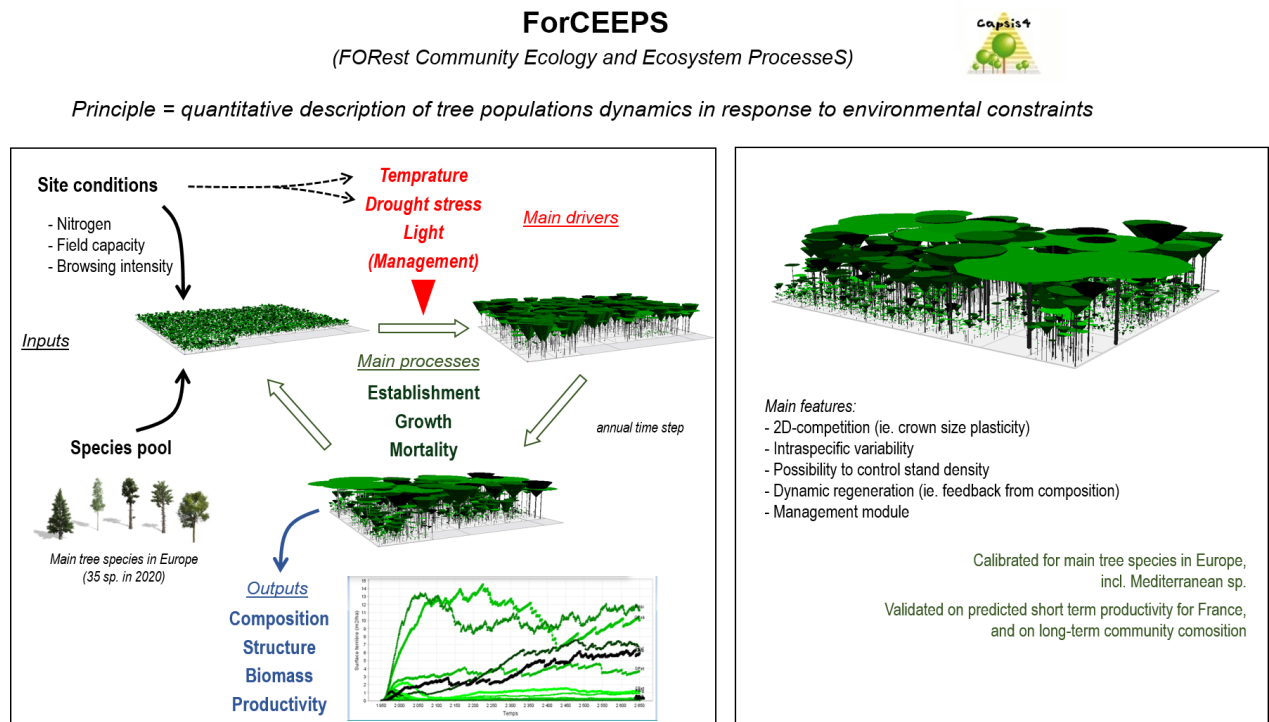


Figure A: Structure and features of ForCEEPS.

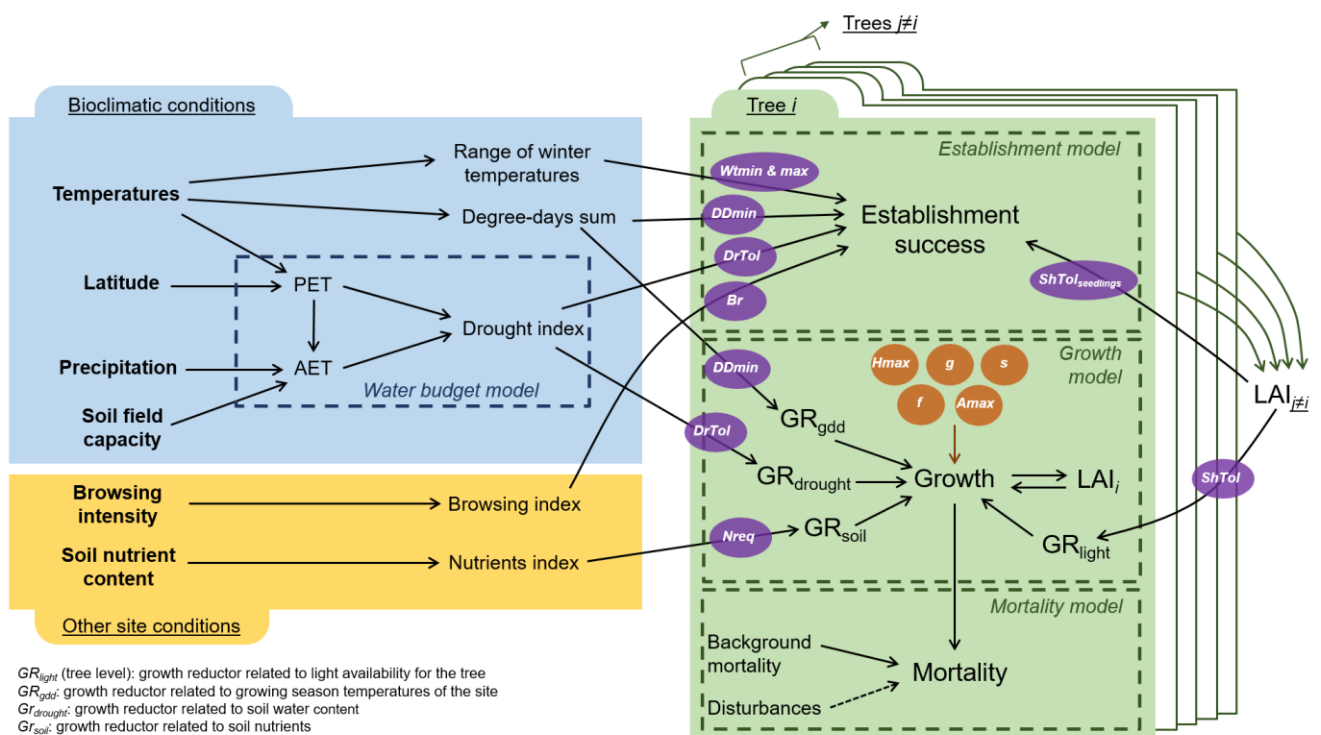


Figure B: Detailed processes embedded in the model. Species parameters (orange: intrinsic parameters; purple: response-to-drivers parameters) are described in Table A.

Detailed description of the model

The core-processes of the model are tree establishment, growth, and mortality are simulated at a yearly time step, and are all possibly constrained by environmental drivers (Fig. A and B).

We first present how the environmental drivers are calculated or assessed, and second we detail how the core-processes are modelled in ForCEEPS.

Environmental drivers

Bioclimatic part

ForCEEPS uses time-series of monthly climate data (monthly mean temperature and precipitation sum). Climatic indices are calculated from these climate data: annual (for evergreen species) or seasonal (for deciduous species) growing degree-days sum (*GDD*), minimum and maximum winter temperatures, and a drought index (*DrI*) (Fig. B).

- Growing degree-days sums (*GDD*) are calculated as follows:

$$GDD = \sum_{m=i}^j \max(T_m - T_0) \times N_{days} \times k_{corr} \quad (\text{Eq. 1})$$

with T_m is the mean monthly temperature, T_0 is the base temperature ($T_0 = 5.5^\circ\text{C}$), N_{days} the average number of days per month ($N_{days} = 30.5$) and k_{corr} being a correction coefficient to avoid bias related to the calculations of degree-days from monthly means (Bugmann 1994):

$$k_{corr} = \begin{cases} 8.52 \cdot 10^{0.165 \cdot T_m} & \text{if } T_m \leq 5.5 \\ 187.2 \cdot 10^{0.0908 \cdot T_m} & \text{if } 5.5 < T_m \leq 15.5 \\ -31.8 + 2.377 \cdot T_m & \text{if } T_m > 15.5 \end{cases} \quad (\text{Eq. 2})$$

For evergreen and deciduous species, $i=1$ and $i=4$, and $j=12$ and $j=10$, respectively.

- Mean winter temperature T_w is the average of the mean temperatures of the three month: December (year $n-1$), January (year n) and February (year n).

- Drought stress index (*DrI*) is assessed through the calculation of soil water content (*SWC*) from a water budget based on monthly calculations of potential (*PET*) and actual

evapotranspiration (AET), and depending on the site-specific soil field capacity (Fig. B), as in the ForClim model (Bugmann & Solomon 2000).

To calculate evapotranspiration and water balance, the more accurate methods require many weather variables with a high temporal resolution. As in ForClim (Bugmann & Solomon 2000), ForCEEPS relies on the model by Thornthwaite & Mather (1957). This is an entirely empirical approach (ie. a «bucket model»), but it is especially useful because it only requires monthly mean temperatures and monthly precipitation sums (and the latitude to derive day length), and has been shown to provide reasonable estimates of PET and AET (Bugmann 1994). We should notice that, at least in this version of the model, this approach assumes that AET is independent of the vegetation cover and composition, and is thus based on an average leaf area index. However, such an assumption is justified by the fact that canopy openings caused by the death of single trees are relatively small and their effect on evapotranspiration rates is moderate.

The drought index DrI is thus calculated from monthly drought indices DrI_m with

$$DrI_m = \begin{cases} 1 - \frac{E_m}{D_m}, & D_m \neq 0 \\ 0, & D_m = 0 \end{cases} \quad (\text{Eq. 3})$$

where E_m is the amount of water transpired by the trees and D_m is their evaporative demand for soil water during month m (Bugmann & Cramer 1998; Bugmann and Solomon 2000). Then DrI is simply the average of DrI_m over the relevant time period, by only considering months when transpiration and demand are significant (ie. with $T_m \geq T_0$), with thus

$$DrI = \text{mean}(DrI_m) \mid i \leq m \leq j, T_m \geq T_0 \quad (\text{Eq. 4})$$

where $T_0 = 5.5^\circ\text{C}$, and $i=1$ and $i=4$, and $j=12$ and $j=10$, for evergreen and deciduous species, respectively.

Other drivers

- Another abiotic factor taken into account in ForCEEPS is soil nutrients content (N_{soil}), which is constant at the site level, while climate conditions do vary among years. N_{soil} is in

kg.ha⁻¹, although it should rather be seen as a quantitative proxy for the edaphic quality of the site's soil.

- A browsing intensity Br can be defined for each site as a continuous value between 0 (no pressure) and 1 (high pressure), constant at the site level across years.

Seedling establishment

By default, the model assumes that there is a constant seed rain in the patches and thus no dispersal limitation. Therefore, each species present in the species list at the beginning of the simulation sends seeds each year. Alternatively it is possible in ForCEEPS to activate a feedback between the actual forest composition at year n and species composition of the new seedlings at year $n+1$. In this case, the composition of the seed rain is determined by the relative biomass of all species actually present in the patches (ie. with adult trees).

Furthermore, in ForCEEPS, seedling establishment can be constrained by defining a maximum number of seedlings potentially colonizing the patches and/or by imposing a feedback of actual forest composition on the composition of colonizing seedlings.

Seedlings are established with a diameter at breast height of 1 cm. Establishment success is simulated as a function of species-specific responses to DrI , GDD , T_W , Br (Didion et al. 2011), and light availability at the forest floor L_{av} (see Eq. 28). More precisely, the probability P_{est_S} of establishment success for each seedling of the species S is calculated as follows:

$$P_{est_S} = P_{T_W} \times P_{GDD} \times P_{Dr} \times P_{Br} \times P_{LA} \times c_{est} \quad (\text{Eq. 5})$$

P_{T_W} is the probability that the seedling can establish according to winter temperature T_W , and $Wtmin_S$ and $Wtmax_S$, respectively the monthly minimum and maximum winter temperature (°C) tolerated for regeneration of species S (species parameters are described in Table A and values for main species in Table B), with

$$P_{Tw} = \begin{cases} 1, & Wtmin_s \leq T_w \leq Wtmax_s \\ 0, & otherwise \end{cases} \quad (\text{Eq. 6})$$

P_{GDD} is the probability that the seedling can establish according to GDD of the year (Eq. 1) and the minimal required annual or seasonal degree-days sum $DDmin_s$, the establishment assumed to be impossible when the annual sum of growing degree-days does not conform to the degree-day requirements of the tree species.

$$P_{GDD} = \begin{cases} 1, & GDD \geq DDmin_s \\ 0, & GDD < DDmin_s \end{cases} \quad (\text{Eq. 7})$$

P_{DrI} is the probability that the seedling can establish according to the drought stress of the year (Eq. 3 and 4) and the species-specific drought tolerance $DrTol_s$, with:

$$P_{Dr} = \begin{cases} 1, & DrI \leq DrTol_s \\ 0, & DrI > DrTol_s \end{cases} \quad (\text{Eq. 8})$$

P_{Br} is the probability that the seedling can establish according to the browsing intensity of the site Br and to Br_s , the browsing susceptibility of seedlings of species S , that both determine the actual browsing susceptibility of seedlings of species S in the site B_{actual} , with:

$$\begin{aligned} \text{if } Br_s = 1, & \quad B_{actual} = Br^4 \\ \text{if } Br_s = 2, & \quad B_{actual} = Br^2 \\ \text{if } Br_s = 3, & \quad B_{actual} = Br \\ \text{if } Br_s = 4, & \quad B_{actual} = Br^{0.5} \\ \text{if } Br_s = 5, & \quad B_{actual} = Br^{0.25} \end{aligned}$$

Then P_{Br} is calculated as:

$$P_{Br} = \begin{cases} 1, & B_{actual} \leq k_{Br} \\ 0, & B_{actual} > k_{Br} \end{cases} \quad (\text{Eq. 9})$$

k_{Br} being a random number between 0 and 1.

P_{LA} is the probability that the seedling can establish according to the light availability at the forest floor L_{av} and the species-specific shade tolerance of seedlings $ShTol_seedling_s$, with:

$$P_{LA} = \begin{cases} 1, & L_{av} \geq ShTol_seedling_s \\ 0, & L_{av} < ShTol_seedling_s \end{cases} \quad (\text{Eq. 10})$$

with $L_{av} = e^{-k \times LA}$, LA being the summed leaf area over all trees in the patch.

The coefficient c_{est} is a random factor comprised between 0 and 1 to introduced stochasticity in the seedling regeneration.

Finally, The establishment of the seedlings of a given tree species S is possible if

$$P_{est_s} \geq k_{est} \quad (\text{Eq. 11})$$

where k_{est} is a random number comprised between 0 and 1.

If seedling establishment is possible for species S , the number of seedlings that actually established is calculated using a random number with uniform distribution in the range $[1 \dots k_{EstNr} \cdot k_{PatchSize} \cdot ShTol_s]$, where k_{EstNr} is the maximum seedling establishment rate ($k_{EstNr} = 0.006$ seedlings per $m^{-2} \cdot yr^{-1}$, Bugmann 1996), $k_{PatchSize}$ is the size of the forest patch in m^2 (see Table D), and $ShTol_s$ is the shade tolerance of the species (integer between 1 – high tolerance - and 9 – low tolerance) to take into account that pioneer species produce more seedlings than late-successional species (Didion et al. 2009).

Tree growth

Potential growth

Annual tree growth is modelled through stem diameter increment at breast height (ΔD).

Following the classical scheme of gap models, ΔD is calculated in two steps.

First, the potential (i.e. maximum) diameter increment (ΔD_{opt}) of each tree is predicted each year using the following empirical equation (Moore 1989):

$$\Delta D_{opt} = g_s \frac{D \left(1 - \frac{H}{H_{max_s}} \right)}{2 \cdot H_{max_s} - b_s \times e^{(c_s \cdot D) \times (c_s \cdot D + 2)}} \quad (\text{Eq. 12})$$

where D is tree diameter at breast height, H is tree height, g_s is the maximum growth rate of species s , H_{max_s} is the maximum height reachable by the species s , and b_s and c_s are species-specific parameters (with $b_s = H_{max_s} - 137$; and $c_s = s_s / b_s$); s_s is a species-specific allometric parameter relating tree height H and tree diameter D as follows (Bugmann 1996):

$$H = a + (H_{max_s} - a) \times \left(1 - e^{\left(\frac{-s_s D}{H_{max_s} - a} \right)} \right) \quad (\text{Eq. 13})$$

with $a = 1.37$ m (i.e. breast height). Therefore, simulating the potential diameter increment of a tree in FORCEEPS requires to determine the values of the species-specific parameters g_s , s_s and H_{max_s} (Tables A and B).

Realized growth

Second, realized tree diameter increment ΔD is calculated by modifying ΔD_{opt} according to abiotic or biotic growth reduction factors (all factors are bounded between 0 and 1) as follows (Bugmann 1996, Didion et al. 2009):

$$\Delta D = \Delta D_{opt} \times \sqrt[3]{GR_{light} \times GR_{gdd} \times GR_{drought} \times GR_{soil}} \quad (\text{Eq. 14})$$

where GR_{light} is the growth reduction factor related to light availability for the tree, GR_{gdd} is the growth reduction factor related to growing season temperatures of the site (GDD), $GR_{drought}$ is the growth reduction factor related to the drought index (DrI), and GR_{soil} is the growth reduction factor related to soil nutrients content (N_{soil}). The effects of each of these growth reduction factors on realized tree growth depend on species-specific parameters: GR_{light} depends on species shade tolerance ShT_s ; GR_{gdd} depends on species minimum sum of growing degree-days GDD_s ; $GR_{drought}$ depends on species drought tolerance DrT_s ; and GR_{soil} depends on species requirements for soil nutrients $NReq_s$ (see Table C). All growth reduction factors vary among site conditions and species, and GR_{light} varies also among trees, because it is influenced by the sizes of the neighbouring trees in the patch (see next section).

More precisely, the growth redactors are calculated as follows:

$$GR_{gdd} = \max(0, 1 - e^{(DDmin_s - GDD) \times q_{corr}}) \quad (\text{Eq. 15})$$

With q_{corr} being the curve slope parameter in degree-day growth function ($q_{corr} = 1/750 \text{ } ^\circ\text{C}^{-1} \cdot \text{day}^{-1}$) (Bugmann 1996).

$$GR_{drought} = \sqrt{\max\left(0, 1 - \frac{DrI}{DrTol_s}\right)} \quad (\text{Eq. 16})$$

$$GR_{soil} = \max(0, 1 - e^{[N1_s \times (N_{soil} - N2_s)])} \quad (\text{Eq. 17})$$

With $N1_s$ and $N2_s$ being species-specific parameters derived from $Nreqs$ as described in Table C.

Growth reduction due to competition for light.

As the trees are not spatialized inside the patches, the interaction for light among trees in ForCEEPS depends on the vertical stratification of tree crowns alone. Following the framework of ForClim 2.9.6 (Didion et al. 2009), the amount of light available for a tree (with H being its total height) is reduced by the leaf area of all trees found in the same patch whose height is greater than H or equal to H . Thus, all the foliage of trees taller than the target tree contribute to the shading. Aiming to reach a more integrative description of the competition for light, ForCEEPS embeds a more realistic competition module, by representing individual crown lengths (Fig. C).

In ForCEEPS, GR_{light} has two components:

$$GR_{light} = GR_{cs} \times GR_{sh} \quad (\text{Eq. 18})$$

with GR_{cs} representing the feedback of crown size on tree growth, i.e., tree leaf area is positively linked to tree growth rate (Mitscherlich and von Gadow 1968). GR_{sh} is the reduction factor related to shading by competing trees. Crowns of individual trees are thus explicitly represented in the vertical space of the canopy (Fig. C). To do so, we introduce crown length cl , calculated as follows for each tree i :

$$cl_i = cs_i \times H_i \quad (\text{Eq. 19})$$

with H being tree height and cs being the ratio of the height with a green crown, which is related to light exposition of the tree (Didion et al. 2009). For each tree i , cs varies between two extreme species-specific values that represent the case where the tree is fully shaded ($cs = cs_{min_s}$) or in full light ($cs = cs_{max_s}$), with:

$$cs_i = cs_{max_s} - (cs_{max_s} - cs_{min_s}) \times k_{LAI_i} \quad (\text{Eq. 20})$$

where the extreme values cs_{max_s} and cs_{min_s} have been derived from the relationship between foliage fresh weight and DBH described in Wehrli et al. (2007) and depends on the foliage type parameter f_s (see Table C), and k_{LAI_i} is the correction factor - ranging from 0 (no shading) to 1 (full shading) - calculated by Didion et al. (2009) as follows:

$$k_{LAI_i} = \min \left[\left(\frac{LAI_{H_i}}{LAI_{max}} \right)^2, 1 \right] \quad (\text{Eq. 21})$$

with LAI_H being the cumulative leaf area index between the top of the canopy and the top of the target tree (i.e. between the top of the canopy and the height H), ie. the cumulative leaf area (in m²) divided by the area of the patch (in m²) and LAI_{max} being the maximum value of double-sided leaf area in a patch resulting from light compensation point in European forests [i.e. $LAI_{max} = 11.98$ (Bugmann 1994, Didion et al. 2009)].

Consequently, to allow the competition among trees whose crowns overlap, the vertical space of the patch p at simulation step $t=t_I$ is discretized in $n(p, t_I)$ layers of a given width w , whose value is bounded between 0 (ground level) to $H_{max}(p, t_1)$ (height of the tallest tree in the patch p at $t=t_I$), with $w = 1$ m. Tree leaf area is assumed to decrease linearly from the top to the base of the crown, i.e. from the highest to the lowest layer in which the crown of the tree is found (Fig. C) (Eermak 1998, Van Pelt et al. 2016). We are aware that tree crown shape and vertical leaf area distribution vary among tree species and are also affected by the size and identity of neighbouring trees (Poorter et al. 2006, Williams et al. 2017, Niklaus et al. 2017). Our assumption should thus be seen as a first parsimonious step that can be refined using species- and context-specific architectural data.

GR_{cs} (Eq. 4) is calculated as follows for each tree i of species s :

$$GR_{cs_i} = \min \left(z \times \frac{cs_i}{cs_{max_s}} \times \frac{LCP_s}{LCP_{mean}}, 1 \right) \quad (\text{Eq. 22})$$

with $z=4/3$, LCP_s is the light compensation point of the species s that directly depends on the shade tolerance parameter $ShTol_s$ as follows

$$LCP_s = LCP_{max} - (LCP_{max} - LCP_{min}) \times \frac{(ShTol_s - ShTol_{max})}{(ShTol_{min} - ShTol_{max})} \quad (\text{Eq. 23})$$

with LCP_{min} and LCP_{max} being the light compensation point of the species with the minimum and maximum value for the shade tolerance parameter $ShTol_s$ respectively, ie. $ShTol_{min}$ ($ShTol_s=9$) and $ShTol_{max}$ ($ShTol_s=1$) (see Table D). LCP_{mean} is the mean light compensation point among the most shade tolerant and the most shade intolerant species across European tree species (Bugmann 1994), ie. $LCP_{mean} = \frac{LCP_{max} - LCP_{min}}{2}$.

For a given patch, foliage area index is calculated for each layer, by summing the foliage area index of all crown parts found in this layer. Thus, for the layer x of width w , the total foliage area index $SumLAI_x$ is:

$$SumLAI_x = \frac{1}{PA} \times \sum_{i|H_i \geq x-w} LA_{i,x} \quad (\text{Eq. 24})$$

with PA being the patch area, H_i the height of tree i , and $LA_{i,x}$ the double-sided leaf area of the crown part of the tree i belonging to layer x , calculated as follows:

$$LA_{i,x} = r_{i,x} \cdot LA \quad (\text{Eq. 25})$$

where $r_{i,x}$ corresponds to the fraction of total foliage found in layer x (assuming a linear decrease in the foliage area, as shown in Fig. C), and the consistency between the layer and whole tree levels being ensured by the fact that:

$$\sum_{x_{H_0} \leq x \leq x_H} r_{i,x} = 1 \quad (\text{Eq. 26})$$

with x_{H_0} and x_H being the layer including the base and the top of the crown of tree i , respectively, and LA being the total double-sided leaf area of a tree, is calculated from tree diameter D as follows (Didion et al. 2009):

$$LA = f'_s \cdot cs \cdot D^{a_s} \quad (\text{Eq. 27})$$

with f'_s and a_s being allometric parameters (see Table C), which depend on the foliage type of the species (parameter f_s , Tables A and B) (Wehrli et al. 2007).

Then, an intermediate variable ($GR_{sh_{i,x}}$) is calculated using light availability L_{av} in the layer according to Beer's extinction law (Botkin et al. 1972, Shugart 1984) to quantify shading intensity in each crown layer of each tree. For a tree i found in layer x , the light availability $L_{av_{i,x}}$ is calculated as follows:

$$L_{av_{i,x}} = r_{i,x} \cdot e^{-k \cdot SumLAI_x} \quad (\text{Eq. 28})$$

with $r_{i,x}$ being the coefficient representing the decrease in foliage area from the top to base of the crown (see Eq. 26) and k is the light extinction coefficient (with $k=0.25$).

Then $GR_{sh_{i,x}}$ is obtained by considering the light response function of a species (Bugmann 1996), as follows:

$$GR_{sh_{i,x}} = \max\left(0, L_{max} + (L_{min} - L_{max}) \times \frac{ShTol_s - ShTol_{max}}{ShTol_{min} - ShTol_{max}}\right) \quad (\text{Eq. 29})$$

with $L_{max} = 1 - c_{max}^{-(L_{av_{i,x}} - 0.05)}$ and $L_{min} = 2.24 \times \left(1 - c_{min}^{-(L_{av_{i,x}} - 0.08)}\right)$, c_{max} and c_{min} being constant ($c_{max} = -4.64$ and $c_{min} = -1.136$), and $L_{av_{i,x}}$ being the light availability for tree i found in layer x (see Eq. 26).

Finally, the reduction factor related to shading by competing trees (GR_{sh_i}) is calculated for a tree i by summing the $GR_{LA_{i,x}}$ of all crown parts of the tree:

$$GR_{sh_i} = \sum_x GR_{sh_{i,x}} \quad (\text{Eq. 30})$$

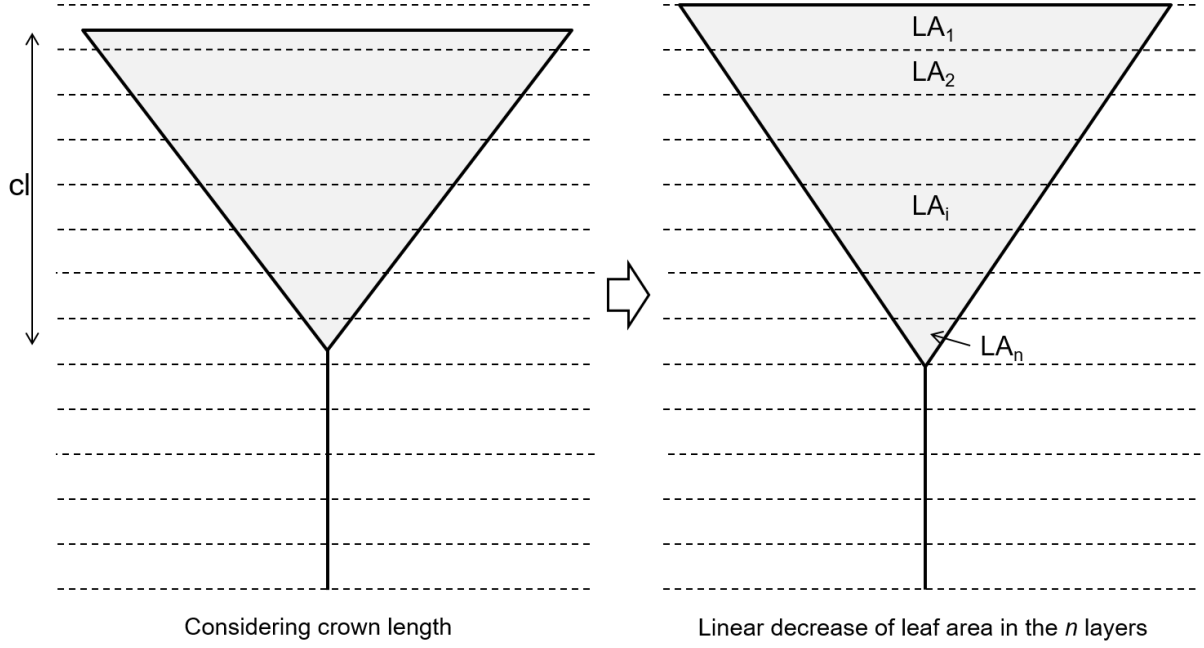


Figure C. Representation of the foliage distribution at the tree level in ForCEEPS. In ForCEEPS, the foliage is distributed in the vertical space along the crown length of the tree (“ cl ” on lower panel), and tree leaf area was assumed to decrease linearly from the top to the base of the crown, through the discretization of the vertical space in layers as represented in the lower panel. H is the total height of the tree.

Tree mortality

The probability $P_{mort,i}$ that tree i dies on year y depends on two components: (i) a “background” mortality P_0 , and (ii) a growth-related mortality P_g :

$$P_{mort,i} = \max(P_0, P_g) \quad (\text{Eq. 30})$$

P_0 is calculated as follows:

$$P_0 = \begin{cases} 0, & m_0 < p_{dist} \\ 1, & m_0 \geq p_{dist} \end{cases} \quad (\text{Eq.31})$$

With m_0 being a random number sorted between 0 and 1, and p_{dist} being a constant representing the background or disturbance probability (see Table D). The background mortality P_0 is thus

purely stochastic and depends on species' maximum longevity, and is implemented to consider mortality events induced by 'random' small-scale disturbances (e.g., attack of pathogen in an endemic phase), but large-scale disturbances (e.g., windthrows, wildfires) can be taken into account by increasing the background mortality rate (ie. p_{dist} , Table D for an example of parameter value)

The growth-related mortality is a proxy for stress conditions and considers that tree mortality probability increases with the decrease in absolute or relative tree growth rates (i.e. tree vigor) induced by abiotic factors or by competition. P_g is calculated as follows:

$$P_g = P_{age} + (1 - P_{age}) \times P_{stress,i} \quad (\text{Eq. 32})$$

P_{age} is the age-related mortality probability, depending on the maximum age of the species A_{maxS} :

$$P_{age} = \frac{k_{death}}{A_{maxS}} \quad (\text{Eq. 33})$$

with k_{death} being a constant, corresponding to a death probability coefficient (Table D).

P_{stress} is the stress-induced mortality probability, which depends on tree growth, calculated as follows:

$$P_{stress,i} = \begin{cases} p_{slowgr}, & \text{SlowGr}_i \geq k_{SlowGrTime} \\ 0, & \text{elsewhere} \end{cases} \quad (\text{Eq. 34})$$

With p_{slowgr} being a constant representing the mortality probability for stressed trees (Table D), SlowGr_i is an index corresponding to the number of ongoing consecutive years for which the growth of tree i is lower than the threshold t_{slowgr} (constant, Table D), and $k_{SlowGrTime}$ is a constant (in years, Table D) representing the number of years of slow growth after which the tree is considered as stressed (Bugmann 1994, Bugmann 1996).

Finally $P_{mort,i}$ is compared to a random number m_{tot} comprised between 0 and 1. If $m_{tot} < P_{mort,i}$ then tree i dies.

Tree biomass

In ForCEEPS, the total aboveground biomass of a tree is divided in its stem wood biomass and foliage weight, that are both estimated by using allometric equations (Bugmann 1994; Werhli et al. 2007; Didion et al. 2009) and are summed to calculate the total aboveground biomass.

Foliage weight F_w depends on stem diameter at breast height D and crown size cs , as follows:

$$F_w = f''_s \times cs \times D^{a_s} \quad (\text{Eq. 35})$$

with f''_s and a_s being allometric parameters (see Table C), which depend on the foliage type of the species (parameter f_s , see Table 1) (Wehrli et al. 2007). Note that $F_w = \frac{f''_s}{f'_s} \times LA$ (see Eq. 26).

Stem wood biomass B only depends on stem diameter at breast height D as follows (Bugmann 1994):

$$B = 0.12 \times D^{2.4} \quad (\text{Eq. 36})$$

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Tables

Table A

Description of species parameters in ForCEEPS.

Parameter	Details	Unit
f_s	Foliage type	Unitless E - evergreen - or D - deciduous and a number between 1 and 5
$Hmax_s$	Maximum height	m
s_s	Allometry	Unitless
g_s	Optimal growth	Unitless
$Amax_s$	Maximum age	years
$DDmin_s$	Minimal required annual or seasonal degree-days sum	°C
$DrTol_s$	Drought tolerance index, to be compared to the evapotranspiration deficit based on a bucket model of soil moisture	Continuous index with values between 0 (sensitive) to 1 (tolerant)
$Nreq_s$	Soil nitrogen requirement	Integer Index with values between 1 (weak requirements) to 5 (strong req.)
$ShTol_s$	Shade tolerance	Integer index with values between 1 (shade tolerant) to 9 (shade intolerant)
$ShTol_seedling_s$	Shade tolerance of seedlings, to be compared to the relative amount of light reaching the ground	Continuous index with values between 0 (tolerant) to 1 (sensitive)
$Wtmin_s$	Monthly minimum winter temperature tolerated for regeneration (°C)	°C
$Wtmax_s$	Monthly maximum winter temperature tolerated for regeneration	°C
Br_s	Browsing susceptibility of seedlings	Integer index with values between 1 (less susceptible) to 5 (more susceptible)

Table B

ForCEEPS parameters for the species calibrated in this study. Parameter description, and literature used to calibrate all or part of the species for specific parameters can be found in Table 1.

	Species	fS	HmaxS	sS	gS	AmaxS	DDminS	DrToIS	NreqS	ShToIS	ShTol_seedlingS	WtminS	WtmaxS	BrS
main species	<i>Abies alba</i>	E5	50	75	350	366	841	0.23	3	1	0.05	-6	5	5
	<i>Picea abies</i>	E5	48	83	355	300	421	0.11	2	5	0.1	-20	3	2
	<i>Pinus halepensis</i>	E4	22	69	399	200	1261	0.48	1	7	0.25	2	13	3
	<i>Pinus pinaster</i>	E4	35	69	350	300	1121	0.4	1	7	0.25	-1	12	3
	<i>Pinus sylvestris</i>	E4	35	58	150	200	631	0.37	1	9	0.3	-20	5	3
	<i>Fagus sylvatica</i>	D3	50	76	260	400	841	0.25	2	1	0.05	-6	9	3
	<i>Quercus ilex</i>	E4	23	48	79	500	1121	0.45	1	5	0.1	0	14	1
	<i>Quercus petraea</i>	D3	45	76	246	1000	981	0.33	2	7	0.2	-7	10	4
	<i>Quercus robur</i>	D3	45	66	249	1000	631	0.3	2	9	0.3	-10	10	4
	<i>Larix decidua</i>	D2	35	72	170	500	600	0.25	1	9	0.4	-8	-5	3
other species	<i>Pinus cembra</i>	E5	25	40	115	1000	600	0.3	1	5	0.2	-9	-2	4
	<i>Acer campestre</i>	D2	23	100	156	170	1051	0.33	3	5	0.1	-8	8	4
	<i>Acer platanoides</i>	D3	30	108	142	200	631	0.25	5	4	0.025	-17	10	4
	<i>Acer pseudoplatanus</i>	D3	30	100	125	500	771	0.25	4	4	0.025	-7	8	4
	<i>Betula pendula</i>	D1	20	103	278	150	491	0.22	1	9	0.3	-15	9	1
	<i>Carpinus betulus</i>	D3	30	104	300	220	898	0.25	4	3	0.075	-9	9	2
	<i>Fraxinus excelsior</i>	D2	32	86	177	250	911	0.16	5	6	0.075	-8	9	3
	<i>Populus tremula</i>	D2	25	126	310	140	421	0.25	2	7	0.2	-20	9	2
	<i>Quercus pubescens</i>	D3	35	60	146	600	981	0.33	2	7	0.3	-4	9	4
	<i>Sorbus aria</i>	D2	22	66	82	180	650	0.33	4	7	0.2	-20	12	4
	<i>Sorbus aucuparia</i>	D1	20	107	167	110	491	0.33	3	7	0.2	-15	7	4
	<i>Ulmus glabra</i>	D3	43	127	153	480	631	0.25	5	3	0.075	-8	9	3

Table C

ForCEEPS species-specific parameters derived from other species parameters.

	Species	fS	NreqS	Derived from fS					Derived from NreqS	
				aS	f'S	f''S	cminS	cmaxS	n1S	n2S
main species	<i>Abies alba</i>	E5	3	1.5	0.45	6	0.09	0.53	-0.020	20
	<i>Picea abies</i>	E5	2	1.5	0.45	6	0.09	0.53	-0.019	10
	<i>Pinus halepensis</i>	E4	1	1.4	0.45	6	0.071	0.346	-0.019	2.5
	<i>Pinus pinaster</i>	E4	1	1.4	0.45	6	0.071	0.346	-0.019	2.5
	<i>Pinus sylvestris</i>	E4	1	1.4	0.45	6	0.071	0.346	-0.019	2.5
	<i>Fagus sylvatica</i>	D3	2	1.7	0.35	12	0.025	0.1084	-0.019	10
	<i>Quercus ilex</i>	E4	1	1.4	0.45	6	0.071	0.346	-0.019	2.5
	<i>Quercus petraea</i>	D3	2	1.7	0.35	12	0.025	0.1084	-0.019	10
	<i>Quercus robur</i>	D3	2	1.7	0.35	12	0.025	0.1084	-0.019	10
other species	<i>Larix decidua</i>	D2	1	1.4	0.35	12	0.048	0.221	-0.019	2.5
	<i>Pinus cembra</i>	E5	1	1.5	0.45	6	0.09	0.53	-0.019	2.5
	<i>Acer campestre</i>	D2	3	1.4	0.35	12	0.048	0.221	-0.020	20
	<i>Acer platanoides</i>	D3	5	1.7	0.35	12	0.025	0.1084	-0.024	50
	<i>Acer pseudoplatanus</i>	D3	4	1.7	0.35	12	0.025	0.1084	-0.022	35
	<i>Betula pendula</i>	D1	1	1.4	0.35	12	0.038	0.1768	-0.019	2.5
	<i>Carpinus betulus</i>	D3	4	1.7	0.35	12	0.025	0.1084	-0.022	35
	<i>Fraxinus excelsior</i>	D2	5	1.4	0.35	12	0.048	0.221	-0.024	50
	<i>Populus tremula</i>	D2	2	1.4	0.35	12	0.048	0.221	-0.019	10
	<i>Quercus pubescens</i>	D3	2	1.7	0.35	12	0.025	0.1084	-0.019	10
	<i>Sorbus aria</i>	D2	4	1.4	0.35	12	0.048	0.221	-0.022	35
	<i>Sorbus aucuparia</i>	D1	3	1.4	0.35	12	0.038	0.1768	-0.020	20
	<i>Ulmus glabra</i>	D3	5	1.7	0.35	12	0.025	0.1084	-0.024	50

Table D

Description of intrinsic parameters in ForCEEPS. Parameters written in blue means that the values can be changed according to the simulation.

Parameter	Value	Unit
LCP_{max}	11.98	-
LCP_{min}	10.10	-
k_{death}	4.605	-
p_{slowgr}	0.368	-
t_{slowgr}	0.03	cm.yr ⁻¹
$k_{SlowGrTime}$	3	yr
k_{EstNr}	0.006	-
$k_{PatchSize}$	1000	m ²
p_{dist}	0.005	-