
ForClim Documentation

Release 4.2

Forest Ecology Group - ETH Zürich

10.02.2025

CONTENTS

1	Model structure	1
1.1	Overview	1
1.2	Novel aspects of <i>ForClim</i> version 4.2.	2
1.3	Features of <i>ForClim</i> version 4.1.	2
1.4	Features of <i>ForClim</i> version 4.0.1.	4
1.5	Model variants	5
2	The Weather submodel	7
2.1	Generation of weather data	7
2.2	Calculation of bioclimatic variables	7
3	The Water submodel	9
4	The Plant submodel	13
4.1	Light environment	13
4.2	Tree growth	14
4.3	Tree establishment	17
4.4	Tree mortality	21
5	The Management submodel	27
5.1	Harvest types	27
5.2	Regeneration	30
6	References	31

MODEL STRUCTURE

1.1 Overview

ForClim is a cohort-based model that was developed to analyze successional pathways of various forest types in Central Europe (Bugmann 1996). Following the standard approach of gap models (e.g. Botkin et al. 1972), *ForClim* simulates the establishment, growth and mortality of trees on multiple independent patches (typically $n = 200$) in annual time steps to derive regional-scale stand dynamics (Bugmann 1996).

Most forest gap models establish tree individuals with very similar sizes (Shugart 1984). Since tree growth in these models is treated deterministically, the size of all the individuals of a given species established in a given year will remain similar throughout their lifespan. Thus, saplings are established in cohorts in the *ForClim* model, whereby the trees of a cohort are assumed to have an identical size. Tree growth can then be calculated once for each cohort instead of each tree.

ForClim is structured in four submodels interconnected by shared variables (Fig. 1). *Weather* provides time-dependent abiotic variables, generates weather data and calculates bioclimatic output variables. *Water* uses the site-specific parameters together with outputs from *Weather* for computing site-specific drought indices. Output variables from *Weather* and *Water* are used in *Plant* to simulate establishment, growth and mortality of trees. In addition, management interventions can be simulated explicitly by applying a wide range of planting, cutting and thinning techniques defined in the *Management* submodel.

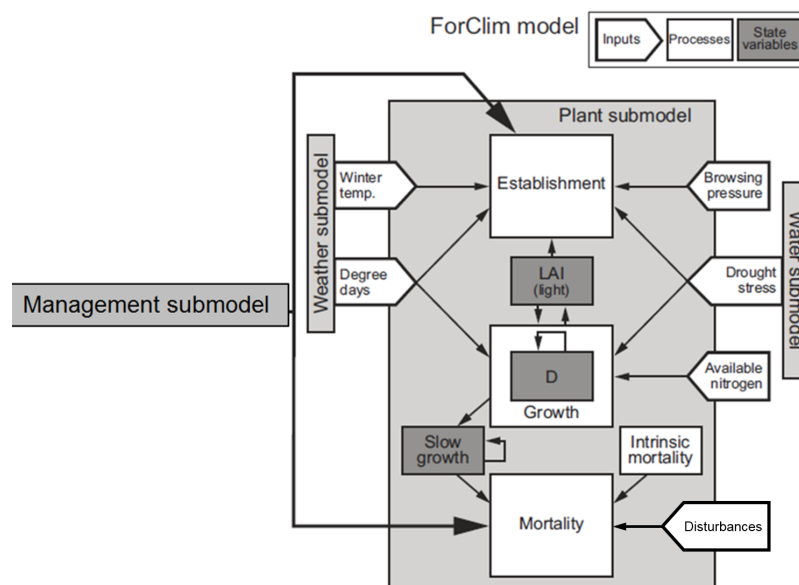


Fig. 1: Structure of *ForClim* (adapted from Rasche et al. 2011).

1.2 Novel aspects of *ForClim* version 4.2.

Compared to the previous *ForClim* versions 4.1. (see section 1.2 below), *ForClim* 4.2 uses an empirically based formulation for estimating bark beetle (mainly *Ips typographus* L.) disturbance probability for Norway spruce was derived to add contributing factors (C) to the PI scheme of *ForClim* v4.1 (Marano et al., 2025; Manion 1981). This was necessary since drought-related spruce mortality is often amplified by bark beetle outbreaks. The bark beetle model consists of a base probability for a beetle outbreak, which is composed of (1) a base annual probability, (2) a flag for a potential year of infestation, and (3) an inciting drought stress term, as explained below

- Base annual probability of bark beetle outbreak: The base annual probability for a bark beetle outbreak (P_{bark}) was derived from the theoretical probability of bark beetle disturbance in spruce-dominated forests (Hlásny et al. 2021, their Fig. 4). We adapted the disturbance map from Hlásny et al. (2021) to obtain a base probability of bark beetle outbreaks for Germany under the climate of 1979-1990 (cf. Hlásny et al., 2021, their Figure 4 and Appendix 2). We converted the original six qualitative classes for the outbreak probability (i.e., No Spruce, Very Low, Low, Medium, High, and Very High) into quantitative values from 0 to 100
- Potential year of infestation: to identify a potential year of infestation, we assessed the estimated number of bark beetle generations in that year (g_{Gen}) against the date the status of trees was based on the intensity of drought within that year. The normal bark beetle generation risk threshold was parameterized based on cumulative spruce saw (mDDAn) from Jakoby et al. (2020).

$$g_{Gen} = \begin{cases} 0, & \text{if } mDDAn \leq 400, \\ \frac{mDDAn - 400}{1600}, & \text{if } 400 < mDDAn \leq 2000, \\ 2, & \text{if } mDDAn \geq 2000, \end{cases} \quad (1.1)$$

- Inciting factor for drought stress: to account for the fact that drought stress weakens spruce trees, we considered a drought-related sensitivity threshold (“drought tolerance,” $k_{Beetle_{DrTol}}$) based on the species-specific drought tolerance parameter (k_{DrTol} , Bugmann and Cramer, 1998) scaled by a factor of $\frac{2}{3}$, in order to allow moderate drought events to have a noticeable effect on spruce vigor.

$$k_{Beetle_{DrTol}} = k_{DrTol} \cdot \frac{2}{3} \quad (1.2)$$

- The overall probability of tree mortality induced by bark beetle (P_{Dist}) was then determined by the interplay of biotic factors (i.e., the number of bark beetle generations g_{Gen}) and environmental stressors (i.e., annual drought stress; $mDrAn$) that identify a potential year of bark beetle infestation, and finally the predisposing factor of the drought memory ($uDrM$) (for details, see Marano et al. 2025):

$$P_{Dist} = \begin{cases} p_{Bark}, & \text{if } (g_{Gen} > 1.5) \wedge (mDrAn > k_{Beetle_{DrTol}}) \wedge (uDrM > 1), \\ 0, & \text{else.} \end{cases} \quad (1.3)$$

Further details on the the new bark beetle model can be found at (Marano et al. submitted),

1.3 Features of *ForClim* version 4.1.

Compared to the previous *ForClim* versions 4.0.1. (see section 1.3 below), *ForClim* 4.1 uses:

- distributed soil buckets across patches: The lognormal probability distribution is often used to model skewed and left-truncated variables (i.e. variables that cannot be negative, neither 0). It was in this case elected to model and attribute to each forest patch its own soil properties, namely the bucket size (kBS). In a first step, a value for kBS_{min} and kBS_{mean} are provided. In a second step, the standard deviation and mean of the lognormal distribution are calculated by the model using these new parameters. (Marano et al. submitted),

- weather timeseries: To accurately capture the influence of drought within specific time frames, such as the notable drought events of 2003, 2015, and 2018, we recognized the necessity of utilizing precipitation and temperature time series data. Such time series provide a detailed account of weather conditions, allowing to model and analyze the drought signals. Stochasticity is also preseved as a unique bucket size value is assigned to each patch. (Marano et al. submitted),
- an alternative growth-reduction factor (*GRF*) formulation, which reduces growth under suboptimal conditions more strongly than the previously applied *GRF*. The new formulation applies the Lieblig’s law of the minimum between the soil moisture growth reduction factor *SMGF* and the degree day growth reduction factor *DDGF*. The formulation is therefore:

$$GRF = \sqrt{CLGF \cdot SNGF \cdot ALGF} \cdot \min(SMGF, DDGF) \quad (1.4)$$

where *GRF* is the overall growth reduction factor, and *CLGF*, *SNGF* and *ALGF* are the crown-related, nitrogen-related and light-related growth factors, respectively. (Marano et al. submitted),

- a re-parameterization of the species-specific minimum degree days (kDD_{\min}) derived by applying the Newton-Raphson algorithm: In the new GRF formulation, we enhanced the growth response to climatic extremes by applying Liebig’s law of the minimum between temperature and soil water dynamics. According to the new formulation, however, the growth reduction associated with temperature (*DDGF*) was substantially smaller in ForClim 4.0.1. than the new DDGF in ForClim v4.1, since it was part of the root function extending to *DDGF* in v4.0.1 but is used as a multiplier in v4.1. This has considerable impacts on forest dynamics, particularly in the extremely cold and/or extremely dry conditions, hence a re-parameterization of this species-specific parameter was necessary. (Marano et al. submitted),
- a new *kRedMax* reduction formulation: When utilizing weather time series in ForClim simulations, it is logical to dynamically calculate the maximum height that trees (*gHMax*) can reach each year, rather than to determine it once based on the assumption of a constant “current” climate (cf. Rasche et al. 2012). This approach is necessary because weather time series are inherently non-stationary, i.e. they usually exhibit variability and trends over time. Rasche et al. (2012) developed the *kRedMax* parameter to quantify the maximum reduction in tree height using data from the Swiss National Forest Inventory (NFI) and Growth-and-Yield plots. This parameter was designed to reflect the maximum height reduction due to environmental stressors, particularly drought and degree-days. However, this approach is severely limited as it considers productive forests, potentially misrepresenting the ecological dynamics at the distributional limits of forests. Therefore we assumed that the minimum height parameter, kH_{\min} , should reflect the minimum height that trees (which survive for a long time) can achieve at their distributional limits, such as the treeline. In this case, we assumed a minimum of 15 m for tree species growing at the treeline limit. (Marano et al. submitted),
- To disentangle predisposing and inciting factors leading to drought-related mortality, we identified short-term (within the year) and long-term (multi-year) stressors linked to drought duration and intensity as well as carbon starvation. We defined drought duration (*gDrD*, Eq. 7) as the ratio of a number of months (*n*) relative to the total number of months *m* in a period (i.e. growing period for deciduous species, m_{gp} ; annual for evergreen species, m_{an}). The algorithm selects only those months in which the monthly temperature (T_m) is above a certain threshold ($j = 5.5^\circ\text{C}$) and at the same time, the monthly transpiration (kEg_m , cm) is considerably below monthly water demand from the soil (gD_m , cm; i.e., $gE_m/gD_m < kEg$; and $SM_m < kBS$).

$$gDrD_{gp} = \frac{1}{m_{gp}} \sum_{m=4}^{10} \mathbb{1}(T_m \geq kI) \cdot \mathbb{1}(SM_m < kBS) \cdot \mathbb{1}\left(\frac{gE_m}{gD_m} < kEg\right) \quad (1.5)$$

Drought duration is used in combination with two other variables to determine an inciting factor for drought stress (*IncFDr*), which we derived by modifying the original drought formulation by Bugmann and Cramer (1998) by applying multiple nested conditions to the monthly soil moisture balance, as:

$$IncFDr = \begin{cases} 1, & gDrD > k \wedge SM_{spring} < kREW_{spring} \cdot kBS \wedge SM_{fall} < kREW_{fall} \cdot kBS \\ 0, & \text{else} \end{cases} \quad (1.6)$$

IncFDr consists of two elements, i.e. 1) the duration of the drought, which has to be longer than a threshold k ; and 2) the seasonal water deficit in spring and fall that is parameterized via two thresholds of ‘relative extractable water’ (REW; Bréda et al., 2006; Granier et al., 1999, SM D.4). The spring component of *IncFDr* reflects the need of trees to mobilize water for bud break and cell growth, while the fall component reflects the need of accumulating reserves for the subsequent year. The factor *IncFDr* thus selects those years in which the overall growing season is characterized by a sub-optimal E/D ratio and a seasonal soil water deficit. The threshold k reflects the fraction of the growing season when soil moisture limits tree-physiological processes. It was set to 0.28, corresponding to two months out of a seven-month growing period ($2/7 \approx 0.28$) for broadleaves and three to four months out of the whole year ($3.5/12 \approx 0.29$) for evergreen species, provided that winters are warm enough (cf. Hidy et al., 2021; Merganičová, 2023). The seasonal soil moisture levels in fall and spring (SM_{fall} , SM_{spring}) are also computed within the growing or annual season, depending on the species.

Lastly, we accounted for the effect of long versus short-lasting droughts by developing a predisposing factor using a drought memory term (*DrM*; Wang et al., 2012), as:

$$DrM = \begin{cases} DrM + 1, & gDr > kDrTh \cdot kDrTol \\ 0, & \text{else} \end{cases} \quad (1.7)$$

The formulation counts all continuous years in which the drought intensity, represented via the ForClim drought index (gDr), exceeds a threshold ($kDrTh$) relative to the species-specific drought tolerance parameter ($kDrTols$). In this manner, we account for the species-specific resistance to multi-annual drought stress based on their drought tolerance. Lastly, we modified the slow growth formulation *SGr* to mimic carbon reserves.

- a new *kPStress* mortality formulation: The overall stress-induced mortality probability ($gPStr$), including the carbon memory and integrating predisposing as well as inciting factors, as:

$$gPStr = \begin{cases} kStressP, & SGr > kSGrT \vee (DrM > kSGrT \wedge IncFDr = 1) \\ 0, & \text{else} \end{cases} \quad (1.8)$$

where $kStressP$ is the stress-induced enhanced mortality probability, *SGr* the slow-growth counter, while $kSGrT$ indicates the number of stress years that are tolerated until mortality probability is enhanced. The first term of the equation (*SGr*), indicates the probability that a tree may die due to slow growth induced by whatever cause (e.g., insufficient light), whereas the second terms (*DrM* and *IncFDr*) reflect that a string of dry years can enhance mortality if a particularly prolonged summer drought period coupled to early and late soil moisture depletion occurs.

The ensemble of these new features results in the model ForClim v4.1. (Marano et al. submitted),

1.4 Features of ForClim version 4.0.1.

Compared to previous *ForClim* versions, *ForClim* 4.0.1. uses

- a re-parameterization of the maximum growth rate (kG) derived from a large set of individual tree-ring chronologies (Huber et al.2020),
- an alternative growth-reduction factor (*GRF*), which reduces growth under suboptimal conditions more strongly than the previously applied *GRF* (Huber et al. 2020),
- revised species parameters (Huber et al. 2020 and Huber et al. in prep.),
- an adapted version of the snow accumulation-and melt module by McCabe and Wolock (2009) (Huber et al. 2019), and

- depending on the model variant applied, an alternative formulation for establishment (E_6/E_6^*), the allocation of growth into height and diameter (A_2), and background mortality (M_1 ; Huber et al. 2020).

1.5 Model variants

In contrast to earlier model versions (up to v3.5), several model variants can be used to account for uncertainties in model structure and parameters (Table 1; Huber et al. 2020, Huber et al. in prep.). These variants differ with respect to the establishment routine (E ; E_0 vs. E_6/E_6^* , where E_0 refers to the standard formulation; see section 4.3.1), the allocation of growth to height vs. diameter growth (A ; A_0 vs. A_2 ; see section 4.2.2), and the background mortality (M ; M_0 vs. M_1 ; see section 4.4.1).

Table 1: Model variants

Variant ID	Establishment	Allocation of growth	Background mortality
1	E_0	A_0	M_0
2	E_0	A_2	M_0
3	E_0	A_0	M_1
4	E_0	A_2	M_1
11	E_6	A_0	M_0
12	E_6	A_2	M_0
13	E_6	A_0	M_1
14	E_6	A_2	M_1
21	E_6^*	A_0	M_0
22	E_6^*	A_2	M_0
23	E_6^*	A_0	M_1
24	E_6^*	A_2	M_1

THE WEATHER SUBMODEL

2.1 Generation of weather data

In *ForClim*, the calculation of bioclimatic indices depends on temperature and precipitation data only (**Table 2**).

Weather generator

As default, the monthly means of temperature (T) and precipitation (P) are sampled stochastically from their respective long-term statistics by taking into account the cross-correlation between the variables. Values of standard deviations and cross-correlation between monthly temperatures and precipitations must be provided in the *ForClim* input file. Precipitation needs to be log-transformed. The actual monthly mean value of the two variables (T and P) is then calculated for each year of the simulation (Bugmann 1994).

For **climate change** applications, the following additional input data are required:

- anomalies for the seasonal mean temperature and its standard deviation are expressed as the absolute difference between baseline and future temperatures;
- seasonal precipitation anomalies are expressed as the relative difference (percent) between the baseline and the future precipitation both for the mean and the standard deviation;
- the anomalies of the monthly cross-correlations expressed as the absolute difference between the corresponding values for the two periods (baseline and future climate).

If climate change is activated, anomalies of the means, standard deviations, and cross-correlations are added (in case of absolute differences) or multiplied (in case of relative differences) to the current climate, and the weather generator is used to derive climate values of a future climate (Didion et al. 2011).

Time series data

If desired, simulations can be run with observed or projected weather time series. In this case, input precipitation (in cm) in the separate weather input file is not log transformed and the weather input flag (*kWI*) is set to True in the setup file.

2.2 Calculation of bioclimatic variables

Winter minimum temperature (uWiT)

Winter minimum temperature (uWiT) is a variable that influences sapling establishment. ForClim uses the minimum of the actual mean temperature of the winter months (December, January, and February) as a proxy for *uWiT*:

$$uWiT = \min(TDec_{y-1}, TJan_y, TFeb_y) \quad (2.1)$$

Degree-days (uDDAn, uDDSe)

The concept of degree-days - a linear dependency of the growth rate on temperature above a threshold temperature - is used in most forest gap models (Shugart 1984). Degree-days have an influence on both establishment and tree growth.

For recognizing that the length of the growing season is restricted by the leafless season for deciduous trees, whereas evergreen trees can fix CO_2 throughout the year as long as temperatures are high enough, the degree-days variable is calculated differently for evergreen (annual degree-day sum $uDDAn$) and deciduous species (seasonal degree-day sum $uDDSe$), respectively:

$$uDDAn = \sum_{T_m \geq k} [MAX(T_m - k, 0) * kDays + gCorr(T_m)] \quad (2.2)$$

$$uDDSe = \sum_{T_m \geq k, m[Apr-Oct]} [MAX(T_m - k, 0) * kDays + gCorr(T_m)] \quad (2.3)$$

T_m is the mean temperature of the month m , $gCorr$ is an empirical function that corrects the bias induced by estimating monthly growing degree-days from monthly mean temperatures, $kDays$ is the average number of days per month (30.5 by default) and k is a threshold temperature (5.5°C; Bugmann 1994).

Table 2: Important parameters and variables of the *Weather* submodel. Variables or parameters in (*italics*) refer to the respective names in *ForClim* input or output files.

Code	Unit	Value	Signification
<i>Site – specific input variables</i>			
mT	[°C]	[-1 to 1]	Long-term mean of monthly mean temperature
mP	[cm/month]		Log-transformed long-term mean of monthly mean precipitation sum
sdT	[°C]		Standard deviation of monthly mean temperatures
sdP	[cm/month]		Standard deviation of mP
rTP	[-]		Long term monthly cross-correlation of temperature and precipitation
CC_start	year		Start year of climate change
CC_end	year		End year of climate change
CC_mT	[°C]		Change in seasonal temperatures (sp, s, f, w) to have occurred by CC_end (spring: mar-may, summer: jun-aug, fall: sep-nov, winter: dec-feb)
CC_mP	[-]		Fraction of mean seasonal precipitation (sp, s, f, w) available by CC_end relative to CC_start
CC_sdT	[°C]		Change in seasonal sdT (sp, s, f, w) to have occurred by CC_end
CC_sdP	[-]		Relative change in seasonal sdP (sp, s, f, w) to have occurred by CC_end
CC_rTP	[-]		Change in seasonal cross-correlation (sp, s, f, w) by CC_end
<i>Other base parameters</i>			
kCC	[-]	[True, False]	Climate change flag (<i>isCC</i>)
kDays	[days]	30.5	Average number of days per month
kDTT	[°C]	5.5	Development threshold temperature (k)
kWI	[-]	[True, False]	Weather input flag (<i>isWeatherInput</i> ; "True" for time series data)
<i>State variables</i>			
T	[°C]		Actual monthly mean temperatures
P	[cm/month]		Actual monthly mean precipitation sums
<i>Output variables</i>			
uDD	[°C*days]		Monthly sum of degree-days
uDDAn	[°C*days]		Annual sum of degree-days
uDDSe	[°C*days]		Seasonal sum of degree-days
uT	[°C]		Actual monthly mean temperatures
uP	[cm/month]		Actual monthly mean precipitation sums
uWiT	[°C]		Minimum winter temperature

THE WATER SUBMODEL

ForClim uses a modified version of the simple soil water balance model by [Thornthwaite and Mather \(1957\)](#) to calculate evapotranspiration, but incorporates essential concepts that were lacking in the model by Thornthwaite, such as the distinction between supply and demand, and an explicit parameterization of canopy interception ([Bugmann and Cramer 1998](#)). Evapotranspiration is calculated in monthly time steps, considering one soil layer (called 'bucket'), based on mean temperature and precipitation sum only (**Table 3**).

Monthly evapotranspiration from the soil (E_m) is assumed to be equivalent to the lesser of a supply function and a demand function:

$$E_m = \min(S_m, D_m) \quad (3.1)$$

where D_m is the evaporative demand from the soil, and S_m is the supply of water from the soil formulated as:

$$S_m = c_w * \frac{\Omega_m}{\Omega_{max}} \quad (3.2)$$

where c_w is a parameter denoting the maximum evapotranspiration rate from saturated soil under conditions of high demand, Ω_m is soil moisture and Ω_{max} is the water holding capacity of the soil.

The demand function is approximated by an estimate of potential evapotranspiration from which intercepted water is subtracted:

$$D_m = PET_m - P_{i,m} \quad (3.3)$$

where PET_m is potential evapotranspiration and $P_{i,m}$ is the intercepted water.

Potential evapotranspiration is calculated as follows:

$$PET_m = lp * \left(\frac{10}{kHi} * \max[T_m, 0] \right)^{kC} \quad (3.4)$$

where lp is a correction function for sun angle and day length depending on latitude ($kLat$), kHi is a 'heat index' calculated from the long-term monthly mean temperatures T_m , and kC is an empirical equation (for details see [Bugmann and Cramer \(1998\)](#)).

Soil moisture is updated as follows:

$$\Omega_{m+1} = \max(\min(\Omega_m + P_{s,m} - E_m, \Omega_{max})) \quad (3.5)$$

where $P_{s,m}$ is surplus precipitation that infiltrates into the soil.

To account for snow, an adapted version of the snow accumulation-and melt module by [McCabe and Wolock \(2009\)](#) can be applied. Depending on monthly mean temperature (uT_m), surplus precipitation reaches the soil either in the form of water or snow ($Psnow_m$):

$$Psnow_m = \begin{cases} uP_m - P_{i,m} & uT_m \leq -1^\circ C \\ (P_m - P_{i,m}) * \frac{T_{rain} - uT_m}{T_{rain} - T_{snow}} & -1^\circ C < uT_m < 3^\circ C \\ 0 & uT_m \geq 3^\circ C \end{cases} \quad (3.6)$$

where T_{snow} and T_{rain} equal -1°C and 3°C , respectively.

P_{snow} is added to a snow bucket (*snow*), which melts as follows (adapted from McCabe and Wolock (2009), Huber et al. 2019):

$$melt_m = \begin{cases} \max(\alpha * (uT_m - T_{snow}) * d, 10) & uT_m < 5.5^{\circ}\text{C} \\ snow & uT_m \geq 5.5^{\circ}\text{C} \end{cases} \quad (3.7)$$

with the snowmelt coefficient α (0.5) and the average number of days per month d (30.5).

Lastly, annual (*uDrAn*) and seasonal (*uDrSe*) drought indices are derived for evergreen and deciduous species, respectively, considering that the length of the growing season is restricted by the leafless season for deciduous trees. The drought indices explicitly consider the amount of water transpired by the trees relatively to the evaporative demand drawing on soil water.

$$uDrAn = 1 - \sum_{T_m \geq k} \left(\frac{E_m}{D_m} \right) \quad (3.8)$$

$$uDrSe = \sum_{T_m \geq k, m[Apr-Oct]} \left(\frac{E_m}{D_m} \right) \quad (3.9)$$

where T_m is the mean temperature of month m , and k is a threshold temperature (5.5°C). This index reflects the proportion of the resulting growing season when water supply to the trees is insufficient for growth (Bugmann and Solomon 2000).

Table 3: Important parameters and variables of the *Water* submodel. Variables or parameters in (*italics*) refer to the respective names in *ForClim* input or output files.

Code	Unit	Value	Signification
<i>Input variables</i>			
uT	[°C]		Actual monthly mean temperatures
mT	[°C]		Long-term mean of monthly mean temperatures
uP	[cm/month]		Actual monthly mean precipitation sums
mP	[cm/month]		Long-term mean of monthly precipitation sums
<i>Site – specific base parameters</i>			
kBS	[cm]		Bucket size
kBSmin	[cm]		lowest value of the Bucket size
kBSmean	[cm]		mean value of the Bucket size
kLat	[deg]		Geographical latitude
kSlAsp	[-]	[-2 to +2]	Slope and aspect correction factor
kEG	[-]	[0.9]	Threshold of the ration between water supply and demand
kDrTh	[-]	[0.2]	Fraction of the species-specific drought tolerance
<i>Other base parameters</i>			
kCw	[cm/month]	12	Maximum evapotranspiration rate
kDTT	[°C]	5.5	Development threshold temperature (<i>k</i>)
kIcpt	[-]	0.3	Fraction of intercepted water (precipitation and snow)
kSnowM	[-]	[True, False]	Snow module flag (<i>isSnowModule</i> ; "True" for snow module)
kWI	[-]	[True, False]	Weather input flag (<i>isWeatherInput</i> ; "True" for time series data)
T _{rain}	[°C]	3	Threshold temperature above which all monthly precipitation is rain
T _{snow}	[°C]	-1	Threshold temperature below which all monthly precipitation is snow
<i>Output variables</i>			
uAET	[cm]		Monthly actual evapotranspiration
uAETAn	[cm]		Annual actual evapotranspiration
uAETSe	[cm]		Seasonal actual evapotranspiration
uDr	[-]	[0 to 1]	Monthly drought index
uDrAn	[-]	[0 to 1]	Annual drought index
uDrSe	[-]	[0 to 1]	Seasonal drought index
uSM	[cm]		Monthly soil moistures
uSnow	[cm]		Monthly snow cover (cm equivalent water)

THE PLANT SUBMODEL

The *Plant* submodel calculates establishment, growth, and mortality of trees on independent forest patches (typically $n = 200$ and patch size = 800 m^2). It requires bioclimatic variables and nitrogen availability as input. The *Plant* submodel is formulated as a discrete-time model with an annual time step. It simulates **Growth** and **Mortality** before **Establishment** (Table 4).

4.1 Light environment

One of the most important constraints on tree growth is shading, which determines the amount of light a tree receives and thus the amount of energy available for photosynthesis (Shugart 1984). In its initial version, *ForClim* calculated the Leaf Area Index (*LAI*) using a static, allometric relationship between foliage weight and diameter at breast height (*DBH*; Bugmann 1996). However, in dense forests, trees usually have short crowns and lower foliage weight than trees growing alone. In consequence, self-pruning of crowns is considered using a light-dependent dynamic relationship, where foliage weight of a tree with a given *DBH* depends on light conditions at the top of the crown, and varies between a species-specific maximum and minimum (Wehrli et al. 2007, Didion et al. 2009b).

Species-specific parameters are grouped in **species types**, that serve the purposes of separating evergreen (coniferous) from deciduous species, defining common parameters within the same group (i.e. $kC1$, $kC2$) and for calculating the relationship between *DBH* and foliage weight. Eleven species types are used.

Foliage weight for each cohort ($gFolW$) is calculated as a function of *DBH* as follows:

$$gFolW = kC1 * gA1 * DBH^{kA2} \quad (4.1)$$

where $gA1$ is an auxiliary variable that can be interpreted as an indirect linear measure for crown length (Wehrli et al. 2007). Since v3.3, it is calculated as follows (Mina et al. 2017):

$$gA1 = \max(kA1_{min}, kA1_{max} - (kA1_{max} - kA1_{min}) * gLAI) \quad (4.2)$$

where $kA1_{max}$ and $kA1_{min}$ are the maximum and minimum envelope of the relationship between foliage fresh weight and *DBH*, respectively (Fig. 2). $gLAI$ represents the leaf area index factor (*LAI*) that ranges from 0 (no canopy shading) to 1 (full canopy shading).

Since v3.3, $gLAI$ is calculated as follows (Mina et al. 2017):

$$gLAI = \min\left(\frac{gLAI_{init}}{kLAI_{max}}, 1\right) \quad (4.3)$$

where $gLAI_{init}$ is the estimated *LAI* at the top of the tree canopy and $kLAI_{max}$ is the maximum *LAI* in a patch that is achievable for the most shade tolerant species (i.e., $kLCP_{La1}$).

Foliage weight is then used for calculating the cohort foliage area ($gFolA$) in the equation:

$$gFolA = \frac{kC2}{kC1} * gFolW \quad (4.4)$$

The cumulative LAI at a certain cohort height ($gLAI_H$) is calculated as:

$$gLAI_H = \frac{1}{kPatchSize} * \sum_{gH_i \geq gH_c}^n gFolA \quad (4.5)$$

where $kPatchSize$ is the size of the forest patch and n is the number of trees present on the patch.

Lambert-Beer's extinction law is then used to calculate the available light at the height of cohort c as a function of leaf area index:

$$gAL_H = e^{-kLatt * gLAI_H} \quad (4.6)$$

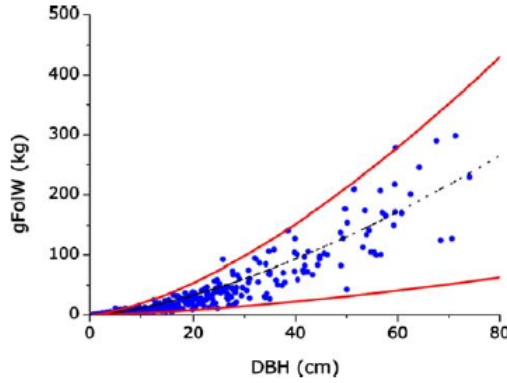


Fig. 2: Relationship between foliage fresh weight ($gFolW$) and DBH for the *Abies alba*–*Picea abies* species group as derived from the data in Burger (1945–1953). The dashed line represents the original relationship included in *ForClim*, solid lines represent the minimum and maximum envelope based on a quantile regression (95%; Wehrli et al. 2007).

4.2 Tree growth

4.2.1 Tree diameter increment

The trees in *ForClim* are characterized by their DBH as a state variable. The simple carbon budget approach proposed by Moore (1989) is used to derive an equation for diameter increment (ΔD). The resulting equation has a form quite similar to the conventional formulation derived by Botkin et al. (1972), but its assumptions conform more to biological expectations:

$$DeltaDBH = kG * DBH * \left(\frac{1 - \frac{H}{kH_{max}}}{2H + f_h * DBH} \right) * GRF \quad (4.7)$$

where H is tree height, kH_{max} is maximum tree height, kG is a growth parameter, f_h is a function that distributes volume growth between diameter and height growth, GRF is a function that reduces maximum growth according to environmental constraints:

$$GRF = \sqrt[2]{DDGF * SMGF * SNGF * ALGF * CLGF} \quad (4.8)$$

with the growth factors for degree days ($DDGF$), soil moisture ($SMGF$), soil nitrogen ($SNGF$), available light ($ALGF$) and crown length ($CLGF$).

In earlier *ForClim* versions (v3.3 to v3.3.5), the following equation was used (Mina et al. 2017):

$$GRF = \sqrt[3]{DDGF * SMGF * SNGF * ALGF * CLGF} \quad (4.9)$$

The new *GRF* (Eq. 4.8) reduces growth under suboptimal conditions more strongly than the earlier *GRF* (Eq. 4.9). It was found to be more appropriate, yet, the growth of trees that are constrained by one factor only (e.g., suppressed trees growing under low-light conditions in otherwise favorable habitat) may be overestimated by both equations (Huber et al. 2020).

Degree-day growth factor *DDGF*

In earlier versions of the model (before v2.9), the effect of summer temperature on tree growth was modeled using a parabolic equation. However, (1) temperatures high enough to inhibit growth never occur even if the warmest parts of temperate tree ranges, and (2) the use of high degree-days levels as a proxy for drought become redundant when drought is introduced as a separate response variable. In consequence, the parabolic function was replaced by an asymptotic version that does not require the specification of the maximum temperature tolerance parameter (Bugmann and Solomon 2000).

$$DDGF = \max \left(0, 1 - e^{(kDDmin - gDD) * kDDSl} \right) \quad (4.10)$$

where *kDDmin* is the species-specific minimal annual degree-day sum, *gDD* is the degree-day index (i.e., *uDDAn* or *uDDSe* for evergreen or deciduous species, respectively) and *kDDSl* is an exponential slope parameter.

Soil moisture growth factor *SMGF*

$$SMGF = \sqrt{\max(0, 1 - gDr / kDrTol)} \quad (4.11)$$

where *gDr* is the annual drought index (i.e., *uDrAn* or *uDrSe* for evergreen or deciduous species, respectively) and *kDrTol* is the species-specific drought tolerance parameter.

Soil nitrogen growth factor *SNGF*

$$SNGF = \max \left(0, 1 - e^{kN1 * (uAvN - kN2)} \right) \quad (4.12)$$

where *kN1* and *kN2* are nitrogen response function parameters and *uAvN* is available nitrogen.

Available light growth factor *ALGF*

The light growth factor of the tree cohort is calculated according to the light response function of the species and the shade tolerance of adult trees (*kLa*):

$$ALGF = \max \left(0, gL1 + (kLa - 1) * \frac{(gL9 - gL1)}{8} \right) \quad (4.13)$$

where *gL1* and *gL9* are the light response functions of shade-tolerant (*gL1*) and shade-intolerant (*gL9*) tree species, respectively, based on light availability (*gALH*, Botkin et al. 1972):

$$gL1 = 1 - e^{-4.64 * (gALH - 0.05)} \quad (4.14)$$

$$gL9 = 2.24 * \left(1 - e^{-1.136 * (gALH - 0.08)} \right) \quad (4.15)$$

Crown length growth factor $CLGF$

$CLGF$ is calculated as an explicit feedback from crown length to tree growth as a decrease in leaf area (at a given diameter and height) of a tree results in a lower growth rate (Didion et al. 2009a, Mina et al. 2017).

$$CLGF = \min \left(\frac{4}{3} * \frac{gA1}{kA1_{max} - kA1_{min}} * \frac{gLCP_{La}}{kLCP_{mean}}, 1 \right) \quad (4.16)$$

where $gLCP_{La}$ is the light compensation point of the specific shade-tolerance class, $gA1$ a relative measure of crown density (Eq. 4.2) and $kLCP_{mean}$ the mean light compensation point for all species parameterized in *ForClim*:

$$kLCP_{mean} = (kLCP_{La1} + kLCP_{La9}) * 0.5 \quad (4.17)$$

where $kLCP_{La1}$ and $kLCP_{La9}$ are the light compensation points for shade-tolerant and shade-intolerant species, respectively.

4.2.2 Tree height growth

In *ForClim*, tree height is a state variable since model version v2.10 (Rasche et al. 2012a). The yearly increase in tree height (ΔH) is simulated as follows:

$$\Delta H = f_h * \Delta DBH \quad (4.18)$$

where the function f_h distributes the volume growth between diameter and height growth:

$$f_h = gS * \left(1 - \frac{H - 1.3}{kH_{max} - 1.3} \right) \quad (4.19)$$

where kH_{max} is maximum tree height and gS expresses the effect of competition (Lindner et al. 1997):

$$gS = kS_{min} + kE_1 * (1 - AL_H) \quad (4.20)$$

where kS_{min} and kE_1 are species-specific parameters and AL_H denotes the relative light availability at the top of the tree crown of a certain cohort.

The parameter values kS_{min} and kE_1 were estimated based on a linear regression between the parameter values of the FORSKA model (Lindner et al. 1997) and the species' shade tolerance (kLa ; Rasche et al. (2012a)):

$$kS_{min} = 1.3 * kLa + 39.5 \quad (4.21)$$

$$kE_1 = 14 * kLa + 13 \quad (4.22)$$

Alternative allocation of growth to height vs. diameter growth A_2

The standard parameterization of kS_{min} (Eq. 4.21) and kE_1 (Eq. 4.22) results in strongly different allocation patterns between shade-tolerant and shade-intolerant species (i.e., leading to very low height growth and strong DBH growth of shade tolerant tree species, particularly *Fagus sylvatica* and *Abies alba*).

In order to reduce this effect, the kLa values are scaled for A_2 to diminish the parameter ranges and thus the very strong differences between shade-tolerant and shade-intolerant species (Huber et al. 2020):

$$kS_{min}(for A_2) = 1.3 * (kLa/3 + 3) + 39.5 \quad (4.23)$$

$$kE_1(for A_2) = 14 * (kLa/3 + 3) + 13 \quad (4.24)$$

Site-specific maximum tree height

The maximum height a tree can reach depends on several factors, most notably available water. Under poor site conditions, stand-specific maximum height is thus reduced by unfavorable temperature (gDD) or drought (gDr) conditions.

In the case of gDr , no reduction of $kHMax$ is assumed when $gDr = 0$ and a maximum reduction ($kRedMax$) was applied when gDr matches $kDrTol$ (i.e. at the dry distribution limit of the species). For intermediate gDr values, a linear decline to $kRedMax$ is assumed (**Fig. 3**).

In the case of gDD , the reduction of $kHMax$ is assumed to be maximal ($kRedMax$) when $gDD = kDDMin$ (species' minimum degree day sum required for growth), using the annual sum of degree-days for evergreen and the seasonal sum for deciduous species.

gDr and gDD are separately used to determine the reduction of $kHMax$ for each species, and subsequently the lower value of both is employed (minimum approach).

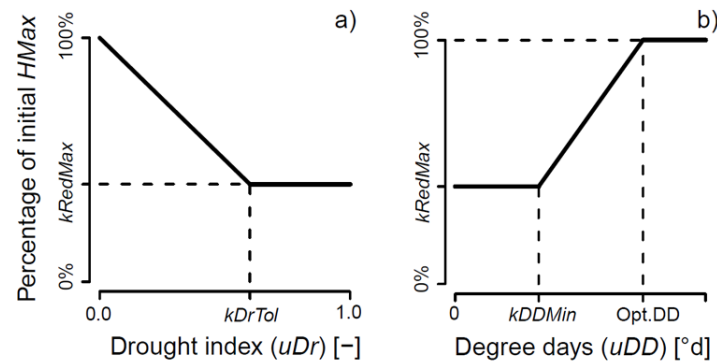


Fig. 3: Site-specific reduction of $kHMax$ based on drought (a) and degree days (b). For the final reduction the lower value is used (Rasche et al. 2012a).

4.3 Tree establishment

ForClim is based on the assumptions that (1) seeds of all species are always present (Botkin et al. 1972) and that (2) establishment of a species is possible only when species-specific environmental and biotic conditions are fulfilled (see section 4.3.2). These are represented by binary "establishment flags" for soil moisture ($SMEF$), winter temperature ($WTEF$), number of growing degree-days ($DDEF$), light availability ($ALEF$), browsing probability ($BPEF$) and immigration ($IMEF$). If a species is able to establish, trees of this species establish as saplings in cohorts of the same species. To facilitate the vertical structuring of cohorts with trees of similar height, normally distributed noise is added on the initial DBH ($kInitDBH$) since *ForClim* version 3.3.5 with a standard deviation of 0.1 ($kInitDBHsd$). In addition, the maximum tree number per cohort is restricted to 50 ($kTreeCohort$).

4.3.1 Establishment routines

In *ForClim* 4.0, two establishment routines can be applied (see section 1.5). The establishment routine E_0 has been used up to model version 3.3.5 and can still be used with the model variants 1-4. The establishment routine E_6/E_6^* has been developed for version 3.3.5 because investigations of the model behavior revealed that the standard assumptions can lead to very strong recruitment limitation of shade-tolerant species that is not supported by recent empirical findings of post-disturbance forest dynamics.

Thus, in contrast to E_0 , the new establishment routine (E_6/E_6^*)

- relaxes the recruitment limitation of shade-tolerant species,

- features a site-specific establishment probability,
- considers interactions within the establishment layer,
- and is less sensitive to the number of species that are used in the simulation and the species' shade tolerances.

Remark: It is suggested to always use E_6^* .

E_0 : Old establishment routine

In addition to the two assumptions introduced above, E_0 assumes that shade-tolerant species establish fewer saplings than shade-intolerant ones (Risch et al. 2005) and that the maximum number of saplings to be established per species in a given year is restricted to a low maximum value (Botkin et al. 1972, Bugmann 1996).

Since interactions within the establishment layer are not considered, the establishment routine is executed iteratively for every species listed in the setup of the respective simulation (Fig. 4). If a species is principally able to establish (i.e., all establishment flags equal 1), the occurrence of sapling establishment is determined by Monte Carlo techniques based on $gPEst$:

$$gPEst = kEstP * SMEF * WTEF * DDEF * ALEF * BPEF * IMEF \quad (4.25)$$

where $gPEst$ is the probability of establishment and $kEstP$ is the establishment probability parameter. Establishment takes place if $gPEst$ is higher than a random number generated within $\cup(0, 1)$. $kEstP$ is used to reduce the probability of establishment $gPEst$ to account for environmental factors that are not considered explicitly by the establishment flags such as pathogens. In the long term, $kEstP$ represents the average fraction of years in which establishment is possible when all five establishment flags have a value of 1. The default value of $kEstP$ is 0.1 (Kienast 1987).

If establishment is allowed for a species, the number of saplings ($nTrs$) is calculated using a random number with uniform distribution in the range $[1 - kEstMax]$ with

$$kEstMax = (int)(0.5 + kEstDens * kPatchSize * kLa) \quad (4.26)$$

where $kEstDens$ is the maximum sapling establishment rate, and $kPatchSize$ is the size of the forest patch (Shugart 1984, Kienast 1987). kLa is the species' shade tolerance serving as a proxy for its rate of seed production (Risch et al. 2005). $kEstMax$ attains values between 60 and 540 saplings/ha for the most shade-tolerant and most shade-intolerant species, respectively.

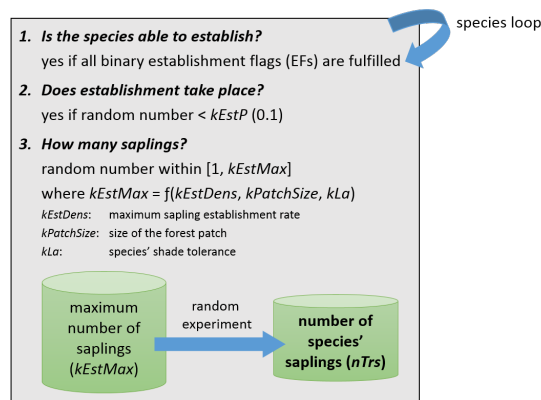


Fig. 4: Old establishment routine of *ForClim*.

E_6 and E_6^* : New establishment routine

In contrast to E_0 , the new establishment routine first deduces the overall number of new saplings based on site and stand characteristics and sub-sequently distributes them across species. In this way, interactions between species can be considered (**Fig. 5**).

First, a random experiment determines whether establishment occurs in the current year or not. Establishment takes place if the establishment probability parameter $kEstP$ is higher than a random number generated within $\cup(0, 1)$. For E_6 , $kEstP$ equals 0.1, while a lower $kEstP$ of 0.04 is assumed for E_6^* . Similar to site-specific maximum tree height, a site-specific $kEstP$ is derived whereby unfavorable temperature or drought conditions reduce $kEstP$. For details, see (Huber et al. 2020).

Second, a species list is generated containing all species for which all establishment flags are fulfilled (i.e., all binary establishment flags equal 1). In addition, continuous establishment flags are calculated (i.e., ranging from 0 to 1; see Huber et al. 2020). For each species, the lowest value is selected (minimum continuous establishment flag: $MinEF$) and stored for use in the last step.

In a third step, the number of new saplings ($nTrs$) is determined. The maximum number of saplings ($gEstMax$) is calculated by reducing maximum tree number ($kTrMax$) by site-specific limitations. These include the number of existing trees, unfavorable temperature and drought, as well as the actual establishment conditions (such as light availability at the forest floor, browsing pressure or chilling requirement). For details, see Huber et al. 2020. Then, the number of saplings ($nTrs$) is determined using a random number with a uniform distribution in the range $[1, gEstMax]$.

Finally, the number of new saplings ($nTrs$) is distributed across the species of the species list (second step) according to their species-specific $MinEF$ s. Thus, a species for which establishment conditions are comparably good is able to establish more saplings than a species for which establishment conditions are harsh. Thus, better-adapted species experience a competitive advantage with respect to sapling number.

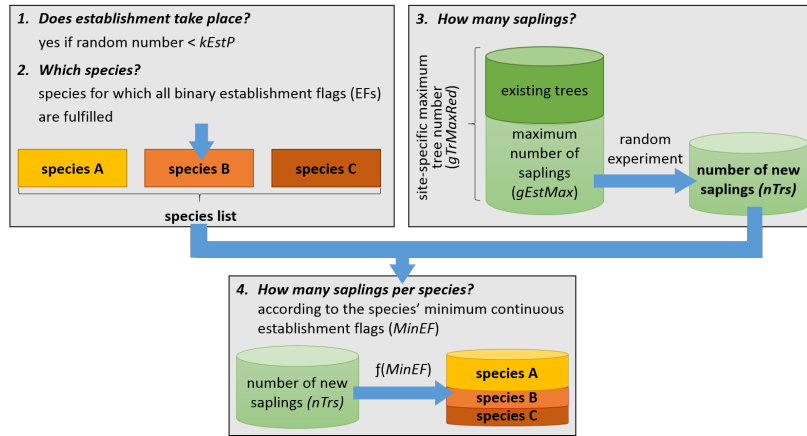


Fig. 5: New establishment routine of *ForClim*.

4.3.2 Establishment flags

The establishment flags are calculated for both establishment routines. They take a value of 1 if current conditions meet the species-specific requirements or 0 if they do not (Bugmann 1994, Bugmann 1996, Didion et al. 2009a) and are calculated as follows:

Soil moisture establishment flag SMEF

$$SMEF = \begin{cases} 1 & kDrTol > uDr \\ 0 & else \end{cases} \quad (4.27)$$

where $kDrTol$ is the species-specific drought tolerance and uDr is the drought index during the growing season.

Winter temperature establishment flag WTEF

$$WTEF = \begin{cases} 1 & kWiT X > uWiT > kWiT N \\ 0 & \text{else} \end{cases} \quad (4.28)$$

where $kWiT X$ and $kWiT N$ are the maximum and minimum threshold of minimum winter temperature tolerated by the species, respectively, and $uWiT$ is the minimum winter temperature. $kWiT X$ and $kWiT N$ were implemented to limit seedling establishment at both southern (chilling requirements) and northern (frost tolerance) areas of the species' distribution range (Bugmann and Solomon 2000).

Degree day establishment flag DDEF

$$DDEF = \begin{cases} 1 & kDDMin < uDD \\ 0 & \text{else} \end{cases} \quad (4.29)$$

where $kDDMin$ is the minimum degree-day requirement of the species and uDD is the sum of degree-days during the growing season.

Available light establishment flag ALEF

$$ALEF = \begin{cases} 1 & kLy < uAL_0 \\ 0 & \text{else} \end{cases} \quad (4.30)$$

where kLy is the sapling shade-tolerance and uAL_0 is the light availability on the floor.

Browsing pressure establishment flag BPEF

$$BPEF = \begin{cases} 1 & U(0,1) > uBrP \\ 0 & \text{else} \end{cases} \quad (4.31)$$

where $U(0,1)$ is a random number with uniform distribution in the range [0-1], and $uBrP$ is the seedling mortality due to browsing. The relationship between browsing pressure ($kBrPr$) and browsing-induced mortality of seedlings ($uBrP$) is

$$uBrP = \left(\frac{kBrPr}{100} \right)^{a_{kBrPr}} \quad (4.32)$$

where $kBrPr$ ranges from 0% (no browsing) to 100% (heavy browsing where no sapling establishment is possible) and a_{kBrPr} is the exponent for five levels of tree species browsing sensitivity ($kBrPr = [1...5]$). The parameter $kBrPr$ is a measure of the browsing related survival probability of seedlings before reaching a DBH of 1.27 cm (Didion et al. 2011).

Immigration establishment flag IMEF

The last factor that modifies sapling establishment rates is introduced to simulate simple immigration scenarios of the tree species:

$$IMEF = \begin{cases} 1 & kImmT < time \\ 0 & \text{else} \end{cases} \quad (4.33)$$

where $kImmT$ is a parameter denoting the first simulation year where the species may establish, and $time$ is the current simulation time.

4.4 Tree mortality

In *ForClim*, overall tree mortality is calculated by combining a background mortality ($gPBgr$), a stress-induced mortality rate ($gPStr$) and a disturbance-related mortality ($gPDist$) (Bugmann 1994).

In contrast to establishment and growth, which are calculated for tree cohorts, the mortality functions are evaluated for each tree individually, *i.e.* the mortality probability does not refer to all the individuals of a tree cohort simultaneously.

The overall mortality probability ($gPMort$) is determined for each tree using Monte Carlo techniques:

$$gPMort = gPDist + (1 - gPDist) * (gPBgr + [1 - gPBgr] * gPStr) \quad (4.34)$$

4.4.1 Background mortality

The background mortality reflects individual tree death due to small-scale disturbance agents that are not modelled explicitly in *ForClim*, such as lightning, attacks by fungi or insects or the death of small trees by falling boles. Two options (M_0 and M_1) can be applied (see section 1.5).

M_0 : Constant background mortality ($gPAge$)

$gPAge$ is calculated by assuming that the annual tree mortality rate is constant throughout tree life (Botkin et al. 1972). This corresponds to the negative exponential curve for survivorship:

$$gS_{t,s} = e^{-gPAge * t} \quad (4.35)$$

where $gS_{t,s}$ is the percentage of survivors of species s at time t . The value of $gP_{m1,s}$ can be determined by assuming that only a small fraction kP of the population reaches maximum age kA_{Max} :

$$gPAge = \frac{-Ln(gS_{t,s})}{t} = \frac{-Ln(kP)}{kA_{Max}} = \frac{kDeathP}{kA_{Max}} \quad (4.36)$$

Assuming $kP = 0.01$ yields $kDeathP = 4.605$, which is the default value of this parameter resulting in constant but species-specific background mortality (Shugart 1984, Bugmann 1994).

Remark: For managed forests, M_0 should be used, especially for sites featuring good growing conditions. This is due to the interplay of GRF and the stress-induced mortality. Investigations of model behavior revealed that the growth of trees that are constrained by one environmental factor only may likely be overestimated, which results in an underestimation of the stress-induced mortality. Since M_0 assumes a higher background mortality probability for trees with small DBH than M_1 , M_0 compensates (at least partly) for the underestimated stress-induced mortality.

M_1 : Size-dependent background mortality ($gPSize$)

The alternative background mortality (M_1) is not constant throughout tree life but increases exponentially with DBH , based on a modified version of the relationship proposed by (Manusch et al. (2012).

$$gPSize = 0.1 * \left(\frac{DBH}{kD_{Max}} \right)^\alpha \quad (4.37)$$

where kD_{Max} represents species-specific maximum DBH and α equals 2.3 (Huber et al. 2020). It can be used since v3.3.5 (see section 1.5).

Remark: M_1 should be used when simulating natural forest dynamics because, in combination with the stress-induced mortality, it represents a U-shaped relationship between DBH and mortality probability. This is in line with ecological theory postulating high competition-induced mortality of small trees and amplified mortality of large trees due to their exposure to a high number of mortality agents. Furthermore, M_0 assumes a distinctly higher background mortality probability for short-lived than long-lived species (due to their lower maximum age), while M_1 assumes a similar, species-independent background mortality probability for small trees, which better adheres to the concept of background mortality.

4.4.2 Stress-induced mortality

The stress-induced mortality ($gPStr$) is based on the assumption that only a small fraction of trees will survive a given number of years when they are subject to stress.

$$gPStr = \begin{cases} kSlowGrP & SGr_c > kSGrT \\ 0 & else \end{cases} \quad (4.38)$$

where SGr_c is the the number of consecutive years the cohort's diameter has increased less than 10% of the maximum diameter increment ($kMinRelInc$) or less than 0.3 mm ($kMinAbsInc$). Hence, SGr_c provides a memory for past environmental stress; therefore it is a state variable:

$$SGr_c(t+1) = \begin{cases} SGr_c(t) + 1 & GRF < kMinRelInc \text{ or } \Delta D_c / \Delta t < kMinAbsInc \\ 0 & else \end{cases} \quad (4.39)$$

V.4.1.: Drought-induced mortality ($gPStr$)

In version 4.1. $gPStr$ is calculated by assuming that a tree can either be killed because of its slow-growth (as in the normal $gPStr$ annual tree mortality probability) or due to a combination of long and short-term stress factors associated to drought-compound events.

$$gPStr = \begin{cases} kStressP, & \text{if } SGr > kSGrT \wedge IncFC = 1 \vee DrM > kSGrT \wedge IncFDr = 1 \\ 0, & else \end{cases} \quad (4.40)$$

(Marano et al. (in preparation)).

Table 4: Important parameters and variables of the *Plant* submodel

Code	Unit	Value	Signification
<i>Base parameters</i>			
$kA1_{max}$	[-]		Maximum for allometric parameter for foliage weight (per species type)
$kA1_{min}$	[-]		Minimum for allometric parameter for foliage weight (per species type)
$kA2$	[-]		Allometric parameter for foliage weight (per species type)
$kAlpha$	[-]	2.3	Exponent in $gPSize$ (α)
$kC1$	[%]		Dry to wet weight ratio of foliage (per species type)
$kC2$	[m ² /kg]		Foliage area per unit foliage weight (per species type)
$kBrPr$	[-]	[0 to 100]	Browsing pressure (site specific)
$kDBHDiffMax$	[cm]	0.5	Maximum difference in DBH to $kInitDBH$
$kDDSI$	[-]	0.001333	Exponential slope parameter in degree-day growth factor
$kDeathP$	[-]	4.605	Mortality probability coefficient
$kDistP$	[-]	[0 to 1]	Probability of occurrence of a disturbance
$kEstDens$		0.006	Maximum sapling establishment rate (for E_0)
$kEstP$	[-]	[0 to 1]	Establishment probability parameter
$kInitDBH$	[cm]		Initial DBH of saplings (1.27 cm) or DBH from inventory for initialization
$kInitDBHMin$	[cm]	0.5	Minimum $kInitDBH$
$kInitDBHSd$	[-]	0.1	Standard deviation of $kInitDBH$
$kLAI_{max}$	[m ² /m ²]		Maximum LAI in a patch
$kLatt$	[-]	0.25	Light attenuation coefficient

Table 4 continued

Code	Unit	Value	Signification
kMinAbsInc	[cm/yr]	0.03	Minimum absolute diameter growth increment
kMinRelInc	[-]	0.1	Minimum relative diameter growth increment
kN1	[-]		Nitrogen response function parameter
kN2	[kg/ha/yr]		Nitrogen response function parameter
kP	[%]		Fraction of population that reaches kA_{Max}
kPatchSize	[m ²]		Size of the forest patch
kSlowGrP	[%]	0.368	Mortality probability for slow-growing tree
kSGrT	[yr]	2	Number of years a tree can grow slowly without being subject to stress-induced mortality (may be set to 3 when using weather time series)
kTreeCohort	[-]		Maximum number of trees established in the same cohort
kTrMax	[individuals/ha]	30000	Maximum tree number (for E_6 and E_6^*)
<i>Species – specific base parameters</i>			
kA_{Max}	[yr]		Maximum age
kBrow	[-]	[1 to 5]	Browsing sensitivity
kDDMin	[°C*days]		Minimal annual degree-day sum
kD_{Max}	[cm]		Maximum <i>DBH</i>
kDrTol	[-]	[0 to 1]	Drought tolerance parameter
kG	[cm/yr]		Growth rate parameter
kHMax	[m]		Maximum possible tree height
kLa	[-]	[1 to 9]	Light requirement of adult trees
kLy	[-]	[1 to 9]	Light requirement of tree saplings
kImmT	[year]		First simulation year the species may establish
kRedMax	[%]	[0 to 100]	Maximal reduction of kH_{max}
kWiTN	[°C]		Minimum winter temperature tolerated
kWiTX	[°C]		Maximum winter temperature tolerated
kREWsp	[-]	[0.9]	Relative Extractable Water Content threshold during spring
kREWau	[-]	[0.5]	Relative Extractable Water Content threshold during autumn
kIncitProb	[-]	[0.5]	Inciting Probability for carbon starvation
<i>State variables</i>			
DBH	[cm]		Tree diameter
H	[cm]		Tree height
<i>Derived variables</i>			
gA1	[-]		Parameter for the allometric relationship between <i>DBH</i> and foliage weight
gA_{LH}	[%]		Light availability at a certain (cohort) height
$gALGF$	[-]		Available light growth factor
$gCLGF$	[-]	[0 to 1]	Crown length growth factor
gDD	[°C*days]		Degree-day index (for evergreen and deciduous species)
$gDDGF$	[-]	[0 to 1]	Degree-day growth factor
gDr	[-]	[0 to 1]	Annual drought index (for evergreen and deciduous species)
$gFolA$	[m ²]		Foliage area
$gFolW$	[kg]		Foliage weight
$gEstMax$			Maximum number of saplings (for E_6 and E_6^*)
$gLAI_H$	[m ² /m ²]		Cumulative leaf area index at a certain (cohort) height
$gLAI_{init}$	[m ² /m ²]		Estimated <i>LAI</i> at the top of the tree canopy (<i>initLAI</i>)
$gLCP_{La}$	[-]		Light compensation point of specific shade-tolerance class
gPAge	[-]	[0 to 1]	Constant background mortality probability (for M_0)
gPBgr	[-]	[0 to 1]	Background mortality probability
gPDist	[-]	[0 to 1]	Disturbance-related mortality probability
gPMort	[-]	[0 to 1]	Probability that a tree dies in a given year
gPSize	[-]	[0 to 1]	Size-dependent background mortality probability (for M_1)
$gSMGF$	[-]	[0 to 1]	Soil moisture growth factor
$gSNGF$	[-]	[0 to 1]	Soil nitrogen growth factor

Table 4 continued

Code	Unit	Value	Signification
gPStr	[-]	[0 to 1]	Stress-related mortality probability
gTrMaxRed			Site-specific maximum tree number (for E_6 and E_6^*)
kE ₁	[-]		Slope of s-change
kHMax	[cm]		Adjusted maximum tree height
kLCP _{La1}	[-]		Light compensation point for shade-tolerant species
kLCP _{La9}	[-]		Light compensation point for shade-intolerant species
kS _{min}	[cm]		Smallest value the s-parameter may take
SGr _c	[year]		Number of years a cohort has grown slowly
MinEF	[-]	[0 to 1]	Species-specific minimum of the continuous establishment flags (for E_6 and E_6^*)
uAL ₀	[%]		Light availability at forest floor
uLAI	[m ² /m ²]		Cumulative leaf area index at forest floor
uAvN	[kg/ha]		Nitrogen availability (corrsponds to site-specific $kAvN$)
ukEstP	[-]	[0 to 1]	Site-specific $kEstP$ (for E_6 and E_6^*)
<i>Output variables</i>			
uBA	[m ² /ha]		Total basal area per ha
uSpBA	[m ² /ha]		Basal area for each species per ha
uSpRelBA	[%]		Relative basal area for each species
uBA7	[m ² /ha]		Total basal area of trees ≥ 7 cm <i>DBH</i> per ha
uBio	[t/ha]		Total biomass per ha
uSpBio	[t/ha]		Biomass for each species per ha
uSpRelBio	[%]		Relative biomass for each species
uDBH	[cm]		Mean <i>DBH</i> of all trees per patch
uDBHDom	[cm]		Mean <i>DBH</i> of the 100 highest trees per ha
uDBHMax	[cm]		Maximum <i>DBH</i> of all trees per patch
uDBHQMD	[cm]		Quadratic mean <i>DBH</i> of all trees per ha
uHDom	[m]		Mean height of the 100 highest trees per ha (<i>mHDom</i>)
uMinAge50	[year]		Minimum age of the trees ≥ 50 cm <i>DBH</i>
uTrs	[#/ha]		Total number of trees per ha
uSpTrs	[#/ha]		Number of trees for each species per ha
uSpRelTrs	[%]		Relative number of trees for each species
uTrs7	[-]		Number of trees ≥ 7 cm <i>DBH</i> per ha
uTrs80	[-]		Number of trees ≥ 80 cm <i>DBH</i> per ha
uVolume	[m ³ /ha]		Total volume per ha
uSpVolume	[m ³ /ha]		Volume for each species per ha
uSpVInc	[m ³ /ha*year]		Volume increment per species
uAL	[%]		Light availability at forest floor
uLAI	[m ² /m ²]		Cumulative leaf area index at forest floor
uSpDDGF		[0 to 1]	Degree-day growth factor for each species
uSpSMGF		[0 to 1]	Soil moisture growth factor for each species
uSpSNGF		[0 to 1]	Soil nitrogen growth factor for each species
uSpALGF			Available lighth growth factor for each species
uSpMGRF		[0 to 1]	Mean growth reduction factor for each species
uSpWTEF		[0 or 1]	Winter temperature establishment flag for each species
uSpALEF		[0 or 1]	Light availability establishment flag for each species
uSpBPEF		[0 or 1]	Browsing perssure establishment flag for each species
uSpDDEF		[0 or 1]	Degree-days establishment flag for each species
uSpIMEF		[0 or 1]	Immigration establishment flag for each species
uSpSMEF		[0 or 1]	Soil moisture establishment flag for each species

Table 4 continued

Code	Unit	Value	Signification
uFL1			Foliage litter typ 1 per patch size
uFL2			Foliage litter typ 2 per patch size
uFL3			Foliage litter typ 3 per patch size
uRL			Root litter per patch size
uTL			Twig litter per patch size
uWL			Woody litter per patch size

THE MANAGEMENT SUBMODEL

This chapter provides an overview of the different management interventions. Detailed descriptions are available in Rasche et al. (2011), Rasche (2012b), Schmid (2014), Mina et al. (2017) and Thrippleton et al. (submitted).

5.1 Harvest types

There are 16 silvicultural treatments available in *ForClim* 4.0. Each of these requires different input data. All of them are provided with a specific **kType** number to select them in the management file (see *ForClim* User's Guide for further details).

5.1.1 kType 0 - Tending

Description: This type simulates the tending of a stand. The goal is to remove a certain amount of small trees to lower the competition of the remaining trees.

Parameters:

kIntensity: With *kIntensity*, the intensity of the thinning can be varied.

kb: The value *kb* defines the shape of the Weibull distribution from which the diameter of the tree to be thinned is drawn. This value should not be changed!

5.1.2 kTypes 1 and 2 - Thinning from below (1) and thinning from above (2)

Description: These two types simulate thinning of a stand. The goal is to remove a certain amount of poles to lower competition for the remaining trees. With thinning from below, trees of the smaller diameter classes are removed; thinning from above removes trees from the higher ones.

Parameters: Same as kType 0.

5.1.3 kTypes 3 and 4 - Strip felling (3) and group selection (4)

Description: These two types simulate strip felling and group selection. In the case of strip felling, an operation is scheduled each year to cut a strip of the stand, so that the entire stand is rejuvenated after a certain time period. In the case of group selection, the cutting starts on small patches, which are widened step by step, until here too, the entire stand is rejuvenated. As *ForClim* does not consider interactions between patches, the patches to be harvested are selected randomly, but are eligible for harvesting only once (Appendix S1 of Rasche et al. 2011).

Parameters:

kArea: In the tag *kArea* the number of patches to be initially harvested should be stated.

5.1.4 kType 5 - Target cutting

Description: A target cut removes those trees of a stand that have reached a certain diameter. This default intervention can be modified to remove certain species only or harvest a certain number of patches only. All trees on all patches are checked in user-defined intervals if the user-specified target diameter has been reached and are then removed (Appendix S1 of [Rasche et al. 2011](#)).

Parameters:

kIntensity: The value *kIntensity* specifies the intensity of the harvest, with *kIntensity* = 1.0 meaning that all eligible trees on the patch are harvested (0.5 means 50% of trees etc.).

kTargetDBH: The value *kTargetDBH* specifies the target diameter [cm].

5.1.5 kType 6 - Clear cutting

Description: Clear cutting removes all trees of a stand.

Parameters:

kIntensity: The value *kIntensity* specifies the intensity of the harvest. For a true clear cut, the intensity should remain 1.0. Lower values result in patches being harvested only partially.

5.1.6 kType 7 - Shelterwood felling

Description: A shelterwood felling removes all trees on a stand except a few. The few trees left are meant to protect the soil and shelter the emerging saplings. They should be removed approximately one decade after the first cut.

Parameters:

kMinH, *kMaxH*: The values *kMinH* and *kMaxH* [cm] define the desired height of the sheltering trees.

kIntensity: The value *kIntensity* defines the intensity of harvested trees, which can, by their height, not serve as shelter trees.

kShelterDens: The value *kShelterDens* specifies the desired density of the sheltering trees. A value of 0.7 means that 70% of the eligible trees ($kMinH \leq H \leq kMaxH$) will stay on the stand while 30% are removed anyway.

5.1.7 kType 8 - Selection forest (“plentering”)

Description: A selection forest is an uneven aged forest with single tree selection. The growing stock should always remain approximately the same, only surplus is removed. The plenter function checks in user-defined intervals the numbers of trees in the diameter classes and removes those that exceed the optimal number or the specified target diameter (Appendix S1 of [Rasche et al. 2011](#)).

Parameters:

kResBA: desired residual basal area of the equilibrium state

kTargetDBH: highest diameter class the stand should have

kClassWidth: the width of the diameter classes [cm]

5.1.8 kType 9 - Absolute stems removals

Description: Allows to remove a desired number of stems of a species in a selected diameter class. The number of removed stems must be calculated proportionally to the simulated size area. Input data must be specified in an separate input file ([Mina et al. 2017](#)).

Parameters:

yearcut: The year of the harvesting operation within the management phase.

class: The upper and lower boundary of each diameter class.

speciesname: The name of the species for which a certain number of stems are removed

stemsremoved: The number of trees that are harvested

5.1.9 kType 10 - Relative Diameter Classes RDC

Description: Allows to remove a certain percentage of stand basal area that is split into five relative diameter classes (RDC). These classes are calculated proportionally depending on the minimum and maximum diameter in the stand in the respective year. In addition, the removal can be assigned to different species (in percentages). Input data must be specified in an separate input file (Mina et al. 2017).

Parameters:

yearcut: The year of the harvesting operation within the management phase.

totremovals: The percentage of total basal area to be harvested.

5.1.10 kType 11 - Absolute Diameter Classes ADC

Description: kType ADC is made for harvesting a predefined share of the stand bole volume and for distributing this share among different diameter classes. During the harvest, patches are selected at random and thereon all trees from the specified diameter class removed until the predefined share is reached (Schmid 2014).

Parameters:

totvolremoval: Share of the stand bole volume that could be harvested

volremoval: Share to be harvested in a specific diameter class

5.1.11 kType 12 - 'Z-Baum'

Description: 'Z-Baum' management is a form of even-aged forest management, practiced mainly in the plateau region of Switzerland. Its main idea is to be cost-effective and it therefore tries to produce high quality timber with the least possible effort. In the selection process, *future trees* (so called 'Z-Bäume') are selected. All thinnings only target the direct competitors of these future trees, i.e. the trees in the immediate surrounding that hinder the future tree's development will be removed. No interventions take place within the secondary crop. Ideally, after the last thinning, there are only future trees left in the dominating canopy layer (Schmid 2014).

Parameters:

volremoval: Minimum fraction of the volume to be removed

5.1.12 kType 13

Description: Allows to remove a certain amount of trees or basal area. The harvest can either happen from below or from above (has been used by Maxime Cailleret).

Parameters:

kCutForm: Defines whether the intervention is based on tree numbers or basal area

kIntensity: Percentage of trees or basal area that should be harvested on one patch

kDirection: Direction of the target cut (below or above)

5.1.13 kType 14

This kType has never been released officially. It's purpose and functionality are unknown.

5.1.14 kType 15 - Mountain Forest Plenter MFP

Description: The mountain forest plentering ('gruppenweise Gebirgsplenterung') aims at a groupwise removal of harvestable trees in small patches ('Baumkollektive', 'Rotten') to improve the structure of the forest and induce regeneration (Thrippleton et al. submitted).

In its *default version*, the MFP module removes all trees in small patches above a user-defined target diameter. A progressive number of patches is harvested until a user-defined amount of timber volume is reached. The harvest intervention is only started if sufficient harvestable timber volume is present, otherwise the intervention is omitted. The harvested patches are selected randomly in respect to their spatial location, but the module assures that each patch is only harvested once until all patches are treated (i.e., one rotation cycle is completed).

The *extended version* allows to specify distinct harvest phases with species-specific target diameters to allow for a more flexible management (e.g., retain certain valuable tree species, such as *Abies alba*). For the *extended version*, input data must be specified in an separate input file.

Parameters:

kTargetDBH: Target diameter

kVolLim: Percentage of total volume that should be harvested at least

kIntensity: The number of trees per cohort to be removed (by default set to 1)

5.2 Regeneration

It is either possible to allow for **natural regeneration**, or to **plant saplings** after the **clear cut**, **target cut** and **shelter-wood felling** interventions. The user can state the number of saplings to be planted per hectare and the desired species. Saplings are then initialized with an average *DBH* of 1.27 cm, the default value used in *ForClim* (Appendix S1 of Rasche et al. 2011).

REFERENCES

- Botkin et al. (1972) Some Ecological Consequences of a Computer Model of Forest Growth. *Journal of Ecology*, 60:849-872
- Bugmann (1994) On the ecology of mountainous forests in a changing climate. <http://dx.doi.org/10.3929/ethz-a-000946508>
- Bugmann (1996) A simplified forest model to study species composition along climate gradients. *Ecology*, 77:2055-2074
- Bugmann and Cramer (1998) Improving the behaviour of forest gap models along drought gradients. *Forest Ecology and Management*, 103:247-263
- Bugmann and Solomon (2000) Explaining forest composition and biomass across multiple biogeographical regions. *Ecological Applications*, 10:95-114
- Didion et al. (2009a) Long-term effects of ungulate browsing on forest composition and structure. *Forest Ecology and Management*, 258:44-55
- Didion et al. (2009b) Gaining local accuracy while not losing generality - extending the range of gap model applications. *Canadian Journal of Forest Research*, 39: 1092-1107
- Didion et al. (2011) Ungulate herbivory modifies the effects of climate change on mountain forests. *Climatic Change*, 109:647-669
- Huber et al. (2019) PET in the context of ForClim's water balance - Has the formulation by Thornthwaite and Mather served its time? In Huber (2019) Towards robust projections of future forest dynamics: why there is no silver bullet to cope with complexity. ETH. PhD thesis.
- Huber, N., Bugmann, H., Lafond, V.(2020). Capturing ecological processes in dynamic forest models: why there is no silver bullet to cope with complexity. *Ecosphere*, 11(5), e03109
- Huber, N., Bugmann, H., Cailleret, M., Bircher, N., Lafond, V.(2021). Stand-scale climate change impacts on forests over large areas: transient responses and projection uncertainties. *Ecological Applications*, 31(4), e02313.
- Kienast (1987) FORECE—A Forest Succession Model for Southern Central Europe. Oak Ridge National Laboratory. ORNL/TM-10575, Oak Ridge, Tennessee, 69 pp
- Lindner et al. (1997) Improving the simulation of stand structure in a forest gap model. *Forest Ecology and Management*, 95:183-195
- Manusch et al. (2012) Tree mortality in dynamic vegetation models - A key feature for accurately simulating forest properties. *Ecological Modelling*, 243:101-111
- McCabe and Wolock (2009) Recent declines in Western U.S. snowpack in the context of twentieth-century climate variability. *Earth Interactions*, 13:1-15
- Mina et al. (2017) Accurate modeling of harvesting is key for projecting future forest dynamics: a case study in the Slovenian mountain. *Regional Environmental Change*, 17:49-64

- Moore (1989) On the maximum growth equation used in forest gap simulation-models. *Ecological Modelling*, 45:63-67
- Rasche et al. (2011) Getting a virtual forester fit for the challenge of climatic change. *Journal of Applied Ecology*, 48:1174–1186
- Rasche et al. (2012a) Enhancing gap model accuracy by modeling dynamic height growth and dynamic maximum tree height. *Ecological Modelling*, 232:133-143
- Rasche (2012b) Bridging the gap between forest growth and forest succession models. ETH. PhD thesis. <http://dx.doi.org/10.3929/ethz-a-007342732>
- Risch et al. (2005) Simulating structural forest patterns with a forest gap model: a model evaluation. *Ecological Modelling* 181:161–172
- Schmid (2014) Bewirtschaftung ausgewählter Wälder der Schweiz unter Klimawandel. Master Thesis. <https://doi.org/10.3929/ethz-a-010335694>
- Shugart (1984) A theory of forest dynamics: The ecological implications of forest succession models. Springer, New York
- Thrippleton et al. (submitted) Climate change impacts on managed mountain forests – dynamic forest modelling as a tool for decision support
- Thornthwaite and Mather (1957) Instructions and tables for computing potential evapotranspiration and the water balance. *Publ. Climatol.*, 10:183-311
- Wehrli et al. (2007) Improving the establishment submodel of a forest patch model to assess the long-term protective effect of mountain forests. *European Journal of Forest Research*, 126:131–145
- Marano et al. (submitted) 2025a. Simulating the recent drought-induced mortality of Euro-pean beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L.) in German forests (submitted). *Geoscientific Model Development*
- Marano et al. (submitted) 2025b. Predicting Drought-Induced Tree Mortality in Swiss Beech Forests Hinges Upon Predisposing and Inciting Factors. *Ecological Monographs*.