Supplementary Materials

# Supplementary Methods

[TODO-ANNEMARIE] sanity-check Bialowieza allometric equations. Seem to be volume – density based (=woody carbon) or aboveground biomass based (=aboveground carbon of every pool, including leaves). If we can help it, we should be consistent. If not, we argue that leaves are a tiny fraction, and they only matter in the boreal region with conifers.

## Model-specific setup descriptions

### BiomeEP

BiomeEP is a derivative of BiomeE (Weng et al. 2015 and 2019), which contains an implementation of the P-model (Prentice et al., 2014; Wang et al., 2017; Stocker et al., 2020) for predicting acclimated photosynthetic parameters, assimilation, and dark respiration rates as a function of the environment. BiomeEP allows for an explicit representation of cohorts of equally sized individuals and for a treatment mortality. A size-dependent mortality rate was specified for the upper-canopy layer, assuming the yearly mortality rate of trees to follow a power law relationship with the tree's diameter. An understory mortality rate was applied to the model setup, with higher mortality rates for the smaller and younger understory cohorts.

## BiomeE-standalone (BiomeES)

BiomeES is a standalone demographic vegetation model, derived from the demographic module of LM3-PPA (Weng et al., 2015). In this model, plants are represented as cohorts of similarly sized individuals arranged in canopy layers following the rules of the Perfect Plasticity Approximation (PPA) model (Strigul et al., 2008). Plant traits define the parameters of physiological and demographic processes, reflecting strategies for competing for and utilizing limited resources under specific environmental (climatic and edaphic) conditions. Demographic processes within the model create and remove cohorts, and adjust the size and density of individuals within these cohorts. By explicitly describing cohort size, organization, and composition throughout the simulation, the model effectively simulates competition for light and soil resources, community assembly, and vegetation structural dynamics (Weng et al., 2017, 2019).

### LPJ-GUESS

LPJ-GUESS (Lund-Potsdam-Jena General ecosystem simulator) is an individual-based gap model (Smith et al 2001), that simulates various ecosystems, including forests, and represents demographic processes such as growth, establishment and mortality. Within-and between PFT competition occurs through cohorts of different sizes competing for light, and patch-scale water and nitrogen competition ( Smith et a, 2014). Patches represent samples across the landscape and variability between these patches is achieved throught stochasticity in the establishment, various mortality processes, including patch-destroying disturbances. It can simulate fire (Nieradzik). Recent extensions include a detailed forest management scheme ( Lindeskog 2021), and arctic and wetland extensions (Pongrazcz, Gustafston).

It was used in its standard setup and parameterisations as from (Smith et al 2014), with PFT-specific changes for BCI following Pugh et al 2019 (see Error: Reference source not found). The number of patches was set to 500 and the simulations were run for 1500 years, which is longer than 450 years in the protocol, in order to be able to obtain a reasonably long equilibrium period.

## ORCHIDEE

ORCHIDEE is the LSM of the IPSL Earth system model (REF). As an LSM, its purpose is to simulate the response of the land surface to changing environmental conditions including unprecedented climate conditions. ORCHIDEE is developed to respond to changes in: (1) atmospheric CO2 (REF), (2) climate (REF), (3) nitrogen inputs (REF), and (4) land cover changes (REF) as well as land management and changes therein (REF). The response variables can be grouped as: (1) energy (among other, surface temperature and albedo) (2) water (among other, evapotranspiration and soil water content) (3) carbon (among other, net biome production and soil carbon), (4) nitrogen (among other, leaching and N2O emissions), and (5) yield (among other, river discharge and wood, grass and crop production) responses. In this study ORCHIDEE r8696 was used with its default parameters except for the number of circumference classes which was set to 10 rather than its default of three. The model was configured in its land-only configuration. Land cover changes, forest management, wind damage, and bark beetle outbreaks were not explicitly accounted for. Hence, the main cause of mortality is self-thinning.

## SEIB-DGVM

SEIB-DGVM version 3.10 (Sato et al., 2023; Sato et al., 2007) was employed for all simulations. The SEIB-DGVM's simulation unit is an individual tree that establishes, competes, and dies at 1-ha forest stands. Hence, the simulation results always fluctuate significantly. To reduce this fluctuation, ten repeated simulations were conducted with the same parameters but different random seeds, and these repeats were averaged.

## EDV3

## CABLE-POP

CABLE-POP (Haverd et al. 2018) is the land surface model CABLE coupled to the woody demography model POP (Populations-Order-Physiology, Haverd et al. 2013, Haverd et al. 2014). In POP, the landscape (or grid cell) is partitioned into a number of patches which differ in their time since last disturbance. Each patch contains a number of cohorts, representing size classes of a PFT. POP receives stem biomass increments from CABLE, calculates establishment, size class distribution, mortality from crowding (self-thinning) and resource limitations, and returns stem biomass turnover rates to CABLE.

## JULES-RED

JULES-RED (Argles et al., 2020) is a development that introduces demographic processes for the vegetation dynamics in the JULES LSM (Clark et al., 2011). The model partitions PFT number density into plant mass bins. To update the number density between bins, the model assumes metabolic scaling theory for the growth rate and, for the simulations, size-invariant mortality. These modelling assumptions have been evaluated for large scale datasets across different biomes (Moore, et al., 2018, 2020). Recruitment of seedling is limited to the gap areas, which is one minus the total PFT canopy cover.

## FATES

Table XX1 Individual Model-PFTs mapped onto site-specific species (plant categories for BCI).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Site | Species | PFT characteristics of species | Model-specific PFTs used | | | | | | | | | |
|  |  |  | LPJ-GUESS | ORCHIDEE | BiomeE | CABLE-POP | EDv3 | FATES | SEIB-DGVM | JULES-RED | BiomeEP |  |
| FIN | Pinus sylvestris | Shade intolerant needleleaf | Boreal shade intolerant needleleaf evergreen (BINE) | Boreal  Needleleaf Evergreen (BoNE) | 2 Shade intolerant needleleaf (PFT1) | Needle-leaf evergreen tree (fraction: 0.95) |  |  |  | - | Shade intolerant needleleaf |  |
|  | Picea abies | Shade tolerant needleleaf | Boreal shade tolerant needleleaf evergreen (BNE) | - | Shade tolerant needleleaf(PFT2) | Needle-leaf evergreen tree (fraction: 0.95) |  |  |  | Needleleaf Evergreen Tree | Shade tolerant needleleaf |  |
|  | Betula pendula | Shade intolerant broadleaf deciduous | Shade intolerant broadleaf summergreen (IBS) | - | Shade intolerant broadleaf deciduous (PFT3) | Broadleaf deciduous tree (fraction: 0.05) |  |  |  | Broadleaf Deciduous Tree | Shade intolerant broadleaf deciduous |  |
|  | Grass | C3 metabolism | C3 | - | C3 | - |  |  |  | C3 Grass | C3 grass |  |
| BIA | Picea abies | Shade tolerant needleleaf | Boreal shade tolerant needleleaf evergreen (BNE) | Temperate needeleaf evergreen (TempNE) | Shade tolerant needleleaf (PFT2) | Needle-leaf evergreen tree (fraction: 0.5) |  |  |  | Needleleaf Evergreen Tree | Shade tolerant needleleaf |  |
|  | Betula spp. | Shade intolerant broadleaf deciduous | Shade intolerant broadleaf summergreen (IBS) | - | Shade intolerant broadleaf deciduous (PFT3) | Broadleaf deciduous tree (fraction: 0.5) |  |  |  | Broadleaf Decidious Tree | Shade intolerant broadleaf deciduous |  |
|  | Carpinus betulus or Tilia cordata | (intermediate) shade tolerant broadleaf deciduous | Temperate shade tolerant broadleaf summergreen (TeBS) |  | Shade tolerant broadleaf deciduous (PFT4) | Broadleaf deciduous tree (fraction: 0.5) |  |  |  | - | Shade tolerant broadleaf deciduous |  |
|  | Grass | C3 metabolism | C3 | - | C3 | - |  |  |  | C3 Grass | C3 |  |
| BCI |  | shade intolerant tropical broadleaf evergreen | Tropical shade intolerant broadleaf evergreen (TrIBE) | - | Tropical shade intolerant evergreen (PFT5) | Broadleaf evergreen tree (fraction: 1) |  |  |  | Broadleaf Evergreen Tropical Tree | Tropical broadleaf evergreen shade intolerant |  |
|  |  | Share tolerant tropical broadleaf evergreen | Tropical shade tolerant broadleaf evergreen (TrBE) | Tropical Broadleaved Evergreen (TrBE) | Tropical shade tolerant evergreen (PFT6) | Broadleaf evergreen tree (fraction: 1) |  |  |  | Broadleaf Deciduous Tree | Tropical broadleaf evergreen shade tolerant |  |
|  |  | Tropical broadleaf deciduous | Tropical shade tolerant broadleaf raingreen (TrBR) | - | 4 Tropical drought-deciduous (PFT7) | Broadleaf evergreen tree (fraction: 1) |  |  |  | - | Tropical broadleaf deciduous |  |
|  |  | C4 metabolism | C4 | - | C4 | - |  |  |  | C4 Grass | C4 |  |

Table XX2 Description of  model-specific modes of biomass reductions that was invoked to enable the complete forest removal after 30 years of simulation. It also documents the capabilities of the models with regards to representing such an event.

|  |  |  |
| --- | --- | --- |
| Model | Mode of biomass reduction | Notes |
| LPJ-GUESS | Patch-destroying disturbance | A feature of LPJ-GUESS that mimics a natural disturbance event which kills all trees. |
| JULES-RED | Mortality rate increase | reduction of biomass down to 97.5% of vegetation (stems, but size independent selection so should be linear with biomass) |
| CABLE-POP | Patch-destroying disturbance | A disturbance event that destroyed all 60 patches was simulated. |
|  | e.g. Reset to bare ground? |  |
| ORCHIDEE | Stand-replacing disturbance | A configuration of ORCHIDEE that mimics a natural disturbance event which kills all trees and adds their biomass to the plant litter. |
| SEIB-DGVM | Stand replacing fire | For woody PFTs, all trees were killed, and their above ground biomass lost. For grass PFTs, all aboveground biomass is lost |
| FATES |  |  |
| EDv3 |  |  |
| BiomeE | Replace current cohorts with the initial cohorts (where the plant size is small). |  |
| BiomeEP | Reset vegetation to initial states | Replace current cohorts with the initial cohorts (where the plant size is small). |

Table XX3 Parameters adjusted from default parameterset  to obtain P0 output.

|  |  |  |
| --- | --- | --- |
| Model | Parameter adjusted | Notes |
| LPJ-GUESS | FIN: default parameters  BIA: default parameters  BCI: for all PFTS (TrBE, TrBR and TrIBE)  maximum crown area  =  default: 50. Updated: 130 m2  leaf to sapwood area ratio = default: 6000 updated: 10000 | The updated values are based on observations [AHES1] and lead to an improved fit at BIA . These values have previously been found to give more realistic dynamics for Tropical Forests than the default values (Pugh et al 2019)[AHES2] |
| BiomeE | FIN: Default parameters  BIA: Annual background mortality of PFT3 ( Intermediate shade-tolderant broadleaf deciduous) was adjusted | Size-related mortality was activated. |
| SEIB-DGVM | FIN: Default parameters  BIA: Annual background mortality of PFT4 (intermediate shade-tolerant broadleaf deciduous) was adjusted from 0.95 to 0.040.  BCI: Default parameters |  |
| FATES | FIN: default parameters.  BIA: default parameters.  BCI:... |  |
| ORCHIDEE | FIN: default parameters.  BIA: default parameters.  BCI: default parameters. | Each test location was simulated as a single PFT. The number of circumference classes in the model was set to 10. These 10 classes were remapped on the diameter classes used in this study. Remapping resulted in fewer classes of the output files being populated then the number of classes in ORCHIDEE. |
| EDv3 |  |  |
| BiomeEP |  | Mortality was size-dependent. |
| CABLE-POP | FIN:  Ksapwood: 0.04  Kbiometric: 35  CrowdingFactor: 0.1  Pmort: 4.0  GE\_min: 0.016  Mort\_max: 0.15  BIA:  Ksapwood: 0.05  Kbiometric: 20  CrowdingFactor: 0.06  Pmort: 2.25  GE\_min: 0.012  Mort\_max: 0.15  BCI:  WoodDensity: 300  KSapwood: 0.11  Kbiometric: 20  CrowdingFactor: 0.05  Pmort: 1.2  GE\_min: 0.01  Mort\_max: 0.12 | The following parameters were manually adjusted to site conditions using observations of stem size distribution, biomass from regrowth curves, and equilibrium biomass.  Ksapwood: sapwood turnover rate (default: 0.067 yr-1)  Kbiometric: parameter in height-diameter relationship (default: 50.0)  CrowdingFactor: Parameter in crowding mortality formulation (Eq. A11 in Haverd et al. 2014, default: 0.043)  Pmort: Exponent in resource mortality equation (Eq. A10 in Haverd et al. 2014, default: 5.0).  GE\_min: minimum Growth efficiency resource mortality equation (Eq. A10 in Haverd et al. 2014, default: 0.012).  Mort\_max: Maximum mortality rate in resource mortality equation (Eq. A10 in Haverd et al. 2014, default: 0.3 yr-1).  WoodDensity: Default: 340 kg m-3 |
| JULES-RED | FIN: BDT (0.025, 0.06), NET (0.0275, 0.06), C3 (0.125, 0.6)  BIA: BDT (0.002, 0.08), NET (0.025, 0.06), C3 (0.125, 0.6)  BCI: BET-Tr (0.05, 0.045), BDT (0.05, 0.04), C4 (0.125, 0.6) | Adjusted the mortality and fraction of assimilate to reproduction. JULES PFTs that were not relevant for the sites (table XX1) assumed default mortality parameters.    Site: PFT (mortality rate, reproduction fraction), …  Broadleaf Evergreen Tropical (BET-Tr), Broadleaf Deciduous Tree (BDT), Needleleaf Evergreen Tree (NET), C3 Grass (C3), C4 Grass (C4). |

## Regrowth curves – Temperate Biome

Testing what regrowth curve makes sense for the Temperate simulations, the situation is the following:

There seem to be no 'mixed' broadleaf and evergreen stands that can be used for generating the regrowth curves. 'mixed' seems to in the data refer to a mix of the same leaf type.

In Bialowieza, we simulate a stand which contains both broadleaves and evergreens, which we will reflect in our PFT-choices.

The graph shows different options and tradeoffs in the data:

Using all broadleaves (topleft), we get the most data.

Using only mixed broadleaf forest to reflect multiple PFTs, we get less data, the upward regrowth trend is similar, is somewhat slower than for the pure forest (bottomleft) - but this might also be an artifact of the data, I do not know..

Since we have a Needleleaf at the BIA site, and will be simulating a needleleaf PFT, I tested the impact on the regrowth curve when mixing Picea abies in (from pure stands), there are only a handfull of 'mixed' P abies stands , in Japan, which are mixes with a differen Picea genus.

Adding P. abies into the mix, reduces the median recovery rate (black lines, bottomright), and also looks like it reduces the median equilibrium carbon content (though after 150 years , not so much anymore, note that the last measurements in that timeseries bottomright are almost only pure picea stands), broadleaf data (n>20) stops after 150 years.

The growth dynamics of picea by itself might be rather different to growth dynamics of picea in a broadleaf mix and vice-versa. At BIA, we have about 60% broadleaves in the mix, so the broadleaf dynamics may be dominating the regrowth dynamcis. I will be going with the dataset containing Broadleaves only (topleft regrowth curve) which has the most and longest data, and some influence of the mixed broadleaf dataset in there.

(recreate/update graph from script Process\_observations, chunk Temperate\_tests)Chart

Description automatically generated

**Foliage removal from Finish regrowth curves:**

[TODO - ANNEMARIE] turn into text and equations:

# regrowth:

#ahes - update regrowth biomass data to remove foliage.

# use existing age-based equations from Lehntonen et al 2004. (table 3)

# (https://www.sciencedirect.com/science/article/pii/S0378112703003840#TBL3)

#I chose the equation for pine, because it is apparently the most dominant

#tree species in Finland.

#To remove a foliage fraction, I am applying the equation reported below

#the table to calculate foliage for the age bins I have and to calculate

#total ABVG for these age bins. Then I use these two to calculate the

#fraction foliage at each age and then apply that fraction to median,

#10percentile and 9th percentile of the regrowth data I got given.

#That way I account for the fact that the BEF for foliage is quite

#sensitive to age.

Also add allometric equations and foliage removal using Repla here?

“Aboveground woody biomass is estimated based on species-specific allometric relationships for birch”

A picture containing diagram

Description automatically generated

Figure 1 Final regrowth curves from chronosequence data and site-specific dynqmic equilibrium biomass observations, without simulation output.

Diagram

Description automatically generated

Figure 2 Stand structure observations. Dots are median values, upper and lower ranges were provided by the data generators-.

## Determination of the self-thinning period and slope

Data on AGW and number of stems was extracted from chronosequence data in Teobaldelli et al. (2009), where we also kept datapoints on stem number /ha, which were marked as “indirect estimation”. We extracted for Broadleaf groups and conifer groups for comparison against BIA and FIN respectively. Modelled periods of when self-thinning is strongest were extracted based on a combination of

Identification criteria of the self-thinning period: 1) Where models contain diagnostic output for multiple mortality mechanisms explicitly (i.e. LPJ-GUESS[greff+thinning], CABLE-POP[crowding], FATES[cstarv]), the selection is based on the 95th percentile of self-thinning related mortality rates explicitly ( thinning/competition based mortality occurs to some extent during any time of the simulation (except directly after establishment), so a threshold above which self-thinning is the dominant mechanism that causes the self-thinning boundary had to be chosen to account for this.

For models with no explicit thinning-related mortality mechanism, the thinning period was either 2) chosen as the period of the 95th percentile of total mortality rate (e.g. BiomeE), or 3) chosen semi-automatically, as the consecutive points between the furthest to the bottom-left and the topright points in the timeseries in self-thining space. Lastly (4) the period was adjusted manually, so that the trajectory of the simulation reflects what looks like a thinning trajectory (e.g. Enquist ). For the explicit thinning models, the period was also manually confirmed and if not, adjusted the time series (Table 1 below).

XXX.

A screenshot of a computer

Description automatically generated

A graph of a cable pop

Description automatically generated

*Figure 4 Example of the plots in the file Benchmark\_self\_thinning\_all\_models\_point\_selection\_methods\_3plots.pdf. Plot 1) grey dots are model output on average individual biomass and stem numbers over time, in "self-thinning space" ( usually starting from bottom-left, and then moving over to bottom right, then up to the top right). The coloured dots are the data points used to fit the self-thinning line. 2) mortality rate over the course of regrowth,plot 3) AGcwood trajectory over the course of regrowth; the dots that coincide with self-thinning are highlighted in red. The self-thinning slope is reported as title of the first plot, and also in Table 1 above. Visualisations of self-thinning period as part of the whole simulation period for each model and each site are found in, file Benchmark\_self\_thinning\_all\_models\_point\_selection\_methods\_3plots.pdf).*

A graph of a cable pop

Description automatically generated

*An example of using method 1) (on CABLE-POP at Barro Colorado Island) where the self-thinning period is automatically identified as all instances where the mortality rate is above the 95th percentile of a thinning-related mortality mechanism, in the case of CABLE-POP: crowding mortality ( see middle plot for crowding mortality, the 95th percentile of the rates are highlighted in red).*

A graph with a line and red dots

Description automatically generated

*An example of using method 2) (BiomeE at Finland), where the self-thinning period is automatically identified as all instances where the mortality rate is above the 95th percentile of total mortality.*

A graph with numbers and symbols

Description automatically generated

*An example of using method 3) (BiomeEP at Bialowieza), where the self-thinning data itself (shown in the first plot) is used to automatically determine the self-thinning period: The period selected is all consecutive years that fall between the “most bottom-right” point, to the “most top left” point, as these are all aligned along the emergent self-thinning behaviour of the model.*

*The selected points are then highlighted in red in the other two plots, on the mortality and the AGcwood timeseries and align well with the timing of initial self-thinning during early establishment. Autoadjusted self-thinning periods can have some small manual adjustments, if large outliers are within the timeseries. They are still considered autoadjusted sequences.*

A graph showing a number of people

Description automatically generated with medium confidence

*An example of using method 4 (JULES-RED), where self-thinning period was manually adjusted, where method 3 selected inappropriate values. Manual adjustment was still made trying to adhere to selecting the years which are the most likely to align along a self-thinning slope trajectory. The upper and lower boundary-years are reported in Table 1 above.*

For method 4, where in doubt, the model developer was consulted in the selection of the points. For example, the basic principle of the self-thinning was documented as in the below graph, and the general behaviour of the model plotted onto it ( step 1) . Then, the self-thinning plot of the model was shown, and the starting and endpoint suggested highlighted, and confirmed with the developer, with potential iterations (step2) .

Step 1 )

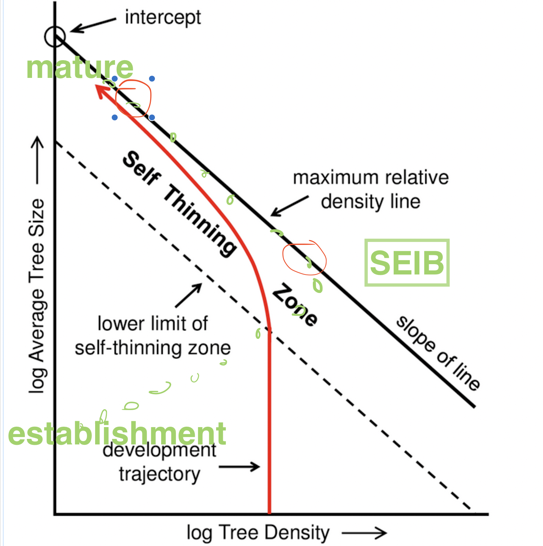


Figure XX\_Modified from Figure 9, Powell, 2000. SEIB-DGVM general behaviour was plotted into the figure to contextualise its dynamics with general self-thinning behaviour.

Step 2)

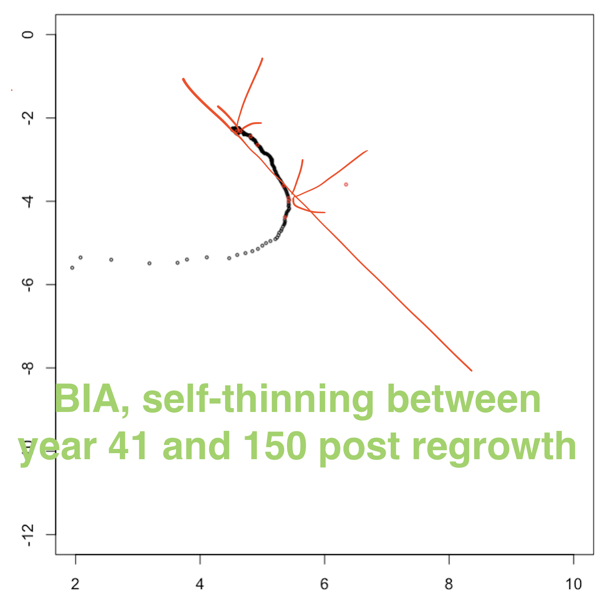


Figure X . An example of SEIB-SGVM at BIA in “self-thinning space” and the procedure of selecting the appropriate start and end point for the self-thinning period.

## Forest Recovery Phase Classification

The results from iterations with modelling groups and forest recovery benchmark variables ( see Table 2, manuscript) are reported in the table below

|  |  |  |  |
| --- | --- | --- | --- |
|  | FIN | BIA | BCI |
| JULES-RED | **Phase 1: open canopy-grass coexistence (5 years).** Evidence: Low mortality rate for trees. Presence of grasses in terms of CA, less pronounced with as % of total cveg. | **Phase 1: open canopy-grass coexistence (5 years).** Evidence: Low mortality rate for trees. Presence of grasses in terms of CA, less pronounced with as % of total cveg. | **Phase 1: open canopy-grass coexistence (5 years).** Evidence: Low mortality rate for trees. Quickest transition to closed-canopy within 70 years |
| FATES |  |  |  |
| LPJ-GUESS | **Phase 1: open canopy - growth (25 years).** Evidence: CA < 10000; high %total of grasses. | **Phase 1: open -canopy growth (10 years).** Evidence:  Evidence: start with CA < 10000 m2 ha-1;. Period with transition of smaller sizeclasses in to larger ones, without nstem loss. | Phase 1: **open canopy (2 years)**. Evidence: v. short period of low mortality rate, followed by rate spike, when self-thinning (reduction in nstem) commences. |
|  |  |  |  |
| CABLE-POP | Phase 2: open-canopy growth(ca 20 years): Evidence: nstems initially increasing, then sharply decreasing. | Phase 2: open-canopy growth (ca 10 years )Evidence: nstems initially increasing, then sharply decreasing. | Phase 2: open-canopy growth (ca 2 years). Evidence: nstems initially increasing, then sharply decreasing. |
| BiomeE: | Phase |  |  |
| ORCHIDEE | Phase 3: Closed canopy, self-thinning ( |  |  |
| SEIB-DGVM | **Phase 1: open canopy- crass coexistence (50 years).** Evidence: Delayed onset in woody establishment, due to strong interference with grasses | **Phase2 : open canopy-grass coexistence ( 49 years)**. Evidence: Delayed onset in woody establishment due to strong interference with grasses. | **Phase 2: open canopy-growth (10 years)**. Evidence: low canopy area, increasing fast. |
| EDv3 | Phase 1: open canopy-grass coexistence (62 years). Evidence: presence of grasses | Phase 1: open canopy- grass coexistence (42 years). Evidence: presence of grasses | Phase 1: open canopy- grass coexistence (42 years). Evidence: presence of grasses |

## Mortality rates

Woody mortality rates **cmort\_rate** (%biomass year-1) were calculated from the pool variable cwood\_size and the flux variable cmort:

To allow for features to emerge and to smoothen out effects from the repeated climatology, cmort\_rate then was smoothed with 30-year rolling mean using the function zoo::rollmean(), with standard settings, k =30 and align ="left". ORCHIDEE was smoothed twice ( first with k=5, then with k=30, since since its mortality rate is can fluctuate strongly between mostly 0 and a high rate and otherwise would have shown dampened oscillations of this mortality mechanism artifact. The aim of reporting the mortality rates smoothes in this was was to present the general annual-mean picture that emerges, and not the way mortality was implemnted.

A graph of different colored lines

Description automatically generated

Figure 3 30-year running mean of woody mortality rates for FIN from first regrowth year to 250 after regrowth.

A graph of different colored lines

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Figure 4 30-year running mean of woody mortality rates for BIA.

A graph of different colored lines

Description automatically generated

Figure 5 30-year running mean of woody mortality rates for BCI.

## Growth rates

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