ODD Description of the BEFORE Beech Forest Model

Supplemental material for Chapter 18 of *Agent-Based and Individual-Based Modeling, Second edition*

This document describes the BEFORE beech forest model described in Section 18.3. It is taken from an appendix to:

> Jakoby, O., Rademacher, C., & Grimm, V. 2010. Modelling dead wood islands in European beech forests: how much and how reliably would they provide dead wood? *European Journal of Forest Research*, 129: 659-668
>
> and:
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> Rademacher, C., Neuert, C., Grundmann, V., Wissel, C., & Grimm, V. 2004. Reconstructing spatiotemporal dynamics of Central European natural beech forests: the rule-based forest model BEFORE. *Forest Ecology and Management* 194:349-368.

1. Purpose and patterns

The purpose of the model is to reconstruct and understand spatiotemporal dynamics of natural beech forests on large spatial and temporal scales, which are of interest for both forest management and conservation.

The model's design was explicitly based on patterns observed in old European beech forests. These patterns are described in Section 18.3.1 of *Agent-Based and Individual-Based Modeling*.

2. State variables and scales

BEFORE has two kinds of entities: vertically compartmented grid cells and individual large beech trees. Trees are tracked as individuals only after they grow out of the "juvenile" stage, explained below.

Horizontally, grid cells are 14.29×14.29-meter (m) squares (corresponding to the area covered by one very large beech; an area of 7×7 cells is one hectare). Vertically, cells have four compartments that each represent a height class of beech:

- *upper canopy*: 30–40 m (maximum height of a beech tree),
- *lower canopy*: 20–30 m,
- *juveniles*: 0.3–20 m, and
- *seedlings*: up to 0.3 m.

The four vertical compartments are represented by these state variables of the cells:

Upper and lower canopy compartments have a list of the trees present in the compartment. Zero to eight trees can be present in each of these compartments. The cells have deduced states (*F4* and *F3*) representing the percent of the cell area occupied by trees in the upper and lower canopy compartments, calculated by adding the percent of cell area occupied by each tree. *F4* and *F3* range from 0 to 100% in steps of 12.5% (see state variable of trees, below), and are used for calculating vertical competition for light.

Juvenile trees and seedlings compartments are represented by cell variables *F2* and *F1*, for the percent of cell area (0-100%) covered by juvenile trees and seedlings (respectively). In these lower compartments, trees are not represented as individuals but only via *F2* and *F1*. The juvenile compartment is also represented by a variable for the number of previous time steps in which *F2* was greater than zero.

Individual trees have different state variables in the two canopy compartments:

Upper canopy trees: These are the highest trees, with vertically unrestricted access to light. They have state variables for their age and "crown area": the fraction of the cell's area occupied by the tree. The crown area is quantified in $1/8^{ths}$ (12.5%) of cell area. A cell could contain, for example, two upper canopy trees with crown areas of 1/8 and 5/8, or two trees with areas of 2/8 and 6/8, or a single giant beech with crown area of 8/8 (the entire cell).

Lower canopy trees: These are rapidly growing trees that can almost reach the upper canopy. But if the canopy is filled by upper canopy trees, the lower canopy trees no longer receive enough light to grow. Beech is shade-tolerant so trees can survive in the lower canopy for about 90 years, and if a gap opens in the upper canopy they fill it quickly. State variables are age and the time spent in this compartment. All trees of this compartment have the same crown area: 1/8 of cell area.

The time step is 15 years. The spatial extent is 54 × 54 grid cells, representing about 60 hectares.

3. Process overview and scheduling

Each time step, nine processes are scheduled in the sequence given below. State variables are updated immediately within each process. The order in which cells execute these processes matter for the last two processes, which include interactions among neighbor cells. The sequence in which the cells are processed depends on one of the eight possible main wind directions (north, northeast, east, etc.). For example, if wind comes from the west, the columns of cells representing the western edge of the forest are processed first, then the next column to the east, and so on.

The processes, described in detail below, are:

1. Competition in the upper canopy,
2. Closing of gaps in the upper canopy,
3. Update of lower canopy,
4. Growth from juveniles to lower canopy,
5. Growth of seedlings into juveniles,
6. Regeneration,
7. Aging and mortality,
8. Neighborhood interaction 'light', and

9. Neighborhood interaction 'wind'.

4. Design concepts

Basic principles: The general modeling approach of BEFORE is representing horizontal patterns in forest structure as arising from a primarily vertical process: competition for light. This approach differs from previous beech forest models that represented horizontal patterns as resulting from a more imposed succession process, with forest patches automatically progressing from one type to the next. BEFORE directly represents this concept of light competition among beech individuals.

Emergence: The dynamic spatial patterns of the forest stage emerge from how storm events open gaps in the canopy and the rules for how trees grow in response to gap openings.

Adaptation: The beech trees adapt to light conditions by growing when openings in the canopy allow them to. The model implicitly assumes that growth, and the longer life it allows, furthers the objectives of individual trees, which is presumably production of offspring. The concepts of *objectives* does not apply because the rules by which model trees respond to gap openings are empirical and closely impose the growth behavior.

Learning and *prediction* are not represented, except for the implicit prediction of trees that if they grow as light allows then their implicit objective of reproduction will be better met.

Sensing: Beech trees of the lower three layers are assumed able to sense and hence respond to the light conditions in their own and the neighboring cells.

Interaction: Trees within each cell interact by competing for available canopy area, as a surrogate for light. Trees in neighboring cells interact via the effects of the "slanted" light and windfall. The rates at which new seedlings are produced, and at which juveniles grow into the lower canopy, depend in part on the presence of gaps in adjacent cells. The presence or absence of canopy gaps in upwind and downwind cells affects the probability of upper canopy trees being killed or damaged by storms.

Stochasticity: BEFORE is highly stochastic, with many traits represented as probabilistic rules. Stochastic traits were used because they provide a relatively simple way to represent the beliefs and data of experts concerning how likely different responses are. Stochasticity is also used in initializing the model, described below.

Collectives: The model contains no collectives.

Observation: Key results of the model are observed by displaying spatial patterns, in the horizontal dimension, in the model forest. To relate model results to typical observations and understanding of real forests, each cell is displayed as belonging to one of three development stages ("growing-up", "optimal", and "decaying") that differ in the percentage cover in the four height classes according to the following table. Additional variables output from BEFORE are the age structure of the canopy (statistical distributions of individual tree ages in the lower and upper canopy) and the spatial distribution of beech "giants" (very old and large trees).

Height class area	Growing-up	Optimal	Decaying
F1	10–70%	0–10%	20–80%
F2	20–50%	0–10%	0–50%
F3	20–50%	0–10%	0–20%
F4	20–80%	85–100%	0–50%

5. Initialization

Initial values must be provided for the state variables of each cell. Initialization is relatively unimportant because the results of typical interest are obtained after a simulation proceeds long enough for the model to achieve a dynamic equilibrium that is independent of the initial condition. BEFORE can simply be initialized by assuming that only seedlings are present: setting *F1* to 1.0 and *F2-F4* to zero, for all cells.

6. Input

The model is not driven by any environmental variables taken from external models or data sets. Instead, the one external process, wind storms, is modeled stochastically.

7. Submodels

The following subsections describe the submodels, in the order they are executed. They are referred to as R1-R9 (rules 1-9) for convenience. Model parameters, their ranges, and reference (standard) values are given in a table after the Submodels section. When events are described here as being modeled stochastically with a specified probability, they actually are modeled as random Bernoulli trials with the specified probability of the event occurring. When individual trees are described as "dying", then are simply removed from the model and their area subtracted from the cell variable *F3* or *F4*.

R1: Competition in the upper canopy

Competition for light is simulated within all cells with closed upper canopy (*F4* of 8/8 or 100%): larger trees grow at the cost of smaller ones. With probability of 0.5, the largest (with respect to crown area) or, if all trees have the same size, the oldest beech, enlarges its crown area by 1/8 of cell area, unless it already occupies the full cell. The smallest (or youngest) tree, if there is one, shrinks by 1/8 of the cell area (possibly reaching size 0 and hence dying).

R2: Closing of gaps in the upper canopy

A gap in the upper canopy may have a size (1-*F4*) ranging from 0 to 8/8 cell area. It will be closed either by trees of the upper canopy in this cell enlarging their crown or by trees of the lower canopy growing into the upper canopy. First, in a random sequence all trees of the upper canopy are allowed to enlarge their crown area by 1/8. This is done until the gap is closed or all trees have grown. Then, if the gap is still not closed, the trees in the lower canopy have a chance to grow into the upper canopy. Only trees which have stayed long enough in this lower canopy ($D3 \geq D3min$ where *D3* is the number of years a tree has spent in the lower canopy) are admitted; this assumption is based on the observation that the minimum age of trees in the upper canopy is 90 yrs and the minimum age in the lower canopy 60 yrs (Korpel, 1995). Hence the required age difference *D3min* equals 30 years or two time steps. Now, ranked by the time they have spent in the lower canopy, the admitted trees grow one after the other into the upper canopy with a crown area of 1/8. If the gap in the upper canopy is still not closed, the new recruits are enlarged one after the other, ranked by age, to area of 2/8. This rule reflects the observation that large canopy gaps can create a burst of growth among the trees of the lower canopy.

R3: Update of lower canopy

As described in R2, only trees which have stayed sufficiently long in the lower canopy compartment ($D3 \geq D3min$) can grow to the upper canopy. But when the light conditions are bad for the whole lifespan of a tree the residence time *D3min* might not be long enough to let the tree grow to the height of 30m. Thus, if the upper canopy is closed during the entire residence time *D3* of a tree, then *D3min* for that tree is increased by 15 years. If a tree stays in the lower canopy for more than 90 years ($D3 > 90$ years), it dies.

R4: Growth from juvenile to lower canopy

The transition of trees from the juvenile compartment to the lower canopy depends on light conditions. For every free position or gap in the lower canopy, a new individual tree is created in the lower canopy as a stochastic event with probability *W*. However, a new tree can only be created if *F2* has been larger than zero for at least two time steps, because trees need adequate time to grow into the lower canopy with its minimum height of 20 m.

The probability *W* depends on the variable $M_{3,4} = (1\text{-}F3)(1\text{-}F4)$, a measure of the area within the juvenile compartment which is not covered by trees from the higher compartments. If light conditions in the cell are favourable ($M_{3,4} \geq 0.5$), *W* depends only on *F2*:

$$W = F2 \times W_{\max}.$$

Otherwise, the amount of light relative to its maximum decreases the probability:

$$W = F2 \times W_{\max} \left(LF / LF_{\max} \right)$$

where W_{max} is a parameter, *LF* (‘light factor’) is a measure of the amount of light in the cell and LF_{max} is the maximum value of *LF* (explained below for submodel R8).

New trees created this way are assigned an age *A3* drawn from a uniform integer distribution between 60 and 120 years, and a value of *D3* of 0 years.

R5 : Growth of seedlings into juveniles

Each time step, the proportion of *F1* equal to (1-*F2*) *F1* grows into the juvenile compartment; this amount is added to *F2*. Then, the other seedlings die: *F1* is set to zero. Thus, recruitment into the juvenile compartment is determined by regeneration (see submodel R6).

R6: Regeneration

Regeneration represents creation of new seedlings. Regeneration only occurs if trees in the upper or lower canopy compartments exist somewhere in the forest. The regeneration rate in a cell, $S_{max\text{-}red}$, is calculated each time step by multiplying parameter S_{max} by a number drawn randomly from a uniform floating point distribution between 0.8 and 1.0, to represent reductions in recruitment due to, for example, browsing. Similar to submodel R4, the variable $M_{2,3,4}$ is calculated as a measure of area not covered by larger beech:

$$M_{2,3,4} = (1 - F2)(1 - F3)(1 - F4).$$

With favourable light conditions ($M_{2,3,4} \geq 0.5$) the area of established seedlings is maximum: $F1 = S_{max\text{-}red}$. Otherwise, the new area of seedlings is reduced:

$$F1 = S_{max,red}\left(LF/LF_{max}\right).$$

R7: Aging and mortality

All trees in the upper canopy have their age increased by one time step, or die as a stochastic event with probability *M4*. A tree's value of *M4* is equal to zero until its age reaches the parameter *agemax*; then *M4* increases by 0.3 each subsequent time step. Therefore, there are no trees older than *agemax* + 60 years.

The lower three compartments have mortality rates *M1*, *M2*, and *M3*, which depend on light conditions in the cell (explained in submodel R8). All trees in the lower canopy have their age increased by one time step, or die as a stochastic event with probability *M3*. The values of *F1* and *F2* are multiplied by a random number drawn from a uniform floating point distribution between 0.8 and 1.0, which takes into account various environmental factors such as browsing. Then, the values of *F1* and *F2* are respectively multiplied by one minus the mortality rate *M1* or *M2*.

R8: Neighborhood interaction 'light'

The growth and mortality of trees in the lower compartments depend on the amount of light available and are thus influenced by gaps in the higher compartments. A "gap" is the proportion of a grid cells area not covered by trees; its size is (1– *F4*) and (1– *F3*) for the upper and lower canopy, respectively. The gaps both within a cell and in its neighbor cells contribute to the light conditions for the cell's lower canopy and juvenile compartments. Thus, the light factor *LF*, which represents the light available in the lower compartments, can be computed from *F3* and *F4* of the relevant cells. Let α be the cell for which *LF* is being calculated and B the set of neighbor cells that contribute to *LF*: the six adjacent cells that are not northeast or northwest of α. (Cells on the border of the space have fewer than six members of B.) Each gap in the two canopy compartments adds to *LF* by the parameters *L3* or *L4*, which represent the average input of light by a gap of 1/8 cell size in the lower and upper canopies. Thus, *LF* can be calculated as:

$$LF_{\alpha} = 4 \times 8\left[\left(1 - F3_{\alpha}\right)L3 + \left(1 - F4_{\alpha}\right)L4\right] + \sum_{\beta \in \mathrm{B}} 8\left[\left(1 - F3_{\beta}\right)L3 + \left(1 - F4_{\beta}\right)L4\right]$$

where the summation is over each member β of the set B of neighbor cells. The values of *L3* and *L4* must be chosen such that $LF \leq 1$. The maximum light factor is LF_{max} = 80 (*L3* + *L4*). Note that gaps within a cell contribute much more (the factor 4) to the light factor than gaps in the neighbor cells.

LF modifies the mortality rates *M1*, *M2*, and *M3* in the same way; for example:

$$M1 = M1_{max} \times \max(1 - LF, 0.2)$$

where $M1_{max}$ is a parameter representing maximum mortality of seedlings.

This means favorable light conditions (*LF* close to 1) reduce mortality, but even with optimal light conditions the mortality rates are at least 20% of the maximum (e.g., $M1_{max}$) because there are always sources of mortality besides unfavourable light conditions.

R9: Neighborhood interaction 'wind'

This submodel calculates (1) whether or not a windstorm occurs over the modeled area, and if so (2) which direction the wind is from, (3) how strong the storm is, and then (4) whether each individual upper-canopy tree is wind-thrown (toppled by the storm), and for each wind-thrown tree (5) which downwind trees are also damaged and by how much.

Whether a storm occurs within a time step is modeled stochastically, with the probability of a storm being the parameter *pwind*. This probability is set to 1.0 because in most of Central Europe storms occur almost every year, so the probability that storm damage occurs within 15 years can safely be assumed 1.0.

The direction from which the storm's wind comes is determined stochastically from among eight possibilities. The frequencies of storms from each direction were estimated from wind data collected at Frankfurt/Main airport, considered typical for Central Europe. These frequencies are: southwest–29%, west–26%, northwest–11%, north–1%, northeast–1%, east–26%, southeast–3%, and south–3%. For each storm, one random number between 0.0 and 1.0 is drawn and compared to these frequencies to determine wind direction.

The strength of a storm is quantified by the variable *pkipp*, which affects the probability that the storm blows down trees in the upper canopy. Three categories of storm are possible: 89% of storms are "normal" and *pkipp* is set to the parameter *pkipp1*; 10% are strong (*pkipp* is set to the parameter *pkipp2*); and 1% are extremely strong (*pkipp*=*pkipp3*). A random number is compared to these three frequencies to determine the strength of a storm.

Whether each tree is wind-thrown by a storm is a stochastic event with a probability (*Kipp*) that depends on storm strength and upper canopy gaps in the tree's cell and in the two cells that are adjacent in the upwind and downwind directions. If the upwind cell has a closed upper canopy ($F4_{upwind}$ = 1.0) then *Kipp* = *pkipp*. If there are gaps in the upper canopy of the upwind cell (quantified as (1- $F4_{upwind}$)) then *Kipp* = *pkipp* × *Epkipp* × (1- $F4_{upwind}$), where the parameter *Epkipp* describes the effect of gaps in neighboring cells. If the downwind cell also has upper canopy gaps (quantified as (1-$F4_{downwind}$)), then *Kipp* is further increased by multiplying it by *pkipp* × *Epkipp* × (1- $F4_{downwind}$).

When a tree is wind-thrown, it dies and can also damage the crowns in the next three cells downwind. If a cell is hit by a falling tree (a tree is windthrown in one of the next three cells in the upwind direction), damage to each of its upper canopy trees is a separate stochastic event with probability 0.5. If this damage occurs to a tree, the amount of damage (crown area lost, in units of 1/8 cell area) is taken at random between 1/8 and the tree's size. If this damage equals the tree's size, the tree dies. Trees of the lower canopy are damaged with a probability of 50%, too, although in this case damage means the tree dies.

Because state variables are updated immediately, and cells are processed from upwind to downwind (see "Process overview and scheduling"), "domino effects" can occur. A wind-thrown canopy tree leaves a gap, which increases the risk of the downwind cell being damaged, etc. In this way, aisles of damaged cells often result from a storm. Even though extreme storm events can damage large areas, these areas typically do not lose all their canopy but remain heterogeneous with some "legacy" of the previous forest structure. Such legacies are common in real beech forests even after extreme disturbance events.

Parameter table

Parameter	Description	Range	Reference value
$M1_{max}$	Mortality rate of seedlings (per 15 years)	1	1
$M2_{max}$	Mortality of juveniles (per 15 years)	0.4–1	1
$M3_{max}$	Mortality in lower canopy (probability)	0–0.4	0.03
M4	Mortality in upper canopy (probability)	0–0.002	
agemax	Maximum age (years)	150–350	300
L4	Measure of additional light by gaps in upper canopy	0.001–0.02	0.008
L3	Measure of additional light by gaps in lower canopy	0–0.003	0.002
pwind	Probability of a storm occurring	1	1
pKipp1	Probability of a tree being wind-thrown by a normal storm	0–0.002	0.001
pKipp2	Probability of a tree being wind-thrown by a strong storm	0.002–0.02	0.002
pKipp3	Probability of a tree being wind-thrown by a extreme storm	0.003 – 1	0.004
Epkipp	Modifier for probability of a tree being wind-thrown by a storm	0.001 – 50	19
W_{max}	Probability of lower canopy trees emerging from juveniles	0.7 – 1	1
S_{max}	Maximum regeneration rate of seedlings (per 15 years)	1	1