# BASFOR: The BASic FORest model

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## 1. Introduction

This document contains general documentation and a user manual for the forest model BASFOR. The name of the model stands for BASic FORest model, reflecting the intention to represent processes in simple ways. Despite this, the aim is to make the model widely applicable by simulating the impacts of a range of environmental drivers. BASFOR simulates the growth and biogeochemistry of forest stands for any period of time, so the user can decide whether to run the model just for a short period or for a sequence of many years. The version of the model documented here is that of 21 April 2015.

### 1.1 Model history

BASFOR was developed in Edinburgh by Marcel van Oijen and David Cameron. The first version of the model was published in 2005, and the model was used in a number of other publications since then: see Chapter 13 on “*Publications on BASFOR and related models*”.

## 2. Quick start

## You can make your own R-files for running BASFOR, but some examples are provided that you can start with and modify if desired. This chapter shows how you can use some of the provided example-files to get going.

### 2.1 TO MAKE EVERYTHING READY FOR RUNNING BASFOR:

* Install R, RStudio and gfortran on your computer.
* Unzip 'BASFOR\_2015-04-21.zip'. [*For details of the unzipped folders and files, see 3.5.2*]

### 2.2 TO RUN THE MODEL for a site with deciduous trees:

* Double-click on 'run\_BASFOR\_DECIDUOUS-1.R' to open the file in RStudio.
* Click on 'Source' to run the file.

### 2.3 TO RUN THE MODEL for a site with coniferous trees:

* Double-click on 'run\_BASFOR\_CONIFEROUS-1.R' to open the file in RStudio.
* Click on 'Source' to run the file.

### 2.4 TO INSPECT MODEL OUTPUT in RStudio after a run:

* Click on the 'Plots' tab and use the arrows to see different plots.
* Study the variable called 'output' which contains the values of all output variables, for every simulated day.
* The names and units of all output variables are listed in variables 'outputNames and 'outputUnits'.

### 2.5 TO RUN THE MODEL FOR A DIFFERENT SITE OR YEAR:

* Make and use your own files 'run\_BASFOR\_[].R' and 'initialise\_BASFOR\_[..].R'.

### 2.6 TO APPLY BAYESIAN CALIBRATION to model parameters using data from a single site

* Run ‘BC\_BASFOR\_DECIDUOUS-1.R’ or ‘BC\_BASFOR\_CONIFEROUS-1.R’ and inspect, outside RStudio, the pdf-files and txt-file that it produces.
  + Note that this calibration uses MCMC which means that the model is run many times in a loop, so this takes longer than a single model run. Also note that the default setting of 100 iterations (= model runs) in the Markov chain (which for this calibration is set in file ‘BC\_BASFOR\_MCMC\_init\_DECIDUOUS-1.R’ resp. ‘BC\_BASFOR\_MCMC\_init\_CONIFEROUS-1.R’ in directory ‘BC’) is actually much too short. Use 104 - 105 runs for proper calibration.

### 2.7 TO APPLY BAYESIAN CALIBRATION to model parameters using data from multiple sites

* Run ‘BC\_BASFOR\_DECIDUOUS-1&2.R’ or ‘BC\_BASFOR\_CONIFEROUS-1&2.R’ and inspect, outside RStudio, the pdf-files and txt-file that are produced.

### 2.8 TO FIND MORE DETAILS OF THESE AND OTHER MODELLING PROCEDURES:

* See other chapters of this manual.

## 3. General overview of the model

### 3.1 What processes does BASFOR simulate?

BASFOR simulates growth and biogeochemistry of deciduous and coniferous forest stands. Interactions with the atmospheric and soil environment are simulated in some detail. This includes the role of management, i.e. thinning and pruning. Three biogeochemical cycles are simulated: carbon, nitrogen and water. BASFOR is a one-dimensional model: no horizontal heterogeneity of the forest is captured.

### 3.2 State variables

BASFOR has 17 state variables. Nine of those variables quantify the state of the trees and eight variables represent the soil.

The nine state variables for the trees can be divided in four categories:

1. *Carbon pools*: branches, leaves, roots, reserves and stems (CB, CL, CR, CRES, CS; kg C m-2),
2. *Nitrogen pool*: leaves (NL; kg N m-2),
3. *Stand density* (treedens; number of trees m-2),
4. *Tree phenology (only for deciduous trees)*: accumulated chill days (chillday; d) and accumulated thermal time (Tsum; °C d).

The seven state variables for the soil can be divided in three categories, according to the three biogeochemical cycles being simulated:

1. Carbon pools: litter (CLITT), soil organic matter with fast turn-over (CSOMF), SOM with slow turn-over (CSOMS), all in units of kg C m-2,
2. Nitrogen pools: same as for carbon but also mineral N (NLITT, NSOMF, NSOMS, NMIN; kg N m-2),
3. Water pool: amount of water in the root zone (WA; kg H2O m-2 = mm).

### 3.3 Inputs

The major inputs to the model are time series of weather variables: radiation, temperature, precipitation, wind speed and humidity. The last two of these are only used in the calculation of potential rates of evaporation and transpiration. Further, the model requires time series indicating at which days the stand is thinned or pruned. Atmospheric CO2 concentration is not provided as a time series but as a function of calendar year. Soil properties, such as parameters of water retention, are provided as constants.

### 3.4 Outputs

The model, in its default set-up, generates 36 different output variables, which include the 17 state variables. This selection of output variables can be altered by the model user. BASFOR does not simulate some variables which are very important in forest production, such as wood quality or pests and diseases.

### 3.5 Technical details

#### 3.5.1 General set-up using FORTRAN and R

BASFOR is written in FORTRAN and R. Simulations are run from script-files in R, which:

1. set the time period of simulation,
2. identify the weather file,
3. set the dates and values for N-deposition, tree thinning and tree pruning,
4. set parameter values,
5. call FORTRAN to iteratively calculate rates and states (= do the simulation),
6. collect the output,
7. make plots.

#### 3.5.2 Directories and files

When the BASFOR zip-file is unzipped, there will be seven directories: the master directory plus seven subdirectories called 'BC', 'data', ‘doc’, 'initialisation', 'model', 'parameters', 'weather'. We shall now give a short overview of the files contained in the seven directories. More details on some of the files will appear in later sections.

The master directory contains:

* 2 script-files in R for model running: 'run\_[].R',
* 4 script-files in R for model calibration: 'BC\_[].R',
* 2 compiled model files: 'BASFOR\_conif.DLL' and 'BASFOR\_decid.DLL',
* 2 batch files for compiling the model: 'compile\_BASFOR\_gfortran\_CONIFEROUS.bat' and 'compile\_BASFOR\_gfortran\_DECIDUOUS.bat',
* 1 script-file in R showing some examples of how you can work (run, plot, tabulate, analyse sensitivity, calibrate) with BASFOR: 'INTRODUCTION\_EXAMPLES\_BASFOR2015.R'.

Subdirectory 'model' contains:

* 2 FORTRAN files for model parameterisation: 'parameters.f90' and 'set\_params.f90',
* 6 FORTRAN files that contain the model proper, i.e. the calculations of rates and states.

Subdirectory 'BC' contains:

* 2 files defining different likelihood functions: 'fLogL[].R',
* 1 script-file in R for general settings of each Bayesian calibration: 'BC\_BASFOR\_MCMC\_init\_general.R',
* 4 script-files in R for initialising Bayesian calibration for specific sites of tree types: 'BC\_BASFOR\_MCMC\_init\_[].R',
* 1 script-file in R for running the Bayesian Calibration by means of the Markov Chain Monte Carlo method of Metropolis: 'BC\_BASFOR\_MCMC.R',
* 1 script-file in R for writing the modes of the prior and posterior parameter distributions plus other calibration results to txt-file: 'BC\_export\_parModes.R',
* 3 script-files in R for plotting calibration results: 'BC\_plot[].R'.

Subdirectory 'data' contains:

* 13 files with calibration data: 'data\_[].txt'.

Subdirectory 'doc' contains:

* 1 file (this one!) with a user guide for the model: 'BASFOR2015\_USER\_GUIDE.docx',
* 2 files (one in HTML, the other in org-mode format) with a short manual giving more details about multi-site Bayesian calibration: ‘Manual\_MULTISITE\_BC\_BASFOR.[]’,
* 1 folder with 8 publications in which BASFOR was used,
* 1 folder with a tutorial on Bayesian calibration.

Subdirectory 'initialisation' contains:

* 1 file with general initialisation settings for BASFOR: ‘initialise\_BASFOR\_general.R’,
* 4 script-files in R for site-specific model initialisation: 'initialise\_BASFOR\_[].R'.

Subdirectory 'model' contains:

* 8 FORTRAN files that together define BASFOR.

Subdirectory 'parameters' contains:

* 1 file with default values of all parameters: ‘parameters.txt’.
* 4 txt-files listing parameters that can be calibrated, with their prior minimum, mode and maximum 'parameters\_BC\_[].txt'

Subdirectory 'weather' contains:

* 4 files with site-specific weather data: 'weather\_[].txt'.

#### 3.5.3 Modules and subroutines

In each FORTRAN file ('[].f90'), the code is organised in one module with the same name as the file, and/or one or more subroutines. Modules make it easy to make variables declared in one file accessible in another. Variables declared in the first lines of module A can be accessed from module B if a 'use A'-statement is inserted in the code for module B. However, we use the module-method only for intermediate variables. [See next section for an explanation of the different variable types.] State and rate variables are passed through the headers of subroutines.

* Each subroutine follows a standardised structure:
  + Subroutine NAME(INPUTS alphabetically,[space or newline],OUTPUTS alphabetically),
  + INPUTS alphabetically,
  + OUTPUTS alphabetically,
  + LOCAL VARIABLES alphabetically,
  + BODY of subroutine,
  + end Subroutine NAME.

#### 3.5.4 Variables, parameters and constants

Like most models, BASFOR contains five types of variables: states, rates, inputs, outputs and intermediate variables. State variables represent basic quantities. Rate variables quantify by how much the states are changed every time step. Rates are calculated as functions of states and input variables read-in by the model. Complicated rate calculations are made readable by the use of intermediate variables. Output variables play no role in the rate calculations, but are calculated only for user interest. Besides variables, BASFOR also contains parameters and constants. Both have fixed values, but parameters are considered uncertain or site-specific whereas the values given to constants are considered known and universal. So only parameters can be calibrated. Complete lists of all variables, parameters and constants in BASFOR can be found in the Appendices.

* Units  
  The dimensions of the variables, parameters and constants are expressed in units according to a common pattern. Time is in days, length in meters, mass in kg carbon, nitrogen or water, temperature in degrees Celsius. For example, leaf biomass is in kg C m-2 and transpiration rate in kg H2O m-2 d-1 (which we refer to as mm d-1). Some output variables do not follow this pattern, e.g. NEE is given in g C m-2 d-1.

#### 3.5.5 Model time-step

The model has a time step of one day.

## 4. Details of processes and algorithms

### 4.1 Weather

The model reads weather data from file. Weather files include daily data for global radiation, temperature, precipitation, wind speed and vapour pressure.

### 4.2 Carbon balance

### BASFOR has eight state variables for carbon. Five of these are located in the trees: the carbon contents in leaves, branches, stems, roots and reserves. The three soil carbon pools are for litter and for soil organic matter with fast resp. slow turnover time. Carbon enters the ecosystem by photosynthesis (4.7) and leaves it through respiration (4.10, 4.12) and dissolved in runoff water (4.4). Export of dissolved carbon (DIC, DOC) in groundwater is not simulated. The eight carbon pools are linked as follows. Reserves in deciduous trees (CRES) are emptied into the leaf pool (CL) during spring flushing. In coniferous trees, the reserve pool stays empty. The leaf and branch pools (CL, CB) are subject to senescence (4.14), causing carbon flows to litter (CLITT). Roots (CR) are also subject to senescence, causing a flow to fast-decomposing soil organic matter (CSOMF). CLITT decomposes to CSOMF plus CO2, CSOMF decomposes to slow-decomposing soil organic matter (CSOMS) plus CO2, and finally CSOMS decomposes, very slowly, to CO2 (4.11).

### 4.3 Nitrogen balance

### BASFOR has five state variables for nitrogen. Only one of these is located in the trees: foliar nitrogen (NL). The nitrogen content of the other tree organ systems is not simulated as nitrogen state variables, but through the carbon state variables multiplied with constant tissue N-C ratios. The four soil nitrogen pools are for litter (NLITT), soil organic matter with fast resp. slow turnover time (NSOMF, NSOMS) and mineral nitrogen (NMIN). Nitrogen enters the system in mineral form through atmospheric deposition and, if the trees are nitrogen fixers, through nitrogen fixation. Nitrogen leaves the system through leaching and through emission of N2O and NO from the soil to the atmosphere. Mineral nitrogen is taken up by the trees from the soil, and nitrogen returns to the soil with senescence of leaves, branches and roots, and also when trees are pruned or thinned. When the nitrogen content of senescing leaves is high, some of the nitrogen from the falling leaves is recycled and is re-used within the trees. The rate of mineral nitrogen uptake by the trees is the minimum of demand and availability. Demand is calculated as the sum of the potential carbon growth rates of the different tree organs times their N-C ratio. The availability of mineral nitrogen is a Michaelis-Menten function of NMIN and is proportional to root biomass (CR). Transformation between the four soil nitrogen pools are described in 4.11; they are similar to those of the carbon pools (4.2) with NMIN taking the role of CO2.

### 4.4 Water balance

The water balance in BASFOR is characterized by just one state variable: the amount of water in the root zone (WA; kg H2O m-2 = mm H2O). Water is added to the soil by precipitation and lost through runoff, transpiration, evaporation, and drainage. Runoff is proportional to precipitation intensity and the sine of the land’s sloping angle, but exponentially reduced with increasing leaf area index. Evaporation and transpiration are calculated using the Penman-formula, as functions of the radiation intercepted by soil and trees, and atmospheric humidity and wind speed. Drainage of ground water results from water infiltration exceeding the water holding capacity of the soil.

#### 4.4.1 Effects of drought on transpiration and other plant processes

The effect of soil water status on plants is mediated by the so-called transpiration realisation factor (fTran). This intermediate variable is calculated as a function of soil water content, soil water retention characteristics (mainly wilting point and field capacity) and plant transpirational demand for water. fTran has a value of one when soil water content is not too far below field capacity, starts to fall when water decreases below a critical level and reaches zero at wilting point. Several plant processes are directly proportional to fTran, including transpiration rate. Other processes affected will be mentioned in the following sections.

### 4.5 Phenology

BASFOR contains no phenological variables when run for coniferous forests; phenology is only simulated for deciduous forests. The dynamics of leaf unfolding, growth and leaf fall, as well as accumulation and release of reserves are calculated using simple functions of thermal and calendar time, day length and accumulated chill days.

### 4.6 Light interception

Light interception is modelled by Beer's law with a constant light extinction coefficient operating on the LAI.

### 4.7 Gross primary productivity

Gross primary productivity is calculated as the product of intercepted radiation and photosynthetic light-use efficiency (LUE), which is a function of CO2, temperature, water and nitrogen availability.

### 4.8 Carbon allocation

Carbon allocation to the different tree organ systems follows fixed allocation coefficients, except that allocation to leaves is restricted in case of water or nitrogen deficiency and in case the maximum LAI has been reached. In those cases, carbon for leaves is allocated to roots instead.

### 4.9 Dynamics of reserves

Reserves are only simulated for deciduous trees. Accumulation of reserves takes place during the short period of leaf fall at the end of the growing season, and all stored reserves are remobilised in spring when leaf flushing takes place.

### 4.10 Autotrophic respiration

BASFOR assumes that tree respiration is a constant fraction of GPP, represented by the parameter GAMMA. So the NPP:GPP ratio is constant too and equal to 1-GAMMA.

### 4.11 Decomposition of litter and soil organic matter

### The soil decomposition chain, as already mentioned in 4.2, proceeds in the direction CLITT -> CSOMF -> CSOMS -> CO2. The first two transformation also produce some CO2, but most decomposed litter becomes CSOMF, and most decomposed CSOMF becomes CSOMS, whereas all decomposed CSOMS is in the form of CO2. The carbon chain is matched by a nitrogen chain ending in mineral N: NLITT -> NSOMF -> NSOMS -> NMIN. In each of the three steps, the fractions of nitrogen that are lost to mineral N are the same as the fractions of carbon that are lost to CO2.

### 4.12 Heterotrophic respiration

Heterotrophic respiration, which is named ‘Rsoil’ in BASFOR (despite the fact that it does not include root respiration), consists of the CO2 production in the decomposition of litter (CLITT) and soil organic matter (CSOMF, CSOMS) (4.11).

### 4.13 Tree morphology

Tree height (H; m) is calculated as an allometric function of stem biomass per tree (CS/treedens; kg C tree-1). Basal area per tree (BAtree; m2 stem area tree-1) is proportional to the ratio of stem volume per tree (= CS per tree divided by a constant wood density; m3 tree-1) and height. Stand basal area (BA; m2 stem m-2) then follows as the product of BAtree and tree density (treedens; m-2). Stem diameter at breast height (DBH; m) is calculated from basal area per tree, assuming that stems are round. Crown area per tree (ACtree; m2 crown tree-1) is calculated as an allometric function of stem biomass (CS). The fraction of ground that is covered by tree crowns (AC; m2 crown m-2) then follows as the product of ACtree and tree density (treedens; m-2), capped at 1 when crowns start overlapping. Leaf area (LA; m2 leaf m-2) is equal to leaf carbon (CL; kg C m-2) times a constant specific leaf area (SLA; m2 leaf kg-1 C). The LAI (m2 leaf m-2 crown area) is calculated by dividing LA with AC. The reference area for LAI-calculation thus is the crown-covered part of the forest, which is less than the total ground area whenever trees are still small, i.e. AC < 1.

### 4.14 Senescence

Branches (CB) and roots (CR) senesce at constant relative rates, which are set by the time constants TCCB and TCCR, both with unit day (d). For leaves (CL), there is a maximum time constant for senescence (TCCLMAX) but the actual time constant is reduced in case of drought. For deciduous trees, the time constant is in the order of a few days, but leaves can only fall in autumn (4.5). For coniferous trees, senescence operates during the whole year, but the time constant is orders of magnitude greater than for deciduous trees. For both tree types, leaf senescence is accelerated when leaves become nitrogen-deficient, irrespective of the season.

### 4.15 Tree management: thinning and pruning

Thinning is simulated as an instantaneous and equal (in relative terms) loss in all tree state variables: CL, CB, CS, CR, CRES, NL, treedens. It is assumed that the harvested CS is removed but that the other harvested carbon and nitrogen is added to litter and soil organic matter. Pruning is also an instantaneous activity, but one that does not reduce tree density, CS or CRES – only a specified fraction of CL, CB and NL is removed and added to litter.

## 5. Installing FORTRAN, R and RStudio

FORTRAN, R and RStudio are freely available from the web.

### 5.1 Install gfortran

* Go to: <http://gcc.gnu.org/wiki/GFortranBinaries> and scroll down to the paragraph called 'MinGW build ("native Windows" build)'. Then click in that paragraph on the link for downloading the latest 'installer (dated 2014-06-29 at the time of writing)' and choose 'Run'.

### 5.2 Install R

* Go to: <http://cran.r-project.org> and follow the instructions for downloading and installing R.

### 5.3 Install RStudio

* Go to: <http://www.rstudio.org/download/desktop> and click on the link to the version of RStudio 'Recommended For Your System'. Run the installer.

## 6. Installing the model files

All that needs to be done for model installation is unzipping the files, but it is important to check that the files are put in the correct place. So verify that the unzipping program has produced the correct directory structure, as outlined in section 3.5.2.

## 7. Compiling the model

This is not often needed. The zip-file already includes the result of model compilation, i.e. the files 'BASFOR\_conif.DLL' and ‘BASFOR\_decid.DLL’. But whenever you change one of the FORTRAN files (with extension '.f90'), the model needs to be recompiled so that an updated version of the DLL is produced.

* The model can be recompiled simply by double-clicking on either the file 'compile\_BASFOR\_gfortran\_CONIFEROUS.bat' or its counterpart for deciduous trees.
* The most common reasons for changing FORTRAN files are when you want to see different output variables than the default ones, or when you want to change the structure of the model.

### 7.1 Removing the previous DLL

If you started an RStudio-session with BASFOR, and during that session recompiled the model outside RStudio, you may need to 'unload' the original DLL to prevent R from continuing to work with it. Use the following statement for this:

* dyn.unload('BASFOR\_[].DLL')

## 8. Initialising the model

Before we run the model, we need to define the simulation period, the characteristics of the environment including the management, parameter values of the grass cultivar etc. This is organised using initialisation-files, in two steps.

### 8.1 Step 1: General initialisation

There is one initialisation file called 'initialise\_BASFOR\_general.R' which is used in every run of the model. This file is stored in subdirectory ‘initialisation’.

#### 8.1.1 'outputNames' and 'outputUnits'

The general initialisation file contains lists of all the model's output variables with their units, called “outputNames” and “outputUnits”. These lists are used for plotting and in Bayesian calibration (to match measured variables to simulated variables).

#### 8.1.2 'plotOutputs'

The general initialisation file also includes the definition of a plotting function, 'plotOutputs', that can be used in RStudio to make plots of selected output variables.

### 8.2 Step 2: Site-specific initialisation

Information on the specific site for which the model is run, is organised in site-specific initialisation files, stored in subdirectory ‘initialisation’. These files:

* define the start year and day of the simulation period, and its length,
* call the general initialisation file,
* read the appropriate weather data from file,
* set the parameter values of the model,
* set the calendars for tree thinning and pruning, and for nitrogen deposition.

#### 8.2.1 Weather files

Weather data, stored in subdirectory ‘weather’, should be provided in the form of ASCII files.

#### 8.2.2 Thinning dates

Thinning dates are defined in each site-specific initialisation file, in lines such as:

* calendar\_thinT[ 1, ] <- c( 1894, 1, 0.4 )
* calendar\_thinT[ 2, ] <- c( 1904, 1, 0.25 )

The numbers in that line refer to the year and doy ('day of the year') at which thinning takes place, and the fraction of trees that are removed.

#### 8.2.3 Parameter values

BASFOR has 59 parameters for which the values are set in a txt-file, 'parameters.txt' located in subdirectory 'parameters'. This txt-file in fact contains 6 different columns of parameter values, because parameterisation differs between sites. In particular the initial values of plant state variables and the parameters that define the soil water retention curve may differ between sites. For any run, the column in 'parameters.txt' from which parameter values are to be taken is specified in the site-specific initialisation file. So if you want to run the model with a new parameter vector, add the new parameter vector as a new column in 'parameters.txt', and modify the site-specific initialisation file to look at that new column.

## 9. Running the model

The model is run from script-files written in R.

### 9.1 Running the model with pre-defined settings

You can run the model using any of the included files called 'run\_BASFOR\_….R':

1. Double-click on the file.
2. This should open the file in RStudio. If not, it is advisable to associate files with extension '.R' with Rstudio.
3. Make sure that RStudio is not still looking at an older version of the file (that can happen if you opened the file before).
4. In RStudio, click on 'Source' - at the top right in the source editor panel - to run the whole script-file in one go. That should produce results that can be examined in the other RStudio-panels.

### 9.2 Running with different settings of your own choosing

This can be done in various ways, but the most tidy method is as follows:

1. Make a new site-specific initialisation file (initialise\_BASFOR\_…R') by editing one of the examples in the 'initialisation' directory and saving it under a different name.
   * If your new settings include the use of new weather data, you also have to place a new weather file in subdirectory 'weather'. Make sure that the new weather file follows the same format as the already available weather files.
2. Make a new 'run\_BASFOR\_…R' file, by copying and editing an existing run-file. In line 2 of your new file 'run\_BASFOR\_….R', call the new initialisation file that you made.
3. Continue as above for pre-defined runs.

## 10. Selecting and examining model outputs

Output variables are specified in two files which must be kept mutually consistent: 'BASFOR.f90' and the general initialisation file 'initialise\_BASFOR\_general.R'. The first is located in directory 'model', the second in directory ‘initialisation’. The first is the FORTRAN-file where the variables are actually quantified, the second is where we give information on variable names and units that RStudio can use for post-processing of the results. In the included model files, 36 output variables are specified, which include the 17 state variables of the model.

### 10.1 Choosing different output variables

It is possible to change the choice of output variables. For example, to add a new variable to the outputs, you need to:

* add the name of the new variable to the outputNameList in "initialise\_BASFOR\_general.R",
* ensure that the variable is visible to 'BASFOR.f90',
  + Most but not all model variables are visible to BASFOR.f90. The ones that are, are either declared at the top of 'BASFOR.f90' itself, like all the model's state and rate variables, or at the top of modules (other .f90 files) for which there is a "use" statement in 'BASFOR.f90'. So the exceptions are variables that are only locally defined inside subroutines. If you want to see one of those variables as output, move its declaration from inside the subroutine where it is defined to the top of its module, before the "contains"-statement. That will make the variable accessible anywhere in the module and in 'BASFOR.f90' because of the "use"-statement there. If the variable was exported from the subroutine where it was defined through the subroutine header, remove it there. Then also check if the variable was present in the header and declaration line of other subroutines in the module, and if so remove them there too.
* Add a line to BASFOR.f90 stating "y(day,40)=[new variable]" (assuming the previous number of output variables was 39).

### 10.2 Examining output

Outputs can be examined in various ways.

#### 10.2.1 Matrix variable 'output'

After every run, a large matrix called 'output' is produced, which can be inspected and analysed in RStudio. The matrix has the same number of rows as there are days in the simulation period, and the same number of columns at there are output variables. In BASFOR terms, the matrix dimensions are NDAYS x NOUT. The matrix does not show the names and units of the output variables, but these can be retrieved by inspecting the R-variable 'outputNames'.

#### 10.2.2 Graphs

The function 'plot\_output' is available (through its definition in the general initialisation file) for easy plotting of results. For examples of the use of this function, see the R-script file ‘INTRODUCTION\_EXAMPLES\_BASFOR2015.R’.

**11. Changing model structure**

If you want to make structural changes to BASFOR, you will be editing one or more of the FORTRAN files. So after that is done, you’ll need to recompile the model. Do so by clicking on either 'compile\_BASFOR\_gfortran\_CONIFEROUS.bat' or 'compile\_BASFOR\_gfortran\_DECIDUOUS.bat'.

## 12. Bayesian calibration (BC)

The model comes with R-files for calibrating the model's parameters using data from measurements. The files implement Bayesian calibration (BC) by means of Markov Chain Monte Carlo (MCMC) simulation using the Metropolis algorithm. The calibration involves six steps:

1. Selecting the parameters that will be calibrated,
2. Defining the prior probability distribution for those parameters,
3. Selecting the data that the parameters will be calibrated against,
4. Defining the likelihood function associated with those data,
5. Running the MCMC,
6. Analysing the outcome of the MCMC.

The file ‘INTRODUCTION\_EXAMPLES\_BASFOR2015.R’ contains calls to Bayesian calibration scripts but does not give more information. In subdirectory ‘doc’ you can find a manual with more details about multi-site Bayesian calibration with BASFOR: ‘Manual\_MULTISITE\_BC\_BASFOR.html’ (there is also an org-mode version of the same file).

## Publications on BASFOR and related models

* Van Oijen, M., Balkovič, J., Beer, C., Cameron, D., Ciais, P., Cramer, W., Kato, T., Kuhnert, M., Martin, R., Myneni, R., Rammig, A., Rolinski, S., Soussana, J.-F., Thonicke, K., Van der Velde, M. & Xu, L. (2014). Impact of droughts on the C-cycle in European vegetation: A probabilistic risk analysis using six vegetation models. Biogeosciences 11: 6357-6375. <http://www.biogeosciences.net/11/6357/2014/bg-11-6357-2014.html> . doi:10.5194/bg-11-6357-2014.
  + *BASFOR is used together with five other vegetation models in a probabilistic risk analysis.*
* Van Oijen, M., Beer, C., Cramer, W., Rammig, A., Reichstein, M., Rolinski, S., Seneviratne, S. & Soussana, J.-F. (2013). A novel probabilistic risk analysis to determine the vulnerability of ecosystems to extreme climatic events. Environmental Research Letters 8: 015032. <http://iopscience.iop.org/1748-9326/8/1/015032>
  + *This paper introduces a new method for risk analysis; BASFOR is used in an example.*
* Cameron, D.R., Van Oijen, M., Werner, C., Butterbach-Bahl, K., Grote, R., Haas, E., Heuvelink, G., Kiese, R., Kros, J., Kuhnert, M., Leip, A., Reinds, G.J., Reuter, H.I., Schelhaas, M.J., de Vries, W. & Yeluripati, J. (2013). Environmental change impacts on the C- and N-cycle of European forests: a model comparison study. Biogeosciences 10: 1751-1773. <http://www.biogeosciences.net/10/1751/2013/bg-10-1751-2013.html>
  + *Outputs are compared from four models: BASFOR, DailyDayCent, INTEGRATOR and Landscape-DNDC.*
* Van Oijen, M., Reyer, C., Bohn, F.J., Cameron, D.R., Deckmyn, G., Flechsig, M., Härkönen, S., Hartig, F., Huth, A., Kiviste, A., Lasch, P., Mäkelä, A., Mette, T., Minunno, F. & Rammer, W. (2013). Bayesian calibration, comparison and averaging of six forest models, using data from Scots pine stands across Europe. Forest Ecology and Management 289: 255-268.
  + *Six forest models, including BASFOR, are calibrated (in a Bayesian way, with model-specific priors) using forest inventory data from four countries (Belgium, Austria, Estonia, Finland), and tested against independent data from permanent sample plots. Results from country-specific calibrations are contrasted to those from calibrations using all data together. In a final analysis, posterior model probabilities are used in Bayesian model averaging which is shown to lead to robust predictions.*
* Van Oijen, M., Cameron, D.R., Butterbach-Bahl, K., Farahbakhshazad, N., Jansson, P.-E., Kiese, R., Rahn, K.-H., Werner, C., Yeluripati, J.B. (2011). A Bayesian framework for model calibration, comparison and analysis: application to four models for the biogeochemistry of a Norway spruce forest. Agriculture and Forest Meteorology 151: 1609-1621.
  + *This paper shows how Bayesian methods for model calibration and comparison can be applied to process-based forest models, and argues that the methods need to be complemented with detailed analysis of prior and posterior model-data mismatch. The models used are BASFOR, COUP, DAYCENT and MoBiLE-DNDC, and the data are on fluxes of NO, N2O and CO2 plus soil water content, all taken from the Höglwald site in southern Germany*.
* Van Oijen, M. & Thomson, A. (2010). Towards Bayesian uncertainty quantification for forestry models used in the United Kingdom Greenhouse Gas Inventory for land use, land use change, and forestry. Climatic Change 103: 55-67.
  + *This paper shows how BASFOR is calibrated against data from two forest sites in the UK and then applied over a country-wide grid, with uncertainty quantified by sampling from the posterior distribution for model parameters.*
* Van Oijen, M., Dauzat, J., Harmand, J.-M., Lawson, G. & Vaast, P. (2010). Coffee agroforestry systems in Central America: II. Development of a simple process-based model and preliminary results. Agroforestry Systems 80: 361-378.
  + *This paper introduces a dynamic model for coffee agroforestry systems, CAF2007. The tree component is BASFOR.*
* Van Oijen, M., Rougier, J. & Smith, R. (2005). Bayesian calibration of process-based forest models: bridging the gap between models and data. Tree Physiology 25: 915-927.
  + *This paper introduces BASFOR and includes a list of model parameters. It explains how the joint probability distribution for the parameters of such process-based models can be calibrated in a Bayesian way using a Markov Chain Monte Carlo (MCMC) algorithm.*

## 14. APPENDIX I: FORTRAN files and subroutines

The following table shows for each BASFOR FORTRAN file which subroutines it contains, and which (if any) rate variables are calculated in those subroutines. The only rate variables listed here are the ones that are part of the state equations in BASFOR.f90, i.e. rate variables that directly affect one of the 17 state variables of the model.

| **File** | **Subroutine** | **Calculated rate variables** |
| --- | --- | --- |
| BASFOR.f90 |  |  |
| belowgroundres.f90 | PETtr | RAINint |
|  | water\_flux | Evap, Tran |
|  | Nsupply |  |
| environment.f90 | set\_weather\_day |  |
|  | DDAYL |  |
|  | N\_dep | Ndep |
| management.f90 | fert\_prune\_thin | thintreedens |
| parameters.f90 |  |  |
| set\_params.f90 |  |  |
| soil.f90 | water | Drain, Runoff |
|  | CNsoil | dCLITT, dCLITTsomf, dCSOMF, dCSOMFsoms, dCSOMS, dNLITT, dNSOMF, dNSOMS, Nemission, Nfixation, Nleaching, NLITTsomf, Nmineralisation, NSOMFsoms, rCLITT, rCSOMF, rNLITT, rNSOMF |
|  | Tsoil\_calc |  |
| tree.f90 | dtsum\_dchillday | dchillday, dTsum |
|  | phenology |  |
|  | morphology |  |
|  | foliarDynamics | dCL, dCRES, dNL, dNLlitt |
|  | NPP |  |
|  | allocation |  |
|  | NdemandOrgans |  |
|  | gtreeNupt | gCB, gCL, gCR, gCRES, gCS, gNL, Nupt, retrNL |
|  | CNtree | dCB, dCR, dCS, dNBlitt, dNRsomf |

## 15. APPENDIX II: Variables

### 15.1 Introductory comments

* Areas (m2) are ground area unless otherwise indicated.
* Soil water amounts are given as "mm" water, which is equivalent to "kg water m-2 ground area".

#### 15.1.1 Types of variables

1. State variables
2. Non-state variables
   * Input variables: Variables whose values are not calculated by the model but defined in the initialization file or imported from an external data file.
   * Intermediate variables: Variables that express intermediate results in the calculation of rate or output variables.
   * Output variables: Variables whose calculation can be deleted without affecting any of the other model results.
   * Rate variables: Variables that directly change state variables. They are part of the state update equations in BASFOR.f90 and their unit includes "d-1".

### 15.2 State variables (BASFOR.f90)

| **State variable** | **Unit** | **Meaning** |
| --- | --- | --- |
| CB | kg C m-2 | Carbon in branches |
| chillday | d | Cumulative chill days |
| CL | kg C m-2 | Carbon in leaves |
| CLITT | kg C m-2 | Carbon in litter |
| CR | kg C m-2 | Carbon in roots |
| CRES | kg C m-2 | Carbon in reserves |
| CS | kg C m-2 | Carbon in stems |
| CSOMF | kg C m-2 | Soil organic carbon with a fast turn-over rate |
| CSOMS | kg C m-2 | Soil organic carbon with a slow turn-over rate |
| NL | kg N m-2 | Nitrogen in leaves |
| NLITT | kg N m-2 | Nitrogen in litter |
| NMIN | kg N m-2 | Soil mineral nitrogen |
| NSOMF | kg N m-2 | Soil organic nitrogen with a fast turn-over rate |
| NSOMS | kg N m-2 | Soil organic nitrogen with a slow turn-over rate |
| treedens | # m-2 | Tree density |
| Tsum | °C d | Thermal time |
| WA | mm | Soil water |

### 

### 15.3 Rate variables (BASFOR.f90)

| **Variable** | **Unit** | **Meaning** |
| --- | --- | --- |
| dCB | kg C m-2 d-1 | Loss of branches to thinning, pruning and senescence |
| dchillday | d d-1 | Increase in cumulative chill days |
| dCL | kg C m-2 d-1 | Loss of leaves to thinning, pruning and senescence |
| dCLITT | kg C m-2 d-1 | Decomposition of litter |
| dCLITTsomf | kg C m-2 d-1 | Decomposed litter becoming “fast” SOM |
| dCR | kg C m-2 d-1 | Loss of roots to thinning and senescence |
| dCRESgrow | kg C m-2 d-1 | Growth of leaf carbon from reserves |
| dCRESgrow \* NCLMAX | kg N m-2 d-1 | Growth of leaf nitrogen from reserves |
| dCRESthin | kg C m-2 d-1 | Loss of reserves to thinning |
| dCS | kg C m-2 d-1 | Loss of stems to thinning |
| dCSOMF | kg C m-2 d-1 | Decomposition of “fast” SOM |
| dCSOMFsoms | kg C m-2 d-1 | Decomposed “fast” SOM becoming “slow” SOM |
| dCSOMS | kg C m-2 d-1 | Decomposition of “slow” SOM |
| dNBlitt | kg N m-2 d-1 | Nitrogen moving to litter from branch senescence |
| dNL | kg N m-2 d-1 | Loss of leaf nitrogen to thinning and senescence |
| dNLITT | kg N m-2 d-1 | Loss of litter nitrogen to decomposition |
| dNLlitt | kg N m-2 d-1 | Nitrogen moving to litter from leaf senescence |
| dNRsomf | kg N m-2 d-1 | Nitrogen moving to “fast” SOM from root senescence |
| dNSOMF | kg N m-2 d-1 | Loss of nitrogen in “fast” SOM to decomposition |
| dNSOMS | kg N m-2 d-1 | Loss of nitrogen in “slow” SOM to decomposition |
| Drain | mm d-1 | Water drainage below the root zone |
| dTsum | °C d-1 | Change in thermal time |
| EVAP | mm d-1 | Evaporation of water from the soil |
| gCB | kg C m-2 d-1 | Growth of branches |
| gCL | kg C m-2 d-1 | Growth of leaves |
| gCR | kg C m-2 d-1 | Growth of roots |
| gCRES | kg C m-2 d-1 | Growth of reserve pool |
| gCS | kg C m-2 d-1 | Growth of stems |
| gNL | kg N m-2 d-1 | Growth of leaves (nitrogen content) |
| Ndep | kg N m-2 d-1 | Atmospheric nitrogen deposition |
| Nemission | kg N m-2 d-1 | Nitrogen emission from the soil |
| Nfert | kg N m-2 d-1 | Nitrogen fertilisation |
| Nfixation | kg N m-2 d-1 | Nitrogen fixation |
| Nleaching | kg N m-2 d-1 | Nitrogen leaching |
| NLITTsomf | kg N m-2 d-1 | Loss of litter nitrogen to “fast” SOM in decomposition |
| Nmineralisation | kg N m-2 d-1 | Nitrogen mineralisation |
| NSOMFsoms | kg N m-2 d-1 | Loss of nitrogen from “fast” to “slow” SOM in decomposition |
| Nupt | kg N m-2 d-1 | Nitrogen uptake by trees |
| RAIN | mm d-1 | Precipitation |
| RAINint | mm d-1 | Interception of precipitation by foliage |
| rCLITT | kg C m-2 d-1 | Loss of litter to runoff |
| rCSOMF | kg C m-2 d-1 | Loss of “fast” SOM to runoff |
| retrNL | kg N m-2 d-1 | Retranslocation of leaf nitrogen |
| rNLITT | kg N m-2 d-1 | Loss of nitrogen in litter to runoff |
| rNSOMF | kg N m-2 d-1 | Loss of nitrogen in “fast” SOM to runoff |
| Runoff | mm d-1 | Runoff |
| thintreedens | # d-1 | Tree thinning |
| TRAN | mm d-1 | Transpiration |

## 16 APPENDIX III: Parameters

### 16.1 Introductory comments

* Areas (m2) are ground area unless otherwise indicated.
* Soil water amounts are given as "mm" water, which is equivalent to "kg water m-2 ground area".

### 16.2 Parameters in BASFOR.f90

| **Parameter** | **Unit** | **Meaning** |
| --- | --- | --- |
| CBtree0 | kg C tree-1 | Initial branch carbon |
| CLITT0 | kg C m-2 | Initial litter carbon |
| CLtree0 | kg C tree-1 | Initial leaf carbon |
| CNLITT0 | kg C kg-1 N | Initial C-N ratio of litter |
| CNSOMF0 | kg C kg-1 N | Initial C-N ratio of SOM with fast turn-over |
| CNSOMS0 | kg C kg-1 N | Initial C-N ratio of SOM with slow turn-over |
| CRtree0 | kg C tree-1 | Initial root carbon |
| CSOM0 | kg C m-2 | Initial SOM carbon |
| CStree0 | kg C tree-1 | Initial stem carbon |
| FCSOMF0 | - | Initial fraction of SOM with fast turn-over |
| FNCLMIN | - | Minimum leaf N-C ratio as a fraction of the maximum value |
| FWCFC | - | Soil water content at field capacity as a fraction of that at saturation |
| GAMMA | - | Ratio of autotrophic respiration to gross photosynthesis |
| NCLMAX | kg N kg-1 C | Maximum N-C ratio of leaves |
| NLAMIN | kg N m-2 leaf | Minimum areal nitrogen concentration of leaves |
| NLAMAX | kg N m-2 leaf | Maximum areal nitrogen concentration of leaves |
| NMIN0 | kg N m-2 | Initial soil mineral nitrogen |
| ROOTD | m | Rooting depth |
| SLA | m2 leaf kg-1 C | Specific leaf area |
| TREEDENS0 | # m-2 | Initial tree density |
| WCST | m3 H2O m-3 soil | Soil water content at saturation |

### 16.3 Parameters in belowgroundres.f90

| **Parameter** | **Unit** | **Meaning** |
| --- | --- | --- |
| FWCAD | - | Soil water content at air dryness as a fraction of that at saturation |
| FWCFC | - | Soil water content at field capacity as a fraction of that at saturation |
| FWCWET | - | Soil water content at full wetness as a fraction of that at saturation |
| FWCWP | - | Soil water content at wilting point as a fraction of that at saturation |
| KNMIN | kg N m-2 | Soil mineral nitrogen content at which supply is half of maximum |
| KNUPT | kg N kg-1 root C d-1 | Maximum nitrogen uptake rate per unit root biomass |
| KRAININT | mm m-2 leaf d-1 | Maximum foliar rain interception per unit leaf area |
| ROOTD | m | Rooting depth |
| TRANCO | mm d-1 | Transpiration coefficient |
| WCAD | m3 H2O m-3 | Soil water content at air dryness |
| WCFC | m3 H2O m-3 | Soil water content at field capacity |
| WCWP | m3 H2O m-3 | Soil water content at wilting point |

### 16.4 Parameters in environment.f90

| **Parameter** | **Unit** | **Meaning** |
| --- | --- | --- |
| LAT | °N | latitude |

### 16.5 Parameters in soil.f90

| **Parameter** | **Unit** | **Meaning** |
| --- | --- | --- |
| FLITTSOMF | - | Fraction of decomposing litter that becomes “fast” SOM |
| FSOMFsoms | - | Fraction of decomposing “fast” SOM that becomes “slow” SOM |
| FWCFC | - | Soil water content at field capacity as a fraction of that at saturation |
| KNEMIT | kg N kg-1 N d-1 | Maximum relative rate of N emission to the atmosphere |
| RFN2O | m3 soil m-3 H2O | Coefficient in logistic function for the dependence of N2O-fraction in atmospheric emission on water-filled pore space |
| RNLEACH | - | Mineral N concentration in drainage water as a fraction of that in root zone water |
| ROOTD | m | Rooting depth |
| TCLITT | d | Time constant for decomposition of litter |
| TCSOMF | d | Time constant for decomposition of “fast” SOM |
| TCSOMS | d | Time constant for decomposition of “slow” SOM |
| TMAXF | °C | Soil temperature at which decomposition of litter and SOM is maximal |
| TSIGMAF | °C | Standard deviation of the Gaussian temperature dependence of decomposition of litter and SOM |
| WCFC | m3 H2O m-3 soil | Soil water content at field capacity |
| WCST | m3 H2O m-3 soil | Soil water content at saturation |
| WFPS50N2O | m3 H2O m-3 | Amount of water-filled pore space at which the N2O-fraction in atmospheric emission is 50% |

### 16.6 Parameters in tree.f90

| **Parameter** | **Unit** | **Meaning** |
| --- | --- | --- |
| BETA | - | Proportionality of LUE-increase with logarithm of normalised [CO2] |
| FB | kg C kg-1 C | Allocation to branches |
| FLMAX | kg C kg-1 C | Maximum allocation to leaves |
| FNCLMIN | - | Minimum leaf N-C ratio as a fraction of the maximum value |
| FS | kg C kg-1 C | Allocation to stems |
| FTCCLMIN | - | Relative leaf longevity under drought |
| GAMMA | - | Ratio of autotrophic respiration to gross photosynthesis |
| KAC | m2 crown tree-1 | Crown area of a tree with 1 kg branch biomass |
| KACEXP | - | Allometric exponent of crown area as a function of branch biomass |
| KBA | m2 basal area tree-1 | Basal area of a tree with a stem volume-height ratio equal to 1. |
| KEXT | m2 m-2 leaf area | Light extinction coefficient |
| KH | m | Height of a tree with 1 kg stem biomass |
| KHEXP | - | Allometric exponent of height as a function of stem biomass |
| NCLMAX | kg N kg-1 C | Maximum N-C ratio of leaves |
| NCR | kg N kg-1 C | N-C ratio of roots |
| NCW | kg N kg-1 C | N-C ratio of wood in branches and stems |
| NLAMIN | kg N m-2 leaf | Minimum areal nitrogen concentration of leaves |
| NLAMAX | kg N m-2 leaf | Maximum areal nitrogen concentration of leaves |
| SLA | m2 leaf kg-1 C | Specific leaf area |
| TCCB | d | Time constant for branches |
| TCCR | d | Time constant for roots |
| TOPT | °C | Optimum temperature for LUE |
| TTOL | °C | Tolerance of LUE to non-optimal temperature |
| WOODDENS | kg C m-3 wood | Wood density of stems |

## 17. APPENDIX IV: Constants

### 17.1 Introductory comments

* Areas (m2) are ground area unless otherwise indicated.

### 17.2 Constants in BASFOR.f90

| **Constant** | **Value** | **Unit** | **Meaning** |
| --- | --- | --- | --- |
|  | 0. | kg C kg-1 C | Initial ratio of reserves carbon to leaf carbon in coniferous trees |
|  | 0.1 | kg C kg-1 C | Initial ratio of reserves carbon to leaf carbon in deciduous trees |
|  | 1000. | kg H2O m-3 | Density of water |
|  | 1000. | g kg-1 | Unit conversion factor |
| NDAYS |  | d | Number of days being simulated |
| NOUT |  | - | Number of output variables |
| NPAR | 100 | - | Maximum number of parameters in the model |
| NWEATHER | 7 | - | Number of weather variables |

### 17.3 Constants in belowgroundres.f90

| **Constant** | **Value** | **Unit** | **Meaning** |
| --- | --- | --- | --- |
|  | 0.001 | m3 kg-1 H2O | Inverse of water density |
|  | 0.01 | m3 H2O m-3 | Minimum soil water content above wilting point that leads to stomatal closure |
|  | 0.15 | - | Reflection coefficient of global radiation onto soil |
|  | 0.25 | - | Reflection coefficient of global radiation onto canopy |
|  | 0.5 | - | Efficiency of transpiration reduction by intercepted rain |
|  | 0.5 | m2 m-2 leaf | Extinction coefficient global radiation |
|  | 0.54 | s m-1 | Constant in wind factor Penman equation |
|  | 0.55 | - | Maximum ratio of net long-wave to black-body radiation |
|  | 0.611 | kPa | Saturation vapour pressure at 0 °C |
|  | 1. | - | Constant in wind factor Penman equation |
|  | 17.4 | - | Constant in calculation saturation vapour pressure |
|  | 2 | - | Power coefficient in temperature derivative of SVP |
|  | 2.63 | kg m-2 d-1 kPa-1 | Constant in wind factor Penman equation |
|  | 4 | - | Power coefficient in calculation black-body radiation |
|  | 239 | °C | Constant in calculation saturation vapour pressure |
|  | 273 | K | Temperature unit conversion factor |
|  | 1000. | kg H2O m-3 | Density of water |
|  | 4158.6 | °C | Constant in temperature derivative of SVP (= 17.4 \* 239) |
|  | 86400 | s d-1 | Time unit conversion factor |
|  | 1.E6 | J MJ-1 | Energy unit conversion factor |
| BOLTZM | 5.668E-8 | J m-2 s-1 K-4 | Stefan-Boltzmann constant |
| DELT | 1 | d | Time step |
| LHVAP | 2.4E6 | J kg-1 | Latent heat of water evaporation |
| PSYCH | 0.067 | kPa °C-1 | Psychrometric constant |

### 17.4 Constants in environment.f90

| **Constant** | **Value** | **Unit** | **Meaning** |
| --- | --- | --- | --- |
|  | 0.0000009 | ppm CO2 y-4 | Constant in polynomial time dependence of [CO2] |
|  | 0.000354 | ppm CO2 y-3 | Constant in polynomial time dependence of [CO2] |
|  | 0.03 | ppm CO2 y-2 | Constant in polynomial time dependence of [CO2] |
|  | 0.5 | J PAR J-1 GR | The fraction of PAR in Global Radiation |
|  | 1.15 | ppm CO2 y-1 | Constant in polynomial time dependence of [CO2] |
|  | 23.45 | degrees | Solar declination at June 21 |
|  | 180 | degrees | Constant in angular unit conversion |
|  | 291 | ppm CO2 | Constant in polynomial time dependence of [CO2] |
|  | 1900 | y | Base year for polynomial time dependence of [CO2] |
| LAT |  | degrees north | Latitude |
| PI | 3.1459265 | radians | Angle in radians corresponding to 180 degrees |
| RAD | pi/180 | radians degree-1 | Angular unit conversion factor |

### 17.5 Constants in soil.f90

| **Constant** | **Value** | **Unit** | **Meaning** |
| --- | --- | --- | --- |
|  | 0.001 | m3 kg-1 H2O | Inverse of water density |
|  | 2. | - | Constant in temperature dependence of decomposition |
|  | 10. | °C | Constant in temperature dependence of decomposition |
|  | 100 | degrees | Angular unit conversion factor |
|  | 1000. | kg H2O m-3 | Density of water |
| DELT | 1 | d | Model time step |
| KNFIX | 0 | kg N kg-1 C | Nitrogen fixation rate per unit of root growth |
| KRUNOFF | 0.5 | m2 m-2 leaf | Coefficient of exponential decrease of runoff with LAI |
| RRUNBULK | 0.05 | kg kg-1 | Ratio of C or N in runoff water as a fraction of that in bulk soil |
| SLOPE | 0 | degrees | Slope of the field |

### 17.6 Constants in tree.f90

| **Constant** | **Value** | **Unit** | **Meaning** |
| --- | --- | --- | --- |
|  | 0.999 | - | Constant in calculation of leaf nitrogen status |
|  | 200. | d | Earliest possible start day of leaf fall in deciduous trees |
| chillstart | 304 | d | Annual start time of chill day accumulation |
| CO20 | 350 | ppm | Reference value of [CO2] for calculating effect on LUE |
| DAYLAUT | 0.4498876 | d d-1 | Day length threshold above which no leaf fall takes place |
| DELT | 1 | d | Time step |
| PI | 3.14159265 | - | Geometric constant |
| Tb | 9.2426324 | °C | Base temperature for thermal time |
| Tc | -3.3501598 | °C d | Temperature threshold for chill days |
| Tcrita | 35.5237816 | °C d | Coefficient in calculation of thermal time required for growth of deciduous trees |
| Tcritb | 1.7617968 | °C d | Coefficient in calculation of thermal time required for growth of deciduous trees |
| Tsumstart | 32 | d | Annual start of thermal time accumulation |