# BASGRA\_N: a model for grassland productivity, quality and greenhouse gas balance

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## 1 Introduction

This document contains general documentation and a user manual for the grassland model BASGRA\_N. The name of the model stands for BASic GRAssland model (Nitrogen-cycle version), 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 wide range of environmental drivers. BASGRA\_N simulates the growth and survival of grassland swards for any period of time, so the user can decide whether to run the model just for a short growing season, a winter period, or for a sequence of whole years. The version of the model documented here is that of April 2018.

### 1.1 Model history

The first version of the model was called ***LINGRA*** and was developed in Wageningen by Ad Schapendonk and colleagues. LINGRA simulated only the growing season. To make the model usable for studying climate change impacts, the effect of CO2 and temperature on the light-use efficiency of the sward was included (Rodriguez et al. 1999).

Most of the further development of the model took place in Saerheim, Norway, at Planteforsk and Bioforsk (now NIBIO). Whereas the Wageningen version of the model was mainly used for perennial ryegrass, the model was changed in Norway to allow simulation of timothy (Phleum pratense) as well. For that purpose, tillering was simulated in greater detail, distinguishing elongating from non-elongating tillers (Höglind et al. 2001; Van Oijen et al. 2005). The next major step was the development of algorithms for winter processes (Thorsen et al. 2010, Thorsen & Höglind 2010). More recently, the model code was translated into FORTRAN by David Cameron, and the 'summer' and 'winter' processes were linked together, producing the year-round model, which was called ***BASGRA***.

After 2014, the model was extended further and is now called ***BASGRA\_N***. This new model version was developed to allow simulation of additional phenomena: (1) the impact of N-supply on the plants and their environment, (2) the dynamics of greenhouse gases in plants and soil, (3) the dynamics of cell-wall content and digestibility of leaves and stems. [The older version of BASGRA remains available for those not needing the extra detail, it is downloadable from Van Oijen et al. 2015, <https://dx.doi.org/10.5281/zenodo.27867> .] BASGRA\_N simulates the carbon-, nitrogen- and water-cycles in the plant-soil system in some detail. The main changes in the computer code, compared to BASGRA, are for the simulation of C and N in the soil, and of N in the plants. The dynamics of cell-wall content and digestibility are simulated using simple empirical functions of phenological stage.

### 1.2 Authorship and ownership

Developing the model has been a team effort with many people involved: see the author lists of the various publications on LINGRA, BASGRA and BASGRA\_N (Chapter 13). Simon Woodward of DairyNZ (New Zealand) gave many useful comments on BASGRA, which led to changes in some algorithms.

BASGRA\_N is fully in the public domain, and can be downloaded and used by anyone.

## 2 Quick start

### 2.1 TO MAKE EVERYTHING READY FOR RUNNING BASGRA\_N

* Install R, RStudio and gfortran on your computer.
* Download BASGRA\_N to your computer (and make sure that the required directory-structure is preserved, see section 3.5.2).

### 2.2 TO RUN THE MODEL for default conditions

* Double-click on 'run\_BASGRA\_Saerheim\_2000\_09\_Grindstad.R' to open the file in RStudio.
* Click on 'Source' to run the file.

### 2.3 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'.

### 2.4 TO RUN THE MODEL FOR A DIFFERENT SITE OR YEAR

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

### 2.5 TO APPLY BAYESIAN CALIBRATION to model parameters

* Run 'BC\_BASGRA\_Saerheim\_nutritive.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 1000 iterations in the Markov chain (which for this calibration is set in file ‘BC\_BASGRA\_MCMC\_init\_Saerheim\_nutritive.R’ in directory ‘BC’) runs is actually too short. Use 10^4 - 10^5 runs for proper calibration.

### 2.6 TO FIND MORE DETAILS of these and other modelling procedures

* See other chapters of this manual.

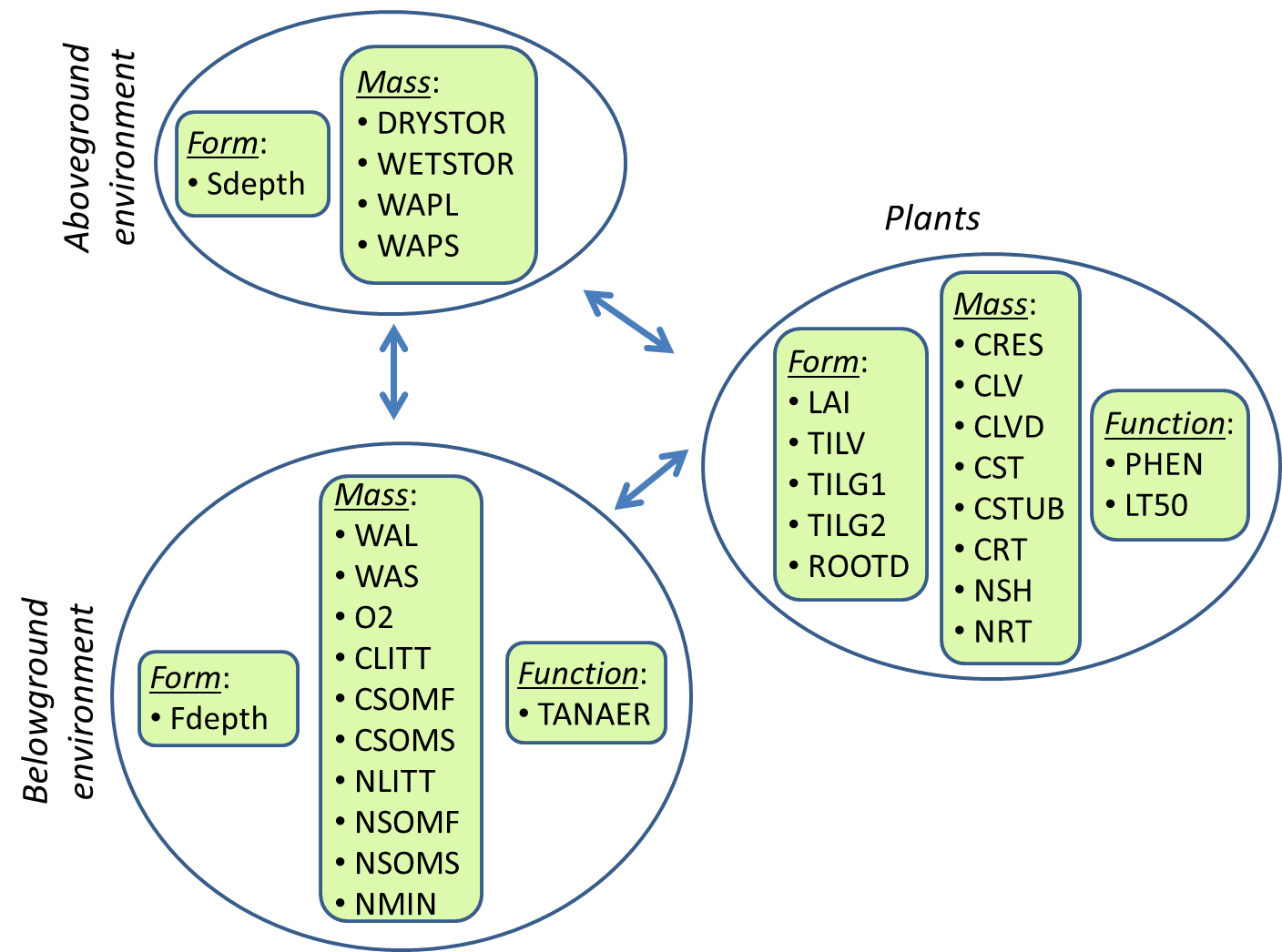
## 3 General overview of the model

### 3.1 What processes does BASGRA\_N simulate?

BASGRA\_N simulates year-round processes in grassland swards: growth and development during the growing season and survival over the winter. Interactions with the atmospheric and soil environment are simulated in some detail. This includes the role of management, i.e. cutting and irrigation. During winter, the model keeps track of the dynamics of water in its various forms: ice-formation below- and aboveground, snow cover, storage of liquid water within snow, soil and surface pools. Damage by frost and by anaerobic conditions under ice accelerate senescence depending on the degree to which the plants were hardened. During the growing season, the environment is less complicated. Water still cycles between soil, plants and atmosphere, but is only present in liquid form. Plant physiology is then very active: photosynthesis, respiration, dynamics of reserves and allocation, leaf area dynamics, tillering, water uptake. Growth depends on the strength of both the source (photosynthesis and remobilisation of reserves) and the sinks (the carbon-demand of growing organs and of the hardening process). The major occasional disturbance is removal of tillers and leaves by cutting, with subsequent regrowth of the sward. Regrowth rate depends on the phenological stage at which cutting took place and on the magnitudes of sources and sinks. BASGRA\_N is a one-dimensional model in that it keeps track of the height of snow cover and the depth to which soil is frozen. Horizontal heterogeneity of soil and sward is not captured.

### 3.2 State variables

BASGRA\_N has 32 state variables. 15 of those variables quantify the state of the plants, the others represent the above- and belowground environment in which the plants grow. Three types of state variables can be distinguished: variables for mass, form and function. The figure shows the state variables in each category, with the names they have in the computer code. Variable names, units and meanings are listed in the Appendices.



### 3.3 Inputs

The major inputs to the model are time series of weather variables (radiation, temperature, precipitation, wind speed, humidity) and nitrogen additions (atmospheric deposition, fertilisation). The model further requires time series indicating at which days the grass is cut. Given the typically short time periods of simulation, atmospheric CO2 concentration is not provided as a time series but as a constant. Soil properties, such as parameters of water retention, are also provided as constants.

### 3.4 Outputs

The model generates as many output variables as the user desires, but will typically include the 32 state variables.

### 3.5 Technical details

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

BASGRA\_N 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 dates and amounts of N-fertilisation and deposition.
4. set the cutting dates,
5. set parameter values,
6. call FORTRAN to iteratively calculate rates and states,
7. collect the output,
8. make plots.

#### 3.5.2 Directories and files

BASGRA\_N should be set up in eight directories: the upper directory plus seven subdirectories called 'BC', 'data', ‘’documentation’, 'initialisation', 'model', 'parameters', 'weather'. We shall now give a short overview of the files to be found in the eight directories. More details on some of the files will appear in later sections.

The upper directory contains:

* script-files in R for model running: 'run\_[].R'
* script-files in R for model calibration: 'BC\_[].R'
* a compiled model file: 'BASGRA.DLL'
* a batch file for compiling the model after any changes in FORTRAN-code: 'compile\_BASGRA\_gfortran.bat'.

Subdirectory 'model' contains:

* 3 FORTRAN files for model parameterisation: 'parameters\_[].f90' and 'set\_params.f90'
* 5 FORTRAN files that contain the model proper, i.e. the calculations of rates and states.

Subdirectory 'BC' contains:

* files defining different likelihood functions: 'fLogL[].R'
* script-files in R for initialising a Bayesian calibration: 'BC\_BASGRA\_MCMC\_init\_[].R'
* a script-file in R for running the Bayesian Calibration by means of the Markov Chain Monte Carlo method of Metropolis: 'BC\_BASGRA\_MCMC.R'
* a 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'
* script-files in R for plotting calibration results: 'BC\_plot[].R'

Subdirectory 'data' contains:

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

Subdirectory 'documentation' contains:

* this User Guide

Subdirectory 'initialisation' contains:

* script-files in R for model initialisation: 'initialise\_[].R'

Subdirectory 'model' contains:

* 8 FORTRAN files that together define BASGRA\_N.

Subdirectory 'parameters' contains:

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

Subdirectory 'weather' contains:

* files with weather data in the required 'Bioforsk' format: '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 there. 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. A table provided as one of the Appendices shows in which subroutine of which file/module each rate variable is being calculated.

* Notes on programming style
  + In cases of modules which contain multiple subroutines (such as in 'plant.f90' and 'environment.f90'), the subroutines are sorted from high to low level, i.e. subroutines that are being called follow the 'calling' subroutines. Low-level subroutines are also indented more.
  + 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, BASGRA\_N 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, BASGRA\_N 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 BASGRA\_N 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 g carbon or kg water, temperature in degrees Celsius. For example, leaf biomass is in g 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. total aboveground biomass is given in kg dry matter m-2.

#### 3.5.5 Model time-step

The model has a time step of one day.

## 4 Details of processes and algorithms

### 4.1 Weather

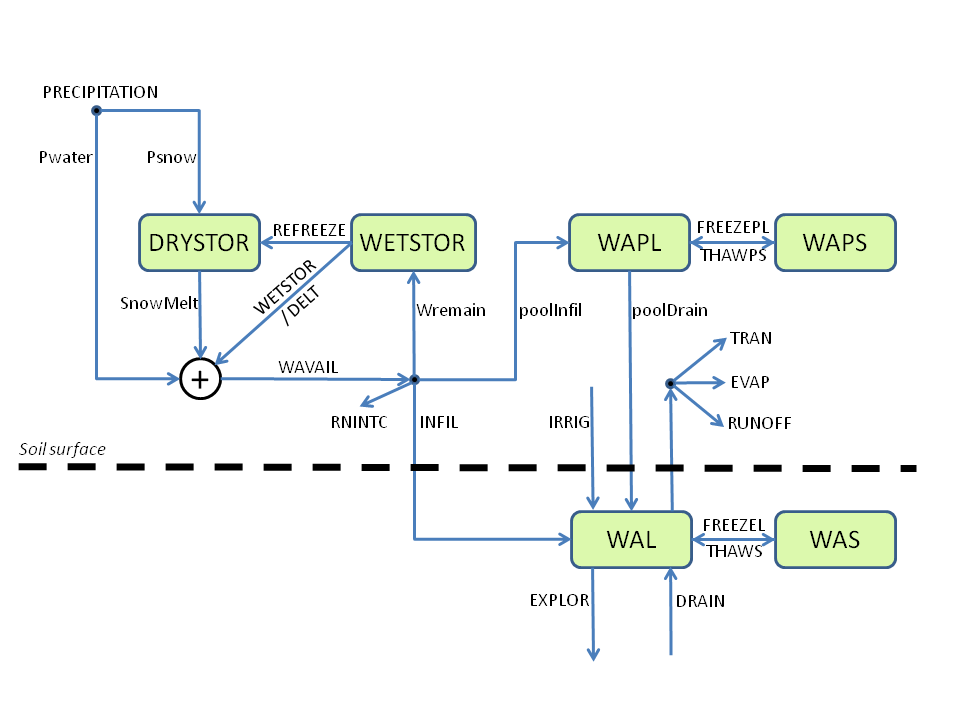
The model reads weather data from file. The files must include daily data for radiation, temperature and precipitation. For other variables there are two options: either relative humidity and wind speed are provided or potential evapotranspiration rate. BASGRA\_N includes an algorithm to determine whether the precipitation falls as rain or snow. More details on the structure of the weather files are given below, in the section on 'Preparing for a model run: input and initialisation files'.

### 4.2 Soil temperature

BASGRA\_N does not calculate the vertical temperature profile in the soil. It does calculate the temperature at the soil surface, as a function of atmospheric temperature, snow depth and soil frost depth. Snow cover makes soil surface temperature closer to zero degrees, the impact of frost depth is more complex.

### 4.3 Water balance

The water balance in BASGRA\_N is characterized by eight state variables. Two of these are variables of form, representing snow cover height and soil frost depth. The remaining six state variables are variables of mass of water in different phases (liquid, snow, ice), above- and belowground. The relationships between the six mass state variables and the rates that modify them are depicted in the figure.



During the growing season all water states tend to be zero, except for the pool of liquid water in the soil (state variable WAL). BASGRA\_N then acts as a model with a single soil layer between surface and rooting depth. Water is added to the soil pool by rain and irrigation, and by root growth leading to exploration of deeper soil. Water availability to plants is determined only by rooting depth, not root mass. Water is lost from the soil through drainage, runoff, evaporation and transpiration by plants. When snow falls, the state variable DRYSTOR (mass of snow per unit ground area) becomes positive, and so is the state variable representing the height of the snow pack. Snow can hold some liquid water, represented by state variable WETSTOR. If soil surface temperature is below the freezing point, soil water will start freezing from the top. This is captured by state variable WAS for the mass of soil ice and state variable Fdepth for its depth. Once frost depth exceeds a threshold of 0.2 m, liquid water can no longer infiltrate the soil and a surface pool of water is formed. The surface pool is subject to freezing and thawing, and thus also requires two state variables to represent the different phases (WAPL, WAPS). The threshold of 0.2 m is based on a study which reported infiltration despite the presence of a frozen soil layer 20-40 cm thick.

#### 4.3.1 Soil frost depth dynamics

The calculation of the rate of frost depth change is based on energy-balance considerations. The rate is given by a simple function of soil surface temperature and the amount of ice between the frost boundary and the surface.

#### 4.3.2 Snow melt

The calculation of snow melt is based on an algorithm used by the Norwegian Water Resources and Energy Directorate (NVE) for operational snow information services. This uses a sinusoidal melt-index curve with maximum snowmelt on day no 174 (23 June), and minimum snowmelt on day no 358 (23 December).

#### 4.3.3 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 (TRANRF). 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. TRANRF 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 TRANRF, including transpiration rate. Other processes affected will be mentioned in the following sections.

### 4.4 Phenology

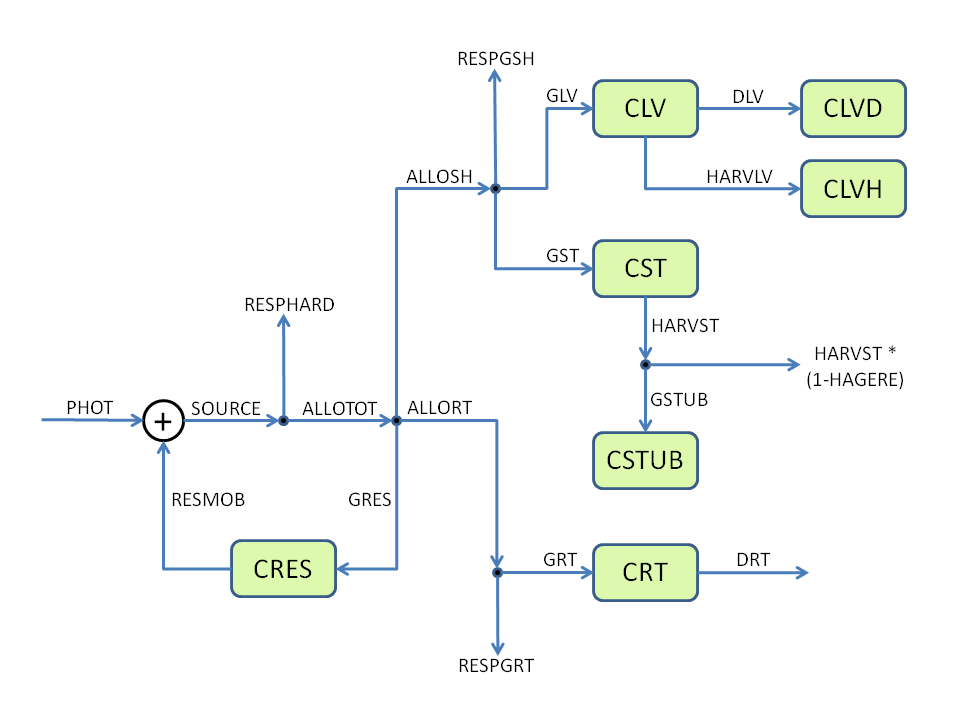
BASGRA\_N contains a state variable PHEN which represents the phenological stage of the plants. PHEN increases daily at a rate that depends on temperature and day length, and it is reset to zero after each cut. Advancing phenological stage leads to reductions in leaf appearance rate (RLEAF) and in the number of elongating leaves on non-elongating tillers. Besides through state variable PHEN, day length also affects some processes directly, as captured in intermediate variable DAYLGE. This variable modifies RLEAF, leaf elongation rate on elongating tillers, and the priorities of sinks in carbon allocation. Some of these phenological algorithms are based on Helge Bonesmo's PhD-thesis model for cv. Bodin.

### 4.5 Light interception

Light interception is modelled by Beer's law with a constant light extinction coefficient operating on the LAI. When there is snow cover, a constant light extinction coefficient for snow operates too. Plants only receive the light not intercepted by snow.

### 4.6 Carbon balance

BASGRA\_N has seven state variables for biomass. Five of these are the carbon contents in roots, reserves, stubble, stems, and leaves. The model also keeps track of carbon in dead and harvested leaves. The seven state variables for carbon pools and the rates that modify them are shown in the figure. The various processes depicted in the figure are discussed in the following paragraphs.



### 4.7 Photosynthesis

The rate of photosynthesis is the product of intercepted radiation and photosynthetic light-use efficiency (LUEMXQ), which is a function of CO2, temperature, light intensity and Rubisco concentration of upper leaves. LUEMXQ accounts for carbon lost to maintenance respiration, but not growth respiration. So the calculated photosynthesis rate is gross photosynthesis minus maintenance respiration. LUEMXQ starts decreasing linearly when temperature drops below one degree Celsius until it becomes zero at minus four degrees. It is also sensitive to drought and decreases conform TRANRF (see section "Water balance").

### 4.8 Carbon allocation

Carbon available for plant use, from photosynthesis and remobilised reserves, is allocated to different sinks according to a system of changing sink priorities and changing sink strengths. There are five sinks: the processes of winter hardening, replenishment of the reserves pool, root growth, stem growth, leaf growth. Sink strengths are defined as the rate at which these processes would proceed with no source limitation. The hardening process has top priority, so its demand is met in full if source strength is large enough, irrespective of the four other sinks. Root growth has lowest priority and depends on carbon unused by other sinks. The other sinks have intermediate priorities which change with day length. When day lengths are short, reserves have higher priority than stems and leaves, with the opposite during the rest of the year. Leaves and stems have equal priority so they receive carbon according to their sink strengths.

### 4.9 Dynamics of reserves

Reserves can be remobilized with a time constant of two days. When temperature drops below five degrees Celsius, remobilisation slows down until it stops completely at zero degrees.

### 4.10 Leaf area dynamics and tillering

BASGRA\_N represents tiller density by thre state variables: TILV (vegetative tillers), TILG1 (non-elongating generative tillers) and TILG2 (elongating generative tillers). The rate at which new vegetative tillers are formed is proportional to leaf appearance rate, but site-filling is reduced when LAI is high or reserve content is low. Leaf appearance rate itself depends on temperature, at a constant phyllochron, but slows down under drought, short day length, and when the sward becomes dominated by elongating tillers at an advanced phenological stage. The rate at which vegetative tillers move to the generative category has a temperature optimum and is reduced at short day lengths. Generative tillers move from the non-elongating to the elongating tillers category at a constant daily rate as long as the day length is above the minimum required for this process. For genotypes with a vernalization requirement, this transition from vegetative to non-elongating generative tillers only occurs after the vernalization requirement has been fulfilled. The vernalization requirement is simulated in a simplistic way using a threshold temperature. As soon as the temperature falls below the threshold value, the vernalization requirement is considered fulfilled and vegetative tillers start moving to the non-elongating generative tiller category.

The sink strength associated with the stem growth of elongating tillers decreases linearly with their size, and is also sensitive to drought. The sink strength associated with the growth of leaves is calculated as potential leaf area growth divided by specific leaf area (SLA). The SLA of new leaf growth decreases linearly with reserve content. Potential growth rate of leaf area is drought-sensitive and proportional to the product of tiller density, the number of elongating leaves per tiller, a constant leaf width and a temperature-dependent leaf elongation rate. All four factors in that product differ between elongating and non-elongating tillers, so the calculation is done separately for the two categories and then summed. Leaf elongation rates increase linearly with temperature, based on relationships determined by Peacock (1976) and observations in Saerheim.

### 4.11 Senescence

The senescence rate of leaves and non-elongating tillers increases with LAI. Leaves, but not tillers, also die faster at higher soil surface temperatures. Two other drivers of foliage death, frost and anaerobic conditions, are discussed in following sections. The model does not simulate senescence of elongating tillers or roots. Stubble does die, but at a constant relative rate.

### 4.12 Hardening and the impact of frost

Sensitivity to frost is measured by the state variable LT50, the "Lethal Temperature 50%", which is the soil surface temperature that would kill half the leaves and non-elongating tillers in one day. Lower temperatures induce the same death rate, higher temperatures are less damaging. The process whereby plants reduce LT50, i.e. increase their level of frost tolerance, is called hardening. Hardening capacity decreases over winter and is zero during spring and early summer. Dehardening, i.e. increasing LT50, is always possible. Hardening proceeds fastest when LT50 is high and temperatures low, and the opposite applies to dehardening. The hardening process, which is energy-demanding, slows down when reserve content is low.

### 4.13 The impact of anaerobic conditions

When there is a surface ice layer (state variable WAPS > 0), anaerobic conditions are assumed present. The number of consecutive anaerobic days is monitored as state variable TANAER. Sensitivity to anaerobic conditions follows a logistic function of TANAER in which the LD50, i.e the lethal duration of anaerobic conditions that kills 50% of leaves and non-elongating tillers, is assumed to be linearly related to LT50 based on data for timothy cultivars Grindstad and Engmo. The logistic function was derived as minus the normalized derivative of the curve for the fraction surviving plants: Relative death rate = -(d fSurv/ dt) / fSurv. Given that the survival curve is well described as 1 / (1 + exp[r(t-LD50)]), the relative death rate is found to be: r / (1 + exp[-r(t-LD50)]). For the parameter r, a value of 0.2 leads to an observed width of the survival curve.

### 4.14 The impact of harvesting

Most plant processes are interrupted during days when a harvest takes place. The cutting removes all elongating tillers, but no non-elongating tillers. Part of the biomass in elongating tillers becomes stubble. All leaf area (and corresponding leaf mass) above a threshold is removed by the cutting, as are most of the reserves.

**4.15 Carbon and nitrogen cycling through plants and soil**

BASGRA\_N has two plant state variables for nitrogen (NSH and NRT, the amount of nitrogen in aboveground plant parts resp. roots; g N m-2) and seven soil state variables representing mineral nitrogen plus C and N in three other soil pools: litter and two forms of organic matter differing in decomposition rate. Nitrogen is not considered to be present in reserves, so there is no nitrogenous counterpart to CRES.

The dynamics of NSH are the net result of growth (incorporating N taken up from the soil and from remobilisation), senescence and harvesting. The dynamics of the seven new soil state variables are simulated in the same way as in the forest model BASFOR (Van Oijen et al. 2005). The pool sizes vary as a result of external inputs (fertilisation, deposition, fixation), decomposition, uptake by plants, and losses to the environment (leaching, gaseous emission). The input time series for fertilisation and for atmospheric deposition are both in units of g N m-2 d-1. New model outputs include crude protein content and ash content, both of which are estimated as linear functions of shoot nitrogen content. The following section gives more detail about the simulation of N-processes in the plants

**4.16 Simulation of N in the plants**

**4.16.1 Availability of N, the "N-source"**

At every time step, the availability of N to the plants is determined by the amount of soil mineral N (state variable NMIN; g N m-2), plus the amount of N that becomes available from within the shoots by remobilisation. N-remobilisation is calculated by comparing the amount of N actually present in the shoots (NSH) to the amount of N that we would have seen if N-C ratio followed the same exponential profile in the sward as light, starting from the maximum N-C value allowed by the model at the top (NCSHMAX). In the model, that "expected" amount of shoot N is called NSHK, which can be read as "the amount of N in shoots if the profile would follow the light extinction coefficient K". The formula for NSHK is the following:

NSHK = CSH \* NCSHMAX \* (1-exp(-K\*LAI))/(K\*LAI),

where CSH = CLV+CST, i.e. carbon in leaves plus stems. The term "CSH\*NCSHMAX" is the maximum possible amount of shoot-N (maximum N-C ratio at all positions), and the final term is the fraction of that maximum that is realised in an exponential profile with coefficient K. Often NSH > NSHK, and we assume that the excess nitrogen (NSH - NSHK) becomes available for growth at a given time constant. That process is called remobilisation. NMIN is available for plant uptake, but not all of it at the same time: the maximum plant uptake rate of soil mineral nitrogen is calculated as NMIN divided by a given time constant. Apart from plant uptake, NMIN is also depleted by loss to the environment (leaching, emission), and it is replenished from decomposition of organic material and from external inputs in the form of deposition, fertilisation and/or fixation. This makes NMIN into a highly dynamic variable that never contains more than a small fraction of total soil N, but one that plays a key role in regulating plant processes. So in the model, the N-source available for growth is equal to the excess of shoot-N plus soil mineral N, both terms divided by their own time constant.

**4.16.2 Requirement for N, the "N-sink"**

In all versions of BASGRA, allocation of carbon to shoot growth depends on the balance between C-availability (from photosynthesis and reserves) and C-demand by leaves and stems. We refer to the shoot demand for C as its "sink strength". In BASGRA\_N, a small N-source reduces shoot sink strength, but does not affect the sink strength of other processes. The effect of a limiting N-source on the shoot sink (for growth in terms of carbon) is assumed to be proportional to the N-source divided by the product of shoot sink and a maximum shoot N-C ratio. The latter product can be viewed as the N-sink of the plants. So shoot carbon sink is proportional to the source-sink ratio for N. In yet other words, when the N-source is too low to support shoot growth at maximum nitrogen concentration, shoot growth rate is reduced proportionately. The proportionality factor is called 'fNgrowth' in the model.

**4.16.3 Effects of N-limitation on other plant processes than growth**

Apart from influencing shoot sink strength and thereby allocation patterns, N-limitation does not have an immediate effect on plant light-use efficiency because the Rubisco-content and N-C ratio of upper leaves (parameter RUBISC, g m-2 leaf; parameter NCSHMAX, g g-1) are assumed to be constant. There is, however, an immediate effect on tillering: the leaf appearance rate, which provides sites for tillering, is also proportional to fNgrowth. Note, however, that all other plant processes will also, but indirectly, be affected in the long-run by any changes in allocation.

**4.16.4 Dynamics of plant N-C ratios**

The overall N-C ratio of stems and leaves, NCSH, is considered variable in BASGRA\_N. In contrast, the N-C ratio of roots is assumed to be constant, and that of reserves is assumed to be zero. Although NCSH is variable, it is not fluctuating strongly, despite the fact that three processes affect it. These processes are growth, senescence and harvesting. All three processes change NCSH by adding or removing tissue that is not at the average N-C ratio. We assume that (1) growth adds young material at a ratio higher than average, (2) harvesting removes tissue also at higher-than-average N-C ratio, while (3) senescence removes tissue at lower than average N-C ratio. Calculation of the N-C ratios at which the three processes proceed is based on the assumption that nitrogen concentration follows an exponential function of LAI, counting from the youngest leaves downward. So a very small amount of shoot growth would have the maximum N-C ratio (parameter NCSHMAX), and greater amounts of new shoot growth would have slightly lower N-C ratios. Likewise, the harvested material from a very small cut would have high N-C ratio whereas big cuts would have lower N-C ratio because older, lower-N tissue would be included in the harvest. The loss of N in senescence also adheres to the concept of an exponential aboveground profile of N, but the assumption is here that the lowest-N tissue dies first, so days with high senescence may have slightly greater losses of N per unit tissue than days with only minor senescence. All these calculations require us to estimate KN, the "extinction coefficient for N" in the sward profile.

**4.16.5 Derivation of the N-extinction coefficient, KN**

Assuming that nitrogen follows an exponentially decreasing curve in the canopy, starting from a given maximum N-C ratio at the top (NCSHMAX), we should in principle be able to calculate KN as a function of total aboveground leaf area (LAI) and nitrogen (NSH). However, as we show now, there is no analytical solution to this problem, so we developed a somewhat intricate approximating equation for KN. As a general observation, we can say that if NSH > NSHK, then KN must be less than K (nitrogen "extinguishes" less quickly than light does) and if NSH<NSHK then KN > K. More precisely, KN can be solved from the following equation, similar to the one for NSHK above but with a different exponential coefficient:

NSH = CSH \* NCSHMAX \* (1-exp(-KN\*LAI))/(KN\*LAI).

Unfortunately that equation cannot be solved analytically for KN, because of the exponential term. In other words, even if all terms apart from KN itself are known, we cannot directly find the value of KN. However, we can find an approximation to KN by replacing the exponential term by its third-order Taylor expansion around KN equal to zero:

1-exp(-KN\*LAI) ≈ KN\*LAI - (KN2\*LAI2)/2 + (KN3\*LAI3)/6.

Plugging that approximation into the equation for NSH gives a quadratic equation that can be solved:

NSH = CSH \* NCSHMAX \* (1 - KN\*LAI/2 + KN2\*LAI2/6),

and the solution of this quadratic equation is:

KN ≈ (3/2 ± 3 \* √(1/4 - (2/3)\*(1-NSH/(CSH\*NCSHMAX)))) / LAI.

Note that NSH/(CSH\*NCSHMAX) must be larger than 5/8 to ensure that the square-root is a real number. The approximation for KN may lead to extreme values of KN when KN\*LAI becomes large, but we can strengthen it by respecting an upper bound (called KNMAX) for KN derived from the equation for NSH as follows. Because the term (1-exp(-KN\*LAI)) < 1, we find that:

KN < KNMAX = CSH \* NCSHMAX / (NSH \* LAI)

We now check the quality of the approximation for KN for two extreme values of NSH: NSH = CSH\*NCSHMAX and NSH = NSHK. We begin with the first case where we have a uniform profile of N with an N-C ratio that is everywhere equal to NCSHMAX. In other words, KN should be zero. We check this by plugging "NSH=CSH\*NCSHMAX" into our approximative equation for KN and find that it simplifies to:

KN\_(NSH uniform) ≈ (3/2 ± 3 \* √(1/4)) / LAI = (3/2 ± 3/2) / LAI,

and this indeed simplifies to KN = 0 provided we choose the "minus"-solution of the quadratic equation. From now on we assume that the minus-solution is the correct one and turn to the second case: NSH = NSHK. In that case we should find - if our approximative equation is any good - that KN is about equal to the light extinction coefficient K. So we plug the equation given above for NSHK into our approximative equation for KN and find:

KN\_(NSH=NSHK) ≈ (3/2 - 3\*√(1/4 - (2/3)\*(1-(1-exp(-K\*LAI))/(K\*LAI)))) / LAI

We checked this result in EXCEL for many values of K and LAI. For small values of K\*LAI, the approximation is excellent. For large values of K\*LAI the approximation becomes increasingly worse, but KN's upper bound (KNMAX = CSH\*NCSHMAX/(NSH\*LAI)) then comes to the rescue: KNMAX becomes increasingly close to the light extinction coefficient K. We can see that as follows:

KN\_(NSH=NSHK) < KNMAX\_(NSH=NSHK)

= CSH\*NCSHMAX/(NSHK\*LAI)

= K / (1-exp(-K\*LAI)),

where the denominator of the ratio gets increasingly close to unity when K\*LAI becomes big. So also for this very different case, the approximative equation for KN, with upper bound, works well.

**4.16.6 KN: rule and role**

The previous paragraph showed how we derived an approximative equation for KN, and an upper bound for it. Taking everything together, we work with the following rule for KN in the model:

If NSH/(CSH\*NCSHMAX) >= 5/8 then KN is assumed equal to the negative-branch solution of the approximative quadratic equation or to KNMAX, whichever is smaller, and if NSH/(CSH\*NCSHMAX) < 5/8 then KN is assumed equal to KNMAX.

The role of KN in the model is to make sure that the effects of growth, harvesting and senescence on NSH are calculated correctly. These processes increase or decrease shoot biomass, and the amount of N that is gained or lost should be consistent with the N-profile as measured by KN. We only show how this is calculated for senescence, but fairly similar equations apply to the two other processes. Daily senescence removes an amount DLAI from the LAI. The amount of carbon lost is less than DLAI/LAI because we assume that stems do not senesce. And the fraction of nitrogen lost in the same process is even less than that because we assume that senescent tissue is at the lower end of the exponential profile of N-C ratio in the canopy. We calculate the fraction of NSH lost in senescence as 1 minus the fraction of N remaining in leaves (stems are disregarded), and for that calculation we use the "nitrogen extinction coefficient" KN. The fraction of leaf biomass remaining (i.e. not senescing) is (LAI-DLAI)/LAI. The fraction of leaf N in the corresponding part of the exponential curve is equal to:

Fraction non-senescing leaf N = (1-exp(-KN\*(LAI-DLAI))) / (1-exp(-KN\*LAI))

So our estimate for the fraction of leaf N lost in daily senescence is 1 minus that amount. We may need to correct that estimate because KN, after all, is only approximated and not exactly known. We ensure that the N-C ratio of the senescing leaf tissue is not so low that the remaining biomass has more than the maximum permitted N-C ratio, NCSHMAX:

DNSH >= NSH - NCSHMAX \* (CSH-DLV),

where DLV is the carbon loss from the shoot (i.e. dying leaves) in senescence. So in the model, we take the loss of shoot N in senescence, DNSH, to be the maximum of our profile-based estimate and the amount needed to ensure that NCSH <= NCSHMAX.

**4.17 Simulation of N in the soil**

The simulation of carbon and nitrogen in the soil follows the scheme for carbon devised by Goudriaan (1990), which we extended with nitrogen dynamics. We distinguish three general pools in the soil: litter ("LITT"), organic matter with a fast turn-over rate ("SOMF"), and organic matter with a slow turn-over rate ("SOMS"). Each type of soil pool contains both C and N, and their ratios can vary to some extent. So there are six state variables called CLITT, CSOMF, CSOMS, NLITT, NSOMF, NSOMS. Shoot senescence contributes to LITT, at the N-C ratio of the senescing material, and root senescence contributes to SOMF at the N-C ratio of the roots which is a constant. Furthermore there are continuously operating transformations from LITT to SOMF to SOMS, in each case with some of the C being lost as CO2 and some of the N being lost to the soil mineral pool NMIN.

**4.18 Simulation of cell-wall content and digestibility**

Our submodel for cell-wall content and digestibility is intermediate in complexity between the models of Gustavsson et al. (1995) and that of Bonesmo & Bélanger (2002). We added a subroutine 'Digestibility' to plant.f90 that calculates cell-wall-content (g g-1 DM) and digestibility (dimensionless) of leaves and stems. The subroutine calculates cell-wall content of:

* leaves
* stems
* shoot dry matter (DMSH = DMLV + DMST + DMRES)
* total aboveground dry matter (DM = DMSH + DMSTUB)

The subroutine calculates digestibility of:

* leaves
* stems
* cell walls overall
* shoot dry matter
* total aboveground dry matter

The algorithm assumes that all dry matter other than cell walls is fully digestible. Digestibility of cell walls decreases linearly with phenological state (PHEN). Leaves, stems and stubble have different cell-wall fractions but cell-wall digestibility itself does not differ among the different plant components. The cell-wall contents of both leaves and stems increase linearly with phenological state and are generally higher in stems than in leaves. Cell-wall content of reserves is zero and of stubble 100%.

## 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 (if you downloaded the model files as a zip-file), 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. The top-level directory, which can have any name, should contain the subdirectories 'BC', 'input', 'model' etc. (see 3.5.2).

## 7 Compiling the model

This is not often needed. The zip-file that comes with model distribution already includes the result of model compilation, i.e. the file 'BASGRA.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 BASGRA.DLL is produced.

* The model can be recompiled simply by double-clicking on the file 'compile\_BASGRA\_gfortran.bat'.
* The most common reasons for changing FORTRAN files are when you want to see different output variables than the model delivers by default, or when you want to change the structure of the model.
* Another reason for recompilation is when you want to change the type of weather file that BASGRA\_N works with. That is discussed in the next chapter.

### 7.1 Removing the previous DLL

If you started an RStudio-session with BASGRA\_N, 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('BASGRA.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\_BASGRA\_general.R' which is used in every run of the model.

#### 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 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:

* call the general initialisation file,
* define the start year and day of the simulation period, and its length,
* read the appropriate weather data from file,
* set the time series of atmospheric nitrogen deposition
* set the calendar of dates and amounts of nitrogen fertilisation
* set the cutting dates of the sward,
* set the parameter values of the model.

#### 8.2.1 Weather files

Weather data should be provided in the form of ASCII files. The weather files should follow the 'Bioforsk' template. The following are the first two lines from a typical Bioforsk-type weather file:

|  |
| --- |
| ST(number) YR(year) doy(day) T(°C) TMMXI(°C) TMMNI(°C) RH(%) RAINI(mmd-1) WNI(ms-1) GR(MJm-2d-1) |
| 42 2000 1 5.9 6.9 4.7 100.0 15.6 2.5 1.2 |

Bioforsk weather files contain a range of weather variables including three for temperature. However, the values for daily maximum and minimum temperature are not used in any of the model calculations, so only the values provided for daily average temperature matter. Also not used anywhere is the value in the first column, which specifies the weather station from which the data originate. Weather data can span multiple years. The doy ('day of the year') for the first year can run to 365 or 366. After that, doy should be starting again from 1 when the data for the next year begin.

#### 8.2.2 Cutting dates

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

* days\_harvest[1,] <- c( 2000, 150 )
* days\_harvest[2,] <- c( 2000, 216 )
* …

The numbers in that line refer to the year and doy ('day of the year') at which harvesting takes place.

**8.2.3 Fertilisation calendar**

Dates and amounts of fertilisation (in g N m-2) are specified in each site-specific initialisation file, in lines such as:

* calendar\_fert[1,] <- c( 2000, 115, 14 ) # 14 g N m-2 applied on day 115 of year 2000
* calendar\_fert[2,] <- c( 2000, 150, 8 ) # 8 g N m-2 applied on day 150 of year 2000
* …

**8.2.4 N-deposition calendar**

Dates and amounts of atmospheric N-deposition (in g N m-2) are specified for selected days, and the model then interpolates the amounts linearly for the other days.

* calendar\_Ndep[1,] <- c( 1900, 1, 0.0006 ) # 0.0006 g N m-2 applied on day 1 of year 1900
* calendar\_Ndep[2,] <- c( 1980, 366, 0.006 ) # 0.006 g N m-2 applied on day 366 of year 1980
* …

#### 8.2.5 Parameter values

BASGRA\_N has 81 parameters for which the values are set in a txt-file, 'parameters.txt' located in subdirectory 'parameters'. This txt-file in fact contains 10 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 differ between sites. Values of non site-specific parameters in file 'parameters.txt', i.e. parameters whose values are the same in every column, are set to the Maximum a Posteriori (MAP) values from multi-site calibration carried out in August 2012. 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 initialisation file to look at that 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\_BASGRA\_….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 is as follows:

1. Make a new site-specific initialisation file (initialise\_BASGRA\_…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 folows the same format as the already available weather files.
2. Make a new 'run\_BASGRA\_…R' file, by copying and editing an existing run-file. In line 2 of your new file 'run\_BASGRA\_….R', call the new initialisation file that you made.
3. Continue as above for pre-defined runs.

### 9.3 Parameter sensitivity analysis

The model comes with a function for carrying out sensitivity analysis. The function is called ‘SA()’ and is defined in the general initialisation file, ‘initialise\_BASGRA\_general.R’. You can use SA() to test the sensitivity of BASGRA\_N output to changes in any parameter. You can specify: (1) the name of the parameter, (2) a range of values for the parameter (relative to the default value), (3) which output variables you want to examine, (4) which conditions to run the model for, i.e. which site-specific initialisation file to use, (5) whether you want the output plots to be in pdf-, jpg- or png-format.

## 10 Selecting and examining model outputs

Output variables are specified in two files which must be kept mutually consistent: 'BASGRA.f90' and the general initialisation file 'initialise\_BASGRA\_general.R'. The first is located in directory 'model', the second in directory ‘BC’. 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, 39 output variables are specified, which include the 23 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:

* increase the value of NOUT in 'initialise\_BASGRA\_general.R' by one.
* add the name of the new variable to the outputNameList (also in "initialise\_BASGRA\_general.R")
* ensure that the variable is visible to 'BASGRA.f90'
  + Most but not all model variables are visible to BASGRA.f90. The ones that are, are either declared at the top of 'BASGRA.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 'BASGRA.f90'. So the exceptions are variables that are only locally defined inside subroutines. If you want to see one of those variables, 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 'BASGRA.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 BASGRA.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 BASGRA\_N 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 'plotOutputs' is available (through its definition in the general initialisation file) for easy plotting of results. The function takes three arguments: number of plot rows, number of plot columns, and a list of names of the selected output variables. An example of a call to that function is:

* plotOutputs( 3, 2, c("CLV","TILTOT","LAI","RDRT","PHEN") )

## 11 Changing model structure

If you want to make structural changes to BASGRA\_N, you will be editing one or more of the FORTRAN files. So after that is done, you need to recompile the model. If you want to do that but somehow keep the option of using the old model version, then you can use the '#ifdef' construct when changing the model. This involves not replacing original code but adding branches to new code such that, at the compilation stage, it is still possible to choose between the old and new code:

* Write code as: #ifdef "label1" <new code> #else <old code> #endif
* To activate the new labelled code, use the D-option, i.e. add the following term to the compile file:
  + … -Dlabel1
* Note that an example of this method is already part of the model: BASGRA\_N can be compiled with or without the "Dweathergen" option depending on the type of weather file you intend to use.

## 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

Each of these steps will be explained in more detail in the following sections. In practice, we shall not do all those steps one by one, but prepare everything before starting the BC, and run everything from one BC script file. One example of such a BC script file is given in the upper directory, 'BC\_BASGRA\_[].R'.

### 12.1 STEP 1: Selecting parameters for calibration

Generally, it is best to include in the BC all parameters about which we are uncertain. The list of selected parameters should be provided in a txt-file that is placed in directory ‘parameters’. An example of such a file is already in that directory, ‘parameters\_BC\_[].txt’.

### 12.2 STEP 2: Defining the prior probability distribution

The file 'parameters\_BC\_[].txt' should contain, besides the list of parameter names in the first column, three columns with numbers, and one with information about sites. The number-columns represent the minimum, mode and maximum of the marginal prior distribution for each parameter, which is assumed to be a beta distribution. The prior distribution represents your uncertainty about the values of the parameters, so to some degree it is subjective, but the distributions must obey some constraints.

The rightmost column indicates for which site(s) the parameter is to be calibrated. This is necessary because calibrations can use data from multiple sites. If the parameter is generic, i.e. assumed to have the same value at all sites, then in the rightmost column we simply specify ‘1:nSites’ (where nSites is the name of the sites-counter in the calibration-code). But if a certain parameter is to get different site-specific values, then we must mention that parameter on multiple rows and in each row indicate for which sites it applies. For example, if we have data from 3 sites, the first two having identical sandy soils and the third one a different type of soil, then our parameter for soil field capacity could appear twice, with the range ‘1:2’ entered in the rightmost column of its first appearance, and a ‘3’ in the other row (without the quotes).

#### 12.2.1 Parameter constraints

Given the structure of BASGRA\_N and the meaning of its parameters, there are various parameter constraints. These need to be taken into account when creating the file 'parameters\_BC.txt'. Important constraints are:

* DLMXGE > DAYLB
* TOPTGE > TBASE
* FSMAX has a theoretical upper limit < 1.
* HAGERE <= 1
* SHAPE <= 1
* SLAMAX > SLAMIN
* TRANCO may have physical limits [a,b] where a>0 and b<infinity.
* YG < 1 because it is the Growth Yield, the fraction of C allocated to growth that actually ends up in new biomass, with the remainder being lost to growth respiration.

### 12.3 STEP 3: Selecting calibration data

During calibration, data from measurements are compared with outputs from BASGRA\_N. So the only kinds of measurement that can act as calibration data are those that correspond to a model output variable. The data must be specified in txt-files, where each row represents one measurement, with the name of the corresponding BASGRA\_N output variable in the first column. Six examples of calibration data files are provided, called 'data\_calibration\_Saerheim\_[].txt'. The values in columns two and three of these files represent the year and day of measurement, and the fourth and last column contains the measurement value.

Note that data for times outside the simulation period should not be part of the calibration files. If the model cannot match its output to each data point in the files (because some data were measured too early or too late), the calibration crashes.

### 12.4 STEP 4: Defining the likelihood function (including data uncertainty)

The likelihood function quantifies the probability of each measurement as a function of the parameter values. If the parameter values lead to model output that differs strongly from measurement, then the likelihood is low, and vice versa. The exact value of the likelihood for each measurement depends on our uncertainty with respect to measurement error. If the data have very low uncertainty, then even a small difference between model and measurement has a low likelihood, and so on. The measurement uncertainties are specified in BC initialisation files, of which one examples is given in subdirectory 'BC', 'BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R'. In this file, measurement uncertainties are specified as follows:

* The default value of the coefficient of variation for calibration data (‘cv\_default’) is set at 0.5;
* For dry matter yield (DM), cv\_DM = 0.05;
* For LAI, cv\_LAI = 0.1;
* For total tiller density (TILTOT), cv\_TILTOT = 0.2;
* For other variables, see the file.
* For LT50, not a relative uncertainty (such as the coefficient of variation) is given but an absolute one, namely a standard deviation of 5 degrees Celsius.

The above uncertainties are all used in a 'Sivia'-distribution likelihood function, which is similar to the Gaussian but has fatter tails and thus is more robust against outliers.

* For the fraction of tillers that is elongating (FRTILG), uncertainty is represented by a beta-distribution on [0.3,0.9] with the mode at the measured value. A beta- rather than Sivia-distribution was chosen for this variable, which implies setting hard bounds on acceptable model output, knowing that FRTILG just before the first cut should definitely be higher than 0.3 or 0.4, and by definition less or equal to 1.

After quantifying the uncertainty and parameter likelihood for each individual measurement, all these likelihoods are multiplied (or rather, the log-likelihoods are summed) to arrive at the overall (log-)likelihood of the parameter vector. Any of the above settings can of course be changed when datasets are used for which the measurement uncertainties are different.

**12.4.2 A note on data uncertainty: coefficients of variation decrease with measurement value**

We explained above that the coefficients of variation (CV) for measurement uncertainty differ between variables, e.g. they tend to be higher for tiller density than for aboveground dry matter. But when comparing different measurements of the same variable, we do in fact not use the same CV-value for each data point, but we use smaller CV-values for larger measurement values. To explain our reasoning behind this idea and our implementation of it, note that in practice two extreme methods for data uncertainty are generally used. In the “constant-SD” method, it is assumed that data uncertainty (i.e. the standard deviation of our measurement uncertainty) does not depend on the data value. In the “constant-CV” method, it is assumed that data uncertainty is proportional to the data value. With constant SD, the largest data-values will dominate the calibration, with constant CV, the smallest data-values will dominate. Our method lies in between the two extremes. Let y be a data value, and let ymax be the highest value for that variable in our whole data set. We begin by specifying a CVymax that is appropriate for ymax. So SDymax = CVymax \* ymax. With those definitions, our intermediate method specifies the following data uncertainty SDy for any data value:

SDy = CVymax \* √( ymax \* y ),

which is equivalent to:

SDy = SDymax \* √( y / ymax ).

Let us look at two examples. If y=ymax, then the above equations return SDy=SDymax, as desired. And if y=ymax/100, then we get SDy=SDymax/10. So this method still assigns the highest data uncertainty (SD) to the highest values of y, but the uncertainty decreases less than proportionately for smaller y. Instead of scaling linearly with the data value y, it now scales with the square root of y. The first of the two equivalent uncertainty-scaling equations above is the one that is implemented in file ‘BC/BC\_BASGRA\_MCMC\_init\_general.R’.

### 12.5 STEP 5: Running the MCMC

We set the length of the parameter vector chain to be generated in the MCMC in the BC initialisation file; in the provided example that is ‘BC\_BASGRA\_MCMC\_init\_Saerheim\_[]’. After that, we start the chain by running the script 'BC\_BASGRA\_MCMC.R' (but remember that this and all other steps tend to be specified in one overarching script file, such as the example ‘BC\_BASGRA\_Saerheim\_[].R’ file in the upper directory).

### 12.6 STEP 6: Analysing the outcome of the MCMC

Assuming you have done your BC with the included standard files for initialising and carrying out a BC, much information will automatically be available at the end of it. Many variables will be visible in RStudio in the panel called 'Workspace', and they can be analysed by entering R-commands in the panel called 'Console'. But there will also be some automatically produced files with BC results, in the working directory.

* 'BC\_parameters\_traceplots\_[].pdf'.
  + This shows trace plots for each parameter in the calibration.
* 'BC\_parameters\_histograms\_[].pdf'.
  + This shows prior and posterior marginal distributions for each parameter in the calibration.
* ‘BC\_parameters\_boxplots\_[].pdf’.
  + Similar information as the histograms, but now in the form of boxplots for the posterior parameter distributions, with a red horizontal line marking the mode of the prior.
* 'BC\_outputs\_data\_[].pdf'
  + These show simulation outputs with uncertainties compared with data. Red solid line: model output for the mode of the prior distribution. Black solid and dotted lines: model output for the posterior mode and uncertainty (5% and 95% quantiles). Green solid line: model output for the maximum likelihood parameter vector.
* 'BASGRA\_parModes\_[].txt'.
  + This is a text-file, best opened in EXCEL, with parameter vectors, including the modes from prior and posterior plus the maximum likelihood vector and the posterior mean. There is also information on the posterior marginal variances for each parameter. These results are given for each of the sites included in the calibration.
  + The parameter vectors are extended to the full complement of model parameters that you can find in 'parameters.txt'. In the BC there may have been fewer parameters, so the default values of the uncalibrated parameters are automatically added.

### 12.7 On single-site BC vs. multi-site BC

We distinguish two kinds of calibration: Single-site and Multi-site. In Single-site BC, all data are from one set of growing conditions (single season, single location), so the model only needs to be run once for every examined parameter vector. In Multi-site BC, we use data from more than one site (or more growing seasons), so that at every iteration in the MCMC the model needs to be run multiple times. The provided example script file 'BC\_BASGRA\_Saerheim\_[].R' carried out Multi-Site BC, but note that the word ‘site’ is used in that example not to distinguish different locations in space, but to distinguish different years and treatments.

**12.7.1 Distinguishing calibration sites from testing sites**

It is possible to include sites for calibration as well as testing in the calibration set-up: there is no need to leave the sites out whose data are not used for calibration. We can list all the sites in the BC-initialisation file 'BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R', but we need to specify there which of the sites are going to be used in the BC, and which sites are only there for testing and plotting. The site-numbers for calibration must be specified in the ‘siteBC’-vector. The idea is to make it easy and quick to check how model calibration affects BASGRA results for test-sites. After the calibration has completed, the subtitles of the plots of output vs. data indicate whether a site was a 'CALIBRATION site' or a 'TEST site'.

**12.7.2 What to do when variable names differ in BASGRA from the ones used in the data sets?**

There is no need to ensure that the names of calibration variables in data sets are identical to BASGRA variable names. If the name of a variable in the data differs from the one used in BASGRA for the same quantity, then we can specify that correspondence in file 'BC\_BASGRA\_MCMC\_init\_general.R'.

### 12.8 On running the BC with different settings and/or different data

There are many possibilities here, depending on what you want to change. Some examples:

* 1. To modify the list of parameters included in the calibration:
  + Change 'BC/parameters\_BC\_[].txt'.
* 2. To change the chain length of the MCMC:
  + Modify 'BC/BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R'. Chain length is called 'nChain', so increase the value of that setting if you need to run longer chains.
* 3. To change the proposal distribution:
  + Modify 'BC/BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R' if you want to change the proposal distribution, e.g. to make on average larger or smaller steps through parameter space. Do so by increasing or decreasing the value of ‘fPropTuning’.
* 4. To use different datasets:
  + Change the existing datafile(s), called 'data/data\_calibration\_…txt', or add new ones.
  + If you add (or delete) new datafiles, insert (or delete) their names in 'BC/BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R'.
  + When adding files that require the model to be run for a different site, also make the appropriate new model initialisation files, 'initialisation/initialise\_BASGRA\_[].txt' and specify the new initialisation files in 'BC/BC\_BASGRA\_MCMC\_init\_Saerheim\_[].R'.

## 13 Publications on BASGRA\_N and related models

* Höglind, M., Cameron, D., Persson, T. & Van Oijen, M. (in prep.). BASGRA\_N: a model for grassland productivity, quality and greenhouse gas balance.
* Höglind, M., Schapendonk, A.H.C.M. & Van Oijen, M. (2001). Timothy growth in Scandinavia: a review of quantitative information on underlying processes and an analysis by means of simulation modelling. New Phytologist 151: 355-367.
* Höglind, M., Van Oijen, M., Cameron, D. & Persson, T. (2016). Process-based simulation of growth and overwintering of grassland using the BASGRA model. Ecological Modelling 335: 1-15.
* Korhonen, P., Palosuo, T., Persson, T., Höglind, M., Jégo, G., Van Oijen, M., Gustavsson, A.-M., Bélanger, G. & Virkajärvi, P. (2018). Modelling grass yields in northern climates - a comparison of three growth models for timothy. Field Crops Research 224: 37-47. <https://doi.org/10.1016/j.fcr.2018.04.014> .
* Persson, T., Höglind, M., Van Oijen, M., Korhonen P., Palosuo, T., Jégo, G., Virkajärvi, P., Bélanger, G. & Gustavsson, A.-M. (in press). Simulation of timothy nutritive value: A comparison of three process-based models. Field Crops Research.
* Rodríguez, D., Van Oijen, M. & Schapendonk, A.H.C.M. (1999). LINGRA\_CC: A sink-source model to simulate the impact of climate change and management on grassland productivity. New Phytologist 144: 359-368.
* Roer Hjelkrem, A.-G., Höglind, M., Van Oijen, M., Schellberg, J., Gaiser, T. & Ewert, F. (2017). Sensitivity analysis and Bayesian calibration for testing robustness of the BASGRA model in different environments. Ecological Modelling 359: 80-91.
* Thorsen, S.M., Roer, A.-G. & Van Oijen, M. (2010). Modelling the dynamics of snow cover, soil frost and surface ice in Norwegian grasslands. Polar Research 29: 110-126.
* Thorsen, S.M. & Höglind, M. (2010). Modelling cold hardening and dehardening in timothy. Sensitivity analysis and Bayesian model comparison. Agricultural and Forest Meteorology 150: 1529-1542.
* Van Oijen, M., Höglind, M., Hanslin, H.M. & Caldwell, N. (2005). Process-based modelling of timothy regrowth. Agronomy Journal 97: 1295-1303.
* Van Oijen, M., Höglind, M., Cameron, D.R., Thorsen, S.M. (2015). BASGRA\_2014. <https://dx.doi.org/10.5281/zenodo.27867>
* Van Oijen, M. & Höglind, M. (2016). Toward a Bayesian procedure for using process-based models in plant breeding, with application to ideotype design. Euphytica 207: 627-643. doi:10.1007/s10681-015-1562-5. <https://link.springer.com/article/10.1007/s10681-015-1562-5>

## 14 References cited

* Bonesmo, H. 1999. Spring growth and regrowth rates of timothy and meadow fescue. Agricultural University of Norway. Doctor scientarium theses 1999:8. ISSN 0802-3220.
* Bonesmo H. & Bélanger G. (2002). Timothy yield and nutritive value by the CATIMO model. 2. Digestibility and fiber. Agronomy Journal 94: 345-350.
* Goudriaan, J (1990). Atmospheric CO2, global carbon fluxes and the biosphere. In: Rabbinge, R. et al. (Eds), Theoretical Production Ecology: Reflections and Prospects.
* Gustavsson, A.-M., Angus, J.F. & Torsell, B.W.R. (1995). An integrated model for growth and nutritional value of timothy. Agricultural Systems 47: 73-92.
* Peacock J.M. 1976. Temperature and leaf growth in four grass species. Journal of Applied Ecology 13: 225–232.
* 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.

## 15 APPENDIX I: FORTRAN files and subroutines

The following table shows for each BASGRA\_N FORTRAN file which subroutines it contains, and which (if any) rate variables are calculated in those subroutines.

| **File** | **Main subroutines** | **Nested subroutines** | **Calculated rate variables** |
| --- | --- | --- | --- |
| BASGRA.f90 |  |  |  |
| environment.f90 |  |  |  |
|  | set\_weather\_day |  |  |
|  | Microclimate |  |  |
|  |  | RainSnowSurfacePool |  |
|  |  | precForm | Psnow |
|  |  | WaterSnow |  |
|  |  | SnowMeltWmaxStore | SnowMelt |
|  |  | WETSTORdynamics | reFreeze |
|  |  | LiquidWaterDistribution | Wremain |
|  |  | SnowDensity |  |
|  |  | SnowDepthDecrease | PackMelt |
|  |  | INFILrunOn | INFIL |
|  |  | SurfacePool | FREEZEPL,poolDrain,poolInfil,THAWPS |
|  | DDAYL |  |  |
|  | PEVAPINPUT |  |  |
|  | PENMAN |  |  |
| parameters\_plant.f90 |  |  |  |
| parameters\_site.f90 |  |  |  |
| plant.f90 |  |  |  |
|  | Harvest |  | GSTUB,HARVLA,HARVLV,HARVPH,HARVRE,HARVST,HARVTG |
|  | Biomass |  |  |
|  | Phenology |  | DPHEN,GPHEN |
|  | Foliage1 |  |  |
|  | LUECO2TM |  |  |
|  | HardeningSink |  |  |
|  | Growth |  | RESMOB |
|  |  | Allocation | GLV,GRES,GRT,GST |
|  | PlantRespiration |  |  |
|  | Senescence |  |  |
|  |  | AnaerobicDamage | DLV,DRT,DSTUB,dTANAER,DTILV |
|  |  | Hardening | DeHardRate,HardRate |
|  | Foliage2 |  | GLAI |
|  | Nplant |  |  |
|  | Digestibility |  | DNRT,DNSH,GNRT,GNSH,HARVNSH,NSHmobsoil,Nupt |
| resources.f90 |  |  |  |
|  | Light |  |  |
|  | EVAPTRTRF |  | EVAP,TRAN |
|  | ROOTDG |  | EXPLOR,RROOTD |
| set\_params.f90 |  |  |  |
| soil.f90 |  |  |  |
|  | SoilWaterContent |  |  |
|  | Physics |  |  |
|  |  | FrozenSoil | Frate |
|  | FRDRUNIR |  | DRAIN,FREEZEL,IRRIG,RUNOFF,THAWS |
|  | O2status |  |  |
|  | O2fluxes |  | O2IN,O2OUT |
|  | N\_fert |  | Nfert |
|  | N\_dep |  | Ndep |
|  | CNsoil |  | dCLITT,dCLITTsomf,dCSOMF,dCSOMFsoms,dCSOMS,dNLITT,dNSOMF,dNSOMS,Nemission,Nfixation,Nleaching,NLITTsomf,Nmineralisation,NSOMFsoms,rCLITT,rCSOMF,rNLITT,rNSOMF |

## 16 APPENDIX II: Variables

### 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".

#### 16.1.1 Types of variables

1. State variables
2. Non-state variables
   * Input variable: 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.
     + Output variables whose identifier is given in quotation marks ("") do not have explicit names in BASGRA.f90, but names are given to them in the plotting routines.
   * Rate variables: Variables that directly change state variables. They are part of the state update equation and their unit includes "d-1".

**16.1.2 Abbreviations**

* DM = dry matter
* SOC = soil organic carbon
* SOM = soil organic matter
* SON = soil organic nitrogen

### 16.2 State variables (BASGRA.f90)

| **State variable** | **Unit** | **Meaning** |
| --- | --- | --- |
| CLITT | g C m-2 | Carbon in litter |
| CLV | g C m-2 | Carbon in leaves |
| CLVD | g C m-2 | Carbon in leaves that died since start simulation |
| CRES | g C m-2 | Carbon in reserves |
| CRT | g C m-2 | Carbon in roots |
| CSOMF | g C m-2 | Carbon in fast-decomposing SOM |
| CSOMS | g C m-2 | Carbon in slow-decomposing SOM |
| CST | g C m-2 | Carbon in stems |
| CSTUB | g C m-2 | Carbon in stubble |
| DRYSTOR | mm | Snow amount as SWE (Soil Water Equivalent) |
| Fdepth | m | Soil frost layer depth |
| LAI | m2 leaf m-2 | Leaf area index |
| LT50 | °C | Temperature that kills half the plants in a day |
| O2 | mol m-2 | Soil oxygen content |
| NLITT | g N m-2 | Nitrogen in litter |
| NMIN | g N m-2 | Nitrogen in mineral form |
| NRT | g N m-2 | Nitrogen in roots |
| NSH | g N m-2 | Nitrogen in shoot |
| NSOMF | g N m-2 | Nitrogen in fast-decomposing SOM |
| NSOMS | g N m-2 | Nitrogen in slow-decomposing SOM |
| PHEN | - | Phenological stage |
| ROOTD | m | Rooting depth |
| Sdepth | m | Snow depth |
| TANAER | d | Time since start anaerobic conditions |
| TILG1 | m-2 | Non-elongating generative tiller density |
| TILG2 | m-2 | Elongating generative tiller density |
| TILV | m-2 | Non-elongating tiller density |
| WAL | mm | Soil water amount: liquid |
| WAPL | mm | Pool water amount: liquid |
| WAPS | mm | Pool water amount: solid (=ice) |
| WAS | mm | Soil water amount: solid (=ice) |
| WETSTOR | mm | Liquid water in snow |

### 

### 16.3 Non-state variables (BASGRA.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| "DM" | g m-2 | Aboveground DM | Output |
| "FRTILG" | - | Elongating tiller fraction | Output |
| "RES" | g g-1 | Reserves per g aboveground DM | Output |
| "SLA" | m2 g-1 | Leaf area per g of vegetative tillers | Output |
| "TILTOT" | m-2 | Total tiller density | Output |
| "Time" | y | Decimal year (approximation) | Output |
| DAVTMP | °C | Daily average temperature | Intermediate |
| day | d | Day index (running from 1 to NDAYS) | Intermediate |
| DAYL | d d-1 | Day length | Intermediate |
| dCLITT | g C m-2 d-1 | Loss of litter C in decomposition | Rate |
| dCLITTsomf | g C m-2 d-1 | Conversion of litter-C to fast SOC | Rate |
| dCSOMF | g C m-2 d-1 | Loss of fast organic C in decomposition | Rate |
| dCSOMFsoms | g C m-2 d-1 | Conversion of fast to slow SOC | Rate |
| dCSOMS | g C m-2 d-1 | Loss of fast organic C in decomposition | Rate |
| DeHardRate | °C d-1 | Dehardening rate (LT50 becoming less negative) | Rate |
| DLAI | m2 leaf m-2 d-1 | Death rate of leaf area | Rate |
| DLV | g C m-2 d-1 | Death rate of leaf mass | Rate |
| DM | g DM m-2 | Dry matter aboveground | Intermediate |
| DMLV | g DM m-2 | Dry matter leaves | Intermediate |
| DMRES | g DM m-2 | Dry matter reserves | Intermediate |
| DMSH | g DM m-2 | Dry matter shoot | Intermediate |
| DMST | g DM m-2 | Dry matter stems | Intermediate |
| DMSTUB | g DM m-2 | Dry matter stubble | Intermediate |
| DM\_MAX | g DM m-2 | Maximum aboveground dry matter since start of run | Output |
| dNLITT | g N m-2 d-1 | Loss of litter N in decomposition | Rate |
| DNRT | g N m-2 d-1 | Loss of root N in senescence | Rate |
| DNSH | g N m-2 d-1 | Loss of shoot N in senescence | Rate |
| dNSOMF | g N m-2 d-1 | Loss of fast SON in decomposition | Rate |
| dNSOMS | g N m-2 d-1 | Loss of slow SON in decomposition | Rate |
| doy | d | Day of year (1 = 1 Jan) | Intermediate |
| DPHEN | d-1 | Rate of decrease of phenological stage | Rate |
| DRAIN | mm d-1 | Drainage rate below the root zone | Rate |
| DRT | g C m-2 d-1 | Death rate of roots | Rate |
| DSTUB | g C m-2 d-1 | Death rate of stubble | Rate |
| dTANAER | d d-1 | Change in days since start anaerobic conditions | Rate |
| DTILV | tillers m-2 d-1 | Death rate of non/elongating tillers | Rate |
| DTR | MJ GR m-2 d-1 | Daily global radiation | Intermediate |
| EVAP | mm d-1 | Evaporation of water from soil surface | Rate |
| EXPLOR | mm d-1 | Increased access to water by root depth growth | Rate |
| FO2 | mol O2 mol-1 gas | Soil oxygen as a fraction of total gas | Intermediate |
| Frate | m d-1 | Rate of increase of frost layer depth | Rate |
| FREEZEL | mm d-1 | Freezing of soil water | Rate |
| FREEZEPL | mm d-1 | Freezing of pool water | Rate |
| F\_ASH | g m-2 | Ash content of shoot dry matter | Output |
| F\_DIGEST\_DM | - | Digestibility of aboveground dry matter | Output |
| F\_DIGEST\_DMSH | - | Digestibility of shoot dry matter | Output |
| F\_DIGEST\_LV | - | Digestibility of leaf dry matter | Output |
| F\_DIGEST\_ST | - | Digestibility of stem dry matter | Output |
| F\_DIGEST\_WALL | - | Digestibility of cell walls | Output |
| F\_PROTEIN | g g-1 DM | Crude protein content of shoot dry matter | Output |
| F\_WALL\_DM | g wall g-1 DM | Fraction of aboveground dry matter that is cell wall | Output |
| F\_WALL\_DMSH | g wall g-1 DM | Fraction of shoot dry matter that is cell wall | Output |
| F\_WALL\_LV | g wall g-1 DM | Fraction of leaf dry matter that is cell wall | Output |
| F\_WALL\_ST | g wall g-1 DM | Fraction of stem dry matter that is cell wall | Output |
| GLAI | m2 leaf m-2 d-1 | Growth of leaf area | Rate |
| GLV | g C m-2 d-1 | Growth of leaf mass | Rate |
| GNRT | g N m-2 d-1 | Growth of root N | Rate |
| GNSH | g N m-2 d-1 | Growth of shoot N | Rate |
| GPHEN | d-1 | Rate of phenological development | Rate |
| GRES | g C m-2 d-1 | Gross growth rate of reserve pool, uncorrected for remobilisation | Rate |
| GRT | g C m-2 d-1 | Growth of roots | Rate |
| GST | g C m-2 d-1 | Growth of stems | Rate |
| GSTUB | g C m-2 d-1 | Growth of stubble due to harvest of elongating tillers | Rate |
| HardRate | °C d-1 | Hardening (LT50 becoming more negative) | Rate |
| HARVLA | m2 leaf m-2 d-1 | Harvested leaf area | Rate |
| HARVLV | g C m-2 d-1 | Harvested leaf mass | Rate |
| HARVNSH | g N m-2 d-1 | Harvesting of shoot N | Rate |
| HARVPH | d-1 | Resetting of phenological stage by harvesting | Rate |
| HARVRE | g C m-2 d-1 | Harvested reserves | Rate |
| HARVST | g C m-2 d-1 | Harvested stem mass | Rate |
| HARVTG | tillers m-2 d-1 | Harvested elongating tillers (apex removed by harvesting) | Rate |
| INFIL | mm d-1 | Water flow into soil from precipitation and snow melt | Rate |
| IRRIG | mm d-1 | Irrigation rate | Rate |
| LERG | m d-1 | Leaf elongation rate per leaf for generative tillers | Intermediate |
| NCDSH | g N g-1 C | N-C ratio of shoot senescence | Intermediate |
| NCGSH | g N g-1 C | N-C ratio of shoot growth | Intermediate |
| NCHARVSH | g N g-1 C | N-C ratio of harvested material | Intermediate |
| Ndep | g N m-2 d-1 | Atmospheric N deposition | Rate |
| NELLVG | tiller-1 | Number of growing leaves per elongating tiller | Intermediate |
| Nemission | g N m-2 d-1 | N emission (NO plus N2O) | Rate |
| NemissionN2O | g N m-2 d-1 | Emission of nitrous oxide | Output |
| NemissionNO | g N m-2 d-1 | Emission of nitric oxide | Output |
| Nfert | g N m-2 d-1 | N fertilisation | Rate |
| Nfert\_TOT | g N m-2 | Cumulative N-fertilisation from start of run | Output |
| Nfixation | g N m-2 d-1 | N fixation | Rate |
| Nleaching | g N m-2 d-1 | N leaching | Rate |
| NLITTsomf | g N m-2 d-1 | Conversion of litter N to fast SON | Rate |
| Nmineralisation | g N m-2 d-1 | N mineralisation | Rate |
| NSHmob | g N m-2 d-1 | Remobilisation of shoot N | Rate |
| NSHmobsoil | g N m-2 d-1 | Remobilised shoot N lost to the soil | Rate |
| NSOMFsoms | g N m-2 d-1 | Conversion of fast to slow SON | Rate |
| Nupt | g N m-2 d-1 | N uptake | Rate |
| O2IN | mol m-2 d-1 | Influx of oxygen into the soil | Rate |
| O2OUT | mol m-2 d-1 | Efflux of oxygen from the soil | Rate |
| PackMelt | m d-1 | Loss of snow height by packing and by melting | Rate |
| PAR | mol PAR m-2 d-1 | Daily photosynthetically active radiation | Intermediate |
| PARAV | mumol PAR m-2 s-1 | Average PAR during the photoperiod | Intermediate |
| PARINT | mol PAR m-2 d-1 | PAR interception | Intermediate |
| PERMGAS | d-1 | Permeability of soil surface to gas exchange | Intermediate |
| PEVAP | mm d-1 | Potential rate of evaporation from the soil | Intermediate |
| poolDrain | mm d-1 | Water flow from pool to soil | Rate |
| poolInfil | mm d-1 | Water flow to pool from other sources than ice thawing | Rate |
| Psnow | mm d-1 | Snow fall | Rate |
| PTRAN | mm d-1 | Potential transpiration rate | Intermediate |
| rCLITT | g C m-2 d-1 | Loss of litter C in run-off | Rate |
| rCSOMF | g C m-2 d-1 | Loss of fast SOC in run-off | Rate |
| refreeze | mm d-1 | Freezing of liquid water stored in snow | Rate |
| RESMOB | g C m-2 d-1 | Mobilisation of reserves | Rate |
| RESPHARD | g C m-2 d-1 | Plant hardening respiration | Intermediate |
| RGRTV | d-1 | Relative rate of tillering | Intermediate |
| RGRTVG | d-1 | Relative rate of tillers becoming elongating tillers | Intermediate |
| RLEAF | leaves tiller-1 d-1 | Leaf appearance rate per tiller | Intermediate |
| rNSOMF | g N m-2 d-1 | Loss of fast SON in run-off | Rate |
| rNLITT | g N m-2 d-1 | Loss of litter N in run-off | Rate |
| RplantAer | g C m-2 d-1 | Aerobic plant respiration | Intermediate |
| RROOTD | m d-1 | Rate of increase in rooting depth | Rate |
| Rsoil | g C m-2 d-1 | Soil respiration | Output |
| RUNOFF | mm d-1 | Loss of water by runoff | Rate |
| SnowMelt | mm d-1 | Snow melting | Rate |
| THAWPS | mm d-1 | Rate of surface ice thawing | Rate |
| THAWS | mm d-1 | Water flow to soil pool from thawing of frozen soil | Rate |
| TRAN | mm d-1 | Transpiration | Rate |
| TRANRF | - | Transpiration realisation factor | Intermediate |
| Tsurf | °C | Soil surface temperature | Intermediate |
| VERN | - | Vernalization status | Intermediate |
| Wremain | mm d-1 | Liquid water stored in snow that remains there | Rate |
| y | (various) | Output variables matrix (NDAYS x NOUT) | Output |
| YIELD | g DM m-2 d-1 | Daily yield | Output |
| YIELD\_LAST | g DM m-2 d-1 | Most recent yield | Output |
| YIELD\_TOT | g DM m-2 | Cumulative yield | Output |

### 16.4 Variables (readweather.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| DOYI | d | Day of year | Input |
| GR | MJ m-2 d-1 | Global radiation | Input |
| PETI | mm d-1 | Potential evapotranspiration | Input |
| PREC | mm d-1 | Precipitation | Input |
| RAINI | mm d-1 | Precipitation | Intermediate |
| RDDI | kJ m-2 d-1 | Global radiation | Intermediate |
| RH | % | Relative humidity | Input |
| T | °C | Temperature | Input |
| TMMNI | °C | Minimum temperature | Input |
| TMMXI | °C | Maximum temperature | Input |
| VPI | kPa | Vapour pressure | Input |
| WNI | m s-1 | Wind speed | Input |
| YEARI | y | Year | Input |

### 16.5 Variables (environment.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| BBRAD | J m-2 d-1 | Black body radiation | Intermediate |
| DAVTMP | °C | Daily average temperature | Intermediate |
| day | d | Day index (running from 1 to NDAYS) | Intermediate |
| DAYL | d d-1 | Day length | Intermediate |
| DEC | radians | Declination of the sun | Intermediate |
| DECC | radians | Declination of the sun, corrected for extreme day lengths | Intermediate |
| DENSITY | kg m-3 | Density of snow | Intermediate |
| doy | d | Day of year (1 = 1 Jan) | Intermediate |
| DOYI | d | Day of year (1 = 1 Jan) | Input |
| DRYSTOR | mm | Snow amount as SWE (Soil Water Equivalent) | State |
| DTR | MJ m-2 d-1 | Daily global radiation | Intermediate |
| DTRJM2 | J GR m-2 d-1 | Daily global radiation | Intermediate |
| EVAP | mm d-1 | Evaporation of water from soil surface | Intermediate |
| Fdepth | m | Soil frost layer depth | State |
| Frate | m d-1 | Rate of increase of frost layer depth | Rate |
| FREEZEPL | mm d-1 | Freezing rate of pool water | Rate |
| INFIL | mm d-1 | Water flow into soil from precipitation and snow melt | Rate |
| LAI | m2 leaf m-2 | Leaf area index | Intermediate |
| Melt | mm °C-1 d-1 | Potential snow melt rate per degree above TmeltFreeze | Intermediate |
| NRADC | J m-2 d-1 | Net radiation absorption by the canopy | Intermediate |
| NRADS | J m-2 d-1 | Net radiation absorption by the soil | Intermediate |
| PackMelt | m d-1 | Loss of snow height by packing and by melting | Rate |
| PAR | mol PAR m-2 d-1 | Daily photosynthetically active radiation | Intermediate |
| PENMD | J m-2 d-1 | Atmospheric drying power term of the Penman equation | Intermediate |
| PENMRC | J m-2 d-1 | Radiation term of the Penman equation for canopy | Intermediate |
| PENMRS | J m-2 d-1 | Radiation term of the Penman equation for soil | Intermediate |
| PERMgas | d-1 | Permeability of soil surface to gas exchange | Intermediate |
| PET | mm d-1 | Potential evapotranspiration | Intermediate |
| PETI | mm d-1 | Potential evapotranspiration | Input |
| PEVAP | mm d-1 | Potential evaporation rate | Intermediate |
| PINFIL | mm d-1 | Wsupply - RNINTC | Intermediate |
| PIrate | m d-1 | Potential rate of pool freezing (if negative, thawing) | Intermediate |
| poolDrain | mm d-1 | Water flow from pool to soil | Rate |
| poolInfil | mm d-1 | Water flow to pool from other sources than ice thawing | Rate |
| poolRUNOFF | mm d-1 | Water runoff from exceedance of surface pool capacity | Intermediate |
| poolVolRemain | mm d-1 | Unused capacity of surface pool | Intermediate |
| poolWavail | mm d-1 | Liquid water potentially available for flow from pool to soil | Intermediate |
| Psnow | mm d-1 | Snow fall | Rate |
| PTRAN | mm d-1 | Potential transpiration rate | Intermediate |
| Pwater | mm d-1 | Rain | Intermediate |
| RAIN | mm d-1 | Precipitation | Intermediate |
| RAINI | mm d-1 | Precipitation | Intermediate |
| RDD | kJ m-2 d-1 | Global radiation | Intermediate |
| RDDI | kJ m-2 d-1 | Global radiation | Intermediate |
| reFreeze | mm d-1 | Freezing of liquid water stored in snow | Rate |
| reFreezeMax | mm d-1 | Maximum refreezing rate | Intermediate |
| RLWN | J m-2 d-1 | Net outgoing long-wave radiation | Intermediate |
| RNINTC | mm d-1 | Interception of precipitation by the canopy | Intermediate |
| runOn | mm d-1 | Water in excess of what can infiltrate the soil | Intermediate |
| Sdepth | m | Snow depth | State |
| SLOPE | kPA °C-1 | Temperature derivative of SVP | Intermediate |
| SnowMelt | mm d-1 | Snow melting | Rate |
| StayWet | mm d-1 | Liquid water in snow remaining liquid | Intermediate |
| SVP | kPa | Saturation vapour pressure | Intermediate |
| SWE | mm | Snow Water Equivalent (solid plius liquid) | Intermediate |
| THAWPS | mm d-1 | Rate of surface ice thawing | Rate |
| TMMN | °C | Minimum temperature | Intermediate |
| TMMNI | °C | Minimum temperature | Input |
| TMMX | °C | Maximum temperature | Intermediate |
| TMMXI | °C | Maximum temperature | Input |
| Tsurf | °C | Soil surface temperature | Intermediate |
| VP | kPa | Vapour pressure | Intermediate |
| VPI | kPa | Vapour pressure | Input |
| WAPL | mm | Pool water amount: liquid | State |
| WAPS | mm | Pool water amount: solid (=ice) | State |
| Wavail | mm d-1 | Liquid water from rain, snow melt and storage in snow | Intermediate |
| WDF | kg m-2 d-1 kPa-1 | Wind factor in the Penman equation | Intermediate |
| WETSTOR | mm | Liquid water in snow | State |
| WmaxStore | mm d-1 | Liquid water storage capacity of the snowpack | Intermediate |
| WN | m s-1 | Wind speed | Intermediate |
| WNI | m s-1 | Wind speed | Input |
| Wremain | mm d-1 | Liquid water staying in snow pack | Rate |
| Wsupply | mm d-1 | Liquid water not staying in snow pack | Intermediate |
| YEARI | y | Year | Input |
| year | y | Year | Intermediate |

### 16.6 Variables (soil.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| alpha |  |  | Intermediate |
| DAVTMP | °C | Daily average temperature | Intermediate |
| dCLITT | g C m-2 d-1 | Loss of litter C in decomposition | Rate |
| dCLITTrsoil | g C m-2 d-1 | Loss of litter C to CO2 in decomposition | Intermediate |
| dCLITTsomf | g C m-2 d-1 | Conversion of litter C to fast SOC | Rate |
| dCSOMF | g C m-2 d-1 | Loss of fast SOC in decomposition | Rate |
| dCSOMFrsoil | g C m-2 d-1 | Loss of fast SOC to CO2 in decomposition | Intermediate |
| dCSOMFsoms | g C m-2 d-1 | Conversion of fast to slow SOC | Rate |
| dCSOMS | g C m-2 d-1 | Loss of fast SOC in decomposition | Rate |
| dNLITT | g N m-2 d-1 | Loss of litter N in decomposition | Rate |
| dNSOMF | g N m-2 d-1 | Loss of fast SON in decomposition | Rate |
| dNSOMS | g N m-2 d-1 | Loss of slow SON in decomposition | Rate |
| DRAIN | mm d-1 | Drainage rate below the root zone | Rate |
| EVAP | mm d-1 | Evaporation of water from soil surface | Rate |
| Fdepth | m | Soil frost layer depth | State |
| fN2O | g N g-1 N | Fraction of N emission that is as N2O | Intermediate |
| FO2 | mol O2 mol-1 gas | Soil oxygen as a fraction of total gas | Intermediate |
| fPerm |  |  | Intermediate |
| Frate | m d-1 | Rate of increase of frost layer depth | Rate |
| FREEZEL | mm d-1 | Freezing rate of soil water | Rate |
| fTsoil | - | Temperature effect on decomposition | Intermediate |
| INFIL | mm d-1 | Water flow into soil from precipitation and snow melt | Rate |
| INFILTOT | mm d-1 | Water flow into soil from aboveground compartments | Intermediate |
| IRRIG | mm d-1 | Irrigation rate | Rate |
| Ndep | g N m-2 d-1 | Atmospheric N deposition | Rate |
| Nemission | g N m-2 d-1 | N emission (NO plus N2O) | Rate |
| NemissionNO | g N m-2 d-1 | Emission of nitric oxide | Output |
| NemissionN2O | g N m-2 d-1 | Emission of nitrous oxide | Output |
| Nfert | g N m-2 d-1 | N fertilisation | Rate |
| Nfixation | g N m-2 d-1 | N fixation | Rate |
| Nleaching | g N m-2 d-1 | N leaching | Rate |
| NLITTnmin | g N m-2 d-1 | Loss of litter N to mineral N | Intermediate |
| NLITTsomf | g N m-2 d-1 | Conversion of litter N to fast SON | Rate |
| Nmineralisation | g N m-2 d-1 | N mineralisation | Rate |
| NSOMFnmin | g N m-2 d-1 | Loss of fast SON to mineral N | Intermediate |
| NSOMFsoms | g N m-2 d-1 | Conversion of fast to slow SON | Rate |
| O2 | mol m-2 | Soil oxygen content | State |
| O2IN | mol m-2 d-1 | Influx of oxygen into the soil | Rate |
| O2MX | mol m-2 | Maximum oxygen content of soil | Intermediate |
| O2OUT | mol m-2 d-1 | Efflux of oxygen from the soil | Rate |
| PERMgas | d-1 | Permeability of soil surface to gas exchange | Intermediate |
| PFrate | m d-1 |  | Intermediate |
| poolDrain | mm d-1 | Water flow from pool to soil | Rate |
| rCLITT | g C m-2 d-1 | Loss of litter C in run-off | Rate |
| rCSOMF | g C m-2 d-1 | Loss of fast SOC in run-off | Rate |
| rNLITT | g N m-2 d-1 | Loss of litter N in run-off | Rate |
| rNSOMF | g N m-2 d-1 | Loss of fast SON in run-off | Rate |
| ROOTD | m | Rooting depth | State |
| RplantAer | g C m-2 d-1 | Aerobic respiration | Intermediate |
| Rsoil | g C m-2 d-1 | Soil respiration | Output |
| RUNOFF | mm d-1 | Loss of water by runoff | Rate |
| Sdepth | m | Snow depth | State |
| THAWS | mm d-1 | Water flow to soil pool from thawing of frozen soil | Rate |
| TRAN | mm d-1 | Transpiration | Rate |
| WAFC | mm | Water in non-frozen root zone at field capacity | Intermediate |
| WAL | mm | Soil water amount: liquid | State |
| WAS | mm | Soil water amount: solid (=ice) | State |
| WAST | mm | Water in non-frozen root zone at saturation | Intermediate |
| WCeff | m3 m-3 | Frozen soil water contributing to heat transport | Intermediate |
| WCL | m3 m-3 | Water concentration in non-frozen soil | Intermediate |

### 16.7 Variables (resources.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| AVAILF | - | Availability of water for evapotranspiration | Intermediate |
| DAYL | d d-1 | Day length | Intermediate |
| DTR | MJ GR m-2 d-1 | Daily global radiation | Intermediate |
| DTRINT | MJ GR m-2 d-1 | Interception of global radiation | Intermediate |
| EVAP | mm d-1 | Evaporation of water from soil surface | Rate |
| EXPLOR | mm d-1 | Increased access to water by root depth growth | Rate |
| Fdepth | m | Soil frost layer depth | State |
| FR | - | Transpiration realisation at sufficient soil water | Intermediate |
| LAI | m2 leaf m-2 | Leaf area index | State |
| PAR | mol PAR m-2 d-1 | Daily photosynthetically active radiation | Intermediate |
| PARAV | mumol PAR m-2 s-1 | Average PAR during the photoperiod | Intermediate |
| PARINT | mol PAR m-2 d-1 | PAR interception | Intermediate |
| PEVAP | mm d-1 | Potential rate of evaporation from the soil | Intermediate |
| PTRAN | mm d-1 | Potential transpiration rate | Intermediate |
| ROOTD | m | Rooting depth | State |
| RROOTD | m d-1 | Root depth growth rate | Rate |
| TRAN | mm d-1 | Transpiration | Rate |
| TRANRF | - | Transpiration realisation factor | Intermediate |
| WAAD | mm | Water in non-frozen soil at air dryness | Intermediate |
| WAL | mm | Soil water amount: liquid | State |
| WCL | m3 m-3 | Water concentration in non-frozen soil | Intermediate |

### 16.8 Variables (plant.f90)

| **Variable** | **Unit** | **Meaning** | **Type** |
| --- | --- | --- | --- |
| ALLOLV | g C m-2 d-1 | Allocation of carbohydrates to leaf growth | Intermediate |
| ALLORT | g C m-2 d-1 | Allocation of carbohydrates to root growth | Intermediate |
| ALLOSH | g C m-2 d-1 | Allocation of carbohydrates to shoot growth | Intermediate |
| ALLOST | g C m-2 d-1 | Allocation of carbohydrates to stem growth | Intermediate |
| ALLOTOT | g C m-2 d-1 | Allocation of carbohydrates to sinks other than hardening | Intermediate |
| CLAI | m2 leaf m-2 | LAI remaining after harvest | Intermediate |
| CLV | g C m-2 | Weight of leaves | State |
| CRES | g C m-2 | Weight of reserves | State |
| CRESMX | g C m-2 | Maximum amount of reserves | Intermediate |
| CRT | g C m-2 | Weight of roots | State |
| CST | g C m-2 | Weight of stems | State |
| CSTAV | g C tiller-1 | Average size of elongating tillers | Intermediate |
| CSTUB | g C m-2 | Weight of stubble | State |
| DAVTMP | °C | Daily average temperature | Intermediate |
| DAYL | d d-1 | Day length | Intermediate |
| DAYLGE | - | Day length effect on allocation, tillering, leaf appearance, leaf elongation | Intermediate |
| DeHardRate | °C d-1 | Dehardening rate (LT50 becoming less negative) | Rate |
| DLAI | m2 leaf m-2 d-1 | Death rate of leaf area | Rate |
| DLV | g C m-2 d-1 | Death rate of leaf mass | Rate |
| DM | g DM m-2 | Dry matter aboveground | Intermediate |
| DMLV | g DM m-2 | Dry matter leaves | Intermediate |
| DMRES | g DM m-2 | Dry matter reserves | Intermediate |
| DMSH | g DM m-2 | Dry matter shoot | Intermediate |
| DMST | g DM m-2 | Dry matter stems | Intermediate |
| DMSTUB | g DM m-2 | Dry matter stubble | Intermediate |
| DNRT | g N m-2 d-1 | Loss of root N in senescence | Rate |
| DNSH | g N m-2 d-1 | Loss of shoot N in senescence | Rate |
| doy | d | Day of year (1 = 1 Jan) | Intermediate |
| doySinceStart | d | Days passed since start of decrease in rehardening capability | Intermediate |
| DPHEN | d-1 | Rate of decrease of phenological stage | Rate |
| DRT | g C m-2 d-1 | Death rate of roots | Rate |
| DSTUB | g C m-2 d-1 | Death rate of stubble | Rate |
| dTANAER | d d-1 | Change in days since start anaerobic conditions | Rate |
| DTILV | tillers m-2 d-1 | Death rate of non-elongating tillers | Rate |
| EFF | mol CO2 mol-1 PAR quanta | Quantum yield of photosynthesis | Intermediate |
| EFFTMP | °C | Effective temperature for leaf elongation | Intermediate |
| fAer | - | Aeration status of soil | Intermediate |
| fNCgrowth | - | Effect of N-limitation on N-C ratio of growing tissue | Intermediate |
| fNgrowth | - | Nitrogen source-sink ratio | Intermediate |
| FO2 | mol O2 mol-1 gas | Soil oxygen as a fraction of total gas | Intermediate |
| FRACTV | - | Fraction of tillers that is not elongating | Intermediate |
| F\_DIGEST\_DM | - | Digestibility of aboveground dry matter | Output |
| F\_DIGEST\_DMSH | - | Digestibility of shoot dry matter | Output |
| F\_DIGEST\_LV | - | Digestibility of leaf dry matter | Output |
| F\_DIGEST\_ST | - | Digestibility of stem dry matter | Output |
| F\_DIGEST\_WALL | - | Digestibility of cell walls | Output |
| F\_DIGEST\_WALL\_MIN | - | Minimum digestibility of cell walls | Intermediate |
| F\_WALL\_DM | g wall g-1 DM | Fraction of aboveground dry matter that is cell wall | Output |
| F\_WALL\_DMSH | g wall g-1 DM | Fraction of shoot dry matter that is cell wall | Output |
| F\_WALL\_LV | g wall g-1 DM | Fraction of leaf dry matter that is cell wall | Output |
| F\_WALL\_LV\_MIN | - | Minimum fraction of leaf dry matter that is cell wall | Intermediate |
| F\_WALL\_ST | g wall g-1 DM | Fraction of stem dry matter that is cell wall | Output |
| F\_WALL\_ST\_MIN | - | Minimum fraction of stem dry matter that is cell wall | Intermediate |
| GAMMAX | ppm CO2 | CO2 compensation point at no mitochondrial respiration | Intermediate |
| GLAI | m2 leaf m-2 d-1 | Growth rate of leaf area | Rate |
| GLAISI | m2 leaf m-2 d-1 | Potential growth rate of leaf area | Intermediate |
| GLV | g C m-2 d-1 | Growth rate of leaf mass | Rate |
| GLVSI | g C m-2 d-1 | Potential growth rate of leaf mass | Intermediate |
| GNmob | g N m-2 d-1 | Contribution of mobilised N to growth | Intermediate |
| GNRT | g N m-2 d-1 | Growth of root N | Intermediate |
| GNSH | g N m-2 d-1 | Growth of shoot N | Rate |
| GPHEN | d-1 | Rate of phenological development | Rate |
| GRES | g C m-2 d-1 | Gross growth rate of reserve pool, uncorrected for remobilisation | Rate |
| GRESSI | g C m-2 d-1 | Sink strength of reserve pool | Intermediate |
| GRT | g C m-2 d-1 | Growth rate of roots | Rate |
| GSHSI | g C m-2 d-1 | Potential growth rate of shoot | Intermediate |
| GST | g C m-2 d-1 | Growth rate of stems | Rate |
| GSTSI | g C m-2 d-1 | Potential growth rate of stems | Intermediate |
| GSTUB | g C m-2 d-1 | Growth of stubble due to harvest of elongating tillers | Rate |
| HardRate | °C d-1 | Hardening (LT50 becoming more negative) | Rate |
| HARV | - | Flag indicating that the current day is a harvest day | Intermediate |
| HARVFR | - | Fraction of leaf and leaf area that is harvested | Intermediate |
| HARVLA | m2 leaf m-2 d-1 | Harvested leaf area | Rate |
| HARVLV | g C m-2 d-1 | Harvested leaf mass | Rate |
| HARVNSH | g N m-2 d-1 | Harvesting of shoot N | Rate |
| HARVPH | d-1 | Resetting of phenological stage by harvesting | Rate |
| HARVRE | g C m-2 d-1 | Harvested reserves | Rate |
| HARVST | g C m-2 d-1 | Harvested stem mass | Rate |
| HARVTG | tillers m-2 d-1 | Harvested elongating tillers (apex removed by harvesting) | Rate |
| KMC | ppm CO2 | Km-value Rubisco for carboxylation | Intermediate |
| KMO | % O2 | Km-value Rubisco for oxygenation | Intermediate |
| KN | m2 m-2 leaf | Nitrogen extinction coefficient | Intermediate |
| KNMAX | m2 m-2 leaf | Maximum value of nitrogen extinction coefficient | Intermediate |
| LAI | m2 leaf m-2 | Leaf area index | State |
| LD50 | d | Duration of anaerobic conditions at which death rate is half the maximum | Intermediate |
| LERG | m d-1 | Elongation rate of leaves on elongating tillers | Intermediate |
| LERV | m d-1 | Elongation rate of leaves on non-elongating tillers | Intermediate |
| LT50 | °C | Temperature that kills half the plants in a day | State |
| LUEMXQ | mol CO2 mol-1 PAR | Light-use efficiency | Intermediate |
| NCDSH | g N g-1 C | N-C ratio of shoot senescence | Intermediate |
| NCGSH | g N g-1 C | N-C ratio of shoot growth | Intermediate |
| NCHARVSH | g N g-1 C | N-C ratio of harvested material | Intermediate |
| NELLVG | tiller-1 | Number of elongating leaves per elongating tiller | Intermediate |
| NOHARV | - | Flag indicating that the current day is not a harvest day | Intermediate |
| NSH | g N m-2 | Nitrogen in shoot | State |
| NSHK | g N m-2 | Nitrogen in shoot if N-profile equals light-profile | Intermediate |
| NSHmob | g N m-2 d-1 | Shoot N | Rate |
| NSHmobsoil | g N m-2 d-1 | Remobilised shoot N lost to the soil | Rate |
| NSHNOR | - | Normalised shoot nitrogen content | Intermediate |
| Nupt | g N m-2 d-1 | N uptake | Rate |
| PARAV | mumol PAR m-2 s-1 | Average PAR during the photoperiod | Intermediate |
| PARINT | mol PAR m-2 d-1 | PAR interception | Intermediate |
| PERMgas | d-1 | Permeability of soil surface to gas exchange | Intermediate |
| PHEN | - | Phenological stage | State |
| PHENRF | - | Effect of phenological stage on leaf elongation and appearance in elongating tillers | Intermediate |
| PHOT | g C m-2 d-1 | Photosynthesis | Intermediate |
| PMAX | micromol CO2 m-2 s-1 | Photosynthesis rate of upper leaves at light saturation | Intermediate |
| RATED | °C d-1 | Potential rate of dehardening, if below limit set by RATEDMX | Intermediate |
| RATEH | °C d-1 | Potential rate of hardening, at non-limiting carbohydrate spply | Intermediate |
| RDRFROST | d-1 | Relative death rate due to frost | Intermediate |
| RDRTOX | d-1 | Relative death rate due to anaerobic conditions | Intermediate |
| RDRS | d-1 | Relative death rate of leaves and non-elongating tillers due to shading | Intermediate |
| RDRT | d-1 | Relative leaf death rate due to high temperature | Intermediate |
| reHardPeriod | - | Day of year dependent hardening capability | Intermediate |
| RESMOB | g C m-2 d-1 | Mobilisation of reserves | Rate |
| RESNOR | - | Normalised concentration of reserves | Intermediate |
| RESPGSH | g C m-2 d-1 | Respiration associated with shoot growth | Intermediate |
| RESPGRT | g C m-2 d-1 | Respiration associated with root growth | Intermediate |
| RESPHARD | g C m-2 d-1 | Plant hardening respiration | Intermediate |
| RESPHARDSI | g C m-2 d-1 | Sink strength from carbohydrate demand of hardening | Intermediate |
| RGRTVG | d-1 | Relative rate of tillers becoming elongating tillers | Intermediate |
| RLEAF | d-1 | Leaf appearance rate per tiller | Intermediate |
| RplantAer | g C m-2 d-1 | Aerobic plant respiration | Intermediate |
| RSR3H | d-1 | Relative frost survival rate | Intermediate |
| RSRDAY | d-1 | Relative frost survival rate | Intermediate |
| SINK1T | g C tiller-1 d-1 | Sink strength of individual elongating tillers | Intermediate |
| SLANEW | m2 leaf gC-1 | SLA of new leaf | Intermediate |
| SOURCE | g C m-2 d-1 | Source strength from photsynthesis and reserve mobilisation | Intermediate |
| T | °C | Temperature | Input |
| TANAER | d | Time since start anaerobic conditions | State |
| TGE | - | Temperature effect on initiation of elongation in tillers | Intermediate |
| TILG | m-2 | Elongating tiller density | State |
| TILV | m-2 | Non-elongating tiller density | State |
| TMPFAC | - | Linear decrease of photosynthetic quantum yield at low temperature | Intermediate |
| TRANRF | - | Transpiration realisation factor | Intermediate |
| Tsurf | °C | Soil surface temperature | Intermediate |
| TV1 | - | Fraction of reserves removed at harvest | Intermediate |
| TV1 | d-1 | Potential leaf appearance rate | Intermediate |
| TV1 | d-1 | Relative leaf death rate due to shading if below the maximum rate | Intermediate |
| TV2 | d-1 | Maxmimum ratio of tiller and leaf apearance, at unlimited reserves | Intermediate |
| TV2 | d-1 | Relative leaf death rate | Intermediate |
| TV2TIL | d-1 | Relative death rate of non-elongating tillers | Intermediate |
| VCMAX | micromol CO2 m-2 leaf s-1 | Maximum carboxylation rate in upper leaves | Intermediate |

## 17 APPENDIX III: Parameters

### 17.1 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".

### 17.2 Parameters in BASGRA.f90

| **Parameter** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- |
| CLITT0 | g C m-2 | Initial value of CLITT | parameters\_site.f90 | parameters.txt |
| CLVI | g C m-2 | Initial value of leaves | parameters\_plant.f90 | parameters.txt |
| CNLITT0 | g C g-1 N | Initial C-N ratio of litter | parameters\_site.f90 | parameters.txt |
| CNSOMF0 | g C g-1 N | Initial C-N ratio of fast SOM | parameters\_site.f90 | parameters.txt |
| CNSOMS0 | g C g-1 N | Initial C-N ratio of slow SOM | parameters\_site.f90 | parameters.txt |
| CRESI | g C m-2 | Initial value of reserves | parameters\_plant.f90 | parameters.txt |
| CRTI | g C m-2 | Initial value of roots | parameters\_plant.f90 | parameters.txt |
| CSOM0 | g C m-2 | Initial value of SOM | parameters\_site.f90 | parameters.txt |
| CSTI | g C m-2 | Initial value of stems | parameters\_plant.f90 | parameters.txt |
| DAYLG1G2 | d d-1 | Minimum day length above which generative tillers can start elongating (by moving from TILG1 to TILG2). | parameters\_plant.f90 | parameters.txt |
| FCSOMF0 | g C g-1 C | Initial fraction of SOC that is fast | parameters\_site.f90 | parameters.txt |
| FGAS | m3 m-3 | Soil pore space (potentially gaseous) | parameters\_site.f90 | parameters.txt |
| FO2MX | mol O2 mol-1 gas | Maximum oxygen fraction of soil gas | parameters\_site.f90 | parameters.txt |
| FRTILGI | - | Initial value of elongating tiller fraction | parameters\_plant.f90 | parameters.txt |
| FRTILGG1I | - | Initial fraction of generative tillers that is still in stage 1 (TILG1) |  |  |
| LAII | m2 m-2 | Initial value of leaf area index | parameters\_plant.f90 | parameters.txt |
| LT50I | °C | Initial value of LT50 | parameters\_plant.f90 | parameters.txt |
| NCSHMAX | g N g-1 C | Maximum N-C ratio of shoot | parameters\_plant.f90 | parameters.txt |
| NMIN0 | g N m-2 | Initial value of soil mineral N | parameters\_site.f90 | parameters.txt |
| PHENI | - | Initial value of phenological stage | parameters\_plant.f90 | parameters.txt |
| RDRTMIN | d-1 | Minimum relative death rate of foliage | parameters\_plant.f90 | parameters.txt |
| RGRTG1G2 | tiller tiller-1 d-1 | Relative rate of TILG1 becoming TILG2 | parameters\_plant.f90 | parameters.txt |
| RHOnewSnow | kg SWE m-3 | Density of newly fallen snow | parameters\_site.f90 | parameters.txt |
| ROOTDM | m | Initial and maximum value rooting depth | parameters\_plant.f90 | parameters.txt |
| TILTOTI | m-2 | Initial value of tiller density | parameters\_plant.f90 | parameters.txt |
| TOPTGE | °C | Optimum temperature for vegetative tillers becoming generative | parameters\_plant.f90 | parameters.txt |
| TVERN | °C | Vernalisation threshold | parameters\_plant.f90 | parameters.txt |
| WCI | m3 m-3 | Initial value of soil water concentration | parameters\_site.f90 | parameters.txt |

### 17.3 Parameters in environment.f90

| **Parameter** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- |
| KSNOW | mm-1 | Light extinction coefficient of snow | parameters\_site.f90 | parameters.txt |
| LAT | °N | Latitude | parameters\_site.f90 | parameters.txt |
| RHOpack | d-1 | Relative packing rate of snow | parameters\_site.f90 | parameters.txt |
| SWret | mm mm-1 d-1 | Liquid water storage capacity of snow | parameters\_site.f90 | parameters.txt |
| SWrf | mm d-1 °C-1 | Maximum refreezing rate per degree below 'TmeltFreeze' | parameters\_site.f90 | parameters.txt |
| TmeltFreeze | °C | Temperature above which snow melts | parameters\_site.f90 | parameters.txt |
| TrainSnow | °C | Temperature below which precipitation is snow | parameters\_site.f90 | parameters.txt |
| WpoolMax | mm | Maximum pool water (liquid plus ice) | parameters\_site.f90 | parameters.txt |

### 17.4 Parameters in soil.f90

| **Parameter** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- |
| FGAS | - | Fraction of soil volume that is gaseous | parameters\_site.f90 | parameters.txt |
| FLITTSOMF | g g-1 | Fraction of decomposed litter becoming fast SOM | parameters\_site.f90 | parameters.txt |
| FO2MX | mol O2 mol-1 gas | Maximum oxygen fraction of soil gas | parameters\_site.f90 | parameters.txt |
| FSOMFSOMS | g g-1 | Fraction of decomposed fast SOM | parameters\_site.f90 | parameters.txt |
| gamma | m-1 | Temperature extinction coefficient of snow | parameters\_site.f90 | parameters.txt |
| KNEMIT | g N g-1 N d-1 | Fraction of mineral N emitted in wet soil | parameters\_site.f90 | parameters.txt |
| KNFIX | g N g-1 C | Nitrogen fixation per unit of root growth | parameters\_site.f90 | parameters\_site.f90 |
| KRTOTAER | - | Ratio of total to aerobic respiration | parameters\_site.f90 | parameters.txt |
| LAMBDAsoil | J m-1 °C-1 d-1 |  | parameters\_site.f90 | parameters.txt |
| RFN2O | - | Sensitivity of N-emission partitioning to soil wetness | parameters\_site.f90 | parameters.txt |
| RNLEACH | g N g-1 N | Relative concentration of mineral N in leaching water | parameters\_site.f90 | parameters.txt |
| RRUNBULK | g g-1 | Relative concentration of soil in run-off water | parameters\_site.f90 | parameters\_site.f90 |
| TCLITT | d | Time constant of litter decomposition at 10 °C | parameters\_site.f90 | parameters.txt |
| TCSOMF | d | Time constant of fast SOM decomposition at 10 °C | parameters\_site.f90 | parameters.txt |
| TCSOMS | d | Time constant of slow SOM decomposition at 10 °C | parameters\_site.f90 | parameters.txt |
| TMAXF | °C | Temperature at which decomposition is maximal | parameters\_site.f90 | parameters.txt |
| TSIGMAF | °C | Resilience of decomposition to temperature change | parameters\_site.f90 | parameters.txt |
| WCFC | m3 m-3 | Water concentration at field capacity | parameters\_site.f90 | parameters.txt |
| WCST | m3 m-3 | Water concentration at saturation | parameters\_site.f90 | parameters.txt |
| WFPS50N2O | - | Water filled pore space at which N-emission is half N2O | parameters\_site.f90 | parameters.txt |

### 17.5 Parameters in resources.f90

| **Parameter** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- |
| K | m2 m-2 leaf | PAR extinction coefficient | parameters\_plant.f90 | parameters.txt |
| ROOTDM | m | Initial and maximum value rooting depth | parameters\_plant.f90 | parameters.txt |
| RRDMAX | m d-1 | Maximum root depth growth rate | parameters\_plant.f90 | parameters.txt |
| TRANCO | mm d-1 | Transpiration coefficient | parameters\_plant.f90 | parameters.txt |
| WCAD | m3 m-3 | Water concentration at air dryness | parameters\_site.f90 | parameters.txt |
| WCFC | m3 m-3 | Water concentration at field capacity | parameters\_site.f90 | parameters.txt |
| WCST | m3 m-3 | Water concentration at full saturation | parameters\_site.f90 | parameters.txt |
| WCWET | m3 m-3 | Water concentration above which transpiration is reduced | parameters\_site.f90 | parameters.txt |
| WCWP | m3 m-3 | Water concentration at wilting point | parameters\_site.f90 | parameters.txt |

### 17.6 Parameters in plant.f90

| **Parameter** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- |
| CLAIV | m2 leaf m-2 | Maxmimum LAI remaining after harvest, when no tillers elongate | parameters\_plant.f90 | parameters.txt |
| COCRESMX | - | Maximum concentration of reserves in aboveground biomass (not stubble) | parameters\_plant.f90 | parameters.txt |
| CSTAVM | g C tiller-1 | Maximum size of elongating tillers | parameters\_plant.f90 | parameters.txt |
| DAYLB | d d-1 | Day length below which phenological stage is reset to zero | parameters\_plant.f90 | parameters.txt |
| DAYLP | d d-1 | Day length below which phenological development slows down | parameters\_plant.f90 | parameters.txt |
| DLMXGE | d d-1 | Day length below which DAYLGE becomes less than 1 | parameters\_plant.f90 | parameters.txt |
| Dparam | °C-1 d-1 | Constant in the calculation of dehardening rate | parameters\_plant.f90 | parameters.txt |
| FNCGSHMIN | - | Relative minimum N-C ratio of growing tissue | parameters\_plant.f90 | parameters.txt |
| FO2MX | mol O2 mol-1 gas | Maximum oxygen fraction of soil gas | parameters\_site.f90 | parameters.txt |
| FSLAMIN | - | Minimum SLA of new leaves as a fraction of maximum possible SLA | parameters\_plant.f90 | parameters.txt |
| FSMAX | - | Maximum ratio of tiller and leaf appearance based on sward geometry | parameters\_plant.f90 | parameters.txt |
| F\_DIGEST\_WALL\_FMIN | - | Minimum digestibility of cell walls as a fraction of the maximum | parameters\_plant.f90 | parameters.txt |
| F\_DIGEST\_WALL\_MAX | - | Maximum digestibility of cell walls | parameters\_plant.f90 | parameters.txt |
| F\_WALL\_LV\_FMIN | g wall g-1 DM | Minimum leaf DM that is cell wall, as a fraction of the maximum | parameters\_plant.f90 | parameters.txt |
| F\_WALL\_LV\_MAX | g wall g-1 DM | Fraction of leaf DM that is cell wall | parameters\_plant.f90 | parameters.txt |
| F\_WALL\_ST\_FMIN | g wall g-1 DM | Minimum stem DM that is cell wall, as fraction of the maximum | parameters\_plant.f90 | parameters.txt |
| F\_WALL\_ST\_MAX | g wall g-1 DM | Fraction of stem DM that is cell wall | parameters\_plant.f90 | parameters.txt |
| HAGERE | - | Fraction of reserves in elongating tillers that is harvested | parameters\_plant.f90 | parameters.txt |
| Hparam | °C-1 d-1 | Hardening parameter | parameters\_plant.f90 | parameters.txt |
| K | m2 m-2 leaf | PAR extinction coefficient | parameters\_plant.f90 | parameters.txt |
| KLUETILG | - | LUE-increase with increasing fraction elongating tillers | parameters\_plant.f90 | parameters.txt |
| KRDRANAER | d-1 | Maximum relative death rate due to anearobic conditions | parameters\_plant.f90 | parameters.txt |
| KRESPHARD | g C g-1 C °C-1 | Carbohydrate requirement of hardening | parameters\_plant.f90 | parameters.txt |
| KRSR3H | °C-1 | Constant in the logistic curve for frost survival | parameters\_plant.f90 | parameters.txt |
| LAICR | m2 leaf m-2 | LAI above which shading induces leaf senescence | parameters\_plant.f90 | parameters.txt |
| LAIEFT | m2 m-2 leaf | Decrease in tillering with leaf area index | parameters\_plant.f90 | parameters.txt |
| LAITIL | - | Maximum ratio of tiller and leaf apearance at low leaf area index | parameters\_plant.f90 | parameters.txt |
| LDT50A | d | Intercept of linear dependence of LD50 on lT50 | parameters\_plant.f90 | parameters.txt |
| LDT50B | d °C-1 | Slope of linear dependence of LD50 on LT50 | parameters\_plant.f90 | parameters.txt |
| LFWIDG | m | Leaf width on elongating tillers | parameters\_plant.f90 | parameters.txt |
| LFWIDV | m | Leaf width on non-elongating tillers | parameters\_plant.f90 | parameters.txt |
| LT50MN | °C | Minimum LT50 | parameters\_plant.f90 | parameters.txt |
| LT50MX | °C | Maximum LT50 | parameters\_plant.f90 | parameters.txt |
| NCR | g N g-1 C | N-C ratio of roots | parameters\_plant.f90 | parameters.txt |
| NCSHMAX | g N g-1 C | Maximum N-C ratio of shoot | parameters\_plant.f90 | parameters.txt |
| NELLVM | tiller-1 | Number of elongating leaves per non-elongating tiller | parameters\_plant.f90 | parameters.txt |
| PHENCR | - | Phenological stage above which elongation and appearance of leaves on elongating tillers decreases | parameters\_plant.f90 | parameters.txt |
| PHY | °C d | Phyllochron | parameters\_plant.f90 | parameters.txt |
| RATEDMX | °C d-1 | Maximum dehardening rate | parameters\_plant.f90 | parameters.txt |
| RDRSCO | d-1 | Relative death rate of leaves and non-elongating tillers due to shading when LAI is twice the threshold (LAICR) | parameters\_plant.f90 | parameters.txt |
| RDRSMX | d-1 | Maximum relative death rate of leaves and non-elongating tillers due to shading | parameters\_plant.f90 | parameters.txt |
| RDRTEM | d-1 °C-1 | Proportionality of leaf senescence with temperature | parameters\_plant.f90 | parameters.txt |
| reHardRedStart | d | Start of period of decrease in rehardening capability | plant.f90 | plant.f90 |
| reHardRedDay | d | Duration of period over which rehardening capability disappears | parameters\_plant.f90 | parameters.txt |
| RGENMX | d-1 | Maximum relative rate of tillers becoming elongating tillers | parameters\_plant.f90 | parameters.txt |
| RUBISC | g m-2 leaf | Rubisco content of upper leaves | parameters\_plant.f90 | parameters.txt |
| RUBISCN | mumol m-2 leaf | Rubisco content of upper leaves | plant.f90 | plant.f90 |
| SHAPE | - | Area of a leaf relative to a rectangle of same length and width | parameters\_plant.f90 | parameters.txt |
| SIMAX1T | g C tiller-1 d-1 | Sink strength of small elongating tillers | parameters\_plant.f90 | parameters.txt |
| SLAMAX | m2 leaf gC-1 | Maximum SLA of new leaves | parameters\_plant.f90 | parameters.txt |
| SLAMIN | m2 leaf g C-1 | Minimum SLA of new leaves (= SLAMAX \* FSLAMIN) | plant.f90 | plant.f90 |
| TBASE | °C | Minimum value of effective temperature for leaf elongation | parameters\_plant.f90 | parameters.txt |
| TCNSHMOB | d | Time constant of shoot N remobilisation | parameters\_plant.f90 | parameters.txt |
| TCNUPT | d | Time constant of soil mineral N uptake | parameters\_plant.f90 | parameters.txt |
| TCRES | d | Time constant of mobilisation of reserves | parameters\_plant.f90 | parameters.txt |
| THARDMX | °C | Maximum surface temperature at which hardening is possible | parameters\_plant.f90 | parameters.txt |
| TsurfDiff | °C | Constant in the calculation of dehardening rate | parameters\_plant.f90 | parameters.txt |
| YG | g C g-1C | Growth yield per unit expended carbohydrate | parameters\_plant.f90 | parameters.txt |

## 18 APPENDIX IV: Constants

### 18.1 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".

### 18.2 Constants in BASGRA.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.069 | g g-1 DM | Ash content at zero protein content | - | BASGRA.f90 |
|  | 0.14 | g g-1 protein | Additional ash content per g protein | - | BASGRA.f90 |
|  | 0.40 | g C g DM-1 | C-content reserves | - | BASGRA.f90 |
|  | 0.45 | g C g DM-1 | C-content leaves, stems, stubble | - | BASGRA.f90 |
|  | 0.5 | d | Constant in calculation decimal year | - | BASGRA.f90 |
|  | 6.25 | g g-1 N | Protein per unit N | - | BASGRA.f90 |
|  | 1000 | l m-3 | Volumetric unit conversion | - | BASGRA.f90 |
|  | 1000 | mm m-1 | Length unit conversion | - | BASGRA.f90 |
|  | 22.4 | l mol-1 | Molar volume | - | BASGRA.f90 |
|  | 366 | d y-1 | Constant in calculation decimal year | - | BASGRA.f90 |
| CLVDI | 0. | g C m-2 | Initial value of cumulative dead leaves | parameters\_plant.f90 | parameters\_plant.f90 |
| CLVHI | 0. | g C m-2 | Initial value of harvested leaves | parameters\_plant.f90 | parameters\_plant.f90 |
| CSTUBI | 0. | g C m-2 | Initial value of stubble | parameters\_plant.f90 | parameters\_plant.f90 |
| DRYSTORI | 0. | mm | Initial value of snow amount | parameters\_site.f90 | parameters\_site.f90 |
| FdepthI | 0. | m | Initial value of depth frozen soil | parameters\_site.f90 | parameters\_site.f90 |
| NDAYS |  | d | Length of simulation period | BASGRA.f90 | initialise\_BASGRA\_[site].R |
| NOUT | 35 | - | Number of output variables | BASGRA.f90 | initialise\_BASGRA\_general.R |
| SDEPTHI | 0. | m | Initial value of snow depth | parameters\_site.f90 | parameters\_site.f90 |
| TANAERI | 0. | d | Initial value of anaerobic days | parameters\_site.f90 | parameters\_site.f90 |
| WAPLI | 0. | mm | Initial value of pool water (liquid) | parameters\_site.f90 | parameters\_site.f90 |
| WAPSI | 0. | mm | Initial value of pool water (solid) | parameters\_site.f90 | parameters\_site.f90 |
| WASI | 0. | mm | Initial value of soil water (solid) | parameters\_site.f90 | parameters\_site.f90 |
| WETSTORI | 0. | mm | Initial value of liquid water in snow | parameters\_site.f90 | parameters\_site.f90 |
| YIELDI | 0. | g DM m-2 d-1 | Initial value of yield | parameters\_plant.f90 | parameters\_plant.f90 |

### 18.3 Constants in read\_weather.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.6108 | kPa | Constant in calculation saturated VP | - | - |
|  | 17.27 | °C-1 | Constant in calculation saturated VP | - | - |
|  | 239 | °C | Constant in calculation saturated VP | - | - |
|  | 100 | % | Fraction unit conversion | - | - |
|  | 1000 | kJ MJ-1 | Energy unit conversion | - | - |
| doy\_start |  | d | Start day of simulation | read\_weather.f90 | initialise\_BASGRA\_[site].R |
| NDAYS |  | d | Length of simulation period | BASGRA.f90 | initialise\_BASGRA\_[site].R |
| ST |  | - | Weather station number | read\_weather.f90 | weather data file |
| year\_start |  | y | Start year of simulation | read\_weather.f90 | initialise\_BASGRA\_[site].R |

### 18.4 Constants in environment.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.001 | m mm-1 | Length unit conversion | - | environment.f90 |
|  | 0.001 | MJ J-1 | Energy unit conversion | - | environment.f90 |
|  | 0.15 | - | Reflection coefficient of global radiation onto soil | - | environment.f90 |
|  | 0.25 | - | Reflection coefficient of global radiation onto canopy | - | environment.f90 |
|  | 0.25 | mm m-2 leaf d-1 | Maximum canopy rain interception efficiency | - | environment.f90 |
|  | 0.5 | - | Efficiency of transpiration reduction by intercepted rain | - | environment.f90 |
|  | 0.5 | d d-1 | Constant in calculation day length | - | environment.f90 |
|  | 0.5 | J PAR J-1 GR | PAR as a fraction of GR | - | environment.f90 |
|  | 0.5 | m2 m-2 leaf | Extinction coefficient global radiation | - | environment.f90 |
|  | 0.54 | s m-1 | Constant in wind factor Penman equation | - | environment.f90 |
|  | 0.55 | - | Maximum ratio of net long-wave to black-body radiation | - | environment.f90 |
|  | 0.611 | kPa | Saturation vapour pressure at zero degrees Celsius | - | environment.f90 |
|  | 1.0 | - | Constant in wind factor Penman equation | - | environment.f90 |
|  | 1.E6 | J MJ-1 | Energy unit conversion | - | environment.f90 |
|  | 10. | d | Difference between 21 June and midyear | - | environment.f90 |
|  | 1000. | mm m-1 | Length unit conversion | - | environment.f90 |
|  | 17.4 | - | Constant in calculation saturation vapour pressure | - | environment.f90 |
|  | 174. | d | Constant in calculation snow melting rate | - | environment.f90 |
|  | 2 | - | Power coefficient in calculation of 'eta' | - | environment.f90 |
|  | 2 | - | POwer coefficient in temperature derivative of SVP | - | environment.f90 |
|  | 2. | - | Constant in calculation of 'PIrate' | - | environment.f90 |
|  | 2. | rad | Angle of a pi-th part of a circle | - | environment.f90 |
|  | 2.0 | - | Constant in calculation daily average temperature | - | environment.f90 |
|  | 2.63 | kg m-2 d-1 kPa-1 | Constant in wind factor Penman equation | - | environment.f90 |
|  | 23.45 | ° | Solar declination at June 21 | - | environment.f90 |
|  | 239 | °C | Constant in calculation saturation vapour pressure | - | environment.f90 |
|  | 273 | K | Temperature unit conversion | - | environment.f90 |
|  | 365. | d | Number of days per year | - | environment.f90 |
|  | 4 | - | Power coefficient in calculation black-body radiation | - | environment.f90 |
|  | 4.56 | mol MJ-1 PAR | Quanta per MJ PAR | - | environment.f90 |
|  | 4158.6 | °C | Constant in temperature derivative of SVP (= 17.4 \* 239) | - | environment.f90 |
|  | 480. | kg m-3 | Maximum snow density | - | environment.f90 |
|  | 86400 | s d-1 | Time unit conversion | - | environment.f90 |
|  | 91. | d | Constant in calculation snow melting rate | - | environment.f90 |
| Ampl | 0.625 | mm °C-1 d-1 | Intra-annual amplitude snow melt at 1 degree > 'TmeltFreeze' | parameters\_site.f90 | parameters\_site.f90 |
| Bias | 4.625 | mm °C-1 d-1 | Average snow melting rate at 1 degree above 'TmeltFreeze' | parameters\_site.f90 | parameters\_site.f90 |
| BOLTZM | 5.668E-8 | J m-2 s-1 K-4 | Stefan-Boltzmann constant |  |  |
| eta | 0.0005777 | m2 K-1 d-1 | Compound parameter (= LAMBDAice/(RHOwater\*LatentHeat)) |  |  |
| Freq | 2.\*pi/365. | rad d-1 | Unit conversion time to annual cycle | parameters\_site.f90 | parameters\_site.f90 |
| LAMBDAice | 1.9354e+005 | J m-1 K-1 d-1 | Thermal conductivity of ice | parameters\_site.f90 | parameters\_site.f90 |
| LatentHeat | 335000 | J kg-1 | Latent heat of water fusion | parameters\_site.f90 | parameters\_site.f90 |
| LHVAP | 2.4E6 | J kg-1 | Latent heat of water evaporation |  |  |
| NMAXDAYS | 365\*200 | d | Maxmimum length of weather data files |  |  |
| pi | 3.1416 | - | ratio of circle circumference and diameter | parameters\_site.f90 | parameters\_site.f90 |
| poolInfilLimit | 0.2 | m | Soil frost depth limit for water infiltration | parameters\_site.f90 | parameters\_site.f90 |
| PSYCH | 0.067 | kPA °C-1 | Psychrometric constant |  |  |
| RAD | pi/180. | radians °-1 | Angular unit conversion |  |  |
| RHOwater | 1000 | kg m-3 | Density of water | parameters\_site.f90 | parameters\_site.f90 |

### 18.5 Constants in soil.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.001 | m mm-1 | Unit conversion | - | soil.f90 |
|  | 1. | mol O2 mol-1 C | Oxygen use in respiration | - | soil.f90 |
|  | 2. | °C-1 | Constant in temperature effect on SOM decomposition | - | soil.f90 |
|  | 10. | °C-1 | Constant in temperature effect on SOM decomposition | - | soil.f90 |
|  | 12 | gC mol-1 | Molar mass of carbon | - | soil.f90 |
|  | 22.4 | l mol-1 | Molar volume of gas | - | soil.f90 |
|  | 1000 | mm m-1 | Length unit conversion | - | soil.f90 |
| DELT | 1 | d | Model time step | parameters\_site.f90 | parameters\_site.f90 |
| DRATE | 50 | mm d-1 | Maximum drainage rate | parameters\_site.f90 | parameters\_site.f90 |
| IRRIGF | 0 | - | Irrigation relative to what would maintain field capacity | parameters\_site.f90 | parameters\_site.f90 |
| LatentHeat | 335000 | J kg-1 | Latent heat of water fusion | parameters\_site.f90 | parameters\_site.f90 |
| RHOwater | 1000 | kg m-3 | Density of water | parameters\_site.f90 | parameters\_site.f90 |

### 18.6 Constants in resources.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.001 | m mm-1 | Length unit conversion | - | resources.f90 |
|  | 0.01 | m3 m-3 | Minimum difference between WCCR and WCWP | - | resources.f90 |
|  | 0.75 | - | Ratio of interception efficiencies for GR and PAR | - | resources.f90 |
|  | 1 | - | Maximum PAR interception | - | resources.f90 |
|  | 1. | - | Maximum availability of water for evapotranspiration | - | resources.f90 |
|  | 1000 | mm m-1 | Length unit conversion | - | resources.f90 |
|  | 1E6 | mumol mol-1 | Quantity unit conversion | - | resources.f90 |
|  | 24 | h d-1 | Time unit conversion | - | resources.f90 |
|  | 3600 | s h-1 | Time unit conversion | - | resources.f90 |
| DELT | 1 | d | Model time step | parameters\_site.f90 | parameters\_site.f90 |

### 18.7 Constants in plant.f90

| **Constant** | **Value** | **Unit** | **Meaning** | **Declared where** | **Quantified where** |
| --- | --- | --- | --- | --- | --- |
|  | 0.01 | °C | Constant in the equation for phenological development | - | plant.f90 |
|  | 0.000144 |  | Constant in the equation for phenological development | - | plant.f90 |
|  | 0.24 | d d-1 | Constant in the equation for phenological development | - | plant.f90 |
|  | 0.25 | - | Constant in calculation of N extinction coefficient | - | plant.f90 |
|  | 0.5 | - | Constant in the equation for the CO2 compensation point | - | plant.f90 |
|  | 0.5 | - | Normalised duration of period without rehardening capability | - | plant.f90 |
|  | 0.5 | - | Sink strength of reserve pool relative to what would fill it maximally | - | plant.f90 |
|  | 0.5 | d-1 | Maximum relative death rate due to frost | - | plant.f90 |
|  | 0.52 | mm d-1 °C-1 | Constant in equation for leaf elongation on non-elongating tillers | - | plant.f90 |
|  | 5/8 | - | Constant in calculation of N extinction coefficient | - | plant.f90 |
|  | 2/3 | - | Constant in calculation of N extinction coefficient | - | plant.f90 |
|  | 0.7 | - | Ratio of chloroplast to atmospheric CO2 concentration | - | plant.f90 |
|  | 0.76 | mm d-1 | Constant in equation for leaf elongation on non-elongating tillers | - | plant.f90 |
|  | 1. | d d-1 | Rate of increase of TANAER when soil permeability to gas is zero | - | plant.f90 |
|  | 1.5 | - | Constant in calculation of N extinction coefficient | - | plant.f90 |
|  | 2.1 | mol PAR mol-1 CO2 | Photon requirement of photosynthesis | - | plant.f90 |
|  | 2.80 | mm d-1 °C-1 | Constant in equation for leaf elongation on elongating tillers | - | plant.f90 |
|  | 3 | - | Constant in calculation of N extinction coefficient | - | plant.f90 |
|  | 4. | °C | Constant in calculation low-temperature reduction of quantum yield | - | plant.f90 |
|  | 4.5 | ppm-1 CO2 | Constant in calculation quantum yield | - | plant.f90 |
|  | 5. | °C | Temperature below which reserve mobilisation slows down | - | plant.f90 |
|  | 5. | °C | Constant in calculation low-temperature reduction of quantum yield | - | plant.f90 |
|  | 5. | - | Constant in calculation of reserve limitation of rehardening sink strength | - | plant.f90 |
|  | 5.46 | mm d-1 | Constant in equation for leaf elongation on elongating tillers | - | plant.f90 |
|  | 10.5 | ppm-1 CO2 | Constant in calculation quantum yield | - | plant.f90 |
|  | 12. | gC mol-1 CO2 | Carbon content of a mole of CO2 | - | plant.f90 |
|  | 24. |  | Constant in the equation for phenological development | - | plant.f90 |
|  | 273. | °C | Constant in temperature dependence of VCMAC, KMC and KMO | - | plant.f90 |
|  | 298. | °C | Constant in temperature dependence of VCMAC, KMC and KMO | - | plant.f90 |
|  | 365. | d | Constant in calculation period of possible rehardening | - | plant.f90 |
|  | 1000. | mm m-1 | Length unit conversion | - | plant.f90 |
|  | 550000 | g mol-1 | Molar mass of Rubisco | - | plant.f90 |
|  | 1.E6 | mumol mol-1 | Quantity unit conversion | - | plant.f90 |
| CO2A | 350 | ppm | CO2 concentration in atmosphere | parameters\_site.f90 | parameters\_site.f90 |
| CO2I | 0.7\*350 | ppm | CO2 concentration in chloroplasts | plant.f90 | plant.f90 |
| DELT | 1 | d | Model time step | parameters\_site.f90 | parameters\_site.f90 |
| doyHA(1:3) |  | d | Harvest days | parameters\_site.f90 | initialise\_BASGRA\_[site].R |
| EA | - |  | Unused constant |  |  |
| EAVCMX | 68000 | J mol-1 | Activation energy for VCMAX | plant.f90 | plant.f90 |
| EAKMC | 65800 | J mol-1 | Activation energy for KMC | plant.f90 | plant.f90 |
| EAKMO | 1400 | J mol-1 | Activation energy for KMO | plant.f90 | plant.f90 |
| KC25 | 20 | mol CO2 mol-1 Rubisco s-1 | Catalytic efficiency of Rubisco at 25 °C | plant.f90 | plant.f90 |
| KMC25 | 460 | ppm CO2 | Km-value Rubisco for carboxylation at 25 °C | plant.f90 | plant.f90 |
| KMO25 | 33 | % O2 | Km-value Rubisco for oxygenation at 25 °C | plant.f90 | plant.f90 |
| KOKC | 0.21 | - | Catalytic efficiency ratio Rubisco oxygenation/carboxylation | plant.f90 | plant.f90 |
| O2 | 21 | % O2 | Oxygen concentration in chloroplasts | plant.f90 | plant.f90 |
| R | 8.314 | J K-1 mol-1 | Universal gas constant | plant.f90 | plant.f90 |
| RDRROOT | 0. | d-1 | Relative death rate of roots | parameters\_plant.f90 | parameters\_plant.f90 |
| RDRSTUB | 0.2 | d-1 | Relative death rate of stubble | parameters\_plant.f90 | parameters\_plant.f90 |
| reHardRedEnd | 91 | d | day of year at which rehardening capability becomes zero | parameters\_plant.f90 | parameters\_plant.f90 |