BASGRA: The BASic GRAssland model

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1 Introduction

This document contains general documentation and a user manual for the grassland model BASGRA. The name of the model stands for BASic GRAssland model, reflecting the intention to represent processes in simple ways. Despite this, the aim is to make the model widely applicable by simulating the impacts of a wide range of environmental drivers. BASGRA 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 19 September 2014.

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 Norway at Planteforsk, Saerheim (now Bioforsk). 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). Algorithms for winter processes were developed by Stig Morten Thorsen and colleagues (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 now called BASGRA.

2 Quick start

2.1 TO MAKE EVERYTHING READY FOR RUNNING BASGRA:

- Install R, RStudio and gfortran on your computer.
- Unzip 'BASGRA_2014-09-19.zip'.

2.2 TO RUN THE MODEL for default conditions:

- Double-click on 'run_BASGRA_Saerheim_00_early_Gri' 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_00_early_Gri.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_00_early_Gri.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.

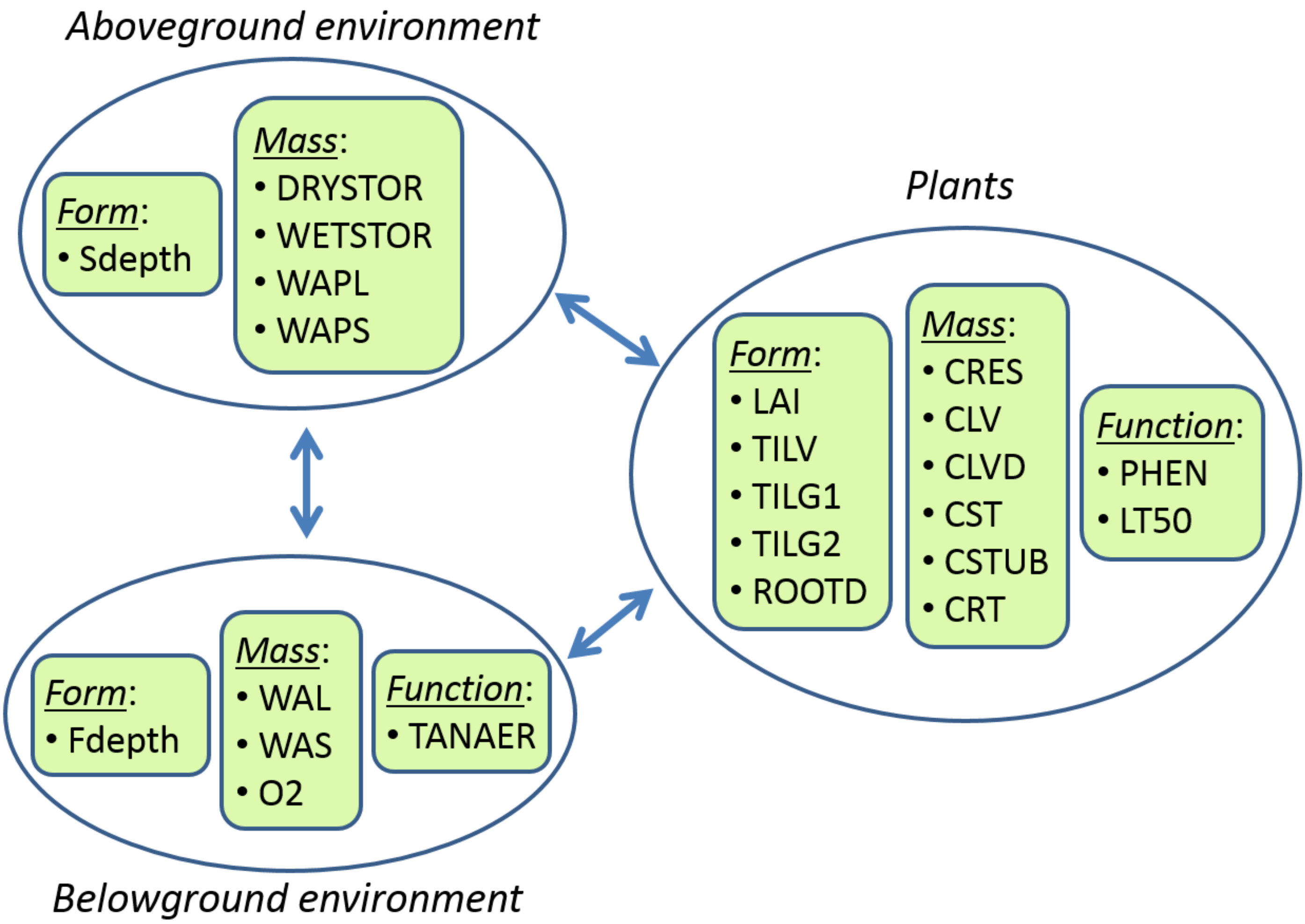
3 General overview of the model

3.1 What processes does BASGRA simulate?

BASGRA 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 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. The model also does not simulate nitrogen relations.

3.2 State variables

BASGRA has 23 state variables. 13 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 and humidity. The last two of these are only used in the calculation of potential rates of evaporation and transpiration. The model can also be used in a different way, where wind speed and humidity are not provided but potential evapotranspiration itself is an input. Further, the model 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 35 different output variables, which include the 23 state variables. BASGRA does not simulate some variables which are very important in grassland productivity, such as digestibility and fibre content of the harvested material, but these are closely related to leaf:stem ration which the model can calculate. The selection of output variables can be altered by the model user.

3.5 Technical details

3.5.1 General set-up using FORTRAN and R

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

1. set the time period of simulation,

2. identify the weather file,
3. set the cutting dates,
4. set parameter values,
5. call FORTRAN to iteratively calculate rates and states,
6. collect the output,
7. make plots.

3.5.2 Directories and files

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

- 2 script-files in R for model running: 'run_[].R'
- 2 script-files in R for model calibration: 'BC_[].R'
- 2 compiled model files: 'BASGRA_[].DLL'
- 2 batch files for compiling the model: 'compile_BASGRA_[].bat'
- 1 script-file in R showing examples of how to work with BASGRA: 'INTRODUCTION_EXAMPLES_BASGRA2014.R'

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:

- 3 files defining different likelihood functions: 'fLogL[].R'
- 3 script-files in R for initialising a Bayesian calibration: 'BC_BASGRA_MCMC_init_[].R'
- 1 script-file in R for running the Bayesian Calibration by means of the Markov Chain Monte Carlo method of Metropolis: 'BC_BASGRA_MCMC.R'
- 1 script-file in R for writing the modes of the prior and posterior parameter distributions plus other calibration results to txt-file: 'BC_export_parModes.R'
- 3 script-files in R for plotting calibration results: 'BC_plot[].R'

Subdirectory 'data' contains:

- 4 files with calibration data: 'data_calibration_[].txt'

Subdirectory 'initialisation' contains:

- 6 script-files in R for model initialisation: 'initialise_[].R'

Subdirectory 'model' contains:

- 8 FORTRAN files that together define BASGRA.

Subdirectory 'parameters' contains:

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

Subdirectory 'weather' contains:

- 1 file with weather data in 'weather generator' format: 'AP_BCM_AB1_2050_year1.txt'
- 2 files with weather data in 'Bioforsk' format: 'weather_[].txt'
- 1 README-file explaining the 'Bioforsk' format

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 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 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 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

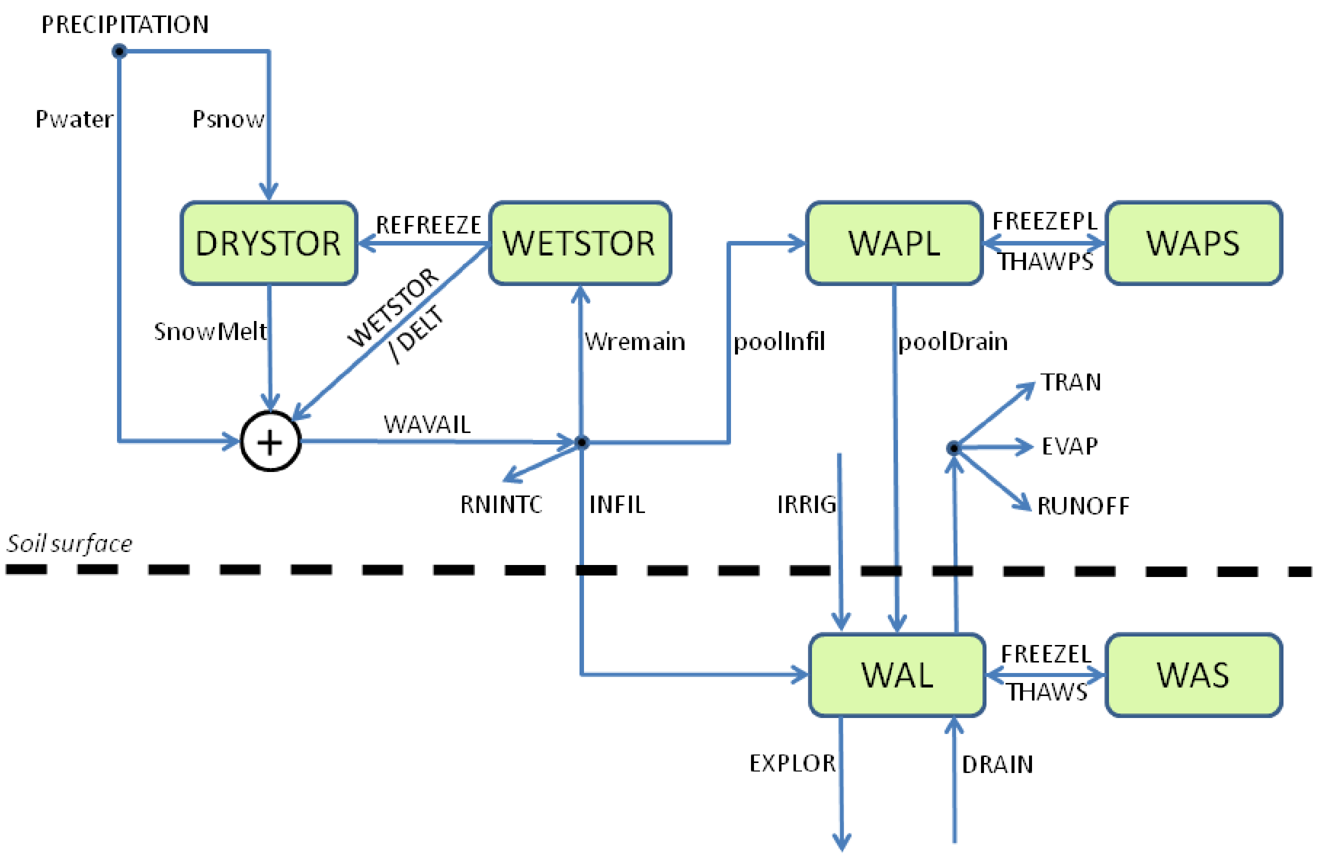
The model reads weather data from file. The files must include daily data for radiation, temperature and precipitation. For other variables there are two options: either relative humidity and wind speed are provided or potential evapotranspiration rate. BASGRA includes an algorithm to determine whether 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 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 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 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

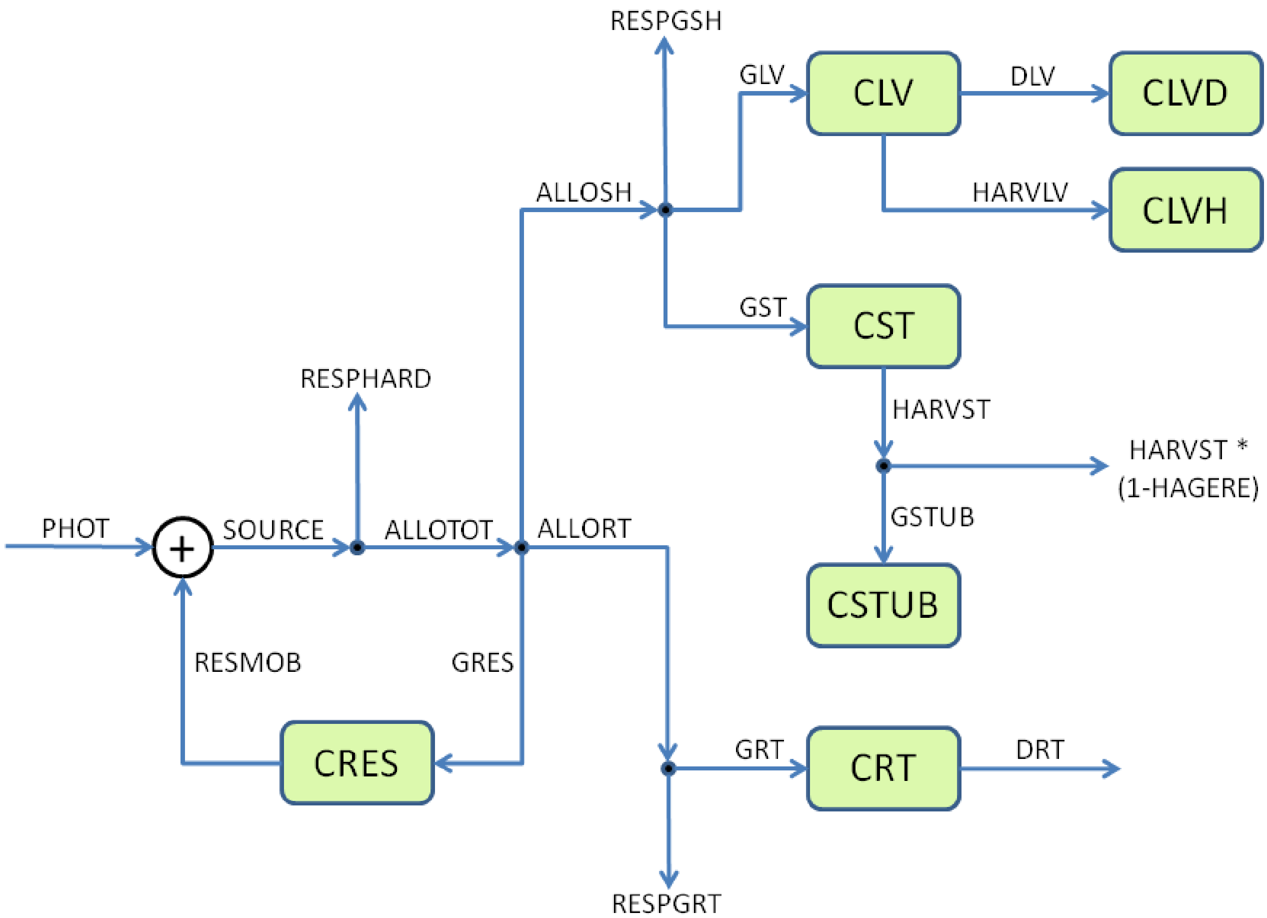
BASGRA contains a state variable PHEN which represents the phenological stage of the plants. PHEN increases daily at a rate that depends on temperature and day length, and it is reset to zero after each cut. Advancing phenological stage leads to reductions in leaf appearance rate (RLEAF) and in the number 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 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 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.

5 Installing FORTRAN, R and RStudio

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

5.1 Install gfortran

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

5.2 Install R

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

5.3 Install RStudio

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

6 Installing the model files

All that needs to be done for model installation is unzipping the files, but it is important to check that the files are put in the correct place. So Verify that the unzipping program has produced the correct directory structure. The top-level directory, which can have any name, should contain three subdirectories, called 'BC', 'input' and 'model'. The files that you should find in the four directories are listed above, in chapter 'General overview of the model', section 'Technical details', paragraph 'Directories and files'.

7 Compiling the model

This is not often needed. The zip-file 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 works with. That is discussed in the next chapter.

7.1 Removing the previous DLL

If you started an RStudio-session with BASGRA, 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. 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 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. Two types of weather file can be handled by the model: (1) files following the 'Bioforsk' template, (2) files generated by the LARS weather generator. The main difference is that the Bioforsk files include all weather variables required to calculate potential evapotranspiration rate (PET) using the Penman equation, whereas the weather generator files already include PET and do not include wind speed and humidity.

- Compilation of BASGRA for different weather files
  To work with either type of weather file, BASGRA needs to be compiled differently. To produce a 'BASGRA.DLL' that works with Bioforsk-files, execute 'compile_BASGRA_gfortran.bat'. For weather generator files, choose 'compile_BASGRA_gfortran_weathergen.bat'. The two compilation files only differ in that the latter one includes the '-Dweathergen' switch, which makes the compiler select different parts of the code in files 'BASGRA.f90', 'environment.f90' and 'read_weather.f90'. The two different types of DLL are in fact included in the zip-file, with filenames 'BASGRA_Bioforsk.DLL' and 'BASGRA_weathergen.DLL'. So instead of recompiling when you

change the weather file type, you can also rename the appropriate DLL-file to 'BASGRA.DLL', but that would of course ignore any changes you made in any of the FORTRAN-files.

- Weather files following the 'Bioforsk' template
The following are the first two lines from a typical Bioforsk-type weather file:

ST(number) YR(year) doy(day) T(degC) TMMXI(degC) TMMNI(degC) 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 files generated by the LARS weather generator
The following are the first two lines from a typical file generated by the LARS weather generator:

station year DOY TMIN °C TMAX °C PREC (mm) Global rad (MJ m-2) Pot evapotranspiration (mm)
46 1 1 -2.4 2.3 8.5 0.25 0

- The first column contains the weather station number which plays no role in model calculations. There are two temperature variables, for daily minimum and maximum temperature, but the model only uses the average of those two in the calculation of temperature effects. So it does not matter whether the true values of minimum and maximum temperature are specified, or whether the daily average is repeated in both columns.

- Weather data for multiple years
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.

- Weather data called by the included site-specific initialisation files
    - The files **initialise_BASGRA_Holt_0506_winter_Gri.R** and **initialise_BASGRA_Saerheim_00_early_Gri.R** call Bioforsk weather files: 'weather_00_Saerheim_format_bioforsk.txt' and 'weather_0506_Holt_format_bioforsk.txt', both in subdirectory 'input'.
    - The file **initialise_BASGRA_Saerheim_1_early_Gri_weathergen.R** calls a weather generator file: 'AP_BCM_AB1_2050_year1.txt'.

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 Parameter values

BASGRA 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 Running a batch job, i.e. a series of runs

You can do this by writing an R-file in which every run is specified. Examples of such batch files are provided: 'run_batch_BASGRA_EXAMPLES.R' and 'run_batch_BASGRA_EXAMPLES_weathergen.R'.

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 the master directory. 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 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, 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 can be compiled with or without the "Dweathergen" option depending on the type of weather file you intend to use (see chapter "Initialising the model").

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 steps one by one, but prepare everything before starting the BC, and run everything from one BC script file. Three examples of such BC script files are given in the master directory, all named '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 listed in a txt-file that is placed in directory ‘BC’. Two examples of such files are already in that directory.

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. These numbers 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.

12.2.1 Parameter constraints

Given the structure of BASGRA 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. 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 output variable in the first column. Examples of calibration data files are provided: 'data_calibration_Holt_0506_winter_Gri.txt' and 'data_calibration_Saerheim_00_early_Gri.txt'. The values in columns two and three of these files represent the day of measurement and the measurement value itself.

12.4 STEP 4: Defining the likelihood function

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 three examples are given in subdirectory 'BC', all named 'BC_BASGRA_MCMC_init_[]_Gri.R'. In these files, measurement uncertainties are specified as follows:

- The default value of the coefficient of variation (CV) for calibration data is set at 0.5;
- For dry matter yield (DM), CV = 0.05;
- For LAI, CV = 0.1;
- For total tiller density (TILTOT), CV = 0.2;
- For LT50, not a relative uncertainty such as the CV is given but an absolute one of 5 degrees C.

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 to have 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.

12.5 STEP 5: Running the MCMC

Before continuing, we need to recompile if a FORTRAN file was altered in STEP 1 ('set_params_BC.f90'). Then we need to set the length of the parameter vector chain to be generated in the MCMC, which is also done in the BC initialisation file. After that, we start the chain by running the script 'BC_BASGRA_MCMC.R'.

12.6 STEP 6: Analysing the outcome of the MCMC

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

- 'BC_parameters_traceplots_[].pdf'.
    - This shows trace plots for each parameter in the calibration.
- 'BC_parameters_priorbeta_histograms_[].pdf'.
    - This shows prior and posterior marginal distributions for each parameter in the calibration.
- '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). Blue 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 (normally 76 or so) parameters that you can find in 'parameters.txt'. In the BC there were fewer parameters, so the default values of the uncalibrated parameters are 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. To see an example of that, inspect, for example, the BC script file 'BC_BASGRA_ Gri.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 change the chain length of the MCMC, or the proposal distribution:
    - Modify 'BC/BC_BASGRA_MCMC_init[_MULTISITE]_….R'. Chain length is called 'nChain' and the covariance matrix of the proposal distribution is called 'vcovProp'.
- 2. To modify the list of parameters included in the calibration:
    - Change 'BC/parameters_BC.txt'.
    - If you deleted parameters from 'BC/parameters_BC.txt', no further changes are needed and you can start the BC in the usual way.
    - If you have added parameters to the existing 'parameters_BC.txt' file: check that your new calibration parameters are also included in 'input/parameters_default.txt'. That is required because the calibration parameters must be a subset of the parameters that the model reads in externally by means of that default parameter file.
    - If your new calibration parameters are not yet in 'input/parameters_default.txt', add them there, and add them also to 'model/set_params.f90'. Furthermore, inspect 'model/parameters_plant.f90' and 'model/parameters_site.f90' to see if those files also need some modification (which may be the case if your new calibration parameters were originally given fixed values in those files.
- 3. To use a different dataset from the same site:
    - Change the existing datafile(s), called 'BC/data_calibration_…txt', or add a new one.
    - If a new datafile is created, insert its name in 'BC/BC_BASGRA_MCMC_init[_MULTISITE].R' instead of the default datafile name.
- 4. To add extra sites to a Multi-site BC:
    - Make new model initialisation files, called 'initialise_BASGRA_…txt', to the top-level directory.
    - Make new data files 'BC/data_calibration_…txt'.
    - Modify the calibration initialisation file 'BC/BC_BASGRA_MCMC_init_MULTISITE_…R', by adding the new filenames to the statements defining 'sitesettings_filenames' and 'sitedata_filenames'.

13 Publications on BASGRA and related models

- 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.

- 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.
- Van Oijen, M., Höglind, M., Hanslin, H.M. & Caldwell, N. (2005). Process-based modelling of timothy regrowth. Agronomy Journal 97: 1295-1303.
- 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.

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.
- Peacock J.M. 1976. Temperature and leaf growth in four grass species. Journal of Applied Ecology 13: 225–232.

15 APPENDIX I: FORTRAN files and subroutines

The following table shows for each BASGRA 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			

File	Main subroutines	Nested subroutines	Calculated rate variables
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
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

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".

16.2 State variables (BASGRA.f90)

State variable	Unit	Meaning
CLV	gC m-2	Weight of leaves
CLVD	gC m-2	Weight of leaves died since start simulation
CRES	gC m-2	Weight of reserves
CRT	gC m-2	Weight of roots
CST	gC m-2	Weight of stems
CSTUB	gC m-2	Weight of 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
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
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	gC m-2 d-1	Death rate of leaf mass	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	gC m-2 d-1	Death rate of roots	Rate
DSTUB	gC 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

Variable	Unit	Meaning	Type
GLAI	m2 leaf m-2 d-1	Growth of leaf area	Rate
GLV	gC m-2 d-1	Growth of leaf mass	Rate
GPHEN	d-1	Rate of phenological development	Rate
GRES	gC m-2 d-1	Gross growth rate of reserve pool, uncorrected for remobilisation	Rate
GRT	gC m-2 d-1	Growth of roots	Rate
GST	gC m-2 d-1	Growth of stems	Rate
GSTUB	gC 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	gC m-2 d-1	Harvested leaf mass	Rate
HARVPH	d-1	Resetting of phenological stage by harvesting	Rate
HARVRE	gC m-2 d-1	Harvested reserves	Rate
HARVST	gC 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
NELLVG	tiller-1	Number of growing leaves per elongating tiller	Intermediate
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

Variable	Unit	Meaning	Type
reFreeze	mm d-1	Freezing of liquid water stored in snow	Rate
RESMOB	gC m-2 d-1	Mobilisation of reserves	Rate
RESPHARD	gC 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
RplantAer	gC m-2 d-1	Aerobic plant respiration	Intermediate
RROOTD	m d-1	Rate of increase in rooting depth	Rate
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

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

Variable	Unit	Meaning	Type
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

Variable	Unit	Meaning	Type
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

Variable	Unit	Meaning	Type
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
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
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
INFIL	mm d-1	Water flow into soil from precipitation and snow melt	Rate

Variable	Unit	Meaning	Type
INFILTOT	mm d-1	Water flow into soil from aboveground compartments	Intermediate
IRRIG	mm d-1	Irrigation rate	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
ROOTD	m	Rooting depth	State
RplantAer	gC m-2 d-1	Aerobic respiration	Intermediate
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

Variable	Unit	Meaning	Type
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	gC m-2 d-1	Allocation of carbohydrates to leaf growth	Intermediate
ALLORT	gC m-2 d-1	Allocation of carbohydrates to root growth	Intermediate
ALLOSH	gC m-2 d-1	Allocation of carbohydrates to shoot growth	Intermediate
ALLOST	gC m-2 d-1	Allocation of carbohydrates to stem growth	Intermediate
ALLOTOT	gC m-2 d-1	Allocation of carbohydrates to sinks other than hardening	Intermediate
CLAI	m2 leaf m-2	LAI remaining after harvest	Intermediate
CLV	gC m-2	Weight of leaves	State
CRES	gC m-2	Weight of reserves	State
CRESMX	gC m-2	Maximum amount of reserves	Intermediate
CRT	gC m-2	Weight of roots	State
CST	gC m-2	Weight of stems	State
CSTAV	gC tiller-1	Average size of elongating tillers	Intermediate
CSTUB	gC m-2	Weight of stubble	State
DAVTMP	°C	Daily average temperature	Intermediate
DAYL	d d-1	Day length	Intermediate

Variable	Unit	Meaning	Type
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	gC m-2 d-1	Death rate of leaf mass	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	gC m-2 d-1	Death rate of roots	Rate
DSTUB	gC 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	degC	Effective temperature for leaf elongation	Intermediate
fAer	-	Aeration status of soil	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
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	gC m-2 d-1	Growth rate of leaf mass	Rate
GLVSI	gC m-2 d-1	Potential growth rate of leaf mass	Intermediate
GPHEN	d-1	Rate of phenological development	Rate
GRES	gC m-2 d-1	Gross growth rate of reserve pool, uncorrected for remobilisation	Rate
GRESSI	gC m-2 d-1	Sink strength of reserve pool	Intermediate
GRT	gC m-2 d-1	Growth rate of roots	Rate
GSHSI	gC m-2 d-1	Potential growth rate of shoot	Intermediate
GST	gC m-2 d-1	Growth rate of stems	Rate
GSTSI	gC m-2 d-1	Potential growth rate of stems	Intermediate
GSTUB	gC m-2 d-1	Growth of stubble due to harvest of elongating tillers	Rate

Variable	Unit	Meaning	Type
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	gC m-2 d-1	Harvested leaf mass	Rate
HARVPH	d-1	Resetting of phenological stage by harvesting	Rate
HARVRE	gC m-2 d-1	Harvested reserves	Rate
HARVST	gC 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
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
NELLVG	tiller-1	Number of elongating leaves per elongating tiller	Intermediate
NOHARV	-	Flag indicating that the current day is not a harvest day	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
PHEN	-	Phenological stage	State
PHENRF	-	Effect of phenological stage on leaf elongation and appearance in elongating tillers	Intermediate
PHOT	gC 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

Variable	Unit	Meaning	Type
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	gC m-2 d-1	Mobilisation of reserves	Rate
RESNOR	-	Normalised concentration of reserves	Intermediate
RESPGSH	gC m-2 d-1	Respiration associated with shoot growth	Intermediate
RESPGRT	gC m-2 d-1	Respiration associated with root growth	Intermediate
RESPHARD	gC m-2 d-1	Plant hardening respiration	Intermediate
RESPHARDSI	gC 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	gC 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	gC tiller-1 d-1	Sink strength of individual elongating tillers	Intermediate
SLANEW	m2 leaf gC-1	SLA of new leaf	Intermediate
SOURCE	gC 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

Variable	Unit	Meaning	Type
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
CLVI	gC m-2	Initial value of leaves	parameters_plant.f90	parameters_default.txt
CRESI	gC m-2	Initial value of reserves	parameters_plant.f90	parameters_default.txt
CRTI	gC m-2	Initial value of roots	parameters_plant.f90	parameters_default.txt
CSTI	gC m-2	Initial value of stems	parameters_plant.f90	parameters_default.txt
FGAS	m3 m-3	Soil pore space (potentially gaseous)	parameters_site.f90	parameters_default.txt
FO2MX	mol O2 mol-1 gas	Maximum oxygen fraction of soil gas	parameters_site.f90	parameters_default.txt
FRTILGI	-	Initial value of elongating tiller fraction	parameters_plant.f90	parameters_default.txt
LAII	m2 m-2	Initial value of leaf area index	parameters_plant.f90	parameters_default.txt
LT50I	°C	Initial value of LT50	parameters_plant.f90	parameters_default.txt
PHENI	-	Initial value of phenological stage	parameters_plant.f90	parameters_default.txt
RHOnewSnow	kg SWE m-3	Density of newly fallen snow	parameters_site.f90	parameters_default.txt
ROOTDM	m	Initial and maximum value rooting depth	parameters_plant.f90	parameters_default.txt

Parameter	Unit	Meaning	Declared where	Quantified where
TILTOTI	m-2	Initial value of tiller density	parameters_plant.f90	parameters_default.txt
WCI	m3 m-3	Initial value of soil water concentration	parameters_site.f90	parameters_default.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_default.txt
LAT	°N	latitude	parameters_site.f90	parameters_default.txt
RHOpack	d-1	Relative packing rate of snow	parameters_site.f90	parameters_default.txt
SWret	mm mm-1 d-1	Liquid water storage capacity of snow	parameters_site.f90	parameters_default.txt
SWrf	mm d-1 °C-1	Maximum refreezing rate per degree below 'TmeltFreeze'	parameters_site.f90	parameters_default.txt
TmeltFreeze	°C	Temperature above which snow melts	parameters_site.f90	parameters_default.txt
TrainSnow	°C	Temperature below which precipitation is snow	parameters_site.f90	parameters_default.txt
WpoolMax	mm	Maximum pool water (liquid plus ice)	parameters_site.f90	parameters_default.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_default.txt
FO2MX	mol O2 mol-1 gas	Maximum oxygen fraction of soil gas	parameters_site.f90	parameters_default.txt
gamma	m-1	Temperature extinction coefficient of snow	parameters_site.f90	parameters_default.txt
KRTOTAER	-	Ratio of total to aerobic respiration	parameters_site.f90	parameters_default.txt
LAMBDAsoil	J m-1 degC-1 d-1		parameters_site.f90	parameters_default.txt
WCFC	m3 m-3	Water concentration at field capacity	parameters_site.f90	parameters_default.txt
WCST	m3 m-3	Water concentration at saturation	parameters_site.f90	parameters_default.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_default.txt
ROOTDM	m	Initial and maximum value rooting depth	parameters_plant.f90	parameters_default.txt
RRDMAX	m d-1	Maximum root depth growth rate	parameters_plant.f90	parameters_default.txt
TRANCO	mm d-1	Transpiration coefficient	parameters_plant.f90	parameters_default.txt
WCAD	m3 m-3	Water concentration at air dryness	parameters_site.f90	parameters_default.txt
WCFC	m3 m-3	Water concentration at field capacity	parameters_site.f90	parameters_default.txt
WCST	m3 m-3	Water concentration at full saturation	parameters_site.f90	parameters_default.txt
WCWET	m3 m-3	Water concentration above which transpiration is reduced	parameters_site.f90	parameters_default.txt
WCWP	m3 m-3	Water concentration at wilting point	parameters_site.f90	parameters_default.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_default.txt
COCRESMX	-	Maximum concentration of reserves in aboveground biomass (not stubble)	parameters_plant.f90	parameters_default.txt
CSTAVM	gC tiller-1	Maximum size of elongating tillers	parameters_plant.f90	parameters_default.txt
DAYLB	d d-1	Day length below which phenological stage is reset to zero	parameters_plant.f90	parameters_default.txt
DAYLP	d d-1	Day length below which phenological development slows down	parameters_plant.f90	parameters_default.txt
DLMXGE	d d-1	Day length below which DAYLGE becomes less than 1	parameters_plant.f90	parameters_default.txt
Dparam	°C-1 d-1	Constant in the calculation of dehardening rate	parameters_plant.f90	parameters_default.txt
FO2MX	mol O2 mol-1 gas	Maximum oxygen fraction of soil gas	parameters_site.f90	parameters_default.txt
FSLAMIN	-	Minimum SLA of new leaves as a fraction of maximum possible SLA	parameters_plant.f90	parameters_default.txt
FSMAX	-	Maximum ratio of tiller and	parameters_plant.f90	parameters_default.txt

Parameter	Unit	Meaning	Declared where	Quantified where
		leaf appearance based on sward geometry		
HAGERE	-	Fraction of reserves in elongating tillers that is harvested	parameters_plant.f90	parameters_default.txt
Hparam	°C-1 d-1	Hardening parameter	parameters_plant.f90	parameters_default.txt
K	m2 m-2 leaf	PAR extinction coefficient	parameters_plant.f90	parameters_default.txt
KLUETILG	-	LUE-increase with increasing fraction elongating tillers	parameters_plant.f90	parameters_default.txt
KRDRANAER	d-1	Maximum relative death rate due to anearobic conditions	parameters_plant.f90	parameters_default.txt
KRESPHARD	gC gC-1 °C-1	Carbohydrate requirement of hardening	parameters_plant.f90	parameters_default.txt
KRSR3H	°C-1	Constant in the logistic curve for frost survival	parameters_plant.f90	parameters_default.txt
LAICR	m2 leaf m-2	LAI above which shading induces leaf senescence	parameters_plant.f90	parameters_default.txt
LAIEFT	m2 m-2 leaf	Decrease in tillering with leaf area index	parameters_plant.f90	parameters_default.txt
LAITIL	-	Maximum ratio of tiller and leaf appearance at low leaf area index	parameters_plant.f90	parameters_default.txt
LDT50A	d	Intercept of linear dependence of LD50 on lT50	parameters_plant.f90	parameters_default.txt
LDT50B	d °C-1	Slope of linear dependence of LD50 on LT50	parameters_plant.f90	parameters_default.txt
LFWIDG	m	Leaf width on elongating tillers	parameters_plant.f90	parameters_default.txt
LFWIDV	m	Leaf width on non-elongating tillers	parameters_plant.f90	parameters_default.txt
LT50MN	°C	Minimum LT50	parameters_plant.f90	parameters_default.txt
LT50MX	°C	Maximum LT50	parameters_plant.f90	parameters_default.txt
NELLVM	tiller-1	Number of elongating leaves per non-elongating tiller	parameters_plant.f90	parameters_default.txt
PHENCR	-	Phenological stage above which elongation and appearance of leaves on	parameters_plant.f90	parameters_default.txt
		elongating tillers decreases		
PHY	°C d	Phyllochron	parameters_plant.f90	parameters_default.txt

Parameter	Unit	Meaning	Declared where	Quantified where
RATEDMX	°C d-1	Maximum dehardening rate	parameters_plant.f90	parameters_default.txt
RDRSCO	d-1	Relative death rate of leaves and non-elongating tillers due to	parameters_plant.f90	parameters_default.txt
		shading when LAI is twice the threshold (LAICR)		
RDRSMX	d-1	Maximum relative death rate of leaves and non-elongating tillers due	parameters_plant.f90	parameters_default.txt
		to shading		
RDRTEM	d-1 °C-1	Proportionality of leaf senescence with temperature	parameters_plant.f90	parameters_default.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_default.txt
RGENMX	d-1	Maximum relative rate of tillers becoming elongating tillers	parameters_plant.f90	parameters_default.txt
RUBISC	g m-2 leaf	Rubisco content of upper leaves	parameters_plant.f90	parameters_default.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_default.txt
SIMAX1T	gC tiller-1 d-1	Sink strength of small elongating tillers	parameters_plant.f90	parameters_default.txt
SLAMAX	m2 leaf gC-1	Maximum SLA of new leaves	parameters_plant.f90	parameters_default.txt
SLAMIN	m2 leaf gC-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_default.txt
		Minimum soil surface temperature for leaf appearance		
TCRES	d	Time constant of mobilisation of reserves	parameters_plant.f90	parameters_default.txt
THARDMX	°C	Maximum surface temperature at which hardening is possible	parameters_plant.f90	parameters_default.txt

Parameter	Unit	Meaning	Declared where	Quantified where
TsurfDiff	°C	Constant in the calculation of dehardening rate	parameters_plant.f90	parameters_default.txt
YG	gC gC-1	Growth yield per unit expended carbohydrate	parameters_plant.f90	parameters_default.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
	0.40	gC gDM-1	C-content reserves	-	BASGRA.f90
	0.45	gC gDM-1	C-content leaves, stems, stubble	-	BASGRA.f90
	0.5	d	Constant in calculation decimal year	-	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.	gC m-2	Initial value of cumulative dead leaves	parameters_plant.f90	parameters_plant.f90
CLVHI	0.	gC m-2	Initial value of harvested leaves	parameters_plant.f90	parameters_plant.f90
CSTUBI	0.	gC 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	BASGRA.f90	initialise_BASGRA_[site].R

Constant	Value	Unit	Meaning	Declared where	Quantified where
			simulation period		
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

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

Constant	Value	Unit	Meaning	Declared where	Quantified where
	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

Constant	Value	Unit	Meaning	Declared where	Quantified where
	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*Latent Heat))		
Freq	2.*pi/365.	rad d-	Unit conversion time to annual	parameters_site.	parameters_site.

Constant	Value	Unit	Meaning	Declared where	Quantified where
		1	cycle	f90	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
	1.	mol O2 mol-1 C	Oxygen use in respiration	-	soil.f90
	1000	mm m-1	Length unit conversion	-	soil.f90
	12	gC mol-1	Molar mass of carbon	-	soil.f90
	22.4	l mol-1	Molar volume of gas	-	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

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
	0.5	-	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

Constant	Value	Unit	Meaning	Declared where	Quantified where
	0.5	d-1	Maximum relative death rate due to frost	-	plant.f90
	0.7	-	Ratio of chloroplast to atmospheric CO2 concentration	-	plant.f90
	1.	d d-1	Rate of increase of TANAER when soil permeability to gas is zero	-	plant.f90
	1000.	mm m-1	Length unit conversion	-	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
	1.E6	mumol mol-1	Quantity unit conversion	-	plant.f90
	2.1	mol PAR mol-1 CO2	Photon requirement of photosynthesis	-	plant.f90
	24.		Constant in the equation for phenological development	-	plant.f90
	0.52	mm d-1 °C-1	Constant in equation for leaf elongation on non-elongating tillers	-	plant.f90
	0.76	mm d-1	Constant in equation for leaf elongation on non-elongating tillers	-	plant.f90
	2.80	mm d-1 °C-1	Constant in equation for leaf elongation on elongating tillers	-	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

Constant	Value	Unit	Meaning	Declared where	Quantified where
	365.	d	Constant in calculation period of possible rehardening	-	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
	550000	g mol-1	Molar mass of Rubisco	-	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

Constant	Value	Unit	Meaning	Declared where	Quantified where
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 degC	plant.f90	plant.f90
KMC25	460	ppm CO2	Km-value Rubisco for carboxylation at 25 degC	plant.f90	plant.f90
KMO25	33	% O2	Km-value Rubisco for oxygenation at 25 degC	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