User's Guide for Biome-BGCMuSo 5.0

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[5 June, 2018]

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1. Introduction

Biome-BGC is a widely used, popular biogeochemical model that simulates the storage and flux of water, carbon, and nitrogen between the ecosystem and the atmosphere, and within the components of the terrestrial ecosystems (Thornton, 2000). Biome-BGC was developed by the Numerical Terradynamic Simulation Group (NTSG), University of Montana (http://www.ntsg.umt.edu/project/biome-bgc). The currently available, official model version (published by NTSG) is 4.2.

Several researchers used and modified the original Biome-BGC model in the past. During the past years our research group developed an updated version of Biome-BGC (called Biome-BGCMuSo – where the abbreviation refers to **Mu**ltilayer **So**il Module – or briefly BBGCMuSo) to improve the ability of the model to simulate carbon and water cycle in managed ecosystems, with options for managed croplands, grasslands and forests. The modifications included structural improvements of the model (e.g., the simple, outdated, one-layer soil module was replaced by a multilayer soil module; drought related plant senescence was implemented; model phenology was improved) and also management modules were developed (e.g. to simulate mowing, grazing, fertilization, ploughing, sowing, harvesting, forest thinning and clearcut). Beyond these modifications, additional modules were developed to simulate cropland management (e.g., planting, harvest, ploughing, application of fertilizers). Forest thinning was also implemented as a possible human intervention, and dynamic (annually varying) whole plant mortality was implemented in the model to enable more realistic simulation of forest stand development. Annually varying management options were also introduced. In BBGCMuSo v4 model version separate pools have been defined for fruit following the method of Ma et al. (2011) to support cropland related simulations. The modifications were published detail in Hidy et al. (2012) and Hidy et al. (2016).

Since the publication of the Hidy et al. (2016) a large number of additional developments were implemented. Alternative photosynthesis and radiation calculation methods were implemented in order to support possible algorithm ensemble modeling within the framework of the model. Optional dynamic allocation algorithm was introduced using predefined phenological phases based on growing degree day method. We also implemented optional temperature dependence of allocation and possible assimilation downregulation as function of temperature. To simulate the functioning of croplands in a more realistic way, germination, photoperiodic effect, genetically programmed leaf senescence and vernalization processes were introduced. We also improved the plant senescence calculation and nitrogen budget simulation of the model. Soil organic matter profile was introduced. Last (but not least) the maintenance respiration calculation was modified correcting one problematic issue related to the non-sturcutral carbohydrate calculation method of the model. Detailed description of the modifications will be presented in a forthcoming technical document (Theoretical basis of Biome-BGCMuSo v5; in prep.).

This User's Guide was created to provide practical information for the use of the improved model. The Hidy et al. (2016) study documented the previous major model version (Biome-BGCMuSo 4.0; note that BBGCMuSo has many version: MuSo v1.0, v1.1 v1.2, v1.3, v2.0, v2.1, v2.2, v2.3, v3.0, v4.0, v5.0), but hereinafter only 5.0 is referred.

Note that NTSG continues to develop the original model with the inclusion of management using a new disturbance handler module. In their implementation disturbance (or management) is described by a separate disturbance descriptor file. Our implementation of disturbance is different from the NTSG approach, as we included management settings in the

INI file of the model (note that in BBGCMuSo there is an option to use additional management rules provided in separate text files; see below).

2. Model description

Prior to using the model, the User might want to get information on the basic model logic. This section provides a brief overview on the model logic, and on the simulation phases that are essential for the preparation of the necessary input data.

2.1 Overview, general model logic

BBGCMuSo was developed from the Biome-BGC family of models (Thornton, 2000) and in this sense it is an extension and generalization of the Forest-BGC model for the description of different vegetation types including C3 and C4 grasslands (Running and Coughlan, 1988; Running and Gower, 1991; Running and Hunt, 1993; Thornton, 1998, 2000; White et al., 2000; Thornton and Rosenbloom, 2005; Trusilova et al., 2009).

The model uses daily time step, and is driven by daily values of maximum and minimum air temperatures, precipitation amount, solar radiation, and vapor pressure deficit. If the user only has basic meteorological data (daily maximum and minimum air temperature, and precipitation amount), the other input meteorological data can be easily estimated by the MT-CLIM model that can be considered as a preprocessor to Biome-BGC and BBGCMuSo (http://www.ntsg.umt.edu/project/mtclim).

BBGCMuSo uses meteorological data, site-specific data, ecophysiological data, carbon-dioxide concentration (CO_2) and N-deposition (N-dep) data to simulate the biogeochemical processes of the given biome. The main simulated processes assessed are photosynthesis, allocation, litterfall, carbon (C), nitrogen (N) and water dynamics in the plant, litter and soil.

The most important blocks of the model are the carbon flux block, the phenological block and the soil flux block. In the carbon flux block gross primary production (GPP) of the biome is calculated using Farquhar's photosynthesis routine (Farquhar et al., 1980). Autotrophic respiration is separated into maintenance and growth respirations. Maintenance respiration is the function of the nitrogen content of living material, while growth respiration is calculated proportionally to the carbon allocated to the different plant compartments. The phenological block calculates foliage development; therefore it affects the accumulation of carbon and nitrogen in leaf, stem, root and litter. The soil block describes the decomposition of dead plant material and soil carbon pools (Running and Gower, 1991).

In BBGCMuSo the main parts of the ecosystem are defined as plant, soil and litter. Since the model simulates water, carbon and nitrogen cycles of ecosystems, the following main pools are defined (some of them are not present in specific ecosystems): leaf (carbon, nitrogen and water), fine root (carbon, nitrogen), fruit (carbon, nitrogen), soft stem (carbon, nitrogen), live wood (carbon, nitrogen), dead wood (carbon, nitrogen), coarse root (carbon, nitrogen), soil (carbon, nitrogen and water) and litter (carbon, nitrogen). Carbon and nitrogen pools have sub-pools, i.e. actual pools, storage pools and transfer pools. Actual sub-pools contain the amount of carbon or nitrogen available on the actual simulation day. Storage sub-pools store the amount that will appear next year (like a core or bud, or nonstructural carbohydrate), while the transfer sub-pools store the whole content of the storage pool after the end of the actual transfer period (defined by model parameters) until the next one, and that will be transferred gradually into the leaf carbon pool (like a germ) in the next transfer period, in the beginning of the growing season.

One major difference between the earlier versions of Biome-BGC and BBGCMuSo is the representation of soil processes. In BBGCMuSo v5 a ten-layer soil submodel was implemented. The thicknesses of the active layers (layers 1-10) from the surface to the bottom are 2, 5, 10, 20, 50, 100, 150, 200, 400 and 1000 cm (Table 1).

Table 1. Soil layers and their depth ranges used in BBGCMuSo v5

Layer 1	0-2 cm
Layer 2	2-5 cm
Layer 3	5-10 cm
Layer 4	10-20 cm
Layer 5	20-50 cm
Layer 6	50-100 cm
Layer 7	100-150 cm
Layer 8	150-200 cm
Layer 9	200-400 cm
Layer 10	400-1000 cm

The depth of each soil layer is represented by the middle level of the given layer (e.g. the thicknesses of the top soil layer is 0.02 m, therefore it is represented at 0.01 m). Soil texture can be defined by the percentage of sand and silt for each layer separately. Clay content is calculated by the model internally so as the sum of the fractions will be 100%.

From a rooting depth parameter (defined by the User in the ecophysiological parameters file; see below) BBGCMuSo calculates the number of the rooting layers (where root can be found). The percolated water (and soluble carbon and nitrogen) from the last rooting soil layer is a net loss, while the upward diffused water (and soluble carbon and nitrogen) from the bottom layer to the active layers is a net gain for the soil system.

2.2 Simulation phases including the novel transient run option and the implemented support for land use change related simulations

The model simulation has basically two phases. The first is the spinup simulation (in other words self-initialization, or equilibrium run), which starts with very low initial level of soil carbon and nitrogen, and runs until a steady state is reached with the climate in order to estimate the initial values of the state variables (mostly soil carbon and nitrogen pools including recalcitrant soil organic matter, the latter is being the primary source of nitrogen mineralization in the model; Thornton, 2000). The second phase, the normal simulation uses the results of the spinup simulation as initial values for the carbon and nitrogen pools. This simulation is performed for a given, predetermined time period.

The usual strategy for CO_2 and N-deposition control is to use constant (preindustrial) values during the spinup phase, then use annually varying CO_2 and N-deposition for the entire normal simulation (representative to present day conditions). However, this logic can lead to undesired transient behavior during the first few simulation years of the normal run as the user may introduce a sharp change for the CO_2 and/or N-dep data (both are important drivers of plant growth).

In order to avoid this undesired sharp change in the environmental conditions between spinup and normal phase, a third simulation phase, a so-called transient simulation was implemented in BBGCMuSo. According to the modifications, now it is possible to make an automatic transient simulation after the spinup phase simply using the spinup INI file settings (and some ancillary files; see later). In other words, now it is possible to initiate 3 consecutive simulations instead of the usual two phases (triggered by the spinup and normal INI file).

As management might play an important role in site history and consequently in the biogeochemical cycles, in BBGCMuSo the new transient simulation can include management, in an annually varying fashion. The settings of management optionally defined within the initialization file of the spinup are only used during the transient run, but not during the regular spinup phase.

Another new feature was added to BBGCMuSo v.5.0 that is also related with the proper simulation of site history. As the spinup phase is usually associated with preindustrial conditions, the normal phase might represent a plant functional type that is different from the one present in the spinup phase. For example, present-day croplands occupy land that was originally forest or grassland, so in this case spinup will simulate forest in equilibrium, and the normal phase will simulate croplands. Another example is the simulation of afforestation that might require spinup for grasslands, and normal phase for woody vegetation. We may refer to these scenarios as land use change (LUC) related simulations. One problem that is associated with LUC is the frequent crash of the model with the error 'negative nitrogen pool' during the beginning of the normal phase. This error is typical if the spinup and normal EPC files differ in terms of plant C:N ratios. The explanation of the error is not simple (and elimination of the error is indeed a hard task) due to the model logic: in BBGC changes within the defined pools due to e.g. allocation, litterfall, litter and soil organic matter decomposition etc. are calculated at the end of each simulation day. Due to this day-end calculations inconsistency might arise between available mineralized N and N demand by the plant, and this might cause negative nitrogen pool.

In order to avoid this error, we have implemented an automatism that solves this problem. According to the changes only the equilibrium carbon pools are passed to the normal phase from the endpoint (restart) file. The endpoint nitrogen pools are calculated by the model code so that the resulting carbon to nitrogen ratios are harmonized with the C:N ratio of the different plant compartments presented in the EPC file of the normal phase. This modification means that equilibrium nitrogen pools are not passed to the normal phase at all, but in our interpretation this issue is compensated with the fact that LUC and site history can be simulated properly.

3. Input files

3.1 Overview

BBGCMuSo uses at least three input files each time it is executed. A brief description of all files is given first, followed by detailed discussions of each file.

The first required input file is called the *initialization* file (INI file in BBGC terminology). It provides general information about the simulation, including a description of the physical and climatic characteristics of the simulation site, a description of the time-frame for the simulation, the names of all the other required input files including optional management files, the names for output files that will be generated, and lists of variables to store in the output files.

The second required input file is the *meteorological data* file. It contains daily values for air temperature, precipitation, humidity (in terms of daylight vapor pressure deficit), radiation, and daylength at the simulation site. It can contain any number of years of data. Important note: BBGCMuSo code assumes that all years have 365 days, so meteorological data files should be edited to remove one day from leap years (we propose to drop 31 December in the Northern hemisphere). A new feature in BBGCMuSo v.5.0 is the possibility to use data from a truncated (incomplete) year as input data for the last simulation year. This means that if the User would like to use the model in the current, ongoing year as the last simulation year, meteorological data can contain data for less than 365 days. In this case the model estimates the missing meteorological data as the average of the daily data from the previous years.

The third required input file is the *ecophysiological constants* file (EPC file). It contains an ecophysiological description of the vegetation at a site, including parameters such as leaf C:N ratio, maximum stomatal conductance, fire and non-fire mortality frequencies, and allocation ratios.

There are also seven optional input files: *carbon-dioxide* file, *nitrogen deposition* file, *mortality* file, *conductance* file, *groundwater* file, *onday* and *offday* file (see below).

The last input file is the special *restart* file, which is the output of spinup and input for normal simulation. Detailed description of the files can be found below.

A NOTE ON THE CHARACTERS STORED IN THE INPUT FILES

For compatibility reasons please do not use non-ASCII characters in your input files! Furthermore, we strongly recommend using either "\" or either "/" consistently for path definition. MS Windows can accept both types, but any other UNIX/UNIX-like systems such as macOS, Free-BSD or GNU/Linux uses only "/". For that reason, if it is not inconvenient for the Windows Users, we recommend to use only "/" for paths. With this little caution your input files will be portable.

3.2 Initialization file (INI file)

Below we introduce the structure of the INI file of the model which was substantially extended in comparison with the Biome-BGC v4.1.1. MPI version. The initialization file is broken into sections with a keyword starting each new section and a special keyword at the end of the file. Keywords must be present and should not be removed in any case!

Additionally, please be very careful not to use empty lines inside the sections. This organization helps to ensure that the proper format for the initialization file is maintained while editing for new simulations. The order of the sections and the order of the lines within each section is critical, and changes in order will result in failed or flawed executions. It is highly recommended that the example INI files be copied to a safe directory for future reference on proper formatting. There is a fair amount of error checking on the INI file format, but it is still possible to scramble the order of lines in a way that the program does not detect. In this case the model will run, but the results will be garbage. Copying the template is the easiest way to make a new INI file with assurance of the correct format, but remember to replace ALL of the parameters with those for the new site. It is not necessary to have blank lines between the end of one section and the keyword for the next section, but keeping them in makes the INI file more readable.

Each line can contain up to 100 characters of comment information, after a keyword or after an input parameter (or after more than one input parameter; see below e.g. the soil texture definition in the SITE block). This information is for your reference in keeping the correct format in the INI file, and is ignored by the program. Every line is required, even if flags are set that mean the information on a line will be ignored. The first line of the file is for header information that helps you keep track of which INI file is for which simulation when you are doing a sequence of simulations. This line can contain up to 100 characters of information. There is no keyword for this header line.

Below we provide examples for the specific sections using `Courier New Font`. A complete example INI file is given in Appendix A.

A NOTE ON INI FILE NAME SELECTION

The name of the INI files is not fixed. However, we propose to use the following filename convention. Name your spinup INI file as something_s.ini, and the normal INI file as something_n.ini where something is arbitrary (note the _s and _n convention). This convention can be useful if you plan to use the so-called RBBGCMuSo R tool developed by our team. The work with RBBGCMuSo is much easier if you follow this convention as it helps the tool to automatically identify the spinup or the normal INI files.

Section MET_INPUT

The first section begins with the keyword MET_INPUT. It has the following three lines:

1) name (including relative path if appropriate [relative path to the model executable file]) of input meteorological data file

2) number of header lines in meteorological data file

3) number of simulation days in the last simulation year (if less than 365, the last simulation year is truncated, and the missing meteorological data are estimated internally by the model)

```
MET_INPUT (keyword - do not remove)
metdata/bugac_2009-2011.mtc43  (filename) met file name
4           (int) number of header lines in met file
365         (int) number of simdays in last simyear (truncated year: < 365)
```

Section RESTART

The next section begins with the keyword RESTART. It has the following five lines:

1) flag (1 or 0) for reading (1) or not reading (0) a restart file from the end of a previous simulation

2) flag (1 or 0) for writing (1) or not writing (0) a restart file at the end of this simulation

3) flag (1 or 0) for met year from restart file (1) or met year reset to beginning of record (0). Met year means the current year from the meteorology input file. We suggest to set this flag to 0.
4) input restart filename (including path if appropriate)
5) output restart filename (including path if appropriate)
Lines 3) and 4) are only relevant when flag in line 1) is set to 1. Line 5) is only relevant when flag in line 2) is set to 1. In most cases the flag in line 3) should be set to 0.

```
RESTART (keyword - do not remove)
1             (flag) 1: read restart 0: don't read restart
0             (flag) 1: write restart 0: don't write restart
0             (flag) 1: use restart metyear 0: reset metyear
restart/bugacI.endpoint     (filename) name of the input restart file
restart/bugacO.endpoint     (filename) name of the output restart file
```

Section TIME_DEFINE
The next section begins with the keyword TIME_DEFINE. It has the following five lines:
1) number of years of data in meteorological input data file
2) number of years to run for this simulation.
3) first simulation year (e.g. 1998)
4) flag (1 or 0) for spinup simulation (1) or normal simulation (0)
5) maximum number of years to run in spinup mode
If line 2) is greater than line 1), then the meteorological data file is "recycled" enough times to satisfy the requested number of simulation years. Line 3) defines the starting point for the simulation output, and is mainly used in the simple text output file (described below). Line 4) sets the simulation mode for either a spinup run or a normal run.
If spinup mode is selected, the meteorological data file will be recycled enough times to establish steady-state conditions in the soil carbon and nitrogen pools. The number of years of simulation for a spinup run will depend on the climate and vegetation characteristics, but will not exceed the number of years specified on line 5). Line 2) has no effect for a spinup run. If a spinup run reaches the maximum number of years specified in line 5), it is likely that the resulting final soil carbon and nitrogen pools are not equilibrated with the climate, usually indicating a long-term net sink of carbon. This is observed, for example, in some boreal climates, where the model predicts long-term accumulation of organic matter (peat formation).

```
TIME_DEFINE (keyword - do not remove)
3                (int) number of meteorological data years
3                (int) number of simulation years
2009             (int) first simulation year
0                (flag) 1: spinup run 0: normal run
6000             (int) maximum number of spinup years
```

Section CLIM_CHANGE
The next section begins with the keyword CLIM_CHANGE. It has the following five lines:
1) temperature offset for maximum air temperature
2) temperature offset for minimum air temperature
3) scaling factor for precipitation
4) scaling factor for vapor pressure deficit
5) scaling factor for incoming shortwave radiation
This section is included to facilitate simulation of simple climate change effects on ecosystem processes. The default values are shown in the example below (also see Appendix A), which result in no changes to the input meteorological data. Increases or decreases in temperature (Tmax and/or Tmin) can be introduced with lines 1) and 2). The values indicated are simply added to the daily values from the meteorological data file. For precipitation, VPD, and

radiation, the daily values from the input file are multiplied by the values on lines 3), 4), and 5) to get new daily values. This mechanism does not allow for the simulation of seasonal differences in climate change.

```
CLIM_CHANGE (keyword - do not remove)
0.0              (degC) offset for Tmax
0.0              (degC) offset for Tmin
1.0              (degC) multiplier for PRCP
1.0              (degC) multiplier for VPD
1.0              (degC) multiplier for RAD
```

Section CO2_CONTROL

The next section begins with the keyword CO2_CONTROL. It has the following 3 lines:

1) flag (0,1) controlling CO_2 concentration: 0=constant, 1=varying using values from an external file
2) the value to use for constant CO_2 concentration (ppm)
3) the filename for annual CO_2 levels (see notes below for format information)

When line 1) is set to 0, then the value on line 2) sets the constant CO_2 level for the entire simulation. When line 1) is set to 1, then the file named on line 3) is used to define the annual timeseries of CO_2 concentration.

```
CO2_CONTROL (keyword - do not remove)
1                   (flag) 0=constant 1=vary with file
290.0               (ppm) constant atmospheric CO2 concentration
co2/CO2_2009-2011.txt           (filename) name of the CO2 file
```

This external text file must have one line for each simulation year (the number given on line 2 of the TIME_DEFINE section), and the format of each line should be like this:

```
1895  294.8
```

where the first value on the line is the year, and the second value is the CO_2 mole fraction (ppm). It is important to note that although the text files contain the year of the actual data, the model neglects the date and uses data from the text files sequentially (first line for the first simulation year, second line for the second etc.).

Section NDEP_CONTROL

The next section begins with the keyword NDEP_CONTROL. It has the following 3 lines:

1) flag (1 or 0) for variable nitrogen deposition (1) or constant nitrogen depostition (0)
2) the value to use for constant atmospheric N deposition (kgN m^{-2} yr^{-1})
3) the filename for annual N-deposition levels (see notes below for format information)

When line 1) is set to 0, then the value set on line 2) is used as constant N-deposition for the entire simulation. When line 1) is set to 1, then the file named on line 3) is used to define the annual timeseries of N-deposition.

```
NDEP_CONTROL (keyword - do not remove)
1                             (flag) 0=constant 1=vary with file
0.001100                      (kgN/m2/yr) wet+dry atmospheric Ndep
nitrogen/Ndep_1901-2000.txt   (filename) name of the N-dep file
```

Similarly to the CO_2 external file, this file also must have one line for each simulation year (the number given on line 2 of the TIME_DEFINE section), and the format of each line should be like this:

```
1895  294.8
```

where the first value is the year, and the second value is the N-deposition (kgN m^{-2} yr^{-1}). It is important to note that although the text files contain the year of the actual data, the model neglects the date and uses data from the text files sequentially (first line for the first simulation year, second line for the second etc.).

A NOTE ON THE CO2_CONTROL AND NDEP_CONTROL SECTIONS

An important feature of the BBGCMuSo model is the possibility to control annually varying CO_2 concentration and N deposition independently, driven by separate text files (this feature was introduced in Biome-BGC v4.1.1 MPI version; Trusilova et al., 2009).

A new feature of BBGCMuSo 5.0 is the possibility to trigger a so-called transient simulation as an extension of the spinup phase (controlled solely by the spinup INI file). This feature was introduced to enable smooth transition from constant CO_2 and N deposition used in the spinup phase (representing preindustrial conditions, up to ~1850) to the higher CO_2 and N deposition values representative to present day (or past ~10-100 years) conditions.

If the User wants to initiate the transient run, he/she can set it in the spinup INI file by simply setting the CO2_CONTROL and/or NDEP_CONTROL flag to 1. It means that first a regular spinup will be performed with constant CO_2 and/or N deposition values set in the INI file, then a second run will be performed using the same meteorological data file defined by the spinup INI file.
The input for the transient run is the endpoint of the regular spinup, and the output of the transient simulation is the input for the normal phase with the same name.
As an example, spinup INI file might contain the following lines:

```
CO2_CONTROL (keyword - do not remove)
1                                (flag) 0=constant; 1=vary with file
280                              (ppm) constant atmospheric CO2 concentration
co2/CO2_1901-2000.txt            (filename) name of the CO2 file

NDEP_CONTROL (keyword - do not remove)
1                                (flag) 0=constant; 1=vary with file
0.001100                         (kgN/m2/yr) wet+dry atmospheric N-dep
nitrogen/Ndep_1901-2000.txt      (filename) name of the N-dep file
```

With these settings first a spinup simulation will be performed re-using the meteorological data (in this example spinup meteorology covers the time period of 1901-2000; not shown here), keeping both CO_2 (280 ppm) and N deposition constant (0.0011 kgN/m^2/yr). Then, as the flags are set to 1, transient simulation will be performed, using the 100-years-long meteorology, and the `CO2_1901-2000.txt` CO_2 data file, and the 100-years long `Ndep_1901-2000.txt` files. Note that the user has to make sure to construct the proper CO_2 and/or N deposition files used for the transient run.
If the CO2_CONTROL and NDEP_CONTROL flags are set to 0, no transient simulation will be performed. CO2_CONTROL can be also set to 1 while NDEP_CONTROL flag is 0 (and vica versa). If this happens, then only CO_2 (or only N deposition) will vary during the transient run.

Section SITE
The next section begins with the keyword SITE. It has the following lines:
1) soil texture: percent sand (by volume in rock-free soil) for the 10 soil layers separately
2) soil texture: percent silt (by volume in rock-free soil) for the 10 soil layers separately
3) soil pH for the 10 soil layers separately
4) site elevation in meters above mean sea level
5) site latitude in decimal degrees (negative values for southern hemisphere)
6) site shortwave albedo for bare soil (albedo is LAI-dependent in BBGCMuSo)

7) mean annual air temperature (Celsius) (representative long term mean)
8) mean annual air temperature range (Celsius) based on monthly mean temperatures
9) maximum height of pond water in mm
8) * user-defined SCS runoff curve number (no data: -9999)
9) * user-defined bulk density of the 10 soil layers (no data: -9999)
10) * user-defined soil water content at saturation of the 10 soil layers (no data: -9999)
11) * user-defined soil water content at field capacity of the 10 soil layers (no data: -9999)
12) * user-defined soil water content at wilting point of the 10 soil layers (no data: -9999)
13) * user-defined hygroscopic soil water content of the 10 soil layers (no data: -9999)

Note that if no data are available regarding to variables marked with asterisks (*), they should be set to -9999, so the model will estimate them based on empirical functions. It is important to note that *all or none* of the user-defined critical SWC and bulk density data should be set by the user in order to avoid discrepancy in soil data (runoff curve number data is independent from the rest).

```
SITE (keyword - do not remove)
78.5 78.5 78.5 84.7 92.7 92.7 92.7 92.7 92.7 92.7 (%) sand percentage by volume for the layers
 8.6  8.6  8.6  6.0  2.9  2.9  2.9  2.9  2.9  2.9 (%) silt percentage by volume for the layers
 7.0  7.0  7.0  7.0  7.0  7.0  7.0  7.0  7.0  7.0 (dimless) soil pH per layer
111.4                                             (m) site elevation
46.69                                             (degrees) site latitude(- for Southern Hem.)
0.20                                              (DIM) site shortwave albedo
11.00                                             (Celsius) mean annual air temperature
13.42                                             (Celsius) mean annual air temperature range
20.00                                             (mm) maximum height of pond water
-9999                                             (dimless) runoff curve number
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (g/cm3) bulk density of layers
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at SAT per layer
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at FC per layer
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at WP per layer
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at HW per layer
```

Section EPC_FILE

The next section begins with the keyword EPC_FILE. It has a single line:
1) the name of the input ecophysiological constants file

```
EPC_FILE (keyword - do not remove)
epc/c3grass.epc                  (file) c3grass
```

Details on the format and interpretation of these files are given in a later section.

Section W_STATE

The next section begins with the keyword W_STATE. It has the following two lines:
1) initial snowpack water content (start of simulation)
2) initial soil water content as a proportion of field capacity (note that in earlier model version it was proportion of saturation)

```
W_STATE (keyword – do not remove) start of water state variable initialization block
0.0            (kg/m2) water stored in snowpack
1.0            (DIM) initial soil water as a proportion of field capacity
```

When using a restart file (which is the result of the spinup/transient phase) these values are ignored. Otherwise, they set the initial conditions for the water state variables (storage components) on the first day of simulation. Line 1) sets the snowpack, and is in water equivalent units, where kg water/m^2 is equivalent to mm of water. The second line controls the initial soil water content. This is set as a proportion of field capacity so that the user is not required to know the field capacity water content of the site (depends on texture and depth). For a spinup run, these values are used as the initial conditions.

Section CN_STATE

The next section begins with the keyword CN_STATE. It has the following lines:

1) peak leaf carbon to be attained during the first simulation year
2) peak fine root carbon to be attained during the first year
3) peak fruit carbon to be attained during the first year
4) peak softstem carbon to be attained during the first year
5) peak live woody stem carbon to be attained during the first year
6) peak live coarse root carbon to be attained during the first year
7) initial coarse woody debris carbon (dead trees, standing or fallen), defined separately for all 10 soil layers
8) initial litter carbon, labile pool for the 10 soil layers
9) initial litter carbon, unshielded cellulose pool for the 10 soil layers
10) initial litter carbon, shielded cellulose pool for the 10 soil layers
11) initial litter carbon, lignin pool for the 10 soil layers
12) soil carbon, fast pool for the 10 soil layers
13) soil carbon, medium pool for the 10 soil layers
14) soil carbon, slow pool for the 10 soil layers
15) soil carbon, slowest pool for the 10 soil layers
16) initial litter nitrogen, labile pool for the 10 soil layers
17) initial soil mineralized nitrogen, ammonium pool for the 10 soil layers
18) initial soil mineralized nitrogen, nitrate pool for the 10 soil layers

```
CN_STATE (keyword - do not remove) start of carbon state variable initialization block
0.001             (kgC/m2) first-year maximum leaf carbon
0.001             (kgC/m2) first-year maximum fine root carbon
0.001             (kgC/m2) first-year maximum fruit carbon
0.001             (kgC/m2) first-year maximum softstem carbon
0.001             (kgC/m2) first-year maximum live woody stem carbon
0.001             (kgC/m2) first-year maximum live coarse root carbon
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) coarse woody debris carbon
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (labile)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (unshield.cellulose)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (shielded cellulose)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (lignin)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (fast microb.recycl.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (medium microb.recyc.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (slow microb.recycl.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (recalcitrant SOM)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) litter nitrogen, labile pool
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) soil mineralized N pool (ammonium)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) soil mineralized N pool (nitrate)
```

Like in the W_STATE section, these values are ignored when using an input restart file, since all the initial conditions are defined by the endpoint from the previous simulation (usually a spinup run and the optional transient run). In starting a spinup run these values have to be supplied. The above example shows the best approach to these initial conditions for a spinup run: start with very low initial leaf area, and no carbon in any of the other pools. This is essentially a primary succession simulation, starting with no organic matter and a very meager colonizing plant cover. The development of soil organic matter depends on the site's climate and external fluxes of nitrogen (deposition, fixation, leaching, volatilization), as well as on the vegetation type. The end result is that soil and litter pools are in equilibrium with climate and N deposition/loss rates. If these values are assigned without performing a spinup/transient run, then the initial model dynamics are likely to represent a transient response to disequilibrium conditions between the specified initial conditions and the specified climate and N deposition/loss. This can produce very misleading signals in net ecosystem exchange of carbon that can persist for many hundreds of years. For this reason it is recommended to start the simulations with a spinup run, then a restart from the spinup conditions.

Section OUTPUT_CONTROL

The next section begins with the keyword OUTPUT_CONTROL. It has the following 6 lines:
1) text string giving the prefix for all output files, including path if appropriate
2) flag (0, 1 or 2) to not write (0), to write binary (1) or to write ASCII (i.e. text, which means that the file can easily be read directly by Excel) (2) output file with daily variables (output variables interpreted on daily scale)
3) flag (0, 1 or 2) to not write (0), to write binary (1) or to write ascii (2) output file with monthly averages of the daily variables
4) flag (0, 1 or 2) to not write (0), to write binary (1) or to write ascii (2) output file with annual averages of the daily variables
5) flag (0, 1 or 2) to not write (0), to write binary (1) or to write ascii (2) output file with annual variables (output variables interpreted on annual scale)
6) flag (1 or 0) to send (1) or not send (0) simulation progress information to the screen

```
OUTPUT_CONTROL (keyword - do not remove)
outputs/bugac_apriori_MuSo5           (filename) output prefix
1          (flag)  writing daily output (0 = no; 1 = binary; 2 = ascii)
0          (flag)  writing monthly average of daily output (0=no; 1=binary; 2=ascii)
0          (flag)  writing annual average of daily output (0=no; 1=binary; 2=ascii)
2          (flag)  writing annual output (0=no; 1=binary; 2=ascii)
1          (flag)  for on-screen progress indicator
```

The user can select two different groups of variables for output; one group that will be used for daily output and the monthly and annual averages of daily values, and a second group that is used for writing year-end (day 365) values for each simulation year. The flag for daily output on line 3) does not need to be set to 1 or 2 in order to get monthly and/or annual averages of the daily output variables. Setting any of the output flags to 1 or 2 (lines 2-5) will result in the creation of an output file, having the specified path and filename prefix (from line 1) and the following suffix depending on which type of output was requested:
daily output suffix: ".dayout"
monthly average output suffix: ".monavgout"
annual average output suffix: ".annavgout"
year-end output suffix: ".annout

Section DAILY_OUTPUT

The next section begins with the keyword DAILY_OUTPUT. The number of lines can vary depending on the number of output variables requested, as follows:
1) the number of daily output variables requested. This value can be 0.
2) the index number for the first requested daily output variable
3) the index number for the second requested daily output variable
4.) etc.

```
DAILY_OUTPUT (keyword)
5                number of daily output variables
3009             gross primary production (kgC/m2/day)
3014             total ecosystem respiration (kgC/m2/day)
171              latent heat flux/evapotranspiration (kgH2O/m2/day)
2520             leaf area index (m2/m2)
3055             total soil carbon (kgC/m2)
```

The number of lines after line 1) must equal the number of daily output variables specified on line 1). There are more than 3000 possible output variables, and the use of an index is the simplest way to allow the User access to all of them without introducing complicated parsing routines that would tend to clutter the code. The index number for each variable is listed in a separate Excel file available at http://nimbus.elte.hu/bbgc/files/MUSO5b_variables.xlsx (they are also extractable from the output_map_init.c and the bgc_struct.h source file, which can be found at the official download page at http://nimbus.elte.hu/bbgc/download.html).
This indexing system is admittedly awkward for new users, since it requires first knowing which data structure element to reference and then getting the index value for that element. On the other hand, it has the advantages of being unambiguous and providing a direct user interface to the logical organization of the data structures used in the code.
As in all INI file lines with one defined value, all text after the first value on each output specification line is ignored by the program. It is recommended that as you add or delete output variable index values, you also add a descriptive comment reminding you what variable is being requested. The variables requested in this section are available for daily output, for monthly average output, and for annual average output, specified by the flags in the OUTPUT_CONTROL section.

Section ANNUAL_OUTPUT
The next section begins with the keyword ANNUAL_OUTPUT. It has exactly the same format as just described for the DAILY_OUTPUT section.

```
ANNUAL_OUTPUT (keyword)
4              number of annual output variables
0              onday - start of the vegetation period (DOY)
1              offday - end of the vegetation period (DOY)
2765           yearly maximum of leaf area index (m2/m2)
3024           cumulative sum of net ecosystem exchange (kgC/m2)
```

The variables requested in this section are reported once each year (yearday 365, that is the last day of the year) and are stored in the *.annout file. This provides a once-in-a-year snapshot of the system state and activity, and so it is most appropriate for recording system states that are changing relatively slowly, such as soil carbon, vegetation carbon, etc. Remember that if annual averages of system behavior or system state are desired, then it is necessary to specify these variables in the DAILY_OUTPUT section, and set the annual averaging of daily output flag to 1 (line 5 in OUTPUT_CONTROL section).

Structure of the MANAGEMENT_SECTION block

The following blocks were defined to describe different management activities on the simulated ecosystem. This block was not present in previous versions of Biome-BGC. Each management type can be activated or deactivated for a given simulation independent of the other management types. Implemented management types are documented in Hidy et al. (2012) and in Hidy et al. (2016) study.
The management section starts with the following lines (this is mandatory):

```
-------------------
MANAGEMENT_SECTION
-------------------
```

Note that management settings can be optionally defined within the spinup INI file, but they are only used during the optional transient run, and not during the regular spinup phase. Note

again that in case of transient run, the endpoint file created by the regular spinup will be overwritten by the endpoint of the transient run.
The management blocks must be present even if the user deactivates them (i.e. the structure of the INI file is fixed, similarly to previous versions of Biome-BGC).
A management type can be activated if the flag in the first line of the block is set to 1, or if there is a filename present in the first line of the block that refers to external management descriptor file (see below, and also Appendix C for examples). Note that the lines which are parts of this external management descriptor file are marked with asterisks (*).
If the flag is 0 it means that the management type is deactivated.
For each management type maximum 10 events can be defined for each year. In case of less than 10 events -9999 should be used to skip some of the events.

Section PLANTING

The first management section begins with the keyword PLANTING. Mainly cropland or grassland related simulations should use this type of management, but it is also applicable in case of forestry. This section has the following 7 lines:
1) flag (0, 1, or filename) to use PLANTING (1 or filename) or do not use planting (0)
2) *day(s) of planting, expressed as day of year (0: 1 January; 364: 31 December in regular years)
3) *germination depth in meter
4) *the quantity of the seed expressed in number of seedling per m^2
5) *weight of 1000-seed in g[1]
6) *carbon content of seed (or seedling) in percent
7) *emergence rate; this is the amount of seed that is germinating; the rest is lost to litter

```
PLANTING (keyword)
0             (flag) do PLANTING? 0=no; 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(yday) PLANTING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(m) germination depth
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(n/m2) number of seedlings
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(g/1000n) weight of 1000-seed
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(%) C content of seed
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(%) emergence rate
```

Section THINNING

The next management section begins with the keyword THINNING. This management type is associated with forest related simulations. Clearcut can also be defined as it is the upper limit of fellings. This section has the following 6 lines:
1) flag (0, 1 or filename) to use THINNING (1 or filename) or not (0)
2) *day(s) of thinning
3) *rate of the thinning (proportion of removed biomass during felling) regarding to aboveground woody plant material (live woody stem and dead woody stem); e.g. 0.5 means that 50% of the woody biomass are removed via felling (note that roots are left at the site and they become part of the coarse woody debris and litter pool depending on root type)
4) *rate of the thinning (proportion of removed biomass during felling) regarding to aboveground non-woody plant material (leaf, fruit); e.g. 0.5 means that 50% of the non-woody biomass are removed via felling
5) *transported part of stem (percent); this is the percent of cut down stem that is removed from the site after intervention
6) *transported part of leaf (percent); this is the fraction of leaf on cut down trees that is removed from the site during thinning

[1] See https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex81

```
THINNING
0            (flag) do THINNING? 0=no; 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(yday) THINNING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(prop) woody thinning rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(prop) non-woody thinning rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of stem
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of leaf
```

Section MOWING

This management section begins with the keyword MOWING. Seven parameters are defined to simulate mowing:

1) flag (0, 1, or filename) to define MOWING (1 or filename) or not (0)
2) flag (0 or 1) for choosing the type of mowing simulation method (0: mowing on predefined day(s) of year; 1: mowing each time the LAI reaches a predefined threshold LAI-value)
3) predefined value of the LAI before mowing (in case of LAI threshold method, i.e. flag is 1 in line 2; note that this value should deviate from the measured value if LAI is overestimated by the model)
4) predefined value of LAI after mowing (in case of the LAI threshold method, i.e. flag is 1 in line 2; see note on LAI overestimation above)
5) *day(s) of the year of mowing (in case of predefined day method, i.e. flag is 0 in line 2)
6) *the value of LAI after mowing (in case of predefined day method; see note on LAI overestimation above)
7) *percent of removed part of mowed grass; this defines the lateral carbon flux caused by mowing which has a strong influence on Net Biome Production (NBP). In case of the predefined day method this data should be supplied for all mowing events. In case of the LAI threshold method this number should be supplied only once, as the number of yearly cuts is not known a priori. In this case the defined ratio will be applied to all events.

```
MOWING (keyword)
0           (flag) do MOWING? 0=no; 1=yes; filepath=reading from file
0           (flag) mowing method? 0 - fixday method, 1 - fixvalue method
-9999       (m2/m2) fixed value of the LAI before MOWING (fixvalue method)
-9999       (m2/m2) fixed value of the LAI after MOWING (fixvalue method)
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(yday) MOWING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(m2/m2)LAI after MOWING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of biomass
```

Section GRAZING

The next management section begins with the keyword GRAZING. 16 parameters are defined to simulate GRAZING by livestock in pastures. Grazing is defined based on the 'livestock unit' (LSU) terminology, where 1 LSU refers to an average animal (the animal-specific exact value can be set below). This section has the following lines:

1) flag (0, 1 or filename) to define GRAZING (1 or filename) or not (0)
2) *first day(s) of the grazing period(s) (day of year, 0-364); continuous grazing is assumed between the first and last grazig days defined here and by line 3). The first number defines the start of the first grazing period, and the second defines the start of the second grazing period. The grazing periods should not overlap. 10 grazing periods can be defined within one year. The other settings should be repeated according to the number of periods defined.
3) *last day(s) of the grazing period(s) (day of year, 0-364); see line 2)
4) *weight equivalent of an averaged animal (live stock unit) in kilograms; this is the average weight of the livestock
5) *animal stocking rate regarding a unit area (number of LSU per hectare)
6) *daily ingested dry matter (DM) regarding a unit LSU (kg dry biomass per LSU per day; carbon content of dry biomass is defined in line 10)
7) *trampling effect coefficient. It defines the increase of senescence coefficient (see theoretical basis document) due to animal movement. The proposed value is 1.5 which means

that the senescence coefficient during the grazing period is 1.5 times higher than the senescence coefficient value set in EPC file.
8) *proportion of ingested dry matter which turns into excrement (percent of consumed grass)
9) *proportion of excrement returning to litter (percent of excrement)
10) *carbon content of dry matter (percent; 40-50% is a realistic estimate)
11) *nitrogen content of excrement (percent)
12) *carbon content of excrement (percent)
13) *manure emission factor for direct N_2O emissions from manure management in kgN2O-N:kgN (IPCC, 2006); we suggest to use the value defined below in the example
14) * default N excretion rate is the fraction of nitrogen excretion left at the site in kgN (1000 kg animal mass)$^{-1}$ day^{-1} (IPCC, 2006; T10.19); we suggest to use the value defined in the example external management file in Appendix C.
15) *manure emission factor for CH_4 emission in kg CH_4 LSU^{-1} year^{-1} (IPCC, 2006; T10.14); we suggest to use the value defined in the example external management file in Appendix C.
16) *fermentation emission factor for CH_4 emission in kg CH_4 LSU^{-1} year^{-1} (IPCC, 2006; T10.11); we suggest to use the defined in the example external management file in Appendix C.

```
GRAZING (keyword)
0                  (flag) do GRAZING? 0=no, 1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) first day of GRAZING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) last day of GRAZING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/LSU) weight equivalent LSU
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(LSU/ha) animal stocking rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg DM/LSU) daily ingested DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(prop) trampling effect
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%)ratio of DMintake to excrement
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%)ratio of excrement to litter
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) carbon content of dry matter
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) N content of manure
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) C content of manure
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN2O-N:kgN) manure EF for N2O
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN/1000 kg/d) N excretion rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgCH4/LSU/y )manure EF for CH4
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgCH4/LSU/y) ferment. EF for CH4
```

Section HARVESTING

The next management section begins with the keyword HARVESTING. Harvest should be used in crop related simulations; for hay meadows the MOWING section should be used; for forest management the THINNING section is applicable. Four parameters are defined to simulate harvesting:
1) flag (0, 1 or filename) to define using harvesting (1 or file) or not (0)
2) *day(s) of harvesting (day of year)
3) *carbon content of soft stem after harvest (kgC/m^2; this is the weight of snag, which is the remaining aboveground soft stem; in the model it is assumed that no living leaves remain at the site after harvest)
4) *percent of harvested leaves and soft stem that is removed from the field; it is assumed that fruit (yield) is always transported away from the field after harvest; fine roots are always left at the field; this parameter controls the lateral carbon flux caused by harvest which has significant implications on Net Biome Production (NBP)

```
HARVESTING (keyword)
1          (flag)do HARVESTING? 0=no,1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) HARVESTING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgC/m2) softstem C after harvest
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) transported part of biomass
```

Section PLOUGHING

The next management section begins with the keyword PLOUGHING. This management type is applicable for croplands and grasslands, but it can also be used in other biome types. Four parameters are defined to simulate PLOUGHING:

1) flag (0, 1 or file) to define using ploughing (1 or file) or not (0)
2) *day of ploughing (day of year)
3) *ploughing depth in meter
4) *dissolving coefficient of ploughed biome to litter (proportion); this parameter was introduced to avoid unrealistic sharp peaks in respiration that is caused by the transformation of ploughed dead plant material to the litter pool

```
PLOUGHING (keyword)
0                  (flag) do PLOUGHING? 0=no,1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(yday) PLOUGHING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(m) PLOUGHING depth
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(prop) dissolving coefficient
```

Ploughing has effect on the predefined soil texture, as it is supposed to homogenize the soil (in terms of texture, temperature and soil water, nitrogen and carbon content) for the depth of the ploughing at the ploughing day. This homogenization means that the model will use soil textures for the affected layers that might differ from those provided by the user within the SITE section.

Note that ploughing causes burial of litter that is usually supposed to reside on the soil surface. To handle this process, BBGCMuSo differentiates between aboveground and belowground litter pools.

Section FERTILIZING

The next management section begins with the keyword FERTILIZING. 11 parameters are defined to simulate fertilization:

1) flag (0, 1 or file) to define using FERTILIZING (1 or file) or not (0)
2) *day(s) of fertilizing (day of year)
3) *total amount of fertilizer per hectare per day (kg fertilizer/ha/day)
4) *dry matter (DM) content of fertilizer in percent
5) *nitrate fraction of the dry matter (kgN/kg fertilizer DM)
6) *ammonium content of fertilizer dry matter content in kgN/kg fertilizer DM
7) *organic nitrogen content of fertilizer dry matter content in case of organic manure in kgN/kg fertilizer DM
8) *organic carbon content of fertilizer dry matter content in case of organic manure in kgC/kg fertilizer DM
7) *labile carbon fraction of fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)
8) *unshielded cellulose fraction of the carbon content within the fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)
9) *shielded cellulose fraction of the carbon content within the fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)
10) *lignin fraction of the carbon within the fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)
11) *emission factor of N additions from mineral fertilizers in kg N_2O–N $(kgN)^{-1}$

```
FERTILIZING (keyword)
0                   (flag) do FERTILIZING?0=no,1=yes file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) FERTILIZING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(m) fertilizing depth
```

```
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/ha/day) amount of fert.
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) dry matter cont. of fert.DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/kg) nitrate cont. of fert.DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/kg) ammonium cont. of fert.DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/kg) organic N cont.of fert.DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/kg) organic C cont.of fert.DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) labile fraction of organic DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) unshielded cellulose fraction
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) shielded cellulose fraction
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) lignin fraction of organic DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN2O-N:kgN) EF for N-additions
```

Parameterizing the fertilization can be difficult in real-world situations. In order to simplify the parameterization we are preparing a technical note that can will support the parameterization. Please contact us if you are interested in that document.

Section IRRIGATION

The next management section begins with the keyword IRRIGATION. Three parameters are defined to simulate irrigation:

1) flag (0, 1 or file) to define using IRRIGATION (1 or file) or not (0)
2) *day(s) of irrigation (day of year)
3) *amount of water from irrigation in kg per m^2 per day (equivalent with mm of precipitation)
4) *utilization coefficient of water

```
IRRIGATION (keyword)
0           (flag) do IRRIGATION? 0=no, 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(yday) IRRIGATION day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(kgH2O/m2/day) amount of water
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(%) utilization coefficient
```

Section END_INIT

The last section of the INI file consists only of the keyword END_INIT, signaling the end of the file. This signal is used to make sure that the proper number of lines have been read from the INI file.

```
END_INIT (keyword) indicates the end of the initialization file
```

<u>OPTION TO USE ANCILLARY MANAGEMENT FILES TO SIMULATE ANNUALLY VARYING HUMAN INTERVENTION</u>

As we mentioned above, BBGCMuSo has a built-in option to define annually varying management settings for all implemented management types. This can be achieved by creating ancillary text files with a given structure. The name(s) of the ancillary management file(s) can be set by the User, but for clarity we suggest to use names that are identical with the name of the management block defined within the INI file (e.g. mowing.txt, fertilizing.txt, grazing.txt, harvesting.txt, planting.txt, ploughing.txt, thinning.txt). These files are supposed to be present next to the model executable. The text files are only utilized if the first line of the given management block in the INI file contains reference to the file. Example ancillary files are presented in Appendix C.

The ancillary management files only contain rows that define the 10 events for the specific management type (data marked with asterisk above). As the management might vary from year to year, these settings must be repeated for each year during the normal simulation.

In other words, the 10-event-lines must be repeated for all years defined by the number given on line 2 of the TIME_DEFINE section.

Similarly to the management setting within the INI file, -9999 means that the given management event should not be considered (applicable if there are less then 10 management events per year; note that there can be years when there is no management at all).

Examples are given in Appendix C separately for each management type.

3.3 Meteorological input file

As described above, the MET_INPUT section of the INI file names a file containing the meteorological data used to drive a BBGCMuSo simulation. This file can contain any number of header lines, followed by numeric values for the meteorological data. The number of header lines must be specified after the filename in the MET_INPUT section of the INI file. Below is an example of the top of a meteorological data file having four header lines:

```
Bugac, 2009-2011: input for MTCLIM v4.3
MTCLIM v4.3 OUTPUT FILE
year yday     Tmax   Tmin  Tday  prcp     VPD    srad   daylen
      °C     °C    °C    cm      Pa    W/m2   s
2009 1 -4.70  -8.05 -6.52 0.00   25.88   40.68    30346
2009 2 -1.10  -5.90 -2.79 0.00  113.53  116.23    30400
2009 3 -2.03 -11.95 -5.54 0.00   56.67  177.67    30459
2009 4 -3.63 -17.26 -8.45 0.00   20.00   58.86    30522
2009 5 -2.76  -9.56 -4.68 0.00   83.68  105.26    30590
2009 6 -1.84  -9.34 -3.95 0.00   88.24  206.67    30662
2009 7 -4.52  -9.35 -5.35 0.00   42.50   29.07    30738
2009 8 -0.51 -10.99 -3.31 0.00  161.18  189.28    30819
```

In this case, the meteorological input file is generated by the MT-CLIM (version 4.3) program, as indicated in the header lines. Meteorological data files generated by MT-CLIM version 4.3 will always have four header lines, with the last two header lines describing the variables and their units. This example also illustrates the required input variables, their units, and their order. BBGCMuSo requires these variables, using these units, and in this order, with no additional variables, for every simulation. The spacing between variables is not important, as long as there is some white space between each value on a line. Do not use commas or other non-white space separators.

The nine values required for each day are as follows:
1) year: the numerical year, repeated for each yearday
2) yday: the numerical day of the year, values must start with 1 and end with 365
3) Tmax: the daily maximum air temperature (°C)
4) Tmin: the daily minimum air temperature (°C)
5) Tday: the average *daytime* air temperature (sunrise to sunset, °C)
6) prcp: the daily total precipitation (cm, *not millimeters!*)
7) VPD: the *daylight average* vapor pressure deficit (Pa)
8) srad: the *daylight average* shortwave radiant flux density (W/m^2)
9) daylen: the daylength (sunrise to sunset, seconds)

The meteorological input data file can contain any number of years of data, and each year must have exactly 365 days, with one line of data per day, and no separations between years.

BBGCMuSo expects each year to have 365 days of data, so leap years will have to be truncated by eliminating one day. We suggest eliminating December 31 of a leap year, since then the yearday numbering doesn't have to be adjusted. We have found that this truncation has negligible effects on most simulations. The rationale for requiring 365-day years is that the met data files are commonly of shorter duration than the intended simulation, so they must be "recycled" enough times to match the number of requested simulation years. Recycling is also essential in the spinup runs. If the number of years in the met data file is not a multiple of four, then the handling of leap days in the code becomes very tedious, and introduces several layers of testing and manipulation between the input and the process algorithms. We have accepted the small errors introduced by eliminating one day from leap years in exchange for code that is clear and easier to maintain. Meteorological data files can be assembled from observations if all of the required parameters have been measured for the site of interest. They can also be generated using the MT-CLIM program using only observations of temperature and precipitation. The MT-CLIM code and documentation is available from the NTSG website: http://www.ntsg.umt.edu/project/mtclim.

A note on the bug related to the calculation of daylight average air temperature

According to the Biome-BGC 4.2 User's Guide there was a bug in the source code of the model that is related to the calculation of daylight average temperature (Thornton and Running, 2002): *„An incorrect parameter was being used in the calculation of the daylight average air temperature in daymet.c. The parameter value in version 4.1.1 was 0.212, and the correct value, for consistency with the MT-CLIM and Daymet code, should be 0.45. The daylight average air temperature (tday) is used in the photosynthesis routine, and in the calculation of daytime leaf maintenance respiration. As an example of the net result of changing to the correct value, the example simulations described later in this guide show an increase in steady state leaf area index of about 10% and an increase in steady state net primary production of about 5%. Thanks to Michael Guzy at Oregon State University for finding this bug."*

We corrected this bug in BBGCMuSo, but not in terms of the parameter in daymet.c, but we modified the model in order to use the daylight average temperature value that is provided by the meteorological input file (MT-CLIM output in many cases). We prefer this solution as the user of the model can use his/her own calculation method for daylight average temperature (e.g. based on hourly measurements), which would be meaningless if the model would re-calculate its value based on daily maximum and minimum temperature.

3.4 Ecophysiological input file (EPC file)

This input file defines the ecophysiological characteristics of the vegetation type being simulated. It is kept separate from the initialization file so that multiple initialization files can reference the same ecophysiology constants without cutting and pasting. Researchers at NTSG have spent considerable effort summarizing a large number of ecophysiological studies from the literature to come up with a set of default parameterizations for a small number of highly aggregated vegetation classes (plant functional types; see White et al., 2000). Model Users should also discover the features of the popular TRY database (Kattge et al., 2011) for parameters. If you have good measurements from your site(s) relating to any of these parameters, you should replace the defaults with your observations.

Users are cautioned that some of these parameters show strong covariance, so replacing some but not others with local observations may reduce the quality of results. For example, canopy average specific leaf area, leaf C:N, and fraction of leaf N in Rubisco tend to co-vary, so if you replace any of these default values you should consider replacing all of them. Consult with your local ecophysiologist if you aren't sure about reparameterization of the default *.epc files. Note that all *.epc files must have the same parameter lines, in the same order, but that not all lines are relevant to all vegetation types.

The following section describes each line of an epc file, in the required order. The line number is followed by the units for the parameter in question and the short text description (some parameters are dimensionless, and these units are given as DIM). This is followed by a detailed description of the parameter(s) in question.

```
line 1
ECOPHYS (keyword) start of canopy ecophysiological constants block
```

This is a keyword used by the code to interpret the start of a block of ecophysiological data. The first line of each *.epc file *must* start with ECOPHYS.

```
line 2-3
-----------------------------------------------------------------------------------
FLAGS
```

This is a dividing line and keyword to indicate the start of the FLAGS block.

```
line 4
(flag) biome type flag (1 = WOODY 0 = NON-WOODY)
```

An integer flag specifying the growth form (biome type), where 1 for woody includes both tree and shrub vegetation types, and 0 for non-woody includes grasses as well as other primarily herbaceous plants.

```
line 5
(flag) woody type flag (1 = EVERGREEN 0 = DECIDUOUS)
```

An integer flag specifying the leaf habit, where 1 for evergreen includes leaf habits that retain at least some of their foliage year-round, and 0 for deciduous includes leaf habits in which all foliage is absent at some point during a year. Either value for this flag can apply to both woody and non-woody growth forms.

```
line 6
(flag) photosynthesis type flag (1 = C3 PSN 0 = C4 PSN)
```

An integer flag specifying the photosynthetic pathway, where 1 indicates that the C3 photosynthesis model should be invoked, and 0 indicates that the C4 model should be invoked. Although this flag can be set to 0 for any combination of the other parameters, use of the C4 model should be restricted to grasses and herbaceous plants. Note that in BBGCMuSo we implemented a new, enzyme-driven C4 photosynthesis routine in the photosynthesis module, based on the work of Di Vittorio et al. (2010).

```
line 7
(flag) phenology flag (1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY)
```

An integer flag specifying how the phenological control for a simulation will be handled. A value of 1 invokes the internal phenology routine (including the optional HSGSI method described in Hidy et al., 2012 or the original Biome-BGC model logic), while a value of 0 indicates that the user will supply information on the yeardays for the start of new growth and the end of the litterfall period within the EPC file. See below for more details on how to set these parameters for the case of user-specified phenology. Note that there is an option to use an external file to define annually varying, user-specified values (see below).
Note that setting this parameter value to 1 will need a decision from the User. If the flag in the 12nd line of the EPC file is set to 1, then the HSGSI method will be used to estimate start and end of the growing season (Hidy et al., 2012). If the flag in the 12nd line of the INI file is zero, the original Biome-BGC v4.1.1 phenology will be used. We propose to use the HSGSI

method for herbaceous vegetation, while we suggest to use the original logic for forests and shrublands. If the simulated biome is a crop (planting and harvesting information is used) this flag should be set to 0 (in this case the start and the end of the vegetation period is the planting and the harvesting date, respectively).

```
line 8
(flag)  transferGDD flag (1= transfer calc. from GDD 0 = transfer calc. from EPC)
```

An integer flag specifying how the transfer period is determined A value of 0 indicates that the model uses the *transfer growth period as fraction of growing season* parameter (line 23) to calculate the limits of the transfer period, while in case of value 1 the transfer period is calculated based on allocation data using growing degree day (GDD) logic. For details see Theoretical basis of MuSo 5 (in prep.) or contact the authors of this document.

```
line 9
(flag)  1: temperature dependent Q10 value 0: constant Q10 value
```

An integer flag that can be used to enable air temperature dependent Q10 for autotrophic respiration (dynamic response of respiration to temperature). If the parameter is zero, then a constant Q10=2 will be used. In case of temperature dependent value (parameter is set to 1), Q10 is the function of the daily averaged air temperature: $Q10=3.22-0.046T_{day}$ where T_{day} is the mean (average of minimum and maximum) temperature for a given day (Smith and Dukes, 2010).

```
line 10
(flag)  0=no acclimation 1=phot acclim 2: resp acclim 3: phot+resp acclim
```

An integer flag specifying whether photosynthesis acclimation and/or maintenance respiration acclimation is enabled or not. A value of 0 means that acclimation is not simulated. If the flag is 1 it means that photosynthesis acclimation is simulated. A value 2 enables the respiration acclimation routine. If the flag is set to 3 it means that both photosynthesis acclimation and respiration acclimation are enabled.
Respiration acclimation is calculated after Tjoelker et al. (2001) and Smith and Dukes (2013). In this routine adjustment of respiration is calculated based on the mean air temperature of the previous 10 days.
Photosynthesis acclimation is simulated in a very simple way, by modifying the relationship between V_{cmax} (maximum rate of carboxylation) and J_{max} (maximum electron transport rate). (Kattge and Knorr, 2007) that was temperature-independent in the original code. Temperature dependency is calculated based on average temperature for the previous 30 days. This simple photosynthesis method is not a complete representation of the acclimation of the photosynthetic machinery (Smith and Dukes, 2013).
Note that we also modified the default (temperature independent) relationship between V_{cmax} and J_{max}, which is activated if the flag in line 10 is set to 0 or 2. The original code used the $J_{max}=2.1V_{cmax}$ relationship. According to Rogers et al. (2014) the $J_{max}=1.97V_{cmax}$ relationship is more realistic based on the dataset published by Wullschleger (1993).

```
line 11
(flag) CO2 conductance reduction flag (0: no effect, 1: multiplier)
```

An integer flag specifying whether stomatal conductance should be affected by changing atmospheric CO_2 concentration or not (Franks et al., 2013). For details see the notes for line 63. We recommend to set this flag to 1.

```
line 12
```

```
(flag) use GSI index to calculate growing season (0: no GSI, 1: GSI)
```

An integer flag controlling the use of the HSGSI method (Hidy et al., 2012) to calculate growing season (1: HSGSI-method, 0: method of original Biome-BGC)

```
line 13
(flag) soil temperature calculation method (0: Zheng, 1: DSSAT)
```

An integer flag specifying the soil temperature calculation method. 0 invokes the Zheng et al. (1993) based method with logarithmic downward dampening of temperature fluctuations within the soil. 1 means that the empirical method of DSSAT/4M (Sándor and Fodor, 2012) will be used. For details see Hidy et al. (2016). The preferred method should be selected based on comparison with measurements at the specific site (if available).

```
line 14
(flag) soil water balance calc method (0: Richards, 1: tipping DSSAT)
```

An integer flag specifying the soil water balance calculation method. 0 means that soil water balance is simulated based on the Richards equation, while 1 means that the so-called tipping bucket method is used. For details see Hidy et al. (2016). There is no recommended value for this flag; the User has the freedom to test both methods and use the most appropriate based on comparison with measured data.

```
line 15
(int)  discretization level of SWC calculation (0: low, 1: medium, 2: high)
```

An integer flag specifying the discretization level of soil water balance calculation method. 0 means low, 1 means medium, while 2 means high accuracy of the finite difference method used for soil water balance. Level 0 is the fastest, level 2 is the slowest. We propose to use level 0 for everyday simulation. It is only applicable in case of the Richards-equation based water balance method (if flag is 0 in line 14).

```
line 16
(flag) photosynthesis calculation method (0: Farquhar, 1: DSSAT)
```

An integer flag specifying the photosynthesis calculation method. 0 means that photosynthesis is simulated based on the Farquhar-method (which was the original method in Biome-BGC), while 1 means that the method of the DSSAT model is used (that is a simple light use efficiency model). For details see Theoretical basis of MuSo 5 (in prep.) or the DSSAT manual. There is no recommended value for this flag; the User has the freedom to test both methods and use the most appropriate based on comparison with measured data.

```
line 17
(flag) evapotranspiration calculation method (0: Farquhar, 1: DSSAT)
```

An integer flag specifying the evapotranspiration (ET) calculation method. 0 means that ET is simulated based on the Penman-Montieth method (original model logic), while 1 means simulation based on the Priestly-Taylor method. For details see Theoretical basis of MuSo 5 (in prep.). There is no recommended value for this flag; the User has the freedom to test both methods and use the most appropriate one based on comparison with measured data.

```
line 18
(flag) radiation calculation method (0: SWabs, 1: Rn)
```

An integer flag specifying the radiation calculation method. 0 means that within the ET routine absorbed shortwave radiation drives ET, while 1 means that the internally calculated net radiation (Rn) drives the ET routine. There is no recommended value for this flag; the User has the freedom to test both methods and use the most appropriate based on comparison with measured data.

```
line 19-20
----------------------------------------------------------------------------------
PLANT FUNCTIONING PARAMETERS
```

This is a dividing line and keyword to indicate the start the PLANT FUNCTIONING PARAMETERS block.

```
lines  21 and 22
(yday) yearday to start new growth (when phenology flag=0)
(yday) yearday to end litterfall (when phenology flag=0)
```

Two integers specifying the day of year for the start of new leaf growth, and the day of year for the end of the litterfall season, respectively. Relevant only when the phenology flag is 0 (see above line 7). There are several important notes about setting these values: to suppress new leaf growth entirely, for example in the case of a simulation concerned with bare soil processes, set both of these values to -1.
Yearday values for these parameters start at 0 and go to 364. Note that BBGCMuSo does not accept leap-years, i.e. all years are by definition 365 days long.
Northern and Southern hemisphere yeardays are treated differently for these parameters. In the northern hemisphere, yearday 0: Jan 1, while in the southern hemisphere yearday 0: July 2. This allows the same yearday values to be used to specify deciduous growth habit in the northern and southern temperate zones.
If the leaf habit flag is set to evergreen (1), and the phenology model flag is set to user-specified (0), these values do not have any effect.

```
lines 23 and 24
(prop.) transfer growth period as fraction of growing season
(prop.) litterfall as fraction of growing season
```

These two parameters determine the duration of the transfer growth and litterfall periods, and are defined as proportions of the period between the start of new growth and the end of litterfall. It is important to keep in mind that if transferGDD flag (line 8) is set to 1, allocation parameters are used to determine transfer period, which means that these parameters have no effect on the simulation! In other cases, these parameters must be set by the user regardless of whether internal model phenology or user-specified phenology is specified in the phenology model flag. These parameters can take any values from 0.0 to 1.0, where a value of 0.0 indicates that all transfer growth or all litterfall occurs in a single day, and a value of 1.0 indicates that transfer growth or litterfall occur throughout the growing season. Transfer growth is the growth derived from carbon and nitrogen resources (i.e. non-structural carbohydrate) stored over the course of the previous growing season. It is the growth that produces the first flush of new leaves in the spring for deciduous plants. NOTE that when the leaf habit flag is set for evergreen (1), both transfer growth and litterfall are assumed to occur at constant rates throughout the year, and the specification of these two parameters has no effect.

```
line 25
(Celsius) base temperature
```

This parameter sets the base temperature for plant processes. In general, base temperature is defined as the lowest air temperature where metabolic processes may result in a net substance gain in aboveground biomass (leaves or stem). (Note that the model does not simulate leaf temperature, only air and soil temperature are used in model calculations.) Base temperature is used to calculate a special growing season index (HSGSI; Hidy et al., 2016) to estimate the start and the end of the vegetation period (Hidy et al., 2012) and to calculate growing degree-day to estimate the phenological phases and genetically programmed senescence. For details see Theoretical basis of MuSo 5 (in prep.).

```
lines 26 and 29
(°C) minimum temperature for growth displayed on current day (-9999: no T-depend.)
(°C) optimal1 temperature for growth displayed on current day (-9999: no T-depend.)
(°C) optimal2 temperature for growth displayed on current day (-9999: no T-depend.)
(°C) maximum temperature for growth displayed on current day (-9999: no T-depend.)
```

These four parameters set specific thresholds to control air temperature dependency of allocation. The temperature dependence of allocation is controlled by a ramp function, with a plateau as optimum. Optimal1 temperature is the smaller temperature when the optimum is reached (optimum means that the function reaches 1). Optimal2 temperature is the highest temperature when the optimum ends and the function starts to decrease. Between minimum and optimal1 temperatures the proportion of growth displayed on current day increases, while between optimal2 and maximum temperature it decreases linearly from zero to 1 and from 1 to zero, respectively. Below minimum temperature (line 26) and above maximum temperature (line 29) the proportion of growth displayed on the current day is zero (all the daily production (i.e. assimilation) goes to the non-structural plant pool, which is represented by the storage pool in the model; for details about changes in the non-structural carbohydrate pool simulation logic see Theoretical basis of MuSo 5; in prep.). Note that all or none of the four parameters driving temperature dependency for growth should be set by the User. Note that temperature dependence for allocation is an experimental feature of the model, and should not be used in typical simulations. Setting all four parameters to -9999 disables the temperature dependency of allocation which means that the original model logic is used.

```
lines 30 and 33
(°C) min. temperature for C-assimilation displayed on current day (-9999: no limit)
(°C) opt1 temperature for C-assimilation displayed on current day (-9999: no limit)
(°C) opt2 temperature for C-assimilation displayed on current day (-9999: no limit)
(°C) max. temperature for C-assimilation displayed on current day (-9999: no limit)
```

These four parameters set optional thresholds on the temperature dependency of carbon assimilation (photosynthesis). If these thresholds are set, the temperature dependence of C-assimilation is controlled by a ramp function, with a plateau as optimum. Optimal1 temperature is the smaller temperature when the optimum is reached (equals 1). Optimal2 temperature is the highest temperature when the optimum ends and starts to decrease from 1 to 0. Between minimum and optimal1 temperatures the limitation of carbon assimilation on current day increases, between optimal2 and maximum temperature it decreases linearly from zero to 1 and from 1 to zero, respectively. Below minimum temperature and above maximum temperature thresholds set by the parameters the carbon assimilation is fully downregulated by the model, so the daily gross primary production is zero on the given day. Note that all or none of the temperature dependency parameters should be set by the User. Setting all four parameters to -9999 disables this additional temperature dependency of assimilation which means that the original model logic is used. Note that the Farquhar photosynthesis routine has inherent temperature dependency in the original model. These four parameters were introduced to set further temperature control on assimilation, to simulate the observed downregulation of photosynthesis at high temperatures for some biomes. We propose that first the high temperature effect should be tested by the User (minimum temperature and optimum1 should be set to e.g. zero in this case). The low temperature related downregulation is just a possibility that might not be used at all.

```
line 34
(1/yr) annual leaf and fine root turnover fraction
```

Determines leaf and fine root turnover for evergreen plants. This is the fraction of the annual maximum leaf and fine root mass that will be dropped in the following year as litter. It is the reciprocal of the leaf longevity, so a plant that retains its leaves an average of two years would have a leaf/fine root turnover of 0.5. Note that leaf and fine root phenology are assumed to be entirely synchronized for all vegetation types. Also note that when the leaf habit is specified as deciduous (0), this parameter is always assumed to be 1.0, and will be reset inside the code if the user specifies any other value.

```
line 35
(1/yr) annual live wood turnover fraction
```

Determines livewood turnover to deadwood for all woody types (deciduous and evergreen). Important note about the definition of livewood and deadwood in BBGCMuSo: livewood is defined as the actively respiring woody tissue, that is, the lateral sheathing meristem of phloem tissue, plus any ray parenchyma extending radially into the xylem tissue. Deadwood consists of all the other woody material, including the heartwood, the xylem, and the bark. It has been common in many tree models, including previous versions of Biome-BGC, to divide the woody tissue into two compartments called "sapwood" and "heartwood", where sapwood is usually defined as the sum of phloem and xylem, with heartwood defined as the non-conducting woody tissue. The current treatment ignores the distinction between water-conducting xylem and non-conducting heartwood.
For herbaceous vegetation the wood related parameters does not affect the simulation.

```
line 36
(1/yr) annual whole-plant mortality fraction
```

This parameter specifies the fraction of all plant pools that will be removed and sent to the litter compartments over the course of a year. In case of woodlands, this is one mechanism by which woody material (live and dead) leaves the plant pool and enters the litter pools to be made available for subsequent decomposition. It is the conceptual equivalent of wind-throw (but not exclusively, as diseases, competetive processes in early development phase or frost damage can also cause mortality of plants), and all plant pools, living and dead, are attenuated at the same rate. This annual proportion is converted internally to a daily rate, and whole-plant mortality is assumed to go on at a constant rate throughout the year. Note that BBGCMuSo has other mechanism for plant mortality, not present in previous versions of Biome-BGC. For example, drought related leaf senescence acts together with annual whole-plant mortality, if applicable. Also, gentically programmed leaf senescence (which is another option in BBGCMuSo) can also cause leaf mortality besides this daily fixed plant mortality. In BBGCMuSo annually varying whole-plant mortality fraction can be set by providing an external file (see later in this manual). In this case the external data overrides this setting in the EPC file.

```
line 37
(1/yr) annual fire mortality fraction
```

This parameter specifies the fraction of plant pools subject to fire, on average, each year. The current treatment ignores the timing of individual fire events, taking a long-term view of the fire process, in which some fraction of the community is subject to fire each year, at a rate commensurate with the long-term fire frequency. For example, in a system with a stand-replacing fire return interval of 100 yrs, this parameter would be set to 0.01.

```
line 38
(kgC/kgN) C:N of leaves
```

Mass ratio of carbon:nitrogen in live leaves. Note that this is one of the most important parameters of the model, so its value should be set by the User with caution. Consider using parameter optimization procedure (like the RBBGCMuSo R package developed by our group) to set this parameter properly.

```
line 39
(kgC/kgN) C:N of leaf litter, after retranslocation
```

Mass ratio of carbon:nitrogen in freshly fallen leaf litter. This can only be higher than or equal to the C:N for live leaves, i.e. retranslocation can only be positive or zero. Retranslocation is the removal of nitrogen from the leaves prior to litterfall. The model does not consider the possibility of retranslocation of carbon out of leaves prior to litterfall.

```
line 40
(kgC/kgN) C:N of fine roots
```

Mass ratio of carbon:nitrogen in fine roots. The model assumes that there is no retranslocation of nitrogen out of fine roots prior to litterfall, so this is the only C:N parameter for fine roots. This should be equal or greater than the C:N for leaf.

```
line 41
(kgC/kgN) C:N of fruit
```

Mass ratio of carbon:nitrogen in fruit. The model assumes that there is no retranslocation of nitrogen out of fruit prior to litterfall. Fruit C:N ratio should be equal or greater than the C:N for leaf.

```
line 42
(kgC/kgN) C:N of soft stem
```

Mass ratio of carbon:nitrogen in soft stem. The model assumes that there is no retranslocation of nitrogen out of soft stem prior to litterfall, so this is the only C:N parameter for soft stem. This should be equal or greater than the C:N for leaf. Soft stem is not present for woody vegetation.

```
line 43
(kgC/kgN) C:N of live wood
```

Mass ratio of carbon:nitrogen for live wood (phloem and ray parenchyma). This will typically be a much smaller value than the average C:N for all woody parts, and is typically found to be close to that for fine roots. As we noted, in case of herbaceous vegetation the wood related parameters does not affect the simulation.

```
line 44
(kgC/kgN) C:N of dead wood
```

Mass ratio of carbon:nitrogen for dead wood (bark, xylem, heartwood). This should be equal or greater than the C:N for live wood.

```
line 45
(DIM) leaf litter labile proportion
```

The proportion of leaf litter mass in the labile fraction, usually defined as that fraction soluble in hot water/alcohol.

```
line 46
(DIM) leaf litter cellulose proportion
```

The proportion of leaf litter mass in the cellulose fraction, usually defined as that fraction soluble in a mild acid solution, after extraction of the water/alcohol soluble fraction. As labile, cellulose, and lignin fractions for leaf litter must sum to 1.0, lignin proportion is calculated by the model as 1-labile-cellulose (defined in lines 45 and 46, respectively).

```
line 47
(DIM) fine root labile proportion
```

The proportion of fine root mass in the labile fraction, usually defined as that fraction soluble in hot water/alcohol.

```
line 48
(DIM) fine root cellulose proportion
```

The proportion of fine root mass in the cellulose fraction, usually defined as that fraction soluble in a mild acid solution, after extraction of the water/alcohol soluble fraction. As labile, cellulose, and lignin fractions for fine root must sum to 1.0, lignin proportion is calculated by the model as 1-labile-cellulose.

```
line 49
(DIM) fruit labile proportion
```

The proportion of fruit mass in the labile fraction, usually defined as that fraction soluble in hot water/alcohol.

```
line 50
(DIM) fruit cellulose proportion
```

The proportion of fruit mass in the cellulose fraction, usually defined as that fraction soluble in a mild acid solution, after extraction of the water/alcohol soluble fraction. As labile, cellulose, and lignin fractions for fruit must sum to 1.0, lignin proportion is calculated by the model as 1-labile-cellulose.

```
line 51
(DIM) soft stem labile proportion
```

The proportion of soft stem mass in the labile fraction, usually defined as that fraction soluble in hot water/alcohol.

```
line 52
(DIM) soft stem cellulose proportion
```

The proportion of soft stem mass in the cellulose fraction, usually defined as that fraction soluble in a mild acid solution, after extraction of the water/alcohol soluble fraction. As labile, cellulose, and lignin fractions for soft stem must sum to 1.0, lignin proportion is calculated by the model as 1-labile-cellulose.

```
line 53
(DIM) dead wood cellulose proportion
```

The proportion of dead wood mass in the cellulose fraction, usually defined as that fraction soluble in a mild acid solution, after extraction of the water/alcohol soluble fraction. As cellulose and lignin fractions for dead wood must sum to 1.0, lignin proportion is calculated by the model as 1-cellulose.

```
line 54
(1/LAI/d) canopy water interception coefficient
```

The proportion of daily rainfall that can be intercepted and retained on the canopy per unit of projected leaf area index.

```
line 55
(DIM) canopy light extinction coefficient
```

The Beer's law extinction coefficient for attenuation of radiation in the canopy, using a projected leaf area basis.

```
line 56
(g/MJ) potential radiation use efficiency
```

The potential radiation use efficiency represents the physiologically potential above ground biomass production per unit of light intercepted by the crop canopy. This parameter is only used if photosynthesis calculation method (line 16) is set to 1 (DSSAT-method).

```
line 57-58
(DIM) radiation parameter1 (Jiang et al.2015)
(DIM) radiation parameter2 (Jiang et al.2015)
```

These are empirical parameters of radiation calculation method (only used if line 18 is set to 1, which means the application of the net radiation calculation – for details see Jiang et al. 2015).

```
line 59
(DIM) all-sided to projected leaf area ratio
```

The ratio between the all-sided area and the projected area for leaves. Projected area for this and all other uses in BBGCMuSo is the projected area of the leaf laid flat with its two longest dimensions parallel to the measurement surface, while all-sided area is the total leaf surface area. For C3 and C4 grasslands and deciduous broadleaf forests this value is fixed to 2 within the model code, so setting line 48 to other value has no effect.

```
line 60
(DIM) ratio of shaded SLA:sunlit SLA
```

Ratio between specific leaf area for leaves in the shaded canopy fraction and specific leaf area for leaves in the sunlit canopy fraction. White et al. (2000) suggest that this parameter should be set to 2.

```
line 61
(DIM) fraction of leaf N in Rubisco
```

The fraction of total live leaf nitrogen occurring in the RuBisCO enzyme. This is an extremely important parameter of the model as V_{cmax} (maximum rate of carboxylation) is calculated from this parameter also using specific leaf area (SLA) and C:N of leaves. SLA is set at the end of the EPC file.

```
line 62
(DIM) fraction of leaf N PEP Carboxylase
```

The fraction of total live leaf nitrogen occurring in the PEP Carboxylase enzyme (Di Vittorio et al., 2010). This parameter is only applicable in case of C4 photosynthetic pathway (see line 6 in the EPC file).

```
line 63
(m/s) maximum stomatal conductance (projected area basis)
```

The maximum stomatal conductance to water vapor, expressed on a projected leaf area basis. This is the conductance under saturating light, low VPD, leaf water potential near 0, and moderate temperatures. Reciprocal of minimum stomatal resistance. Note that BBGCMuSo uses the Jarvis multiplicative stomatal regulation method (Jarvis, 1976). Also note that by setting the parameter in line 11 to 1 this value might be subject to change during the model run, and in that case this value refers to ~ end of the 20th century/beginning of the 21st century conditions (~present day). If this is the case, the maximum stomatal conductance to water vapor and also to CO_2 are varying according to ambient CO_2 concentration (Franks et al., 2013). In elevated CO_2 concentration this modification will cause down-regulation of maximum stomatal conductance thus it might improve water use efficiency of the biome (see Hidy et al., 2016 for details).

```
line 64
(m/s) cuticular conductance (projected area basis)
```

The conductance of the leaf cuticle to water vapor, expressed on a projected area basis. Assumed constant under all environmental conditions.

```
line 65
(m/s) boundary layer conductance (projected area basis)
```

Leaf boundary layer conductance to water vapor, expressed on a projected area basis. This is also referred to as the aerodynamic conductance. It is defined as the conductance for water vapor entering the atmosphere from a free water surface on the leaf surface (a raindrop on the leaf). It is assumed constant under all environmental conditions, although it is in reality a strong function of wind speed. A constant wind speed of 1 m/s is assumed in defining values of this parameter for various leaf morphologies.

```
line 66
(DIM) relative soil water content (prop. to FC) to calculate soil moisture limit 1
```

This parameter defines the critical relative soil water content ($RSWC_{FC}$, i.e. actual soil water content divided by field capacity) where drought related soil moisture limitation starts to affect plant processes. If actual SWC is larger than critical SWC calculated from this parameter, then soil moisture does not affect stomatal conductance, evapotranspiration and root water uptake. Linear ramp function is defined between this critical value (where limitation starts) and wilting point (complete limitation). Note that saturation, field capacity and wilting point can be given within the INI file by the User, or alternatively they can be estimated from soil texture using empirical relationship (by setting their value to -9999 in the

SITE section of the INI file). If there is no available data for this parameter, the User should set it to 1 (in this case moisture limitation starts at field capacity, which means that there is no water stress above field capacity; note that another stress is defined close to saturation which is controlled by line 67, so here we mean stress caused by soil moisture deficit). If soil water potential is used to calculate this limitation factor (see below), the User should set this parameter to -9999.
See Hidy et al. (2016) for details on drought related plant mortality which might use this parameter.

```
line 67
(DIM) relative soil water content (prop. to SAT) to calculate soil moisture limit 2
```

Critical relative soil water content ($RSWC_{SAT}$; actual soil water content divided by saturation value) where elevated soil moisture content starts to affect stomatal conductance and decomposition, thus acts as limitation factor. The idea behind introducing this parameter is that presence of elevated groundwater or a wet, rainy period can negatively affect stomatal conductance and decomposition. If actual SWC is smaller than critical SWC calculated from this parameter then soil moisture does not affect stomatal conductance (at least due to elevated soil moisture), evapotranspiration, decomposition, and root water uptake. Linear ramp function is defined between this critical value (limitation starts) and saturation (complete limitation). If no available estimation is available, set this parameter to 1 (in this case the parameter will be saturation, which means that no stress will occur below saturation; note that in this case drought related stress can still be active, as defined by line 66). If soil water potential is used to calculate this limitation factor, User should set this parameter to -9999.

```
line 68
(MPa) soil water potential to calculate soil moisture limit1
```

This parameter defines the critical soil water potential where drought related soil moisture limitation starts. The difference between lines 66 and 68 is only the calculation method: in case of line 68 the critical soil water content value is calculated from critical soil water potential instead of critical relative soil water content. If no estimation is available or if soil water content is used to calculate this limitation factor, the User should set this parameter to -9999. If both critical relative soil water content and soil water potential data are defined by the User (lines 66 and 68) the model will use the critical relative soil water content data.
See Hidy et al. (2016) for details on drought related plant mortality which might use this parameter.

```
line 69
(MPa) soil water potential to calculate soil moisture limit 2
```

Critical soil water potential where elevated soil moisture content starts to affect stomatal conductance and decomposition. The difference between lines 67 and 69 is only the calculation method: in case of line 69 critical soil water potential is used instead of critical relative soil water content. If no estimation is available or if soil water content is used to calculate this limitation factor, the User should set this parameter to -9999. If both critical relative soil water content and soil water potential data are defined by the User (lines 67 and 68) the model will use the critical relative soil water content data.

```
lines 70 and 71
(Pa) vapor pressure deficit: start of conductance reduction
(Pa) vapor pressure deficit: complete conductance reduction
```

These two parameters set the endpoints for a linear control on stomatal conductance due to the water vapor pressure difference (VPD) between the interior of the leaf and the air adjacent to the leaf. The first parameter sets the VPD at which conductance reduction begins, and the second parameter sets the VPD at which stomatal conductance is reduced to 0. In the range between these values, reduction of stomatal conductance is a linear function of VPD.

```
line 72
(m) maximum height of plant
```

A new feature of Biome-BGCMuSo 5.x is the option to simulate plant height. For herbaceous vegetation the height of the plant is simulated based on empirical functions of the DSSAT model using the carbon content of the softstem. For woody ecosystems the model uses empirical functions from the CLM 4.5 model using the carbon content of livestem and deadstem. For these calculations maximum possible plant height has to be provided by the User.

```
line 73
(kgC/m2) stem weight at which maximum height attended
```

This is a woody vegetation related parameter, therefore in case of herbaceous vegetation it does not affect the simulation. Beside the carbon content of livestem and deadstem, this critical stem weigth is used in the empirical estimation of the woody plant height.

```
line 74
(m) maximum depth of rooting zone
```

This parameter sets the maximum rooting depth for the biome. Timing of root growth is controlled by allocation parameters. The actual length of the root is simulated based on empirical function in case of non-woody biomes (grass: method of Campbell and Diaz (1988); crops: empirical function of the 4M model). In case of forests, fine root growth is assumed to be present in the entire root zone represented by coarse roots. In case of forest this depth does not change with time which is a limitation of the model.

```
line 75
(DIM)  root distribution parameter
```

Empirical exponential root distribution parameter (where the shape of the exponential root profile is controlled by this single scalar) to calculate the distribution of roots within the soil layers (Jarvis, 1989). The proposed value is 3.67.

```
lines 76 and 77
(kgC/m2) rootlenght parameter 1 (estimated max root weight)
(prop.)  rootlenght parameter 2 (slope)
```

These two parameters are used in the empirical rooting depth calculation of crops (based on the method of 4M model).

```
line 78
(DIM) growth respiration per unit of C gain
```

This parameter controls the growth respiration cost per unit of carbon growth (GPP). In the original model this parameter was fixed within the source code. The proposed value of the parameter is 0.3. Some studies suggest that this parameter might deviate from 0.3, and it is important to properly set the adequate value of this parameter.

```
line 79
(kgC/kgN/d) maintenance respiration in kgC/day per kg of tissue N
```

This parameter defines the maintenance respiration in kgC per kg of tissue N per day. The proposed value is 0.218.

```
lines 80 and 81
(DIM) theoretical maximum prop. of non-structural and structural carbohydrates
(DIM) prop. of non-structural carbohydrates available for maintenance respiration
```

In the model it is assumed that plants try to maintain a minimum level of non-structural carbohydrate (NSC) concentration that is needed for long term survival (after Martínez-Vilalta et al., 2016). It means that NSC pool is handled in such a way that NSC level is kept above a given fraction of the theoretical maximum of NSC pool where the latter is estimated as a fixed fraction of the actual structural carbon pool. For details about non-structural pool simulation see Theoretical basis of MuSo 5 (in prep.).

```
line 82
(kgN/m2/yr) symbiotic+asymbiotic fixation of N
```

This parameter defines the annual rate of symbiotic + asymbiotic nitrogen fixation for the plant in kgN m^{-2} yr^{-1}. In previous Biome-BGC versions this parameter was defined within the SITE section of the INI file. Due to the complexity associated with the definition of this parameter we moved it to the EPC file so the User might want to adjust its value through model optimization (calibration). Total external N input to the ecosystem is the sum of symbiotic + asymbiotic nitrogen fixation and the reactive N deposition from the atmosphere where the latter is defined within the INI file (see above).

```
lines 83 and 84
---------------------------------------------------------------------------------
CROP SPECIFIC PARAMETERS
```

This is a dividing line and keyword used by the code to interpret the start of a block of crop specific parameters.
One of the new features of Biome-BGCMuSo v5 is the possibility to simulate crop development and yield similarly to mechanistic crop models. One of the core elements of crop simulations is the explicit handling of crop phenophases (see below). In this section crop specific parameters can be set where some of them are related to the phenophases that are defined later in the EPC file, in the PHENOLOGICAL (ALLOCATION) PARAMETERS block. Note that in case of crop related simulations planting and harvest is supposed to be set by the User in the INI file. In this case the growing season starts with sowing, and ends with the harvest. **IMPORTANT NOTE: in non-cropland simulations these CROP SPECIFIC PARAMETERS should not be used.** This can be done easily by setting some of the lines of this block to -9999. Appendix B contains an example EPC file where the crop specific parameters are completely switched off.

```
lines 85 and 86
(DIM) number of phenophase of germination (from 1 to 7; 0: NO specific)
(DIM) number of phenophase of emergence (from 1 to 7; 0: NO specific)
```

The interval of germination is the transfer period when carbon and nitrogen content of the transfer pools (equivalent with the planted seeds) goes into actual carbon and nitrogen pools. The interval of emergence is the time period when the aboveground biomass emerges. These two intervals are defined by the number of phenophases that are associated with the processes (see line 170 for the definition of the phenophases). The number of the corresponding phenological phases can be set by the User, and it can range from 1 to 7. 0 means that these periods are not specified. In this latter case transfer period is defined by line 23.

```
line 87
(prop.) critical relative SWC (prop. to FC) in germination
```

The only limitation factor for germination (beside the critical heatsum set by phenological parameters) is the actual soil water content of the soil layer where germination happens. The critical soil water content below which the germination is hampered (i.e. it is slower) can be set by this critical relative soil water content parameter ($RSWC_{FC}$, i.e. actual soil water content divided by field capacity). To disable this feature set this parameter to zero which means that SWC in the germination layer will not affect the speed of germination.

```
line 88
(DIM) number of phenophases of photoperiodic effect (from 1 to 7; -9999: NO effect)
```

Photoperiodic effect means that the length of the daylight period (from sunrise to sunset) can limit the development of the plant. If we assume photoperiodic effect in a given phenophase, the growing degree calculation is modified using photoperiodic development rate (multiplier used in the heatsum calculation). The number of the phenophases of photoperiodic effect can vary from 1 to 7. If no photoperiodic effect is assumed, the User can set this parameter to -9999.

```
line 89
(hour) critical daylength for photoperiodic effect
```

If the User assumes photoperiodic effect on plant development (line 88 is set and its value ranges from 1 to 7), the critical daylenght for the photoperiodic calculation is defined by this parametes (defined in hours unit).

```
line 90
(DIM) slope of relative photoperiodic effect development rate
```

If the User assumes photoperiodic effect on plant development (line 88 is set and its value ranges from 1 to 7), the slope of the photoperiodic development rate is defined by this parametes. In other words, this parameter defines the strength of the photoperiodic effect.

```
line 91
(DIM) number of phenophases of vernalization (from 1 to 7; -9999: NO)
```

Many plants in temperate climates must experience a period of low (but not too low) winter air temperature (required for vernalization) to support the flowering process This ensures that reproductive development and seed production occurs in spring and winters. The vernalization calculation is based on vernalization development rate (VDR), which can vary between 0 and 1. The number of the phenophases of vernalization can vary from 1 to 7. If no vernalization is assumed, the User should set this parameter to -9999.

```
lines 92-95
(Celsius) critical vernalization temperature 1
(Celsius) critical vernalization temperature 2
(Celsius) critical vernalization temperature 3
(Celsius) critical vernalization temperature 4
```

Vernalization development rate (VDR) is based on the relative vernalization effectiveness, which is the function of the critical vernalization temperatures: minimum (1), optimal1 (2), optimal2 (3) and maximum (4). Below minimum and above maximum vernalization temperature vernalization development rate is zero. Between optimal temperatures vernalization development rate is 1. Between minimum and optional1 the VDR increases linearly. Between optional2 and maximum temperature the VDR decreases linearly.

```
line 96
(DIM) slope of relative vernalization development rate
```

As we mentioned above, the venalization calculation is based on VDR. The slope of VDR is defined by line 96. If vernalization is disabled, this parameter has no effect.

```
line 97
(n) required vernalization days (in vernalization development rate)
```

VDR is the function of the difference between required (line 97) and actual vernailziation days (relative vernalization effectiveness). This parameter sets the number of days needed for vernalization.

```
line 98
(DIM) number of flowering heat stress phenophases (from 1 to 7; -9999: NO effect)
```

Many plants in temperate climates are sensitive to heat stress during flowering (in other words anthesis). During flowering heat stress can affect seed fertilization, which is considered by decreasing the amount of carbon and nitrogen content of fruit (i.e. yield). The number of the phenophases when heat stress can affect flowering can vary from 1 to 7. If no heat stress effect on flowering is assumed, the User can set this parameter to -9999.

```
lines 99 and 100
(Celsius) critical flowering heat stress temperature 1
(Celsius) critical flowering heat stress temperature 2
```

The calculation of heat stress effect on flowering is based on predefined critical air temperatures. Below critical temperature 1 the multiplier of heat stress parameter (defined in line 101) is zero, above critical temperature 2 it is 1; between critical temperatures the effect increases linearly. Set these parameters to very high values to disable the feature.

```
line 101
(prop.) maximum of flowering heat stress mortality parameter
```

The flowering heat stress calculation method is based on the mortality parameter which is the result of multiplication of maximum flowering heat stress mortality parameter (defined in line 101) and a multiplier (based on critical temperatures, defined in lines 99-100).

```
lines 102 and 103
-----------------------------------------------------------------------------------
SENESCENCE AND SOIL PARAMETERS
```

This is a dividing line and keyword used by the model to interpret the start of a block of senescence and soil parameters.

```
lines 104-106
(prop.) maximum senescence mortality coefficient of aboveground plant material
(prop.) maximum senescence mortality coefficient of belowground plant material
(prop.) maximum senescence mortality coefficient of non-structured plant material
```

Soil moisture stress related mortality coefficients control the extent of plant senescence, namely the fraction of non-woody plant material (carbon and nitrogen) that dies during one day due to long lasting drought. User can define different mortality coefficients regarding

aboveground biomass (leaves and in case of herbaceous vegetation soft stem also), belowground biomass (fine root) and non-structural carbohydrate pools (transfer and strogae pools). Line 106 might be important to simulate the carry-over effect of drought stress during the consecutive year as drought might also affect the storage/transfer pools.
The fraction of wilted biomass (aboveground/belowground/non-structural) is calculated from this parameter, but this value (the maximum possible value of mortality coefficient) is modified to take into account the soil moisture stress coefficient (which is the function of the severity and the length of the drought). For details about senescence mortality see Theoretical basis of MuSo 5 (in prep.). Its proposed value is 0.05, which means that maximum 5% of the actual carbon and nitrogen pool is lost during one day due to the drought stress (in case of total stress). The User might want to adjust this parameter. The 0.05 value was set based on experiences on drought prone grassland in the Hungarian Great Plain.

```
line 107
(prop) effect of extreme high temperature on senescence mortality
```

As it is described above, in case of senescence mortality parameters, the fraction of wilted biomass is calculated from senescence mortality coefficient, but it can also be affected by extreme high air temperatures as well. Line 107 determines the multiplier (based on critical temperatures and actual air temperature) which can increase the fraction of senescenced biomass due to extreme high temperature. For details about senescence mortality see Theoretical basis of MuSo 5 (in prep.).

```
lines 108-109
(Celsius)  lower limit extreme high temperature effect on senescence mortality
(Celsius)  upper limit extreme high temperature effect on senescence mortality
```

Lines 108-109 determine the critical air temperatures of extreme high temperature effect on plant mortality (see line 107). Line 108 contains the lower limit, below which the extreme temperature effect is zero and line 109 contains the upper limit above which the extreme temperature effect is equal to the maximal value (defined by line 107). Between lower and upper limit the coefficient of extreme temperature effect increases linearly from zero to the maximal value. For details about senescence mortality see Theoretical basis of MuSo 5 (in prep.).

```
line 110
(Celsius) maximum lifetime of plant tissue  (-9999: no genetically programmed
senescence)
```

Genetically programmed mortality causes the senescence of leaf plant material based on the the age of the plant tissue in leaves (in contrast to the drought related senescence that is handled by lines 104-106). Maximum lifetime of plant tissue defines the age of the plant after which it is wilted. This parameter defines the maximum lifetime in accumulated GDD (Celsius). For details about genetically programmed senescence mortality see Theoretical basis of MuSo 5 (in prep.).

```
line 111
0.1    (prop.)  turnover rate of wilted standing biomass to litter
```

Turnover rate of standing dead biomass (senescenced leaves) to litter. The proposed value is 0.01 which means that 1% of the standing dead biomass turns into the litter pool during one day. This parameter is introduced to enable more realistic simulation of dead leaves behavior which can eventually stay intact for a longer time period before they touch the ground so that decomposition can start. The concept of standing dead biomass was introduced in

BBGCMuSo (see Hidy et al. 2016), and it was not present in the predecessor Biome-BGC versions.

```
lines 112-113
0.047    (prop.)  turnover rate of non-woody cut-down biomass to litter
0.01     (prop.)  turnover rate of woody cut-down biomass to litter
```

Turnover rate of cut-down (but not removed) non-woody (line 112) and woody (line 113) biomass to litter. The proposed value is 0.05. Non-woody parameter (line 112) controls the speed of transformation of harvested plant residues in croplands or clipped grass leaves in case of mown grasslands to litter. In case of forests this parameter controls the fate of (previously living) leaves on cut down trees (if thinning option is switched on). Woody parameter (line 113) controls the turnover of dead coarse root (stump) into coarse woody debris (cwd). Implementation of this turnover process was necessary to avoid C and N balance errors caused by large fluxes between specific pools.

```
line 114
(prop.)  drought tolerance parameter (critical value of DSWS)
```

As it is described above, in case of senescence mortality parameters the fraction of wilted biomass is calculated from senescence mortality coefficient, which is the function of the severity (soil water content) and the longevity (days since water stress occurs) of the drought. The drought tolerance parameter defines the critical number of drought related water stress days after which water stress is complete (it causes maximal plant mortality – set in lines 104-106 in the EPC file). We propose to use 30 days for grasslands based on experiences gained in drought-prone grasslands in Central Europe. For forests a higher value might be more realistic. The User might revise this parameter in other, drought-prone ecosystems. See Hidy et al. (2016) for details on drought related plant mortality simulation.

```
line 115
(prop.)  denitrification rate per g of CO2 respiration of SOM
```

Denitrification rate controls the fraction of the respiration of soil organic matter which is available to volatilization each day. Its original value is 0.02 (Parton et al., 2001). For details about the newly implemented denitrification routine see Theoretical basis of MuSo 5 (in prep.).

```
lines 116-117
(prop.)  nitrification coefficient 1
(prop.)  nitrification coefficient 2
```

Nitrification coefficients are used in the empirical function of the nitrification simulation. For details about implementation of nitrification in BBGCMuSo v5.x see Theoretical basis of MuSo 5 (in prep.).

```
line 118
(prop.)  coefficient of N2O emission of nitrification
```

Coefficient of N_2O emission of nitrification is used in the empirical function of nitrification. For details about nitrification see Theoretical basis of MuSo 5 (in prep.).

```
line 119
(prop.)  proprortion of NH4 content of N-deposition
```

Proprortion of NH_4 content of N-deposition is needed as BBGCMuSo 5 handles ammonium and nitrate pools separately.

```
line 120-121
(prop.)  NH4 mobilen proportion
(prop.)  NO3 mobilen proportion
```

Mobile Nitrogen proportions (line 120: regarding to ammonium; line 121: regarding to nitrate) are the proportions of mineralized N that is available for leaching and different biological processes (such as nitrification or denitrification).

```
line 122
10      (m)   e-folding depth of decomposition rate's depth scalar
```

In the original Biome-BGC model decomposition rate of SOM is limited by temperature and soil moisture. In BBGCMuSo v5 we included a limitation by the depth via an exponential decrease using e-folding depth of decomposition rate (see Koven et al., 2013).

```
lines 123-126
0.001 (prop.)  fraction of dissolved part of SOIL1 organic matter
0.001 (prop.)  fraction of dissolved part of SOIL2 organic matter
0.001 (prop.)  fraction of dissolved part of SOIL3 organic matter
0.001 (prop.)  fraction of dissolved part of SOIL4 organic matter
```

Beside N-leaching, the leaching of soil organic carbon pools were also implemented in Biome-BGCMuSo v5. Leaching calculation is based on the function of the presumed proportion of the soil organic carbon pools calculated by dissolved fraction parameters, soil water content and percolation fluxes.

```
line 127
0.6 (DIM)      ratio of bare soil evaporation and pot.evaporation
```

If precipitation reaching the bare soil is greater than the potential evaporation, the model (similarly to the original Biome-BGC) assumes that the evaporation of soil is less than its potential value. This ratio is defined by this parameter.

```
line 128-129
-----------------------------------------------------------------------------------
RATE SCALARS
```

This is a dividing line and keyword used by the code to interpret the start of a block of rate scalars

```
lines 130-135
0.39   (DIM)        respiration fractions for fluxes between compartments (l1s1)
0.55   (DIM)        respiration fractions for fluxes between compartments (l2s2)
0.29   (DIM)        respiration fractions for fluxes between compartments (l4s3)
0.28   (DIM)        respiration fractions for fluxes between compartments (s1s2)
0.46   (DIM)        respiration fractions for fluxes between compartments (s2s3)
0.55   (DIM)        respiration fractions for fluxes between compartments (s3s4)
```

Respiration fractions for allocation fluxes between litter (labile, cellulose, lignin) and soil (fast microbial, medium microbial, slow microbial and recalcitrant SOM/humus compartments). The default values are 0.39, 0.55, 0.29, 0.28, 0.46 and 0.55, respectively. We propose to leave these parameters intact unless there is strong evidence that the actual values differ from those presented here (and proposed by Thornton, 1998).

```
lines 136-143
0.7     (DIM) rate constant scalar of labile litter pool
```

```
0.07    (DIM) rate constant scalar of cellulose litter pool
0.014   (DIM) rate constant scalar of lignin litter pool
0.07    (DIM) rate constant scalar of fast microbial recycling pool
0.014   (DIM) rate constant scalar of medium microbial recycling pool
0.0014  (DIM) rate constant scalar of slow microbial recycling pool
0.0001  (DIM) rate constant scalar of  recalcitrant SOM (humus) pool
0.001   (DIM) rate constant scalar of physical fragmentation of coarse woody debris
```

Base values of rate constants to calculate the non-nitrogen limited decomposition fluxes between litter and soil compartments. The default values are 0.7, 0.07, 0.014, 0.07, 0.014, 0.0014, 0.0001 and 0.001, respectively. We propose to leave these parameters intact.

```
lines 144-145
-----------------------------------------------------------------------------------
GROWING SEASON PARAMETERS
```

This is a dividing line and keyword used by the model to interpret the start of the block of growing season control parameters.

BBGCMuSo-specific growing season index (details see in Hidy et al., 2012 and Hidy et al., 2016) is calculated based on the combination of daily minimum air temperature (TMIN), vapor pressure deficit (VPD), daylength and n-day (n is defined in line 153) heatsum. Heatsum is calculated as the sum of mean daily temperatures minus base temperature (defined in line 25) for each n days long period (Hidy et al., 2012). The effect of the different environmental variables is considered using indices (indexTmin, indexVPD, indexDAYLENGTH, indexHTSM). To calculate index for each variable we set threshold limits, similarly to the method of Jolly et al. (2005) within which the relative phenological performance of the vegetation is assumed to vary from inactive (0) to unconstrained (1). The values of the limits regarding to the different variables can be set by the parameters below (line

```
line 146
5       (kg/m2)     critical amount of snow limiting photosynthesis
```

Beside HSGSI the start of the vegetation pediod is affected by the presence of snow. Above a critical amount of snow (defined by this parameter) the photosynthesis is limited.

```
lines 147-148
20 (Celsius) limit1 (under:full constrained) of HEATSUM index
60 (Celsius) limit2 (above:unconstrained) of HEATSUM index
```

The threshold limits of HEATSUM: limit1 – below which the index of HEATSUM is zero; limit2 – above which the index of HEATSUM is 1 (between limit1 and limit2 it increases linearly).

```
lines 149-150
0 (Celsius)  limit1 (under:full constrained) of TMIN index
5 (Celsius)  limit2 (above:unconstrained) of TMIN index
```

The threshold limits of TMIN: limit1 – below which the index of TMIN is zero; limit2 – above which the index of TMIN is 1 (between limit1 and limit2 it increases linearly).

```
lines 151-152
4000 (Pa) limit1 (above:full constrained) of VPD index
1000 (Pa) limit2 (under:unconstrained) of VPD index
```

The threshold limits of VPD: limit1 – above which the index of VPD is zero; limit2 – below which the index of VPD is 1 (between limit1 and limit2 it decreases linearly).

```
lines 153-154
0 (s) limit1 (under:full constrained) of DAYLENGTH index
0 (s) limit2 (above:unconstrained) of DAYLENGTH index
```

The threshold limits of DAYLENGTH: limit1 – below which the index of DAYLENGTH is zero; limit2 – above which the index of DAYLENGTH is 1 (between limit1 and limit2 it increases linearly).

```
line 155
10 (day) window length for smoothing (to avoid the effects of extreme events)
```

In order to avoid the effects of extreme events in HSGSI calculation the n-day (n is defined by this parameters) moving average of heatsum is used.

```
lines 156-157
0.10 (dimless) HSGSI limit1 (greater that limit -> start of vegper)
0.01 (dimless) HSGSI limit2 (less that limit -> end of vegper)
```

If on a given day HSGSI is greater than a limit1 we assume that the start of the growing season is found. After finding the start of the growing season its last day is searched, and if on a given day (after start of the growing season) HSGSI is less than limit2 we assume that the end of the growing season is reached.

```
lines 158-159
---------------------------------------------------------------------------------
CH4 PARAMETERS
```

This is a dividing line and keyword used by the code to interpret the start of a block of methane parameters.

```
lines 160-161
(DIM) param1 for CH4 calculations (empirical function of bulk density)
(DIM) param2 for CH4 calculations (empirical function of bulk density)
```

Empirical parameters for CH_4 flux estimation using bulk density of the soil based on the method of Hashimoto et al. (2011). The default values are 212.5 and 1.81, respectively. The description of the estimation can be found in Hidy et al. (2016).

```
lines 162-163
(DIM) param1 for CH4 calculations (empirical function of VWC)
(DIM) param2 for CH4 calculations (empirical function of VWC)
(DIM) param3 for CH4 calculations (empirical function of VWC)
(DIM) param4 for CH4 calculations (empirical function of VWC)
```

Empirical parameters for CH_4 flux estimation using soil water content following the method of Hashimoto et al. (2011). The default values are -1.353, 0.2, 1.781 and 6.786, respectively. The description of the estimation can be found in Hidy et al. (2016).

```
line 164
(DIM) param1 for CH4 calculations (empirical function of Tsoil)
```

Empirical parameter for CH_4 flux estimation using soil temperature based the method of Hashimoto et al. (2011). The default value is 0.01. The description of the estimation can be found in Hidy et al. (2016).

```
lines 167-169
---------------------------------------------------------------------------------
PHENOLOGICAL (ALLOCATION) PARAMETERS (7 phenological phases)
```

```
phase1 phase2 phase3 phase4 phase5 phase6 phase7  (text) name of the phenophase
```

This is a dividing line and keyword used by the model to interpret the start of a block of phenological parameters. The User can define up to 7 different phenological phases (with different names for easier identification; it means you may adjust the words phase1 phase2… phase7 above).

```
line 170
500    200     500    200    400     200    100   (Celsius) length of phenophase (GDD)
```

Sets the length of the phenophases based on growing degree days.

```
lines 171-178
0.4    0.4     0.4    0.4    0.4     0.4    0.4   (ratio) leaf ALLOCATION
0.2    0.2     0.2    0.2    0.2     0.2    0.2   (ratio) fine root ALLOCATION
0.2    0.2     0.2    0.2    0.2     0.2    0.2   (ratio) fruit ALLOCATION
0.2    0.2     0.2    0.2    0.2     0.2    0.2   (ratio) soft stem ALLOCATION
0      0       0      0      0       0       0    (ratio) live woody stem ALLOCATION
0      0       0      0      0       0       0    (ratio) dead woody stem ALLOCATION
0      0       0      0      0       0       0    (ratio) live coarse root ALLOCATION
0      0       0      0      0       0       0    (ratio) dead coarse root ALLOCATION
```

Sets the allocation ratio of leaf, fine root, fruit (e.g. crop yield), soft stem, live stem, dead stem, coarse root and dead coarse root. These are constant values in a given phenological phase but the User can defined 7 different values regarding to the 7 phenological phase. Soft stem is applicable to herbaceous ecosystems only, woody parameters are only applicable to woody ecosystems. Note that the sum of allocation parameters should be 1 in every phenological phases. If the User wants to use the original model logic, all 7 parameters per line can be set to the same value which means static allocation.

```
line 179
49     49      49     49     49      49      49   (m2/kgC) canopy average SLA
```

Projected area per unit of leaf carbon mass, averaged over the canopy during the different phenophases. The option to provide varying SLA is a novel feature in BBGCMuSo 5.0. Note that SLA is a very important parameter of the model, so selection of SLA is critical. Consider using parameter optimization of these parameters together with C:N content of leaf and fraction of leaf N in Rubisco parameters as they jointly determine the most important photosynthesis parameters. Note that if the User wans to use a single SLA (which is independent of the phenophases) all 7 values should be set to the same value. This means backward compatibility with earlier Biome-BGC and BBGMuSo versions.

```
line 180
0.5    0.5     0.5    0.5    0.5     0.5     0.5  (prop.) current growth proportion
```

These parameters set the proportion of daily production that is displayed immediately as new growth, with the remainder stored for the next year's transfer growth. If the new growth in the next year is not possible due to e.g. crop harvest in autumn, this parameter can be set to zero. In this case all photosynthate will be allocated to new growth, and plant growth in the consecutive year will be suppressed until sowing. Note that some mechanism is implemented in BBGCMuSo that can override this parameter (see lines 26-29).

Note that in the original Biome-BGC model there were only 43 EPC parameters. BBGCMuSo 5 has a much higher number of EPC parameters, which means that the number of parameters increased substantially. We are fully aware that high number of adjustable parameters might complicate calibration and application of the model. However, our intention was to extend the EPC file with some of the parameters that were „burned in” within the source code but might need adjustment. Implementation of the new, multilayer soil module and fruit also involved the definition of new EPC parameters, similarly to drought related processes. In the simplest case these extra parameters should be left intact by the user. In any case, sensitivity analysis is needed to check whether the new parameters have strong influence on the variability of the output or not. The sensitivity analysis and the model optimization might be executed using the RBBGCMuSo R-based tool that is developed by our group. Contact us if you would like to use the R tool.

3.5 Restart file

Restart file provides all the information required to start one simulation from the endpoint of a previous simulation. The results of the restarted simulation are exactly the same as if the original simulation had been carried out for additional years. This option is typically used in conjunction with the spinup mode (described above) to initialize the soil carbon and nitrogen components for a site without adequate measurements of these characteristics. Users need only know the names of input and output restart files, and need not be concerned with the file contents.

3.6 Optional input files

3.6.1 Carbon-dioxide concentration and nitrogen-deposition files

As we mentioned in the description of INI file, it is possible to use annual varying CO_2 concentration and/or N-deposition data for transient and normal simulation phase. These files must have one line for each simulation year: the first value on the line is the year, and the second value is the CO_2 concentration and/or N-deposition data. It is important to note that although the text files contain the year of the actual data, the model neglects the date and uses data from the text files sequentially (first line for the first simulation year, second line for the second etc.).

3.6.2 Mortality and conductance files

In order to enable more realistic simulation of forest stand development (or disturbance events for other biomes) we implemented an option for supplying annually varying whole plant mortality to BBGC MuSo. It is also possible to set maximum stomatal conductance in an annually varying fashion (note that this can also be done automatically using line 8 in the EPC file). During the transient and the normal phase of the simulation the model can either use constant mortality and stomatal conductance, or it can read annually varying mortality and/or conductance defined by a text file (mortality_transient.txt, mortality_normal.txt, conductance_transient.txt, conductance_normal.txt – the filenames are fixed) which is/are supposed to be present next to the model executable (during spinup only constant mortality and conductivity is possible). The structure of these files is the same as the structure of the annually varying CO_2 concentration file or the annually varying N deposition file. Note that the current model version does NOT take into account the year field in the mortality.txt or conductance.txt file (this is also true for the CO_2 and N deposition file): for the first year of the simulation the first line is used (regardless of the value of the year field); for the second year the second line is used etc. If external file(s) are provided by the User, the settings of whole plant mortality and/or maximum stomatal conductance within the EPC file are ignored by the model.

3.6.3 Groundwater file

Poorly drained forests (e.g. in boreal regions or in lowland areas) are special ecosystems where groundwater and flooding play an important role in soil hydrology and plant growth (Pietsch et al., 2003; Bond-Lamberty et al., 2007). In order to enable groundwater (vertically varying soil water saturation) effect on the ecosystems in BBGCMuSo we implemented an option to supply external information about the depth of the water table.

Groundwater depth is controlled by prescribing the depth of saturated zone (groundwater) within the soil. We assume that the User has information about groundwater depth from measurements or from another model (e.g. watershed hydrology model).

During the spinup and transient phase of the simulation the model can only use daily average data for one typical simulation year, defined by a text file (groundwater_spinup.txt; it must contain data exactly for 365 days). During the normal phase of the simulation the model can read daily groundwater information defined by another external text file (groundwater_normal.txt). These files are supposed to be present next to the model executable. If the files are not present, no groundwater manipulation is happening (using this logic groundwater effect can not be represented at all, or can be represented only in spinup run (including transient), only in normal run, or in both phases if both txt files are present).

The structure of groundwater.txt and groundwater_spinup.txt is simple (it is similar to the structure of the annually varying CO_2 concentration file or the annually varying N deposition file: day of year, then groundwater depth in meters (positive value!) for the given day; note that in the other external files the first column is typically the year, so this file format is a special one). Note that the current model version does NOT take into account the day of year field in the file: for the first day of the simulation the first line is used (regardless of the value of the day field); for the second day the second line is used etc. The User should check whether the length of the groundwater file is in accordance with the length of the normal simulation.

The handling of the externally supplied groundwater information is the following. If the depth of the water table reaches the bottom boundary of the given soil layer, the groundwater-affected part of the given layer becomes saturated, therefore the average soil water content of the given layer increases. If the depth of the water table reaches the upper boundary of the given soil layer, the given layer becomes saturated.

Note that groundwater simulation was tested with the Richards equation based soil water balance method. The tipping bucket method that can be optionally used for soil water balance calculations might cause water balance error in some situations when groundwater file is present. We propose to set line 9 in the EPC file to 0 (Richards method) when using groundwater simulation.

3.6.4 External file to control growing season ("onday" and "offday" files)

In order to prescribe the phenological phases of plants based on diverse information sources (e.g. based on remote sensing observations of from external phenology models), we implemented an option to use annual varying, but user-defined yearday to start new growth and yearday to end litterfall (in brief, onday and offday). As we mentioned above, setting the parameter in line 5 of the EPC file to 0 means that the User provides onday and offday in lines 12 and 13 within the EPC file, which will be the same in each simulation year. This new model feature overrides this restriction.

During the transient and the normal phase of the simulation the model can either use constant onday and/or offday, or it can read annually varying onday and/or offday defined by a text file (onday_transient.txt, onday_normal.txt, offday_transient.txt, offday_normal.txt – the names of the files are fixed) which is supposed to be present next to the model executable. During spinup only constant onday and offday are possible, that is defined by the EPC file.

The structure of these files is the same as the structure of the annually varying CO_2 concentration file or the annually varying N deposition file. Note that the current model version does NOT take into account the year field in the txt file (this is true for the CO_2 and N deposition file): for the first year of the simulation the first line is used (regardless of the value of the year field); for the second year the second line is used etc.

4. Output files

There are two different styles of output produced by BBGC MuSo. The first type includes the output files controlled through the initialization file with information from the OUTPUT_CONTROL, DAILY_OUTPUT, and ANNUAL_OUTPUT sections. This is the most flexible output mechanism, since the user can control exactly which model variables to include in the output files, and what level of averaging to perform. The second type of output is a very simple formatted text file that contains annual summary information for each year of the simulation. This text output file is produced for all non-spinup simulations, and it uses a fixed list of output variables. These two output types are described in greater detail below.

4.1 Binary or ASCII output files

In BBGCMuSo 5.x the User can select the format of the output files. In BBGCMuSo 5.0 we introduced the possibility to create ASCII output files (=text files, which can be read by any text editor, word processor, Microsoft Excel, R or any other popular software). Binary file creation is still possible for backward compatibility and efficiency, but note that we moved to double precision floating point format, which means 8 byte storage space per number. Binary files are not text files, and you will not be able to read them with a text editor or word processor. Instead, they are data files containing binary representations of the values of the output variables (the common name of this file format is „flat binary"). Each value is written as a double precision IEEE floating point binary number (IEE, 2008) (using 8 bytes per number; see https://people.eecs.berkeley.edu/~wkahan/ieee754status/IEEE754.PDF for details). These values can be read directly using simple code written in C/C++, FORTRAN, BASIC, PASCAL, IDL, Python, R and other programming languages. They can also be read by many commercially available software packages. Interpretation and visualization of the model results is much easier in case of the ASCII files.

4.2 Annual text output

Because it can take some time to get used to the binary output formats, we also include a formatted text output file with annual summary information. For many applications this may be all the information required. In any case it allows a quick look at the results before proceeding with more detailed analyses. The name of the file is the user-supplied output prefix plus the following suffix "_ann.txt". Note that in BBGCMuSo we have added new output types to the annual output file including NBP and management related lateral carbon fluxes.

4.3 Log file

In BBGCMuSo some of the variables (mostly related to soil processes) are calculated internally by the model code, so they are not accessible by the user in a simple way. Also, due to options related to soil water content/temperature and phenology calculations, information about the actual configuration might not be available after model execution in a simplistic way. Another problem is that getting information about the successfulness of the simulation is not always possible in batch processing mode (e.g. during Monte-Carlo simulations).

Based on this reasoning we have extended the model to create another file with essential information about the model simulation in terms of configuration and technical aspects. This file is called as the log file (with .log extension; they are pure text files). Spinup and normal runs have their own log file. Using the log file it is easy to decide whether the model simulation was successful or not: the last line of the log file shows the simulation status [0 - failure; 1 - success]. If no log file is generated, then the model clearly failed, so this is another option to check model simulation status. The log file also contains information about the most important, model-calculated parameters and optional input files.

Appendix D contains an example for the log file.

5. Code History

The BBGCMuSo ecosystem process model has a long heritage, and many people have contributed extensively to its development over many years. The following is a short synopsis of some of the most prominent code versions preceeding the current version BBGCMuSo 4.0.

Biome-BGC MuSo v5.0, Dóra Hidy, 2018 (C/C++)
Biome-BGC MuSo v4.1, Dóra Hidy, 2016 (C/C++)
Biome-BGC MuSo v4.0, Dóra Hidy, 2015 (C/C++)
Biome-BGC MuSo v1.0-3.0.8, Dóra Hidy (C/C++)
Biome-BGC version 4.1.1, Peter E. Thornton, 2000 (C/C++)
Biome-BGC version 4.1, Peter E. Thornton, 2000 (C/C++)
Biome-BGC version 2.0 (CRB-BGC), Peter E. Thornton, 1995 (C/C++)
Biome-BGC version 1.37, E. Raymond Hunt, Jr., 1993 (Pascal)
Forest-BGC, Joseph C. Coughlan, 1986 (Pascal)
DAYTRANS-PSN, Steven W. Running, 1981
DAYTRANS, Steven W. Running, 1975

Others who have contributed to the code in various ways and at various stages include: Galina Churkina, Tom Gower, Kathy Hibbard, Bob Keane, John Kimball, Lars Pierce, Joseph White, Michael White, Peter Anthony, Emil Cienciala, Beverly Law, Shaoxiu Ma, Ryan Anderson, Ben Bond-Lamberty, Nándor Fodor.

Please contact the authors for the source code of the model ot check the website of the model at http://nimbus.elte.hu/bbgc/. See also https://github.com/bpbond/Biome-BGC for useful information. Contact us if you would like to try the RBBGCMuSo R tool that will cover a wide functionality to support the application of Biome-BGCMuSo including sensitivity analysis, parameter estimation (i.e. calibration), visualization and others.

Acknowledgements

The research was funded by the Széchenyi 2020 programme, the European Regional Development Fund and the Hungarian Government (GINOP-2.3.2-15-2016-00028). Supported by grant "Advanced research supporting the forestry and wood-processing sectors adaptation to global change and the 4th industrial revolution", No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by OP RDE". During the years the model developments were supported by the Hungarian Scientific Research Fund (OTKA K104816), by BioVeL (Biodiversity Virtual e-Laboratory Project, FP7-INFRASTRUCTURES-2011-2, project number 283359), by GHG-Europe (Greenhouse gas management in European land use systems, FP7-ENVIRONMENT, EU contract number 244122), and by the CarpathCC project (ENV.D.1/FRA/2011/0006). Testing of different versions of the model was performed in the desktop grid test environment of the MTA SZTAKI PERL within a partnership agreement, and EDGeS@home desktop grid volunteer computing services are provided by the IDGF. We thank Galina Churkina for her continuous support in model development and application. We are also grateful to Eszter Lellei-Kovács for valuable suggestions regarding the model logic. We are extremely grateful to Shaoxiu Ma for providing us the source code of ANTHRO-BGC that led us to the simulation of fruit yield within BBGC MuSo. We also thank Ryan Anderson for providing us the source code of BBGCMuSo 4.3 beta, which enabled the inclusion of the new, enzyme-driven C4 photosynthesis routine into the model. We are grateful to Laura Dobor, Maša Zorana Ostrogović, Hrvoje Marjanović, Ferenc Horváth, Borbála Balázs, Krisztina Pintér and Klára Pokovai for model beta testing and overall support. We are grateful to Péter Ittzés and Attila Marosi for helping us in the implementation of desktop grid applications of BBGC MuSo. The authors acknowledge the financial support of MTA PD 450012.

Appendix A

EXAMPLE INI FILE FOR BBGCMUSO 5.0

```
BBGC_MuSo simulation (missing data: -9999)

MET_INPUT  (keyword - do not remove)
metdata/bugac_2009-2011.mtc43  (filename) met file name
4           (int) number of header lines in met file
365         (int) number of simdays in last simyear (truncated year: < 365)

RESTART
1             (flag) 1: read restart 0: don't read restart
0             (flag) 1: write restart 0: don't write restart
0             (flag) 1: use restart metyear 0: reset metyear
restart/bugacI.endpoint     (filename) name of the input restart file
restart/bugacO.endpoint     (filename) name of the output restart file

TIME_DEFINE
3                (int) number of meteorological data years
3                (int) number of simulation years
2009             (int) first simulation year
0                (flag) 1: spinup run 0: normal run
6000             (int) maximum number of spinup years

CLIM_CHANGE
0.0              (degC) offset for Tmax
0.0              (degC) offset for Tmin
1.0              (degC) multiplier for PRCP
1.0              (degC) multiplier for VPD
1.0              (degC) multiplier for RAD

CO2_CONTROL
1               (flag) 0=constant 1=vary with file
290.0           (ppm) constant atmospheric CO2 concentration
co2/CO2_2009-2011.txt           (filename) name of the CO2 file

NDEP_CONTROL
1               (flag) 0=constant 1=vary with file
0.001100        (kgN/m2/yr) wet+dry atmospheric Ndep
nitrogen/Ndep_1901-2000.txt         (filename) name of the N-dep file

CO2_CONTROL
1                 (flag) 0=constant; 1=vary with file
280               (ppm) constant atmospheric CO2 concentration
co2/CO2_1901-2000.txt            (filename) name of the CO2 file

NDEP_CONTROL
1                 (flag) 0=constant; 1=vary with file
0.001100          (kgN/m2/yr) wet+dry atmospheric N-dep
nitrogen/Ndep_1901-2000.txt      (filename) name of the N-dep file

SITE (keyword - do not remove)
78.5 78.5 78.5 84.7 92.7 92.7 92.7 92.7 92.7 92.7 (%) sand percentage by volume
8.6 8.6 8.6 6.0 2.9 2.9 2.9 2.9 2.9 2.9      (%) silt percentage by volume
7.0 7.0 7.0 7.0 7.0 7.0 7.0 7.0 7.0 7.0      (dimless) soil pH
111.4              (m) site elevation
46.69              (degrees) site latitude (- for S.Hem.)
0.20               (DIM) site shortwave albedo
11.00              (Celsius) mean annual air temperature
13.42              (Celsius) mean annual air temperature range
20.00              (mm) maximum height of pond water
-9999              (dimless) runoff curve number
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (g/cm3) bulk density
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at SAT
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at FC
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at WP
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999  (m3/m3) SWC at HW

EPC_FILE (keyword - do not remove)
epc/c3grass.epc                  (file) c3grass

W_STATE (keyword) start of water state variable initialization block
```

```
0.0            (kg/m2) water stored in snowpack
1.0            (DIM) initial soil water as a proportion of field capacity

CN_STATE (keyword) start of carbon state variable initialization block
0.001             (kgC/m2) first-year maximum leaf carbon
0.001             (kgC/m2) first-year maximum fine root carbon
0.001             (kgC/m2) first-year maximum fruit carbon
0.001             (kgC/m2) first-year maximum softstem carbon
0.001             (kgC/m2) first-year maximum live woody stem carbon
0.001             (kgC/m2) first-year maximum live coarse root carbon
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) coarse woody debris carbon
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (labile)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (unshield.cellulose)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (shielded cellulose)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) litter carbon (lignin)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (fast microb.recycl.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (medium microb.recyc.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (slow microb.recycl.)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) soil carbon (recalcitrant SOM)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) litter nitrogen, labile pool
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) soil mineralized N pool (ammonium)
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgN/m2) soil mineralized N pool (nitrate)

OUTPUT_CONTROL (keyword - do not remove)
outputs/bugac_apriori_MuSo5           (filename) output prefix
1          (flag)  writing daily output (0 = no; 1 = binary; 2 = ascii)
0          (flag)  writing monthly average of daily output (0=no; 1=binary; 2=ascii)
0          (flag)  writing annual average of daily output (0=no; 1=binary; 2=ascii)
2          (flag)  writing annual output (0=no; 1=binary; 2=ascii)
1          (flag)  for on-screen progress indicator

DAILY_OUTPUT (keyword)
5            number of daily output variables
3009              gross primary production (kgC/m2/day)
3014              total ecosystem respiration (kgC/m2/day)
171               latent heat flux/evapotranspiration (kgH2O/m2/day)
2520              leaf area index (m2/m2)
3055              total soil carbon (kgC/m2)

ANNUAL_OUTPUT (keyword)
4              number of annual output variables
0              onday - start of the vegetation period (DOY)
1              offday - end of the vegetation period (DOY)
2765           yearly maximum of leaf area index (m2/m2)
3024           cumulative sum of net ecosystem exchange (kgC/m2)

-------------------
MANAGEMENT_SECTION
-------------------
PLANTING (keyword)
0             (flag) do PLANTING? 0=no; 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(yday)  PLANTING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(m) germination depth
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(n/m2) number of seedlings
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(g/1000n) weight of 1000-seed
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(%) C content of seed
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(%) emergence rate

THINNING
0             (flag) do THINNING? 0=no; 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(yday) THINNING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(prop) woody thinning rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(prop) non-woody thinning rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of stem
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of leaf


MOWING (keyword)
0           (flag) do MOWING? 0=no; 1=yes; filepath=reading from file
0           (flag) mowing method? 0 - fixday method, 1 - fixvalue method
-9999       (m2/m2) fixed value of the LAI before MOWING (fixvalue method)
-9999          (m2/m2) fixed value of the LAI after MOWING (fixvalue method)
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(yday) MOWING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(m2/m2)LAI after MOWING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999   *(%) transported part of biomass

GRAZING (keyword)
```

```
0                  (flag) do GRAZING? 0=no, 1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) first day of GRAZING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) last day of GRAZING
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/LSU) weight equivalent LSU
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(LSU/ha) animal stocking rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg DM/LSU) daily ingested DM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(prop) trampling effect
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%)ratio of DMintake to excrement
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%)ratio of excrement to litter
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) carbon content of dry matter
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) N content of manure
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) C content of manure
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN2O-N:kgN) manure EF for N2O
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN/1000 kg/d) N excretion rate
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgCH4/LSU/y )manure EF for CH4
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgCH4/LSU/y) ferment. EF for CH4

HARVESTING (keyword)
1                  (flag)do HARVESTING? 0=no,1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) HARVESTING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgC/m2) softstem C after harvest
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) transported part of biomass

PLOUGHING (keyword)
0                 (flag) do PLOUGHING? 0=no,1=yes or file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(yday) PLOUGHING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(m) PLOUGHING depth
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999     *(prop) dissolving coefficient

FERTILIZING (keyword)
0                  (flag) do FERTILIZING?0=no,1=yes file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(yday) FERTILIZING day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(m) fertilizing depth
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kg/ha/day) amount of fert.
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) dry matter content of fert.
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN/kg) nitrate cont. of fertDM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN/kg) ammonium cont. of fertDM
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN/kg) organic nitrogen content
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgC/kg) organic carbon content
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) labile fraction of fertilizer
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) unshielded cellulose fraction
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) shielded cellulose fraction
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(%) lignin  fraction of
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 *(kgN2O-N:kgN) EF for N-additions

IRRIGATION (keyword)
0            (flag) do IRRIGATION? 0=no, 1=yes; filepath=reading from file
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(yday) IRRIGATION day
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(kgH2O/m2/day) amount of water
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999    *(%) utilization coefficient

END_INIT
```

Appendix B
EXAMPLE EPC FILE FOR BBGCMUSO 5

```
ECOPHYS FILE -    C3 grass muso5
--------------------------------------------------------------------------------------
FLAGS
0 (flag)  biome type flag (1 = WOODY 0 = NON-WOODY)
0 (flag)  woody type flag (1 = EVERGREEN 0 = DECIDUOUS)
1 (flag)  photosyn. type flag (1 = C3 PSN 0 = C4 PSN)
1 (flag)  phenology flag (1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY)
0 (flag)  transferGDD flag (1= transfer calc. from GDD 0 = transfer calc. from EPC)
1 (flag)  q10 flag (1 = temperature dependent q10 value; 0= constans q10 value)
0 (flag)  acclimation flag (1 = acclimation 0 = no acclimation)
1 (flag)  CO2 conductance reduction flag (0: no effect, 1: multiplier)
1 (flag)  use GSI index to calculate growing season (0: no GSI, 1: GSI)
0 (flag)  soil temperature calculation method (0: Zheng, 1: DSSAT)
1 (flag)  soil hydrological calculation method (0: Richards, 1: tipping DSSAT)
0 (int)   discretization level of SWC calculation (0: low, 1: medium, 2: high)
0 (flag)  photosynthesis calculation method (0: Farquhar, 1: DSSAT)
0 (flag)  evapotranspiration calculation method (0: Penman-Montieth, 1: Priestly-Taylor)
0 (flag)  radiation calculation method (0: SWabs, 1: Rn)
--------------------------------------------------------------------------------------
PLANT FUNCTIONING PARAMETERS
0   (yday)  yearday to start new growth (when phenology flag = 0)
364 (yday)  yearday to end litterfall (when phenology flag = 0)
0.5 (prop.)  transfer growth period as fraction of growing season (when transferGDD_flag = 0)
0.5 (prop.)  litterfall as fraction of growing season (when transferGDD_flag = 0)
5   (Celsius)  base temperature
0   (Celsius)  minimum  temperature for growth displayed on current day (-9999: no T-dep.)
10  (Celsius)  optimal1 temperature for growth displayed on current day (-9999: no T-dep.)
30  (Celsius)  optimal2 temperature for growth displayed on current day (-9999: no T-dep.)
40  (Celsius)  maxmimum temperature for growth displayed on current day (-9999: no T-dep.)
0  (Celsius) minimum  temperature for carbon assimilation displayed on current day (-9999: no)
10 (Celsius) optimal1 temperature for carbon assimilation displayed on current day (-9999: no)
30 (Celsius) optimal2 temperature for carbon assimilation displayed on current day (-9999: no)
50 (Celsius) maxmimum temperature for carbon assimilation displayed on current day (-9999: no)
1.   (1/yr)  annual leaf and fine root turnover fraction
0.00 (1/yr)  annual live wood turnover fraction
0.05 (1/yr)  annual whole-plant mortality fraction
0.0  (1/yr)  annual fire mortality fraction
25.0 (kgC/kgN) C:N of leaves
45.0 (kgC/kgN) C:N of leaf litter, after retranslocation
50.0 (kgC/kgN) C:N of fine roots
25.0 (kgC/kgN)  C:N of fruit
25.0 (kgC/kgN)   C:N of soft stem
0.0  (kgC/kgN) C:N of live wood
0.0  (kgC/kgN) C:N of dead wood
0.68 (DIM)  leaf litter labile proportion
0.23 (DIM)  leaf litter cellulose proportion
0.34 (DIM)  fine root labile proportion
0.44 (DIM)  fine root cellulose proportion
0.68 (DIM)  fruit litter labile proportion
0.23 (DIM)  fruit litter cellulose proportion
0.68 (DIM)  soft stem litter labile proportion
0.23 (DIM)  soft stem litter cellulose proportion
0.00 (DIM)  dead wood cellulose proportion
0.01 (1/LAI/d) canopy water interception coefficient
0.50 (DIM)  canopy light extinction coefficient
2.0  (g/MJ)   potential radiation use efficiency
0.781  (DIM)  radiation parameter1 (Jiang et al.2015)
-13.59 (DIM)  radiation parameter2 (Jiang et al.2015)
2.0    (DIM)  all-sided to projected leaf area ratio
2.0    (DIM)  ratio of shaded SLA:sunlit SLA
0.2    (DIM)  fraction of leaf N in Rubisco
0.03   (DIM)  fraction of leaf N in PEP Carboxylase
0.004    (m/s) maximum stomatal conductance (projected area basis)
0.00006 (m/s) cuticular conductance (projected area basis)
0.04     (m/s)  boundary layer conductance (projected area basis)
1.00     (prop)  relative SWC (prop. to FC)  to calc. soil moisture limit 1 (-9999: not used)
0.99     (prop)  relative SWC (prop. to SAT) to calc. soil moisture limit 2 (-9999: not used)
-9999    (prop)  relative PSI (prop. to FC)  to calc. soil moisture limit 1 (-9999: not used)
```

```
-9999 (prop)  relative PSI (prop. to SAT) to calc. soil moisture limit 2 (-9999: not used)
1000  (Pa)  vapor pressure deficit: start of conductance reduction
5000  (Pa)  vapor pressure deficit: complete conductance reduction
1.5   (m)   maximum height of plant
250   (kgC/m2)  stem weight at which maximum height attended
1.0   (m)   maximum depth of rooting zone
3.67  (DIM)   root distribution parameter
0.4   (kgC/m2) rootlenght parameter 1 (estimated max root weight)
0.5   (prop.)  rootlenght parameter 2 (slope)
0.3   (prop.)  growth resp per unit of C grown
0.218  (kgC/kgN/d)  maintenance respiration in kgC/day per kg of tissue N
0.1    (DIM)      theoretical maximum prop. of non-structural and structural carbohydrates
0.3    (DIM)  prop. of non-structural carbohydrates available for maintanance respiration
0.0005 (kgN/m2/yr)  symbiotic+asymbiotic fixation of N
-------------------------------------------------------------------------------------
CROP SPECIFIC PARAMETERS
0     (DIM)      number of phenophase of germination (from 1 to 7; 0: NO specific)
0     (DIM)      number of phenophase of emergence (from 1 to 7; 0: NO specific)
0.5   (prop.)    critical relative SWC (prop. to FC) in germination
-9999 (DIM)      number of phenophase of photoperiodic slowing effect (from 1 to 7; -9999: NO)
20    (hour)     critical photoslow daylength
0.005 (DIM)      slope of relative photoslow development rate
-9999 (DIM)      number of phenophase of vernalization (from 1 to 7; -9999: NO)
0     (Celsius)  critical vernalization temperature 1
5     (Celsius)  critical vernalization temperature 2
8     (Celsius)  critical vernalization temperature 3
15    (Celsius)  critical vernalization temperature 4
0.04  (DIM)      slope of relative vernalization development rate
50    (n)        required vernalization days (in vernalization development rate)
-9999 (DIM)      number of flowering phenophase (from 1 to 7; -9999: NO effect)
35    (Celsius)  critical flowering heat stress temperature 1
40    (Celsius)  critical flowering heat stress temperature 2
0.2   (prop.)    mortality parameter of flowering thermal stress
-------------------------------------------------------------------------------------
SENESCENCE AND SOIL PARAMETERS
0.05    (prop.)  maximum senescence mortality coefficient of aboveground plant material
0.05    (prop.)  maximum senescence mortality coefficient of belowground plant material
0.0     (prop.)  maximum senescence mortality coefficient of non-structured plant material
2       (prop)   effect of extreme high temperature on senesncene mortality
30      (Celsius) lower limit extreme high temperature effect on senescence mortality
40      (Celsius) upper limit extreme high temperature effect on senescence mortality
-9999   (Celsius) maximal lifetime of plant tissue  (-9999: no gen.prog.senescence)
0.01    (prop.)  turnover rate of wilted standing biomass to litter
0.05    (prop.)  turnover rate of non-woody cut-down biomass to litter
0.01    (prop.)  turnover rate of woody cut-down biomass to litter
30      (prop.)  drought tolerance parameter (critical value of DSWS)
0.02    (prop.)  denitrification rate per g of CO2 respiration of SOM
0.5     (prop.)  nitrification coefficient 1
0.4     (prop.)  nitrification coefficient 2
0.02    (prop.)  coefficient of N2O emission of nitrification
0.5     (prop.)  proprortion of NH4 flux of N-deposition
0.5     (prop.)  NH4 mobilen proportion
1.0     (prop.)  NO3 mobilen proportion
10      (m)      e-folding depth of decomposition rate's depth scalar
0.001   (prop.)  fraction of dissolved part of SOIL1 organic matter
0.001   (prop.)  fraction of dissolved part of SOIL2 organic matter
0.001   (prop.)  fraction of dissolved part of SOIL3 organic matter
0.001   (prop.)  fraction of dissolved part of SOIL4 organic matter
0.6     (DIM)      ratio of bare soil evaporation and pot.evaporation
-------------------------------------------------------------------------------------
RATE SCALARS
0.39    (DIM)   respiration fractions for fluxes between compartments (l1s1)
0.55    (DIM)   respiration fractions for fluxes between compartments (l2s2)
0.29    (DIM)   respiration fractions for fluxes between compartments (l4s3)
0.28    (DIM)   respiration fractions for fluxes between compartments (s1s2)
0.46    (DIM)   respiration fractions for fluxes between compartments (s2s3)
0.55    (DIM)   respiration fractions for fluxes between compartments (s3s4)
0.7     (DIM)   rate constant scalar of  labile litter pool
0.07    (DIM)   rate constant scalar of cellulose litter pool
0.014   (DIM)   rate constant scalar of lignin litter pool
0.07    (DIM)   rate constant scalar of  fast microbial recycling pool
0.014   (DIM)   rate constant scalar of  medium microbial recycling pool
0.0014  (DIM)   rate constant scalar of  slow microbial recycling pool
0.0001  (DIM)   rate constant scalar of  recalcitrant SOM (humus) pool
0.001   (DIM)   rate constant scalar of  physical fragmentation of coarse woody debris
-------------------------------------------------------------------------------------
GROWING SEASON PARAMETERS
```

```
5    (kg/m2)  crit. amount of snow limiting photosyn.
20   (Celsius)  limit1 (under:full constrained) of HEATSUM index
60   (Celsius)  limit2 (above:unconstrained) of HEATSUM index
0    (Celsius)  limit1 (under:full constrained) of TMIN index
5    (Celsius)  limit2 (above:unconstrained) of TMIN index
4000 (Pa)  limit1 (above:full constrained) of VPD index
1000 (Pa)  limit2 (under:unconstrained) of VPD index
0    (s)   limit1 (under:full constrained) of DAYLENGTH index
0    (s)   limit2 (above:unconstrained) of DAYLENGTH index
10   (day) moving average (to avoid the effects of extreme events)
0.10 (dimless)  GSI limit1 (greater that limit -> start of vegper)
0.01 (dimless)  GSI limit2 (less that limit -> end of vegper)
-------------------------------------------------------------------------------------
CH4 PARAMETERS
212.5  (DIM)   param1 for CH4 calculations (empirical function of BD)
1.81   (DIM)   param2 for CH4 calculations (empirical function of BD)
-1.353 (DIM)   param1 for CH4 calculations (empirical function of VWC)
0.2    (DIM)   param2 for CH4 calculations (empirical function of VWC)
1.781  (DIM)   param3 for CH4 calculations (empirical function of VWC)
6.786  (DIM)   param4 for CH4 calculations (empirical function of VWC)
0.010  (DIM)   param1 for CH4 calculations (empirical function of Tsoil)
-------------------------------------------------------------------------------------
PHENOLOGICAL (ALLOCATION) PARAMETERS (7 phenological phases)
phase1 phase2 phase3 phase4 phase5 phase6 phase7 (text) name of the phenophase
500    200   500     200    400    200   100     (Celsius) length of phenophase (GDD)
0.4    0.4   0.4     0.4    0.4    0.4   0.4     (ratio) leaf ALLOCATION
0.2    0.2   0.2     0.2    0.2    0.2   0.2     (ratio) fine root ALLOCATION
0.2    0.2   0.2     0.2    0.2    0.2   0.2     (ratio) fruit ALLOCATION
0.2    0.2   0.2     0.2    0.2    0.2   0.2     (ratio) soft stem ALLOCATION
0      0     0       0      0      0     0       (ratio) live woody stem ALLOCATION
0      0     0       0      0      0     0       (ratio) dead woody stem ALLOCATION
0      0     0       0      0      0     0       (ratio) live coarse root ALLOCATION
0      0     0       0      0      0     0       (ratio) dead coarse root ALLOCATION
49     49    49      49     49     49    49      (m2/kgC) canopy average specific leaf area
0.5    0.5   0.5     0.5    0.5    0.5    0.5    (prop.) current growth proportion
```

Appendix C
EXAMPLES FOR ANCILLARY MANAGEMENT FILES

Examples are given here for the content of the externally defined ancillary management types that is a new feature of BBGC MuSo. Note that these examples assume that the simulation is performed for 3 years (i.e. the 7-event-lines are repeated 3 times). In any case, the 7-event lines have to be defined separately for each simulation years in each block.

Ancillary file for annually varying planting

```
(yday)  PLANTING day
154 -9999 -9999 -9999 -9999 -9999 -9999
141 -9999 -9999 -9999 -9999 -9999 -9999
166 -9999 -9999 -9999 -9999 -9999 -9999
(m) germination depth
0.1 -9999 -9999 -9999 -9999 -9999 -9999
0.1 -9999 -9999 -9999 -9999 -9999 -9999
0.1 -9999 -9999 -9999 -9999 -9999 -9999
(n/m2) number of seedlings
7   -9999 -9999 -9999 -9999 -9999 -9999
7   -9999 -9999 -9999 -9999 -9999 -9999
7   -9999 -9999 -9999 -9999 -9999 -9999
(g/1000 seed) 1000-seed weight
300 -9999 -9999 -9999 -9999 -9999 -9999
300 -9999 -9999 -9999 -9999 -9999 -9999
300 -9999 -9999 -9999 -9999 -9999 -9999
(%)  C content of seed
40  -9999 -9999 -9999 -9999 -9999 -9999
40  -9999 -9999 -9999 -9999 -9999 -9999
40  -9999 -9999 -9999 -9999 -9999 -9999
(%) emergence rate of seed
95  -9999 -9999 -9999 -9999 -9999 -9999
95  -9999 -9999 -9999 -9999 -9999 -9999
95  -9999 -9999 -9999 -9999 -9999 -9999
```

Ancillary file for annually varying thinning

```
THINNING day
200  -9999 -9999 -9999 -9999 -9999 -9999
250  -9999 -9999 -9999 -9999 -9999 -9999
300  -9999 -9999 -9999 -9999 -9999 -9999
thinning rate
0.5  -9999 -9999 -9999 -9999 -9999 -9999
0.7  -9999 -9999 -9999 -9999 -9999 -9999
0.6  -9999 -9999 -9999 -9999 -9999 -9999
transported part of stem
100. -9999 -9999 -9999 -9999 -9999 -9999
100. -9999 -9999 -9999 -9999 -9999 -9999
100. -9999 -9999 -9999 -9999 -9999 -9999
transported part of leaf
100. -9999 -9999 -9999 -9999 -9999 -9999
100. -9999 -9999 -9999 -9999 -9999 -9999
100. -9999 -9999 -9999 -9999 -9999 -9999
```

Ancillary file for annually varying mowing

```
MOWING day
150  234  -9999 -9999 -9999 -9999 -9999
200 -9999 -9999 -9999 -9999 -9999 -9999
140  224  -9999 -9999 -9999 -9999 -9999
value of the LAI after MOWING (method0)
1.0 1.0  -9999 -9999  -9999 -9999 -9999
1.0 1.0  -9999 -9999  -9999 -9999 -9999
1.0 1.0  -9999 -9999  -9999 -9999 -9999
transported part of plant material
95. 95.  -9999 -9999 -9999 -9999 -9999
95. 95.  -9999 -9999 -9999 -9999 -9999
95. 95.  -9999 -9999 -9999 -9999 -9999
```

Ancillary file for annually varying grazing

```
(yday) first day of GRAZING
149     273   -9999   -9999   -9999   -9999   -9999
149     273   -9999   -9999   -9999   -9999   -9999
149     273   -9999   -9999   -9999   -9999   -9999
(yday) last day of GRAZING
211     349   -9999   -9999   -9999   -9999   -9999
211     349   -9999   -9999   -9999   -9999   -9999
211     349   -9999   -9999   -9999   -9999   -9999
(kg/LSU) weight equivalent of one unit
381.    381.   -9999   -9999   -9999   -9999   -9999
381.    381.   -9999   -9999   -9999   -9999   -9999
381.    381.   -9999   -9999   -9999   -9999   -9999
(LSU/ha) animal stocking rate: Livestock Units per hectare
1.4     1.4   -9999   -9999   -9999   -9999   -9999
1.4     1.4   -9999   -9999   -9999   -9999   -9999
1.4     1.4   -9999   -9999   -9999   -9999   -9999
(kg dry matter/LSU) daily ingested dry matter
8.6     8.6   -9999   -9999   -9999   -9999   -9999
8.6     8.6   -9999   -9999   -9999   -9999   -9999
8.6     8.6   -9999   -9999   -9999   -9999   -9999
(prop) trampling effect (standing dead biome to litter)
1.50    1.50   -9999   -9999   -9999   -9999   -9999
1.50    1.50   -9999   -9999   -9999   -9999   -9999
1.50    1.50   -9999   -9999   -9999   -9999   -9999
(%) ratio of DM intake formed excrement
25.0    25.0   -9999   -9999   -9999   -9999   -9999
25.0    25.0   -9999   -9999   -9999   -9999   -9999
25.0    25.0   -9999   -9999   -9999   -9999   -9999
(%) ratio of excrement returning to litter
100.    100.   -9999   -9999   -9999   -9999   -9999
100.    100.   -9999   -9999   -9999   -9999   -9999
100.    100.   -9999   -9999   -9999   -9999   -9999
(%) carbon content of dry matter
43.     43.   -9999   -9999   -9999   -9999   -9999
43.     43.   -9999   -9999   -9999   -9999   -9999
43.     43.   -9999   -9999   -9999   -9999   -9999
(%) N content of manure
2.0     2.0   -9999   -9999   -9999   -9999   -9999
2.0     2.0   -9999   -9999   -9999   -9999   -9999
2.0     2.0   -9999   -9999   -9999   -9999   -9999
(%) C content of manure
40.     40.   -9999   -9999   -9999   -9999   -9999
40.     40.   -9999   -9999   -9999   -9999   -9999
40.     40.   -9999   -9999   -9999   -9999   -9999
(kgN2O-N:kgN) manure emission factor for direct N2O (T10.21)
0.01    0.01   -9999   -9999   -9999   -9999   -9999
0.01    0.01   -9999   -9999   -9999   -9999   -9999
0.01    0.01   -9999   -9999   -9999   -9999   -9999
(kgN/1000 kg animal mass/day) default N excretion rate (T10.19)
0.35    0.35   -9999   -9999   -9999   -9999   -9999
0.35    0.35   -9999   -9999   -9999   -9999   -9999
0.35    0.35   -9999   -9999   -9999   -9999   -9999
(kgCH4/LSU/yr*) manure emission factor for CH4 (T10.14)
8.0     8.0   -9999   -9999   -9999   -9999   -9999
8.0     8.0   -9999   -9999   -9999   -9999   -9999
8.0     8.0   -9999   -9999   -9999   -9999   -9999
(kgCH4/LSU/yr*) fermentation emission factor for CH4 (T10.11)
58.0    58.0   -9999   -9999   -9999   -9999   -9999
58.0    58.0   -9999   -9999   -9999   -9999   -9999
58.0    58.0   -9999   -9999   -9999   -9999   -9999
```

Ancillary file for annually varying harvesting

```
(yday) HARVESTING day
256 -9999 -9999 -9999 -9999 -9999 -9999
243 -9999 -9999 -9999 -9999 -9999 -9999
276 -9999 -9999 -9999 -9999 -9999 -9999
(kgC/m2) soft stem C content after HARVESTING
0.01 -9999 -9999 -9999 -9999 -9999 -9999
0.01 -9999 -9999 -9999 -9999 -9999 -9999
0.01 -9999 -9999 -9999 -9999 -9999 -9999
```

```
(%) transported part of plant material
70. -9999 -9999 -9999 -9999 -9999 -9999
70. -9999 -9999 -9999 -9999 -9999 -9999
70. -9999 -9999 -9999 -9999 -9999 -9999
```

Ancillary file for annually varying ploughing

```
(yday) PLOUGHING day
152 -9999 -9999 -9999 -9999 -9999 -9999
139 -9999 -9999 -9999 -9999 -9999 -9999
164 -9999 -9999 -9999 -9999 -9999 -9999
(m) PLOUGHING depth
0.3 -9999 -9999 -9999 -9999 -9999 -9999
0.3 -9999 -9999 -9999 -9999 -9999 -9999
0.3 -9999 -9999 -9999 -9999 -9999 -9999
(prop) dissolving coefficient of ploughed biome to litter
0.10 -9999 -9999 -9999 -9999 -9999 -9999
0.10 -9999 -9999 -9999 -9999 -9999 -9999
0.10 -9999 -9999 -9999 -9999 -9999 -9999
```

Ancillary file for annually varying fertilizing

```
(yday) FERTILIZING day
151   -9999  -9999   -9999   -9999  -9999 -9999
138   -9999  -9999   -9999   -9999  -9999 -9999
163   -9999  -9999   -9999   -9999  -9999 -9999
(m) fertilizing depth
0.10  -9999  -9999  -9999  -9999 -9999 -9999
0.10  -9999  -9999  -9999  -9999 -9999 -9999
0.10  -9999  -9999  -9999  -9999 -9999 -9999
(kg fertilizer/ha/day) amount of fertilizer
159  -9999  -9999  -9999  -9999  -9999  -9999
152  -9999  -9999  -9999  -9999  -9999  -9999
131  -9999  -9999  -9999  -9999  -9999  -9999
(%) dry matter content of fertilizer
6  -9999  -9999  -9999  -9999  -9999  -9999
6  -9999  -9999  -9999  -9999  -9999  -9999
6  -9999  -9999  -9999  -9999  -9999  -9999
(kgN/kg fertilizer DM) nitrate content of fertilizer
0      -9999   -9999  -9999  -9999  -9999  -9999
0      -9999   -9999  -9999  -9999  -9999  -9999
0      -9999   -9999  -9999  -9999  -9999  -9999
(kgN/kg fertilizer DM) ammonium content of fertilizer
1.00    -9999   -9999  -9999  -9999  -9999  -9999
1.00    -9999   -9999  -9999  -9999  -9999  -9999
1.00    -9999   -9999  -9999  -9999  -9999  -9999
(kgN/kg fertilizer DM) organic nitrogen content of fertilizer
0.0559  -9999   -9999  -9999  -9999  -9999  -9999
0.0613  -9999   -9999  -9999  -9999  -9999  -9999
0.0642  -9999   -9999  -9999  -9999  -9999  -9999
(kgC/kg fertilizer DM) organic carbon content of fertilizer
0      -9999   -9999  -9999  -9999  -9999  -9999
0      -9999   -9999  -9999  -9999  -9999  -9999
0      -9999   -9999  -9999  -9999  -9999  -9999
(%) labile fraction of fertilizer organic DM
70    -9999   -9999  -9999  -9999  -9999  -9999
70    -9999   -9999  -9999  -9999  -9999  -9999
70    -9999   -9999  -9999  -9999  -9999  -9999
(%) unshielded cellulose fraction of fertilizer organic DM
0    -9999   -9999  -9999  -9999  -9999  -9999
0    -9999   -9999  -9999  -9999  -9999  -9999
0    -9999   -9999  -9999  -9999  -9999  -9999
(%) shielded cellulose fraction of fertilizer organic DM
0     -9999   -9999  -9999  -9999  -9999  -9999
0     -9999   -9999  -9999  -9999  -9999  -9999
0     -9999   -9999  -9999  -9999  -9999  -9999
(%) lignin  fraction of fertilizer organic DM
0    -9999   -9999  -9999  -9999  -9999  -9999
0    -9999   -9999  -9999  -9999  -9999  -9999
0    -9999   -9999  -9999  -9999  -9999  -9999
(kgN2O-N:kgN) emission factor for N-additions (IPCC 2006 Table 11.1.)
0.01  -9999  -9999  -9999  -9999  -9999  -9999
0.01  -9999  -9999  -9999   -9999  -9999 -9999
0.01  -9999  -9999  -9999  -9999  -9999  -9999
```

Ancillary file for annually varying irrigation

```
yday) IRRIGATION day
187     200     220     235     -9999   -9999   -9999
180     194     210     225     -9999   -9999   -9999
200     205     211     218     -9999   -9999   -9999
(kgH2O/m2/day) amount of water
130     130     130     130     -9999   -9999   -9999
130     130     130     130     -9999   -9999   -9999
130     130     130     130     -9999   -9999   -9999
(%) utilization coefficient of water
90      90      90      90      -9999   -9999   -9999
90      90      90      90      -9999   -9999   -9999
90      90      90      90      -9999   -9999   -9999
```

Appendix D

EXAMPLE LOG FILE CREATED BY BBGCMUSO 5

Abbreviations:
SWC: soil water content
PSI: soil water potential
SGS, EGS: start and end of growing season
GSI: growing season index (Hidy et al., 2012)
WPM: annual whole plant mortality
MSC: maximum stomatal conductance
GPP: gross primary production
NEE: net ecosystem exchange
ET: evapotranspiration
LAI: leaf are index
SOM: soil organic matter

```
NORMAL RUN


Critical SWC (m3/m3) and PSI (MPa) values of top soil layer
saturation:            0.440     -0.0007
field capacity:        0.250     -0.0128
wilting point:         0.090     -2.3146
hygroscopic water:          0.059   -158.4893
bulk density:          1.560
Clapp-Hornberger b parameter:    5.260


Soil calculation methods
hydrology   - DSSAT
temperature - MuSo


Data sources
SGS data - GSI method
EGS data - GSI method
WPM data - constant
MSC data - constant
management  - YES
groundwater - NO


Limitation values of SWC (m3/m3) and PSI (MPa) in top soil layer
SWC (limit1 and limit2):    0.250   0.436
PSI (limit1 and limit2):  -0.0128      -0.0007


Information about SGS and EGS values (yday of onday and offday)
SGS value (min and max):     62    106
EGS value (min and max):    288    324


Some important annual outputs from last simulation year
Cumulative sum of  GPP (gC/m2/year):           214.3
Cumulative sum of  NEE (gC/m2/year):           -13.3
Cumulative sum of  ET  (kgH2O/m2/year):        252.9
Cumulative sum of N2O flux (gN/m2/year):         0.1
Maximum projected LAI (m2/m2):             1.94
Humus carbon content (0-10 cm) (gC/kg soil):          10.0
SOM carbon content (0-10 cm) (gC/kg soil):       11.1
SOM nitrogen content (0-10 cm) (gN/kg soil):      1.7
Soil ammonium content (0-10 cm) (mgN/kg soil):         0.9
Soil nitrate content (0-10 cm) (mgN/kg soil):          3.2
SWC on last simulation day (0-4 m) (m3/m3):          0.159


10-base logarithm of the maximum carbon balance diff.:     -14.7
10-base logarithm of the maximum nitrogen balance diff.:   -15.4
10-base logarithm of the maximum water balance diff.:      -11.6
10-base logarithm of the C-N calc. numbering error:        -13.6


SIMULATION STATUS [0 - failure; 1 - success]
1
```

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