User's Guide for Biome-BGCMuSo 7.0

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Contents

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. Since 2007 our group has been developing 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 The modifications included structural improvements of the model (e.g., the simple, outdated, one-layer soil module was replaced by a multilayer soil module; drought related plant senescence was implemented; model phenology was improved) and management modules were also developed (e.g. to simulate mowing, grazing, fertilization, mulching, forest thinning, coarse woody debris extraction and clearcut). Beyond these modifications, additional modules were developed to simulate cropland management (e.g., planting, harvest, irrigation, ploughing, and application of fertilizers). Dynamic (annually varying) whole plant mortality and temporally varying maximum stomatal conductance parametrization was implemented in the model to enable more realistic simulations. Annually varying management options were also introduced. Since the Biome-BGCMuSo v4 model version, separate pools have been defined for yield following the method of Ma et al. (2011) to support cropland related simulations. In Biome-BGCMuSo v5.0 alternative photosynthesis and radiation calculation methods were implemented 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 (SOM) profile was introduced in the multilayer framework. The maintenance respiration calculation was modified correcting one problematic issue related to the non-structural carbohydrate calculation method of the original model. In recent model version crop rotation possibility was implemented to improve the simulation capability of agroecosystems. Using the crop rotation implementation now it is possible to define different plant types even within the same year. Plant type change is implemented with the usage of multiple *ecophysiological constants* (EPC) files. Conditional management (irrigation and mowing) was introduced to analyze the effect of different management strategies under climate change. Conditional mowing means that grass-cutting happens if the leaf area index reaches a predefined critical value. Conditional irrigation can be set such that irrigation happens if the soil moisture content reaches a critical value. Calculation of soil moisture stress index was corrected and simplified. We improved the simulation of harvest and fertilization as well. The input file structure has been significantly modified: the INI file contains the initialization information of the simulation, but meteorological, ecophysiological, soil properties and management data are handled separately (in previous versions prior to v6.0 soil properties and management data were all part of the INI file). New input (e.g. measured drain coefficient, measured hydraulic coefficient, ratio of dry matter and carbon content) and new output variables (e.g. cumulated evaporation and transpiration) were introduced in the new model versions. Due tot he latest developments, Biome-BGCMuSo v7.0 is capable of simulating upward capillary flow from groundwater (Hidy et al., 2022), making it suitable for assessing the influence of shallow groundwater and soil moisture interactions on nutrient and carbon balance, crop physiological processes and yield responses. The new version also has the ability to simulate the water and nutrient infiltration from river flooding.

A **new and highly useful feature of Biome-BGCMuSo** is that the model now uses the time stamp data in the input files (daily meteorology input, annual carbon-dioxide concentration, annual nitrogen deposition, management, groundwater, flooding) and extracts data according to the time settings in the INI file. (Previous model versions neglected the year information in these files and the model simply used the text files sequentially: it used information from the beginning of the files regardless of the time information within these files! See also Section 3.3 of this document.) This feature significantly simplifies the construction of the input meteorology and ancillary files. Given the importance of this new development, we demonstrate this feature with an example. Assume that the User would like to run the model for the 2000-2017 time period (normal run), using spinup meteorology for the 1901-2000 time period. In previous model version this would imply the construction of *two separate* meteorology files – one that covers the 1901-2000 time period, and a second that covers the 2000-2017 time period. Thanks to the new developments now the User only has to construct *one meteorology file* covering the 1901-2017 time period. During the spinup run, appropriate data will be used from the meteorology file in case of proper INI file settings (first simulation year: 1901, number of simulation years: 100). During the normal phase the model will extract the 2000-2017 time period from the meteorology file and use it for the simulation, again, in case of appropriate INI file settings (first simulation year: 2000, number of simulation years: 18)! The same applies to the N deposition, CO_2 concentration and management input files. Additionally, now there is a new possibility to use data from an incomplete year as input data for the last simulation year (it means that simulation can be done for the ongoing, unfinished year until a given day).

The latest version of the model is Biome-BGCMuSo 7.0. The majority of the model modifications were published in Hidy et al. (2012), Hidy et al. (2016) and Hidy et al. (2022). We have a manuscript under preparation that focuses on the recent plant related developments. At the website of the model the CHANGELOG file contains a detailed list of modifications for the current model version.

This User's Guide was created to provide complete, application-oriented information for the use of the improved model. Note that Biome-BGCMuSo has many versions: v1.0, v1.1 v1.2, v1.3, v2.0, v2.1, v2.2, v2.3, v3.0, v4.0, v5.0, v6.0, v6.1, v6.2), but hereinafter only 7.0 is referred. Starting from Biome-BGCMuSo 6.0 it is possible to retrieve the model version with the command `muso.exe -v`.

Note that NTSG developed the original model with the inclusion of management using a novel disturbance handler module. In their implementation disturbance (or management) is described by a separate disturbance descriptor file. Our implementation of disturbance is similar to the NTSG approach in this sense, but the content of the management file differs substantially from the one used by NTSG.

2. Model description

Prior to application, the User might want to get information on the basic model. 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, daylight 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 validated and reliable 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), N-deposition (N-dep) and optional management 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 biomass, 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 the dynamics of 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 as structural biomass. Storage sub-pools store the amount that will appear next year (like a core or bud, or non-structural 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, 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 that in BBGCMuSo standing dead biomass and cut-down dead biomass pools are also defined. Another major difference is the representation of soil processes. In BBGCMuSo v7.0 a ten-layer soil submodel was implemented. The thicknesses of the active layers (layers 1-10) from the surface to the bottom are 3, 7, 20, 30, 30, 30, 30, 50, 200 and 600 cm (Table 1).

Table 1. Soil layers and their depth ranges used in BBGCMuSo v7.0

Layer 1	0-3 cm
Layer 2	3-10 cm
Layer 3	10-30 cm
Layer 4	30-60 cm
Layer 5	60-90 cm
Layer 6	90-120 cm
Layer 7	120-150 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 0.03 m, therefore it is represented at 0.015 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 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 a major source of nitrogen mineralization in the model; Thornton, 2000). The spinup phase consists of a number of "meteorological cycles" (the length of a cycle is determined by the number of simulation years set in the TIME_DEFINE section of the INI file; see below). The model examines the changes of soil and total carbon content of the ecosystem between these meteorological cycles. If the change is smaller than a pre-defined limit (a constant defined within the source code of Biome-BGCMuSo), the spinup phase ends. A new feature since BBGCMuSo v6.4 is that spinup ends at the end of the meteorological cycle if total soil carbon exceeds a predefined value (critical total soil carbon parameter in soil file, see later) − even if the soil and total carbon is not in equilibrium with the climate. 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 set by the User.

The usual strategy for CO_2 and N-deposition control is to use constant (preindustrial) values during the spinup phase, then to 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 behaviour 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 v7.0 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, 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.

A new feature of Biome-BGCMuSo 7.0 is the option for the modification of soil water content, soil organic carbon content, soil ammonium and nitrate content within the restart file (which defines the initial condition for the normal run). This additional control on the initial soil water content in the normal run resolves possible inconsistencies between spinup and normal simulation if soil parameters are changed. Another new feature is that the transient run now creates its own output file: an additional "_T" string marks the output filename to be different from the spinup output file.

3. Input files

3.1 Overview

BBGCMuSo uses at least four 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 (MET file). It contains daily values for air temperature, precipitation, humidity (in terms of daylight vapor pressure deficit), radiation (daylight average downward shortwave radiation), and daylength at the simulation site. It can contain any number of data records**. It is important to keep in mind that the 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 v7.0 is the possibility to use data from a truncated (incomplete) year as input 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, specific leaf area (SLA), maximum stomatal conductance, fire and non-fire mortality frequencies, allocation ratios, root morphology descriptors, parameters that affect V_{cmax} (maximum rate of carboxylation) and others.

The fourth required input file is the *soil properties* file (SOI file, having .soi file extension). It contains the detailed description of the soil at the site, including parameters such as soil composition, characteristic soil water content values (saturation, field capacity, wilting point, and hygroscopic water), bulk density, nitrogen cycle related parameters, decomposition related parameters etc. Some of the parameters were previously included in the EPC file in v4 and v5. **Note that a major re-arrangement of the EPC and SOI file was implemented in Biome-BGCMuSo relative to the earlier versions, so the User should check the proper format and content of the EPC and SOI file in case of migration from v4, v5 or v6.**

The most important optional input file is the *management* file (MGM file, having .mgm file extension) which allows the simulation of different human intervention (such as mowing, grazing, sowing, harvest, ploughing, irrigating, fertilizing and thinning). Note that new management parameters were introduced in MuSo7, so the User should check the proper management parameters.

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

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

Important note: there are some parameters (EPC and SOI, detailed in the following sections) where -9999 can be used as indicator of missing data. **-9999 cannot be used in other cases unless specifically stated in the manual!**

A NOTE ON USING SPECIAL CHARACTERS 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 consists of 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 are 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 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). 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 so that information in a specific 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.

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 (https://github.com/hollorol/RBBGCMuso). The work with RBBGCMuSo is much easier if you follow this convention as it helps the package to automatically identify the spinup or the normal INI files.

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

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)
MET/bugac_2009-2011.met  (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 (0, 1 or 2) for reading (1) or not reading (0) a restart file from the end of a previous simulation. (2) is used for a special case when the model uses the restart file except the soil water content information which is initialized in *Section W_STATE* (see below).
2) flag (1 or 0) for writing (1) or not writing (0) a restart file at the end of this simulation
3) input restart filename (including path if appropriate)
4) output restart filename (including path if appropriate)

Line 3) is only relevant when flag in line 1) is set to 1. Line 4) is only relevant when flag in line 2) is set to 1.

```
RESTART (keyword - do not remove)
1                  (flag) 1: read restart 0: don't read restart 2: read restart with VWCinit
0                  (flag) 1: write restart 0: don't write restart
bugacI.rst     (filename) name of the input restart file
bugacO.rst     (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 to run for this simulation
2) first simulation year (e.g. 1998)
3) flag (1 or 0) for spinup simulation (1) or normal simulation (0)
4) maximum number of spinup cycles to run in spinup model (note that the meaning of this variable changed in Biome-BGCMuSo v7.0; see below)

Line 1) should be equal to or less than the number of years of data in meteorological input data file. Line 2) defines the starting point for the simulation output, and is mainly used in the simple text output file (described below). Line 3) 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. **In the latest model version, there is a major change that should be considered. In v7.0 the maximum number of cycles has to be defined instead of the maximum number of years (that was the case in the previous model versions)!** One cycle means the number of years that is defined by line 1) starting with the year that is defined by line 2). The number of cycles of simulation for a spinup run will depend on the climate and vegetation characteristics.
There is a new option for a more flexible spinup control in this model version. If the critical (user-defined) total soil carbon content parameter (line 9 in SOI file) is -9999, then the spinup length is the function of soil carbon balance as described above. **However, if it is a positive number, the spinup length is determined by the provided number handled as the maximum number of spinup cycles!** If the simulated total soil carbon content reached the critical value (set in SOI file) in this case the spinup process stops even if the soil organic matter is not in equilibrium with the current climate. (This can be associated with some ecosystems e.g. in boreal climates, where the model can predict long-term accumulation of organic matter.)
Another new feature is the differentiation of spinup tolerance parameter (threshold that is used to reach equilibrium with the climate and is used to control the length of the spinup phase). In case of woody biomes, it is 0.0005, while it is 0.005 for non-woody biomes. This is justified by the dact that the interannual variability of soil carbon content is larger for non-woody biomes than for woody biomes, therefore the tolerance parameter is higher.

```
TIME_DEFINE (keyword - do not remove)
3               (int) number of simulation years
2009            (int) first simulation year
```

```
0               (flag) 1: spinup run 0: normal run
60              (int) maximum number of spinup cycles
```

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 during the simulation: 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 (typically used for spinup with preindustrial concentration around 290 ppm). 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_2009-2011.txt        (filename) name of the CO2 file
```

This external CO_2 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). BBGCMuSo v7.0 uses the year time stamp which was not the case for the predecessor model. Note that extended CO^2 files are also usable where only a subset is used for a given simulation (e.g. assume that the User constructed CO_2 data from 1958 to 2024 but the simulation only uses data from 2010 to 2020 from the extended file).

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
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, and the format of each line should be like this:

```
1895  0.015
```

where the first value is the year, and the second value is the N-deposition (kg N m^{-2} yr^{-1}). Time stamp is used (i.e. the year data) which means that extended N-deposition files are also usable where only a subset is used.

IMPORTANT NOTE: There is an option for extra N-addition during the spinup phase in order to accelerate the spinup. If this option is enabled, mineral N is added to the different soil layers during spinup to meet the demand. This function is optional in Biome-BGCMuSo 7.0 (in contrast to the original model versions). It is applicable only if the value used for constant atmospheric N deposition has a negative sign in the NDEP_CONTROL section of INI file.

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 7.0 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. As a result, 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, the 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_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
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. The User can simulate management in the transient phase (setting of management; see later).
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) site elevation in meters above mean sea level
2) site latitude in decimal degrees (negative values for southern hemisphere)

3) site shortwave albedo for bare soil (note that albedo is LAI-dependent in BBGCMuSo)

```
SITE (keyword - do not remove)
111.4                         (m) site elevation
46.69                         (degrees) site latitude(- for Southern Hem.)
0.20                          (DIM) site shortwave albedo
```

Section SOI_FILE
The next section begins with the keyword SOI_FILE. It has a single line:
1) the name of the input soil file

```
SOI_FILE (keyword - do not remove)
bugac_apriori_MuSo6.soi       (filename) SOI filename
```

Details on the format and content of this file are given later in this document.

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)
c3grass.epc                     (filename) EPC filename
```

Details on the format and content of this file are given later in this document.

Section MGM_FILE
The next section begins with the keyword MGM_FILE (management file). It has a single line:
1) the name of the input management file

```
MGM_FILE
none                            (filename) MGM filename (or "none")
```

In this example management is not used by the model. Details on the format and content of this file are given later in this document.

Section SIMULATION_CONTROL
The next section begins with the keyword *SIMULATION_CONTROL*.
In previous BBGCMuSo versions this block was part of the EPC file. These flags control the model simulation in terms of selected processes. There are so-called method flags (see below) that select specific algorithm of some processes. The default value of the method flags are 0 in all cases (from soil temperature calculation method flag to Ksat-estimation method flag).
Using these flags so-called algorithm ensemble can be performed which means that the selected simulation can be repeated using alternative logic for some processes (e.g. photosynthesis).
Note that in the previous versions of BBGCMuSo (starting from MuSo v1.0) an alternative soil hydrological calculation method was also available (based on Richards-method), but in BBGCMuSo v7.0 only tipping bucket method is available due to its better reliability.
SIMULATION_CONTROL the following lines:

1) **phenology flag**: it specifies how plant phenology will be handled during the simulation. A value of 1 invokes the internal phenology routine (including the optional HSGSI method, or the original model logic; see next paragraph), 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 (that will be constant across the years, which means zero interannual variability). 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 (calculated by e.g. another model; see below).

2) **GSI index to calculate growing season**: this switch is used to control the phenology submodel. It only has effect on the simulation if the 1) phenology flag (see previous paragraph) is set to 1. If this line 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 is set to 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 (i.e. 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).

3) **transferGDD flag**: it specifies 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 11 in the EPC file) 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. GDD is a measure of heat accumulation (calculated by taking the integral of temperature above a base temperature). In in case of natural ecosystems, the default value is 0, which means that the transfer rate is defined to be a linearly decreasing function that reaches zero on the last day of the transfer period. In case of arable crops the default value is 1, which means that the transfer period is defined by the EPC file by line 78) the extent of the transfer (flux from transfer pool to actual pool) is the linear function of GDD-increase).

4) **Q10 value flag**: the binary flag can be used to enable air temperature dependent (dynamic) 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=3.22-0.046Tday where Tday is the mean (average of minimum and maximum) temperature for a given day (Smith and Dukes, 2010).

5) **photosynthetic acclimation flag**: an integer flag specifying whether photosynthesis 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 based on the method of Dyukarev (2017). A value of 2 enables photosynthesis acclimation that 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) which were temperature-independent in the original code (Kattge and Knorr, 2007). Temperature dependency is calculated based on average temperature for the previous 30 days.

6) **respiration acclimation flag**: a binary flag specifying whether 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 acclimation is simulated. 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.

7) **CO_2-conductance reduction flag**: specifying whether maximum stomatal conductance should be affected by changing atmospheric CO_2 concentration or not (Franks et al., 2013). We recommend setting this flag to 1. This mechanism was missing from the original Biome-BGC.

8) **soil temperature calculation flag**: it specifies 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. The preferred method should be selected based on comparison with measurements at the specific site (if available).

9) **photosynthesis calculation flag**: this flag specifies 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). 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.

10) **evapotranspiration calculation flag**: specifying the evapotranspiration (ET) calculation method. 0 means that ET is simulated based on the Penman-Monteith method (original model logic), while 1 means simulation based on the Priestley-Taylor method. Note that the Priestley-Taylor method was implemented only in the latest (7.0) model version (in case of earlier model versions this flag must be set to 0).

11) **radiation calculation flag**: it specifies the radiation calculation method. 0 means that within the ET routine absorbed shortwave radiation drives ET, while 1 and 2 means that the internally calculated net radiation (Rn) drives the ET routine. In case of 1, Rn is estimated based on the method of Jiang et al. (2005), in case of 2, Rn is s calculated as the difference between net shortwave and net longwave radiation. 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.

12) **soilstress calculation method**: it specifies the soil moisture stress calculation method. Soil moisture stress affects photosynthesis, evapotranspiration and decomposition of SOC). 0 means that soil water stress is based on difference between the actual and the characteristic soil water content values. This method defines a value between 0 and 1 based on the amount of soil water that can be taken up from the root zone, which is used to characterise the degree of stress. 1 means that stress is based on transpiration demand. This alternative method compares the amount of daily evaporation with the amount of water in the root zone and produces a number between 0 and 1 to express the stress.

13) **canopy water interception calculation method**: it specifies the interception calculation method. 0 means that interception is simulated using the newly implemented method (starting from version 7.0), based on projected leaf area index. 1 means that interception is simulated using the original Biome-BGC logic based on live all-sided leaf area index. We have no recommendation for this flag. Testing is needed to see which one provides better simulation results.

14) **MR-deficit calculation method**: this flag specifies the calculation method of maintenance respiration deficit (MR-deficit). In previous Biome-BGCMuSo model versions and in the original Biome-BGC, maintenance respiration flux demands of different plant compartments were covered only from the photosynthate C pool, and therefore it could turn into negative if not enough new photosynthate was available (e.g. during the leafless season in mid-latitudes). This "credit-method" was not realistic; carbon demand should be covered from previously assimilated and stored carbon stocks (that is the storage/transfer pool in the model). Therefore, different types of deficit calculation methods were implemented. 0 means non-separated MR-deficit calculation, which means that all types of plant compartment associated storage carbon pools are available for all types of respiration demand. In other words, the non-structural carbohydrate is not tied to the specific plant compartments (stem, leaves, roots), but is hypothesized as one large pool of carbohydrate. 1 means compartment-separated MR-deficit calculation, meaning that the maintenance respiration cost of leaf/stem/yield/root should be covered from leaf/stem/yield/root storage pools. 2 means partially compartment-separated MR-deficit calculation (maintenance respiration cost of non-woody and woody biomass is handled separately, but e.g. within the woody biomass the

storage is handled together). 3 means that the C pool-deficit is enabled and negative C pool can be created (original method).

15) **Ksat-estimation method:** it specifies the calculation method of saturated hydraulic conductivity parameter (Ksat). If the flag is equal to 0, the model uses Ksat estimation based on exponential function of soil water content; if flag is equal to 1, Ksat estimation is based on power function of soil water content. Previous Biome-BGCMuSo versions and the original Biome-BGC used the power function estimation based on Cosby et al. (1984). Since BBGCMuSo v6.1, we switched to the exponential function methodology originating from the DSSAT model. In Bome-BGCMuSo 7.0 both methods can be used by adjusting this flag.

```
SIMULATION_CONTROL
1       (flag) phenology flag (1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY)
1       (flag) use GSI index to calculate vegper if MODEL PHENOLOGY is used (0:original,1:GSI)
0       (flag) transferGDD flag (1= transfer calc. from GDD 0 = transfer calc. from EPC)
1       (flag) q10 flag (1 = temperature dependent q10 value; 0= constant q10 value)
1       (flag) acclimation flag of photosynthesis (0 = no acc, 1 = Dyukarev, 2 KattgeKnorr)
1       (flag) acclimation flag of respiration (1 = acclimation 0 = no acclimation)
1       (flag) CO2 conductance reduction flag (0: no effect, 1: multiplier)
0       (flag) soil temperature calculation method (0: Zheng, 1: DSSAT)
0       (flag) photosynthesis calculation method (0: Farquhar, 1: DSSAT)
0       (flag) evapotranspiration calculation method (0: Penman-Monteith)
0       (flag) radiation calculation method (0: SWabs, 1: Rn (Jiang et al. 20005), 2:Rn=SW-LW)
0       (flag) soilstress calculation method (0: based on SWC, 1: based on transp. demand)
0       (flag) interception calculation method (exp. func. of LAI, 1: linear func. of LAI)
0       (flag) MR-deficit calculation method (0:non-sep, 1:organ-sep, 2:w-nw sep, 3:original)
0       (flag) Ksat-estimation method (0: exp. func., 1: power function of soil content)
```

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 defined as proportion of saturation which is no longer applicable)

```
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.
New feature of BBGCMuSo7.0 that line 2) can be used to set the initial water content of the normal run if the reading restart file flag (see above in *Section RESTART*) is set to 2.

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 soft stem 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 soft stem 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) C content of fast microb.recycl.soil pool
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) C content of medium microb.recyc.soil pool
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) C content of slow microb.recycl.soil pool
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0    (kgC/m2) C content of stable.soil pool
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). During 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 first-year plant carbon pool values, and no carbon in litter and soil pools. This is essentially a primary succession simulation, starting with no organic matter and a very meagre colonizing plant cover. The development of soil organic matter depends on the site's climate and external fluxes of nitrogen (deposition, fixation, leaching, and volatilization), as well as on the vegetation type. The final result is that soil and litter pools are in equilibrium with the 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 the User should use the restart from the spinup conditions.
A new feature in BBGCMuSo7.0 is the option to define initial CWD, litter, SOC and mineral N pools for the simulation. From line 12) to line 15) the User can set the initial value of soil organic carbon content, then from line 17) to line 18) the initial value of ammonium and nitrate content can be defined in each soil layers at the beginning of normal run.

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 CONDITIONAL_MANAGEMENT_STRATEGIES
This section begins with keyword CONDITIONAL_MANAGEMENT_STRATEGIES. It has the following 8 lines:
1) flag (0 or 1) to use (1) or not use (0) CONDITIONAL MOWING option
2) fixed value of leaf area index before CONDITIONAL MOWING
3) fixed value of leaf area index after CONDITIONAL MOWING
4) transported part of plant material after CONDITIONAL MOWING
5) flag (0, 1 or 2) for CONDITIONAL IRRIGATION (condIRGflag): 0 - no, 1 - based on SWCratio, 2 - based on SMSI
6) SWC ratio of rootzone before CONDITIONAL IRRIGATION (only if condIRGflag=1)
7) SMSI of rootzone before CONDITIONAL IRRIGATION (only if condIRGflag=2)
8) average soil water content ratio of root zone after CONDITIONAL IRRIGATION
8) maximum amount of irrigated water in CONDITIONAL IRRIGATION

```
CONDITIONAL_MANAGEMENT_STRATEGIES (keyword - do not remove)
0.0             (flag)  conditional mowing ? 0 - no, 1 - yes
0.0             (m2/m2) fixed value of the LAI before MOWING
0.0             (m2/m2) fixed value of the LAI after MOWING
0.0             (%)     transported part of plant material after MOWING
0               (flag)  conditional irrigation? 0 - no, 1 - yes
0.0             (prop)  SWCratio of rootzone before cond. IRRIGATION (only if condIRGflag=1)
0.0             (prop)  SMSI of rootzone before cond. IRRIGATION (only if condIRGflag=2)
0.0             (prop)  SWCratio of root zone after cond. IRRIGATION
0.0             (kgH2O/m2) maximum amount of irrigated water
```

This section is included to support implementation of different management strategies, but not in the usual way (where the latter means that management action happens on a predefined day; those "usual" management activities are defined in a separate management file), but instead it is triggered if a particular condition is met. In case of grasslands conditional mowing happens if the leaf area index of the grass reaches a threshold value (fixed value of the LAI before MOWING). The extent of the mowing is determined by the "fixed value of the LAI after MOWING" parameter. Conditional irrigation occurs if the soil moisture content of the simulated soil decreases below a threshold value. This critical value can be set by the critical soil water content ratio. The irrigated amount of water is determined by the soil water content ratio of the root zone after conditional irrigation parameter.

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, 2 or 3) not to write (0), to write file in binary output format (1) to write file in ASCII format (i.e. text, which means that the file can easily be read directly by Excel or Notepad) (2) or to write on the screen (3) the daily variables (output variables interpreted on daily scale)
3) flag (0, 1, 2 or 3) not to write (0), to write file in binary output format (1) to write file in ASCII format (i.e. text, which means that the file can easily be read directly by Excel or Notepad) (2) not to write (0), to write file in binary output format (1) to write file in ASCII format (i.e. text, which means that the file can easily be read directly by Excel or Notepad) (2) or to write on the screen (3) the annual averages of the daily variables
5) flag (0, 1, 2 or 3) not to write (0), to write file in binary output format (1) to write file in ASCII format (i.e. text, which means that the file can easily be read directly by Excel or Notepad) (2) or to write on the screen (3) the 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)
bugac_grass            (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)
3              number of daily output variables
3009           daily_gpp
3014           daily_tr
2520           proj_lai
```

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 the website of the model (https://nimbus.elte.hu/bbgc/files/MUSO7_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 https://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. There is one important exception if the User selected ASCII for the output file format in the OUTPUT_CONTROL section of the INI file. In this case the User must provide a descriptive comment (explanatory text for the output variable) after the index of the output parameter. This is needed as the header of the ASCII output file contains the descriptive comments of the variables. In case of binary or on-screen output writing descriptive comments are not necessary (there are no header lines in these cases).
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)
3              number of annual output variables
3060           litrc
3061           soilc
3063           sminn
```

The variables requested in this section are reported once each year (yearday 365, that is the last day of the year even in leap years) 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 organic 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).
Just like in case of DAILY_OUTPUT, if the User selected ASCII for the annual output file format in the OUTPUT_CONTROL section of the INI file, the User has to provide a descriptive comment (explanatory text for the output variable) after the index of the output parameter. This is needed as the header of the ASCII output file contains the descriptive comments of the variables. In case of binary or on-screen output writing descriptive comments are not necessary (there are no header lines in these cases as the binary output is flat binary without metadata).

Section END_INIT

The last section of the INI file consists only of the keyword END_INIT, signalling 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
```

3.3 Meteorological input file (MET 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.

In Biome-BGCMuSo 7.0 the model uses the year information (i.e. the time stamp in the file) for the normal simulation (this was not the case in earlier Biome-BGC and some earlier Biome-BGCMuSo versions - see also the Introduction). It means that the User might create a long meteorological data file covering many years and the model will use the appropriate years if model run is initiated for a subset of years (set by the INI file, using the 'first simulation year' defined within the *TIME_DEFINE* section). This new logic provides flexibility for the Biome-BGC community that was never available before.

Below is an example for a meteorological data (showing the first few lines) with four header lines:

```
Bugac, 2009-2011: input for MTCLIM v4.3
MTCLIM v4.3 OUTPUT FILE
year day 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  117.03    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 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 formatted spacing between the 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 (this is not a .csv file!).

The nine values required for each day are as follows:
1) year: the numerical year, repeated for each yearday in a given year
2) yday: the numerical day of the year, values must start with 1 (maximum is 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 (except in case of truncated last simulation year that is set in the MET_INPUT block of INI file; *number of simdays in last simyear, truncated year: <= 365*), with one line of data per day, and no separations between years.

As BBGCMuSo expects each year to have 365 days of data as maximum, leap years will have to be truncated by eliminating one day. **We suggest eliminating 31 December 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 spinup simulation, so they must be "recycled" enough times to match the number of requested simulation years. 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 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 daily max/min temperature and precipitation. The MT-CLIM code and documentation is available from the NTSG website: http://www.ntsg.umt.edu/project/mtclim. Automatic meteorological file retrieval is also possible within the RBBGCMuso package (using ERA5 reanalysis data).

In Biome-BGCMuSo v7.0 there is a major change in the simulation logic performed at the southern hemisphere (SH). Starting from version 7.0, in case of simulations performed at the southern hemisphere the first simulation day is always 3 July (DOY 184). This shift also affects the end of the simulation. The model internally estimates the shifted meteorological data (missing 184 days after the last meteorological year) as the average of the daily data from the previous years presented as a truncated meteorological dataset.

This logic is supplemented by a new feature in BBGCMuSo which is the possibility to use meteorological data from an incomplete (truncated) 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. Starting with Biome-BGCMuSo 7.0 the numbering of the simulation days starts from 1 (instead of 0) also in the daily output data.

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 Soil properties input file (SOI file)

This input file defines the physical, chemical and biological characteristics of the soil being simulated (including soil texture, decomposition constants and nitrogen cycle related parameters). Soil information is separated from the initialization file so that multiple initialization files can refer to the same soil properties file without any additional effort. Note that all SOI files must have the same structure (strictly following the predefined order), but not all lines are relevant to all vegetation types.

The following section describes the structure of the SOI file. The line number refers to the number of line in the text file (counting starts from 1; note that the text files might be in Windows or UNIX/Linux format as well). We provide the units for the parameter in question and a short text description (note that some parameters are dimensionless, and for such cases units are given as DIM). This is followed by a description of the given parameter.

During the development of the model it was inevitable to adjust some internal model parameters that were fixed in the source code of previous model versions. In Biome-BGCMuSo 7.0 a new SOI file structure was defined to support flexible adjustment of some additional soil parameters.

```
line 1
SOILPROP FILE - BBGCMuSo 7
```

The first line of each SOI file may start with the SOILPROP keyword, but this is optional. Some text must be present in the first line in any circumstances.

```
lines 2-3
-----------------------------------------------------------------------------------
SOIL GENERIC PARAMETERS
```

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

```
line 4
(m) depth of soil
```

This parameter defines the depth of the soil at a given site, which determines the potential maximum rooting depth of plants to be grown. Bedrock is supposed to act as the boundary at the bottom of the soil.

```
line 5
(prop.)   C:N ratio of labile soil pool (soil1)
```

Through this parameter the User can set the C:N ratio of fast microbial recycling soil organic matter pool. Proposed value is around 10.

```
line 6
(prop.)   C:N ratio of medium soil pool (soil2)
```

Through this parameter the User can set the C:N ratio of medium microbial recycling soil organic matter pool. Proposed value is around 15.

```
line 7
(prop.)   C:N ratio of slow soil pool (soil3)
```

Through this parameter the User can set the C:N ratio of slow microbial recycling soil organic matter pool.

```
line 8
(prop.)   C:N ratio of stable soil pool (soil4)
```

Through this parameter the User can set the C:N ratio of stable soil organic matter pool (recalcitrant SOM pool). Proposed value is around 12.

```
line 9
(kgC/m2)      total SOC content (critical value for spinup run
```

Through this parameter the User can affect the length of the spinup phase thus the initial condition for the normal run. If this parameter is set to a given value (total SOC in in the soil solumn in kgC/m^2), the spinup run ends when the total soil organic carbon content reaches this value. In absence of this predefined data (this happens if the User sets this parameter to -9999) the model will internally estimate the length of the spinup run using the equilibrium logic described above.

```
lines 10
(prop.)  NH4 mobilen proportion
```

Mobile ammonium proportion is the fraction of mineralized ammonium that is available for leaching and different biological processes (such as nitrification or denitrification and plant uptake). The proposed value is 0.1, but this value is uncertain. We assume that the entire nitrate amount is mobile (thus no quantification of nitrate mobile proportion is required).

```
line 11
(s/m) aerodynamic resistance of the soil surface
```

Aerodynamic resistance represents the evaporation from a wet surface. In potential evaporation calculation it is assumed that the resistance to vapor transport is equal to the resistance to sensible heat transport. In previous model versions this was set as a constant, and it was taken from observations over bare soil in tiger-bush in south-west Niger (it was 107 s m^{-1}). In this version we let the User adjust this parameter to increase flexibility.

```
lines 12-13
----------------------------------------------------------------------------------
DECOMPOSITION, NITRIFICATION AND DENITRIFICATION PARAMETERS
```

This is a dividing line and keyword to indicate the start of the decomposition, nitrification and denitrification block of the soil file.

```
lines 14-15
(prop) VWC ratio to calc. decomposition limit 1 (prop. to FC-HW)
(prop) VWC ratio to calc. decomposition limit 2 (prop. to SAT-FC)
```

These parameters define the optimum range of soil water content for decomposition, and the shape of the piecewise ramp function that drives decomposition during suboptimal conditions. Four points determine the function: hygroscopic water, limit 1, limit 2 (set by these two lines) and saturation. Below the lower optimum (limit 1, that is defined as the threshold soil water content divided by the difference between field capacity and hygroscopic water) the decomposition is limited: a linear ramp function is defined between hygroscopic water (where limitation starts to be non-zero allowing decomposition) and this critical value (optimum decomposition). Above the upper optimum (limit 2, that is defined as the threshold soil water content divided by the difference between saturation and field capacity) the decomposition is also limited: a linear ramp function is defined between this critical value (where limitation starts) and saturation (complete limitation). Note that nonlinearity is also allowed (see next line).

```
lines 16
(dimless) curvature of decomposition limitation function
```

In previous Biome-BGCMuSo versions the decomposition was controlled by a linear ramp function between above mentioned critical values (lines 14-15). Starting from BBGCMuSo 7.0, the shape of this limitation function can be set using this curvature parameter. This new parameter is introduced to provide mechanism for soil texture dependent limitation (caused by texture-specific matric potential). The proposed value is 1.0, which assumes a linear function that is the original logic. By adjusting this parameter, the function that defines the suboptimal decomposition can be convex or concave.

```
lines 17-20
(dimless)     parameter 1 for Tsoil response function of decomposition
(dimless)     parameter 2 for Tsoil response function of decomposition
(dimless)     parameter 3 for Tsoil response function of decomposition
(dimless)     parameter 4 for Tsoil response function of decomposition
```

The decomposition of the SOM pools are function of the potential rate constants and the integrated response function that accounts for the impact of multiple environmental factors (Hidy et al., 2022). The integrated response function of decomposition is a product of the response functions of depth, temperature and SWC. These four lines define the shape of the function for the decomposition calculation as the empirical function of soil temperature. The default values are 1.75, 17, 2.6 and 40, respectively. In this case the model uses the empirical, bell-shaped function based on the method of Parton et al. (2001). If the first Tsoil response parameter is set to -9999, the model uses the original Tsoil response function (based on the method of Lloyd and Taylor, 1994). In this case, the proposed values are -9999, 1, 308.56, and 71.02, respectively. For details see Hidy et al. (2022).

```
lines 21
(Celsius)     minimum soil temperature for decomposition
```

This parameter defines the minimum temperature for decomposition and nitrification, below which no decomposition/nitrification is assumed.

```
line 22
(m)   e-folding depth of decomposition rate's depth scalar
```

In the original Biome-BGC model decomposition rate of SOM was limited by temperature and soil moisture only. In BBGCMuSo v7.0 we included a limitation by depth of the soil column via an exponential decay using e-folding depth of decomposition rate (see Koven et al., 2013). Its proposed value is 10.

```
lines 23-24
(prop.)  net mineralization proportion of nitrification
(prop.)  maximum nitrification rate
```

These nitrification related parameters are used in the empirical function of the nitrification simulation. The proposed values are 0.2 and 0.1, respectively. For details about implementation of nitrification in BBGCMuSo v7.0 see Hidy et al. (2022).

```
line 25
(prop.)  coefficient of N2O emission of nitrification
```

Coefficient of N_2O emission of nitrification is used in the empirical function of nitrification. Its proposed value is 0.02. For details about nitrification see Hidy et al. (2022).

```
lines 26-29
(dimless)    parameter 1 for pH response function of nitrification
(dimless)    parameter 2 for pH response function of nitrification
(dimless)    parameter 3 for pH response function of nitrification
(dimless)    parameter 4 for pH response function of nitrification
```

In Biome-BGCMuSo 7.0 the nitrification flux is the function of the net mineralization and the response functions of soil temperature, soil water content and pH in the actual layer (Hidy et al., 2022). These four lines define the function for the nitrification calculation as the empirical, exponential function of pH (Parton et al., 2001). The proposed values are 0.15, 1.0, 5.2 and 0.55, respectively.

```
lines 30-33
(dimless)    parameter 1 for Tsoil response function of nitrification
(dimless)    parameter 2 for Tsoil response function of nitrification
(dimless)    parameter 3 for Tsoil response function of nitrification
(dimless)    parameter 4 for Tsoil response function of nitrification
```

In Biome-BGCMuSo 7.0 the nitrification flux is the function of the net mineralization and the response functions of soil temperature, soil water content and pH in the actual layer (Hidy et al., 2022). These four lines define the function for the nitrification calculation as the empirical function of soil temperature. The proposed values are 1, 12, 2.6 and 30, respectively. In this case the model uses the empirical bell function based on the method of Parton et al. (2001). If the first Tsoil response parameter is set to -9999, the model uses the original Tsoil response function (based on the method of Lloyd and Taylor, 1994). In this case, the proposed values are -9999, 1, 308.56, 72.02, respectively. For details see Hidy et al. (2022).

```
lines 34-37
(prop.)  minimum WFPS for scalar of nitrification calculation
(prop.)  lower optimum WFPS for scalar of nitrification calculation
(prop.)  higher optimum WFPS for scalar of nitrification calculation
(prop.)  minimum value for saturated WFPS scalar of nitrification calculation
```

In the previous versions of BBGCMuSo the nitrification was the function of relative soil water content (used also in decomposition calculation). In BBGCMuSo v7.0 the nitrification is the function of water filled pore space (WFPS) based on the method proposed by Parton et al. (2001). These four lines define the piecewise function for the nitrification calculation as function of WFPS. See Fig. 3 in Parton et al. (2001).

```
line 38
(1/gCO2) soil respiration related denitrification rate
```

In Biome-BGCMuSo denitrification is estimated as a function of size of the nitrate pool, WFPS, and total respiration from SOM decomposition where the latter is a proxy for microbial activity. This parameter adjusts the denitrificaiton rate per heterotrophic respiration. Its proposed value is 0.05 (Parton et al., 2001) but this parameter is subject to optimization. For details about the newly implemented denitrification routine see the Hidy et al. (2022) paper.

```
lines 39
(prop.)  denitrification related N2/N2O ratio multiplier
```

The denitrification related N_2/N_2O ratio multiplier modifies the ratio of N_2 and N_2O gas fluxes during denitrification. The proposed value is 2 but this might need revision.

```
lines 40
(prop.)  critical WFPS value for denitrification
```

This parameter sets the minimum WPFS value for calculating denitrification based on the method of Parton et al. (2001). The proposed value is 0.55.

```
lines 41-42
----------------------------------------------------------------------------------
RATE SCALARS
```

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

```
lines 43-48
(DIM)        respiration fractions for fluxes between compartments (l1s1)
(DIM)        respiration fractions for fluxes between compartments (l2s2)
(DIM)        respiration fractions for fluxes between compartments (l4s3)
(DIM)        respiration fractions for fluxes between compartments (s1s2)
(DIM)        respiration fractions for fluxes between compartments (s2s3)
(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/stable 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 49-56
(1/day) rate constant scalar of labile litter pool
(1/day) rate constant scalar of cellulose litter pool
(1/day) rate constant scalar of lignin litter pool
(1/day) rate constant scalar of fast microbial recycling pool
(1/day) rate constant scalar of medium microbial recycling pool
(1/day) rate constant scalar of slow microbial recycling pool
(1/day) rate constant scalar of recalcitrant SOM (humus) pool
(1/day) 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. These parameters might need revision but their adjustment is not a simple task. We are aware that the rate scalar of the recalcitrant SOM pool is unrealistic in the original model (with ~27 year turnover time), but given the fact that decomposition is coupled with N mineralization the adjustment is not simple. More research is needed here to improve the rate constants so that the model performance should be comparable with e.g. the CENTURY model.

```
(1/day) fraction of direct decomposition of labile litter pool
(1/day) fraction of direct decomposition of cellulose litter pool
(1/day) fraction of direct decomposition of lignin litter pool
```

In previous model versions nitrogen mineralization was only associated with the decomposition of soil organic carbon (mostly recalcitrant SOC) due to the changing C:N ratios and the model structure (converging cascade scheme; Thornton and Rosenbloom, 2005). In other words, litter decomposition did not contribute to plant available nitrogen pool.

In some circumstances this led to nitrogen limitation and/or the accumulation of litter. In order to solve this problem, in Biome-BGCMuSo 7.0 we introduced an additional mechanism affecting litter decomposition. Here we refer to this process as the *direct decomposition of litter*, during which a fixed part of the litter pool (defined by these three parameters) decomposes without entering the SOC cascade. During this process the affected carbon content of the litter is respired to the atmosphere, and the released nitrogen becomes accessible for plants as mineralized N (ammonium and nitrate). The User might disable this feature by setting these parameters to zero (which is equivalent with the original model logic). We would like to stress that this is an experimental feature and throughout testing is still under way. In any case, under some circumstances the litter decomposition can be adjusted to be more realistic, even though not for the right reasons.

```
lines 60-61
----------------------------------------------------------------------------------
SOIL MOISTURE PARAMETERS
```

This is a dividing line and keyword used by the code to interpret the start of a block of the parameters in connection to soil moisture calculations

```
line 62
(mm)      limitation of soil evaporation
```

Actual soil evaporation is calculated from potential soil evaporation based on the method proposed by Ritchie (1972). If the cumulated soil evaporation (calculated from the last rainfall event) is greater than this parameter, the actual soil evaporation is limited (less than the potential value). The proposed value of this parameter is 6 mm, but can be less in some soils.

```
line 63-64
(DIM)      coefficient 1 of soil evaporation calculations
(DIM)      coefficient 2 of soil evaporation calculations
```

Actual soil evaporation is calculated in two stages: the constant rate stage (stage 1, if cumulated evaporation is less than limitation of soil evaporation parameter in line 62) in which evaporation is limited only by the supply of energy to the surface, and the so-called falling rate stage (stage 2, if cumulated evaporation is greater than limitation of soil evaporation parameter in line 62) in which soil evaporation limitation is calculated as the function of the last rainfall event. Coefficient 1 is used in the empirical function of days since last rainfall event (the higher the value, the more limited the evaporation), while coefficient 2 is used in the empirical function of soil evaporation in phase 2 (the higher the value, the less the evaporation limitation). The proposed values of these parameter are 0.4 and 3.5, respectively.

```
line 65
(mm) maximum height of pond water
```

If the soil water content reaches the saturation level of the given soil column (or in other words, stagnating water appears), pond is generated. The maximum height of pond is supposed to be the function of soil type, but the User has the freedom to define it using this parameter. Its proposed value is 10.

```
line 66
(DIM) runoff curve number (-9999: no data, model estimation)
```

The runoff curve number (RCN) is an empirical parameter used for predicting direct runoff after a large precipitation event. Its proposed value is 60. In absence of local estimation the model will internally estimate its value (if the User sets this parameter to -9999).

```
lines 67-70
(prop.)  fraction of dissolved part of SOIL1 organic matter
(prop.)  fraction of dissolved part of SOIL2 organic matter
(prop.)  fraction of dissolved part of SOIL3 organic matter
(prop.)  fraction of dissolved part of SOIL4 organic matter
```

Besides N-leaching, the leaching of soil organic carbon was also implemented in Biome-BGCMuSo v7.0. SOC leaching calculation is based on the function of the presumed proportion of the soil organic carbon pools subject to leaching calculated by these dissolved fraction parameters, soil water content and percolation fluxes. The proposed values are 0.01 for all four SOC pools.

```
lines 71-72
(dimless)    mulch parameter: layer effect
(kg/m2)      mulch parameter: critical amount
```

A major novel feature in Biome-BGCMuSo v7.0 is the simulation of the effect of surface residue (litter)/mulch (for simplicity here we refer to any kind of surface coverage as mulch being natural or human-induced). Natural mulch is estimated based on aboveground litter and coarse woody debris. Since the surface biomass cannot be associated exclusively with the upper layer for proper decomposition simulation (see later for how to set this up), the amount of above-ground biomass needs to be estimated. If this organic matter is higher than this critical value (line 71), the mulch has a temperature equalizer effect in the top soil layers. The number of the affected layers is also a soil parameter (line 71). The critical amount defines the amount of soil cover above which the presence of the mulch starts to affect processes. The proposed values are 2 and 10, respectively.

```
lines 73-75
(dimless)    parameter 1 for mulch function
(dimless)    parameter 2 for mulch function
(dimless)    parameter 3 for mulch function
```

In addition to its effect on soil temperature, the mulch affects soil evaporation by limiting its magnitude. This effect is simulated using a power function based on the method of Rawls et al. (1980). The surface coverage of mulch is a power function of the amount of mulch (residue). These lines define the parameter of the power function. The proposed values are 100, 0.75and 0.75, respectively.

```
line 76
(dimless)    mulch parameter: evaporation reduction
```

The evaporation limiting effect is estimated based on a power function of the surface coverage using the method of Rawls et al. (1980) defined by this parameter. Note that this mechanism is still in the test phase. Its proposed value is 1.0 (no effect) but it needs further testing against observations.

```
lines 77-78
---------------------------------------------------------------------------------
CH4 PARAMETERS
```

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

```
lines 79-80
(DIM) param1 for CH4 calculations (empirical function of bulk density)
(DIM) param2 for CH4 calculations (empirical function of bulk density)
```

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

```
lines 81-84
(DIM) param1 for CH4 calculations (empirical function of SWC)
(DIM) param2 for CH4 calculations (empirical function of SWC)
(DIM) param3 for CH4 calculations (empirical function of SWC)
(DIM) param4 for CH4 calculations (empirical function of SWC)
```

These four lines define empirical parameters for CH_4 flux estimation using soil water content following the method of Hashimoto et al. (2011). The proposed 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 85
(DIM) param1 for CH4 calculations (empirical function of Tsoil)
```

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

```
lines 86-87
------------------------------------------------------------------------------------
SOIL COMPOSITION AND CHARACTERISTIC VALUES (-9999: no measured data)
```

This is a dividing line and keyword used by the model code to interpret the start of a block of soil composition and characteristic values.

```
lines 88-89
(%) sand percentage by volume
(%) silt percentage by volume
```

Soil is a mixture of organic matter, minerals, gases and liquids. The mineral components of soils are sand, silt and clay, and their relative proportions determine a soil's texture (physical composition). These parameters are defined by lines 90-91 separately for each soil layer. The clay component is calculated by the model internally based on the sand and silt percentage (sand+silt+clay = 100%).

```
line 90
(dimless) soil pH
```

Soil pH is a measure of the acidity or basicity of a soil. This is a new variable of BBGCMuSo and it is used in the nitrification submodel of Biome-BGCMuSo. Its default value is 7.0.

```
line 91
(dimless) soilB (Clapp-Hornberger parameter
```

SoilB is the Clapp-Hornberger parameter which is used in hydrological calculations of the Richards-method (in case of the tipping bucket method this parameter has no effect). This value can be set by the User or can be estimated by the model internally based on empirical functions if no data are available regarding to this variable (for internal estimation the parameter should be set to -9999).

```
line 92
(g/cm3) bulk density
```

Bulk density is a property of soil granules and it is defined as the mass of the bulk of particles of the material divided by the total volume they occupy. It is used in the estimation of methane fluxes and in the soil temperature calculations, and also it is used to convert soil organic carbon mass into mass concentration. This value can be set by the User or can be estimated by the model internally based on empirical functions if no data are available regarding to this variable (for internal estimation it should be set to -9999).

```
lines 93-96
(m3/m3)SWC at saturation
(m3/m3)SWC at field cap.
(m3/m3)SWC at wilting point
(m3/m3)SWC hygroscopic
```

Volumetric water content or moisture content is the quantity of water contained within the soil. The most important characteristic soil moisture values are soil type dependent: saturation (fully saturated soil), field capacity (soil moisture few days after a larger rain event or irrigation), wilting point (minimum soil moisture at which a plant wilts), and hydroscopic water (remaining water at high tension; it is also referred as inaccessible water for the plants). These values can be set by the User or can be estimated by the model internally if no data are available regarding to these variables (in this latter case they should be set to -9999).

```
line 97
(DIM) drainage coefficient
```

Drainage coefficient is the amount of water (as a portion of SWC above field capacity) removed from the soil layer moving downwards during a day (loss of water due to gravity). It is the function of the soil type. This value can be set by the User or can be estimated by the model based on empirical functions if no data are available regarding to this variable (in this case it should be set to -9999).

```
line 98
(cm/day) hydraulic conductivity at saturation
```

Hydraulic conductivity is a property of the soil that describes how easily water can move through pore spaces or fractures. This value can be set by the User or can be estimated by the model internally based on empirical functions if no data are available regarding to this variable (in this case it should be set to -9999).
It is important to note that in the previous model versions (prior to 7.0) all or none of the User-defined soil properties (critical SWC, bulk density, drainage coefficient and hydraulic conductivity) was supposed to be set by the User in order to avoid discrepancy in soil data (runoff curve number data is independent from the rest). In Biome-BGCMuSo v7.0 this restriction no longer applies, which means that some lines can be defined but others an be set with -9999 for all layers.

```
line 99
(m) capillary fringe
```

Groundwater may affect soil hydrological and plant physiological processes if the water table is closer than the thickness of the capillary fringe (in which water is sucked up from groundwater by soil pores). If not set by the User, the thickness of the capillary fringe can be estimated by the model internally (in this case the User should set this parameter as -9999).

```
lines 100-101
(dimless)     parameter 1 for diffusion calculation
(dimless)     parameter 2 for diffusion calculation
```

These parameters define the shape of the diffusion function which is used in soil water diffusion calculation. For details see Hidy et al. (2022). Note that in previous model versions these parameters were layer-independent, but experiments have shown that these parameters can be dependent on soil composition, and therefore it is essential to set them layer by layer for inhomogeneous soils. The default values are 0.88 and 35.4, respectively. If User set these parameters as -9999, the model uses default values.

```
lines 102
(cm/day)      limit of assumed diffusivity in tipping calculation
```

This parameter defines the maximum of the diffusion flux. For details see Hidy et al. (2022). Note that in previous model versions this parameter was layer-independent, but examinations have shown that this parameter is also strongly dependent on soil composition, and therefore it is essential to set it layer by layer for inhomogeneous soils. The default values are also soil type dependent: the values vary between 5 (sand) and 100.

```
line 103
(DIM) curvature of soil stress function
```

In previous Biome-BGCMuSo versions the soil moisture stress function was a linear ramp function between field capacity (or other critical soil water content value set by the User in the EPC file) and wilting point. Starting from BBGCMuSo 6.2, the shape of this soil stress function can be set using this curvature parameter. This new parameter is introduced to provide mechanism for soil texture dependent drought stress (caused by texture-specific matric potential). The proposed value is 1.0, which assumes a linear soil stress function that is the original logic. New feature of BBGCMuSo 7.0 is that this parameter can be set layer by layer, because it value is highly soil type dependent.

```
line 104
(prop) role of the layer in the decomposition
```

In previous Biome-BGCMuSo versions, in order to support litter decomposition (which means that there should be enough inorganic nitrogen in the soil for decomposition related immobilization), dead organic matter (litter) was not only associated with the top soil layer, but also with the top three layers, according to their thickness (10, 23.34 and 66.66%, respectively). From BBGCMuSo7 .0 the role of the layer (the above-mentioned proportion) can be set by the User layer by layer. This new logic supports a more flexible litter decomposition mechanism.

3.5 Ecophysiological input file (EPC file)

This input file defines the ecophysiological characteristics of the vegetation being simulated. It is kept separate from the initialization file and the soil properties file so that multiple initialization files can reference the same ecophysiology constants without editing the file. 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 possible parameter ranges and values. If you have good measurements from your site(s) related to any of these parameters, you should replace the defaults with your observations. There are of course some parameters which are not measurable directly, since they can be thresholds for some processes or empirical coefficients of some statistical equations. In those cases, model calibration might be a suitable tool.

Users are cautioned that some of these parameters show strong covariance, so replacing some of them but not others with local observations may reduce the quality of results. For example, canopy average specific leaf area (SLA), leaf C:N ratio, and fraction of leaf N in Rubisco tend to co-vary (and most importantly, these parameters define maximum photosynthesis capacity V_{cmax}), so if you replace any of these values you should consider replacing all of them and check the consistency of the data. 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. Some parameters are only relevant if a given algorithm is enabled in the INI file (see above the description about the algorithm ensemble). For example, potential radiation use efficiency (line 54 in the EPC file) is only active if the photosynthesis calculation method is set to 1 in the INI file (see above). Also, the crop-specific parameters are irrelevant for other biome 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 (header) start of canopy ecophysiological constants block
```

This is a recommended header line for EPC file (the first line must contain some text).

```
lines 2-3
-------------------------------------------------------------------------------------
FLAGS
```

This is a dividing line and header 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 including arable land crops.

```
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 used. 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).

```
lines 7-8
---------------------------------------------------------------------------------
PLANT FUNCTIONING PARAMETERS
```

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

```
lines 9-10
(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 1 in SIMULATION_CONTROL block of INI file). 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 -9999.
Yearday values for these parameters can start at 0 and end with 364. Note that BBGCMuSo does not accept leap-years, i.e. all years are 365 days long by definition.
Northern and Southern hemisphere yeardays are treated differently for these parameters. In the northern hemisphere, yearday 0 is 1 January, while in the southern hemisphere yearday 0 is 1 July. 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 (line 5 is set to 1) or in case of crop simulation (planting and harvest is defined in management section – see below), the phenology model flag in the INI file is assumed to set to User-specified (0), so these values do not have any effect.

```
lines 11 and 12
(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 (see above line 3 in the SIMULATION_CONTROL block of INI file) 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 selected in the phenology model flag of the INI file. 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, 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 13
(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 optionally 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.

```
lines 14 and 17
(°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 14) and above maximum temperature (line 17) 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). Note that all or none of the four parameters should be set by the User. Also 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 18 and 21
(°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 for the temperature dependency of carbon assimilation (photosynthesis). If these thresholds are set, the temperature dependence of C-assimilation is further 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, while 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 (that is not implemented in the original Farquhar routine). 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 22
(°C) temperature threshold for the Priestley-Taylor based ET-calculation (in case
of the Penman-Monteith method it should be set to -9999)
```

This parameter sets threshold for the ET calculation if the Priestley-Taylor method is used. Above this predefined critical temperature the potential evaporation is the function of daylight average shortwave flux and maximum air temperature. Below this temperature potential evaporation is the function of daylight average shortwave flux only.

```
line 23
(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 converted in the following year to 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, this parameter is always assumed to be 1.0, and will be reset inside the code if the User specifies any other value.

```
line 24
(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 25
(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 years, this parameter would be set to 0.01.

```
line 26
(1/year) 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 the 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, competitive 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 proportion is related to the whole year, and whole-plant mortality is assumed to go on at a constant rate throughout the year. (Note that in BBGCMuSo 6.0 the whole plant mortality parameter was related only to the vegetation period). 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, genetically 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 also 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 27
0.2    (prop)         dead stem biomass combustion proportion
```

This parameter specifies the proportion of dead stem biomass which is assumed to have been burnt during fire events. In previous BBGCMuSo versions and in original Biome-BGC this parameter was fixed in the source code. The default value is 0.2.

```
line 27
0.3    (prop)         coarse woody biomass combustion proportion
```

This parameter specifies the proportion of coarse woody biomass which is assumed to have been burnt during fire events. In previous BBGCMuSo-versions and in original Biome-BGC this parameter was fixed in the source code. The default value is 0.2.

```
line 29
(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. We would like to stress here that leaf C:N ratio changes throughout the lifecycle of leaves, and laboratory analysis does not necessarily capture the C:N ratio that is relevant to provide reasonable photosynthesis. In many cases leaf C:N ratio is estimated from senescence leaves which might strongly overestimate the peak vegetation leaf C:N. Given the fact that maintenance respiration is proportional to the N content of the plant compartments, this parameter also affects respiration.

```
line 30
```

```
(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 (i.e. the removal of nitrogen from the leaves prior to litterfall) can only be positive or zero. One of the important new features of BBGCMuSo v7.0 is the retranslocation of N not only during litterfall but during senescence as well. This parameter (more precisely the ratio of C:N of leaf litter and C:N of leaves) is used to calculate the amount of retranslocated N from the different plant pools (fruit, soft stem and fine root). Given the fact that maintenance respiration is proportional to the N content of the plant compartments, this parameter also affects respiration.

```
line 31
(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. Given the fact that maintenance respiration is proportional to the N content of the plant compartments, this parameter also affects respiration.

```
line 32
(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 33
(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 34
(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 35
(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.

```
lines 36-42
0.4    (kgC/kgDM)   dry matter carbon content of leaves
0.4    (kgC/kgDM)   dry matter carbon content of leaf litter
0.4    (kgC/kgDM)   dry matter carbon content of fine roots
0.4    (kgC/kgDM)   dry matter carbon content of fruit
0.4    (kgC/kgDM)   dry matter carbon content of soft stem
0.4    (kgC/kgDM)   dry matter carbon content of live wood
```

```
0.4    (kgC/kgDM)   dry matter carbon content of dead wood
```

One of the new features of BBGCMuSo v7 is that the User can calculate the amount of plant parts from output variables in kg dry matter m^{-2} units (beside kg C m^{-2}). The ratios required for the carbon-dry matter conversion are defined by these parameters. These values typically vary between 0.4 and 0.5.

```
lines 43-44
(DIM) leaf litter labile proportion
(DIM) leaf litter cellulose proportion
```

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

```
lines 45-46
(DIM) fine root labile proportion
(DIM) fine root cellulose proportion
```

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

```
lines 47-48
(DIM) fruit labile proportion
(DIM) fruit cellulose proportion
```

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

```
lines 49-50
(DIM) soft stem labile proportion
(DIM) soft stem cellulose proportion
```

The proportion of soft stem mass in the labile fraction, usually defined as that fraction soluble in hot water/alcohol. 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 51
(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 52
(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 53
(DIM) canopy light extinction coefficient
```

The Beer's law extinction coefficient for attenuation of radiation in the canopy, using a projected leaf area basis. This parameter affects the amount of radiation that reaches the soil in case of vegetation presence thus affects soil evaporation and soil temperature. This parameter affects photosynthesis as well since photosynthetically active radiation is the exponential function of leaf area index and this parameter. Field crops are known to have larger canopy light extinction.

```
line 54
(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 9 in the SIMULATION_CONTROL section of INI file) is set to 1 (DSSAT-method, that is the well-known light use efficiency model).

```
line 55-56
(DIM) radiation parameter1
(DIM) radiation parameter2
```

These are empirical parameters of radiation calculation method (only used if line 11 in the SIMULATION_CONTROL section of INI file is set to 1), which means the application of the net radiation calculation method – for details see Jiang et al. (2015).

```
line 7
(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. White et al. (2000) suggest that this parameter should be set to 2 for C3 and C4 grasslands and deciduous broadleaf forests.

```
line 58
(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 59
(DIM) fraction of leaf N in Rubisco (FLNR)
```

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. Larger FLNR is associated with larger maximum photosynthesis capacity. FLNR is almost always considered during model optimisation.

```
line 60
(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 61
(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. This is the reciprocal of minimum stomatal resistance. Note that BBGCMuSo uses the Jarvis multiplicative stomatal regulation method (Jarvis, 1976). Also note that by setting the CO_2 reduction flag to 1 (line 7 in SIMULATION_CONTROL block of INI file) 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 62
(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 63
(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. Consider changing this parameter in windy sites.

```
line 64
(m)    maximum height of plant
```

A new feature of Biome-BGCMuSo 6 was 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 based on the carbon content of livestem and deadstem. For these calculations maximum possible plant height has to be provided by the User.

```
lines 65-66
(kgC/m2)  stem weight corresponding to maximum height
(DIM)     plant height function shape parameter (slope)
```

Beside the carbon content of livestem and deadstem and the maximum possible plant height (see above in line 64), the critical stem weight (corresponding to maximum height) and the slope of the plant height function are used in the empirical estimation of the plant height.

```
line 67
(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. If the rooting depth of the simulated biome defined in this line is greater than the depth of the soil (line 4 in SOI file), the rooting depth is limited by the depth of the soil. It means that the maximal rooting depth cannot be greater than the soil depth.

```
line 68
(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, but this should be reconsidered by the User as root morphology changes among species considerably.

```
lines 69-70
(kgC/m2) root weight corresponding to max root depth
(DIM)    root depth function shape parameter (slope)
```

Beside the carbon content of root and the maximum possible rooting depth (see above in line 67), these two parameters are used in the empirical rooting depth calculation of plants (based on the method of 4M model). Preliminary studies indicate that these two parameters should be adjusted for different biomes as the root water uptake and drought sensitivity can be affected by adjusting these values.

```
line 71
(m/kg)        root weight to root length conversion factor
```

This parameter is a conversion factor to calculate root length from root weight in order to calculate water and nutrient uptake potential. NOTE THAT THIS PARAMETER HAS NO EFFECT ON THE SIMULATION IN BIOME-BGCMUSO V7.0 (to be implemented in forthcoming model versions).

```
line 72
(DIM) growth respiration per unit of C gain
```

This parameter controls the growth respiration cost per unit of carbon allocation. 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 73
(kgC/kgN/d) maintenance respiration in kgC/day per kg of tissue N
```

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

```
lines 74-75
(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. As maintenance respiration is covered from the NSC pool, the model does not allow depletion of the NSC pool below a given level defined by these two parameters.

```
line 76
(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). This parameter can be adjusted to resolve issues with N availability.

```
line 77
(day)  time delay for temperature in photosynthesis acclimation
```

In BBGCMuSo v6 photosynthetic acclimation to temperature change is simulated based on the method of Dyukarev (2017). This parameter describes the time delay in days that is used to modify photosynthesis acclimation state. If this is set to zero than acclimation method is not used.

```
lines 78-79
-----------------------------------------------------------------------------------
CROP SPECIFIC PARAMETERS
```

This is a dividing line and header used by the code to interpret the start of the block of crop specific parameters. One of the new features of Biome-BGCMuSo v7.0 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 external management file. In this case the growing season starts with sowing, and ends with the harvest. Note that in non-cropland simulations these CROP SPECIFIC PARAMETERS are usually not used. This can be achieved easily by setting some of the lines of this block to -9999 or 0. Appendix B contains an example EPC file where the crop specific parameters are completely switched off.

```
lines 80-81
(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 126 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 11.

```
line 82
(prop.) critical SWCratio (proportion to FC-WP) 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 ratio parameter (i.e. actual soil water content divided by the difference between field capacity and wilting point). 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 83
(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 day 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 84
(hour) critical daylength for photoperiodic effect
```

If the User assumes photoperiodic effect on plant development (line 83 is set and its value ranges from 1 to 7), the critical daylength for the photoperiodic calculation is defined by this parameter (defined in hours unit).

```
line 85
(DIM) slope of relative photoperiodic effect development rate
```

If the User assumes photoperiodic effect on plant development (line 83 is set and its value ranges from 1 to 7), the slope of the photoperiodic development rate is defined by this parameter. In other words, this parameter defines the strength of the photoperiodic effect.

```
line 86
(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 in summer. The vernalization calculation is based on vernalization development progress (VDP), 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. If vernalization is delayed, it causes shift the start of the next phenophases and therefore the whole plant development.

```
lines 87-90
(Celsius) critical vernalization temperature 1
(Celsius) critical vernalization temperature 2
(Celsius) critical vernalization temperature 3
(Celsius) critical vernalization temperature 4
```

Vernalization development progress (VDP) 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 VDP increases linearly. Between optional2 and maximum temperature the VDP decreases linearly. In the vernalization phenological stage the model is cumulating the daily VDP values.

```
line 91
(DIM) slope of relative vernalization development progress
```

The vernalization development status (VDS) is calculated by multiplying the cumulative VDP value with the slope of the relative VDP that is defined in line 91. If vernalization is disabled, this parameter has no effect.

```
line 92
(n) required vernalization days (in vernalization development rate)
```

This parameter sets the number of days needed for vernalization. The simulated plant stays in the vernalization stage until the vernalization development status (VDS) reaches the required number of vernalization days.

```
line 93
(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 pollination, 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 94-95
(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 96) 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 96
(prop.) theoretical 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 93) and a multiplier (based on critical temperatures, defined in lines 94-95).

```
lines 97-98
---------------------------------------------------------------------------------
STRESS AND SENESCENCE PARAMETERS
```

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

```
line 99
(prop) SWC ratio (prop. to FC-WP) to calculate soil moisture limit 1
```

This parameter defines the critical soil water content ratio (i.e. actual soil water content divided by the difference between field capacity and wilting point) where drought related soil moisture limitation starts to affect plant processes. If actual SWC is larger than the 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 soil properties file by the User, or alternatively they can be estimated from soil texture using empirical relationship (by setting their value to -9999 in the SOIL COMPOSITION AND CHARACTERISTIC VALUES section of the SOI file in lines 90-91; see above). 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 and ends at wilting point, which means that there is no water stress above field capacity and there is full water stress below wilting point. Note that another stress is defined close to saturation which is controlled by the next line (line 100), so here we mean stress caused by soil moisture deficit. Note that (unlike original Biome-BGC and previous versions of BBGCMuSo) in the model now it is not possible to use soil water potential to calculate this limitation factor. See Hidy et al. (2022) for details on drought related plant mortality which might use this parameter.

```
line 100
(DIM) SWC ratio to calc. soil moisture limit 2 (prop. to SAT-FC)
```

This parameter defines the critical soil water content ratio (i.e. actual soil water content divided by the difference between saturation and field capacity) where elevated soil moisture content starts to affect stomatal conductance (thus transpiration and photosynthesis) 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 due to anoxic conditions. 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), decomposition, and root water uptake. Linear ramp function is defined between this critical value (limitation starts) and saturation (complete limitation). If no 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 99. Note that (unlike original Biome-BGC and previous versions of BBGCMuSo) in BBGCMuSo v7 it is not possible to use soil water potential to calculate this limitation factor.

```
line 101
(day) critical length (days) of full water stress (in the rootzone) leading to
complete plant mortality
```

This parameter specifies the duration (in days), after which the plant will completely die if all rooting layers are fully stressed, due to drought or excess water.

```
lines 102-103
(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 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. This parameter thus expresses the atmospheric drought effect on the stomate.

```
lines 104-106
(prop.) maximum senescence mortality coefficient of leaf
(prop.) maximum senescence mortality coefficient of soft stem and fine root
(prop.) multiplier for senescence mortality calculation of non-stuctured 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 (i.e. senescence) during one day due to prolonged drought. The User can define different mortality coefficients regarding to leaf biomass in line 104 (separately from other plant compartments, because this part of the plant is the most vulnerable to wilting), and regarding to other non-woody plant parts in line 105 (soft stem and fine root biomass). The fraction of wilted biomass (leaf/other) 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). 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 (NSC). This parameter calculates the fraction of depleted (lost) non-structured biomass (e.g. transfer and storage leaf pools) from fraction regarding to actual parameter (e.g. leaf) and this multiplier. For details about senescence mortality see Hidy et al. (2022). A realistic value for this parameter is 0.005, 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 since it can strongly vary among biomes. The 0.005 value was set based on experiences on drought prone grassland in the Hungarian Great Plain.

```
lines 107-108
(Celsius)  lower limit extreme high temperature effect on senescence mortality
(Celsius)  upper limit extreme high temperature effect on senescence mortality
```

These parameters determine the thresholds of extreme high temperature effect on plant mortality. In case of senescence mortality parameters, the fraction of wilted biomass is calculated from senescence mortality coefficient, which is the function of drought, and the effect of extreme air temperature. Line 107 contains the lower limit, below which the extreme temperature effect is zero, and line 108 contains the upper limit above which the extreme temperature effect is equal to the maximal value. Between lower and upper limits, the coefficient of extreme temperature effect increases linearly from zero to the maximal value. The default values are 30 and 40 Celsius, respectively, but this is subject to change.

```
line 109
(prop.)  turnover rate of wilted standing biomass to litter
```

Turnover rate of standing dead biomass (senescenced leaves) to litter. The proposed value is 0.05 which means that 5% 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 behaviour 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 4.0 (see Hidy et al. 2016), and it was not present in the predecessor Biome-BGC versions. In case of croplands, we propose to set lower values as the crop can be intact before harvest with completely dysfunctional but standing biomass.

```
lines 110-111
(prop.)  turnover rate of non-woody cut-down biomass to litter
(prop.)  turnover rate of woody cut-down biomass to litter
```

Turnover rate of cut-down (but not removed) non-woody (line 110) and woody (line 111) biomass to litter. The proposed values are 0.05 and 0.01. Non-woody parameter (line 110) 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 111) 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 112
(prop.)  critical value of water stress length leading to excess mortality
```

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 and the effect of extreme air temperature. The critical value of water stress length 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. (2022) for details on drought related plant mortality simulation.

```
line 113
(dimless) effect of soilstress factor on photosynthesis (1: full, 0: no effect)
```

In previous BBGCMuSo versions soil water stress did not affect the photosynthesis apparatus directly, only via stomatal conductance. Starting from BBGCMuSo 7.0 we introduced option for non-stomatal SWC stress effect on photosynthesis with the modified photosynthesis stress simulation. According to the new feature soil water stress can down-regulate the carbon assimilation independent of stomatal aperture. Note that up to version 7.0 of BBGCMuSo C4 photosynthesis was NOT affected by stomatal aperture art all. This new feature enables an alternative control on photosynthesis in C3 and C4 plants as well (in case of C3 plants stomatal and non-stomatal effect can act parallel).

```
lines 114-115
-----------------------------------------------------------------------------------
GROWING SEASON PARAMETERS
```

This is a dividing line and header 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 1215) heatsum. Heatsum is calculated as the sum of mean daily temperatures minus base temperature (defined in line 13) 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 116
(kg/m2)      critical amount of snow limiting photosynthesis
```

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

```
lines 117-118
(Celsius)    limit1 (under:full constrained) of HEATSUM index
(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 119-120
(Celsius)    limit1 (under: fully constrained) of TMIN index
(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 121-122
(Pa) limit1 (above: fully constrained) of VPD index
(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 123-124
(s) limit1 (under:full constrained) of DAYLENGTH index
(s) limit2 (above:unconstrained) of DAYLENGTH index
```

The threshold limits of DAYLENGTH (in other words photoperiod): 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 125
(day) window length for smoothing (to avoid the effects of extreme events)
```

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

```
lines 126-127
(dimless) HSGSI limit1 (greater that limit -> start of vegper)
(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 and growth starts. 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 128-129
----------------------------------------------------------------------------------
PHENOLOGICAL (ALLOCATION) PARAMETERS (7 phenological phases)
```

This is a dividing line and header used by the model to interpret the start of a block of phenological parameters. Note that in this block of the EPC file the User should define **seven values** for the different phenological phases in one line, even if some phenophases are not used.

```
line 130
(text) name of the phenophase
```

In this line User can define up to 7 different phenological phases with different names for easier identification.

```
line 131
(Celsius) length of phenophase (GDD)
```

In this line the User can set the length of the seven phenophases based on growing degree days (GDD) logic in the different phenophases. Note that GDD is the function of the base temperature parameter defined in line 13.

```
lines 132-139
(ratio) leaf ALLOCATION
(ratio) fine root ALLOCATION
(ratio) fruit ALLOCATION
(ratio) soft stem ALLOCATION
(ratio) live woody stem ALLOCATION
(ratio) dead woody stem ALLOCATION
(ratio) live coarse root ALLOCATION
(ratio) dead coarse root ALLOCATION
```

In these lines the User can set the allocation ratio of leaf, fine root, fruit (e.g. crop yield), soft stem, live stem, dead stem, live coarse root and dead coarse root for each phenophase. These are constant values in a given phenological phase, but the User can define different values regarding to the 7 phenological phase. Soft stem is applicable to herbaceous ecosystems only, while woody parameters are only applicable to woody ecosystems. Note that the sum of allocation parameters must equal 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. Alternative solution is to use only one very long phenophase defined in line 132 and use only the first allocation column.

```
line 140
(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 7.0. 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 wants 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 141
(prop.) current growth proportion
```

These parameters set the proportion of daily assimilation that is displayed immediately as new growth (structural biomass like stem, root etc.), with the remainder stored for the next year's transfer growth (i.e. NSC). 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 14-17).

```
line 142
(°Cd) maximum lifetime of plant tissue (-9999: no gen. programmed senescence)
```

Genetically programmed mortality causes the senescence of leaf plant material based on the age of the plant tissue in leaves (in contrast to the soil water content related senescence that is handled by lines 99-100 and 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 Hidy et al. (2022).

Note that in the original Biome-BGC model there were only 43 EPC parameters. BBGCMuSo 7 has a much higher number of EPC parameters, which means a major change. 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 required the definition of new EPC parameters, similarly to drought and crop-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, visual testing of the model and the model optimization might be executed using the RBBGCMuSo R-based tool that is developed by our group (RBBGCMuSo). New development support visual parameter adjustment (via the tuneMuso graphical user interface) that is strongly recommended for new model users. Contact us if you would like to use the R tool.

3.5 Management file (MGM file)

In contrast to the previous versions of BBGCMuSo, in BBGCMuSo v6 and onwards the management data are handled separately from the INI file. There is a major change in terms of the format of the definition of management events: now the original "vertical" structure is changed to a "horizontal" design where one management event is completely defined in one single line with a timestamp. This feature supports the easy parameterization of the model which was a major issue in the past.

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

The following management parameters were defined to describe different management activities on the simulated ecosystem. Each management type can be activated or deactivated for a given simulation independent of the other management types. Implemented management types are documented in the Hidy et al. (2012) and in Hidy et al. (2016) study. Note that some management features (like panting and ploughing) might interfere which means that it is advisable to avoid setting some management events to the same day. For example, if planting and ploughing happened in the same day in reality, we suggest adjusting the timing of ploughing so that planting should be set one day after ploughing. In other case ploughing might destroy the seeds and move them to the litter pool.

In the management file (MGM file) the management blocks must be present even if the User deactivates them (i.e. the structure of the MGM file is fixed, similarly to EPC, INI and SOI files). Out proposal is to use the *.mgm extension for file name convention.
The management text file starts with the following line (this is mandatory):

```
MANAGEMENT_INFORMATION
```

This header is followed by the 8 sections. The structures of the sections are the same:

- first line is a dividing line: ---------------
- second is the keyword: `PLANTING`, `THINNING`, `MOWING`, `GRAZING`, `HARVESTING`, `PLOUGHING`, `FERTILIZING`, `IRRIGATING`, `MULCHING`, `CWD-EXTRACT`
- third line is the flag of the given management action (0: management type is deactivated, 1: management type is activated)
- fourth line (optionally - only if the management flag is 1): the name of the given management file. There is no filename convention for the management files.

Note that the number of the lines in the different management files is the function of the number of the management actions defined by the User. This is a major change compared to earlier model versions. This solution provides maximum flexibility as the same file can define annually varying management options (like in crop rotations) or management activities in uniform fashion (for large scale simulations with prescribed management for countries/continents).
There is one major restriction that affects crop rotation simulations: the number of planting events must be equal to the harvest events even if harvest did not happen yet (e.g. when simulation winter wheat in a given year but the consecutive year is not part of the simulations). In other case the model will crash.

Here we refer to Appendix D where complete examples are provided for the different management files.

PLANTING file

If the first management section in the MGM file is activated, the external PLANTING file is used by the model. **Only cropland related simulations should use this type of management with planting AND harvest information.** Planting assumes a non-natural vegetation with human-defined start and end of vegetation period (planting and harvesting date). PLANTING file should begin with a header (e.g. with the name and unit of the parameters). PLANTING file has the following 6 columns:

1) date of planting (e.g. 2013.04.20)

2) germination depth in meter

3) the quantity of the seed expressed in number of seedling per m^2

4) weight of 1000-seed in g[1] (1000-kernel weight)

5) carbon content of seed (or seedling) in percent

6) EPC filename and path of the planted crop

```
DATE         GERMDEPTH(m)    SEEDNUM(n/m2) 1000seedWGHT(g) seedC(%) CROP(file)
2013.04.20    0.06            7              300             40      epc/maize.epc
```

Crop rotation is handled here with the option to define different EPC files per planting event. Monocultures can be defined with a single EPC file (which means we can revert to the original model logic). **There are no other management options where alternative EPC can be defined.**

THINNING file

If the second management section in MGM file is activated, THINNING file is used by the model. This management type is associated with forest related simulations. Clearcut can also be defined as it is the upper limit of fellings. THINNING file should begin with a header (e.g. with the name and unit of the parameters). THINNING file has the following 5 columns:

1) date of thinning (e.g. 2001.04.20)

2) rate of the thinning (proportion of removed biomass during felling) regarding to aboveground woody plant material (live woody stem and dead woody stem in %); e.g. 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)

3) rate of the thinning (proportion of removed biomass during felling in %) regarding to aboveground non-woody plant material (leaf, fruit); e.g. 50% of the non-woody biomass are removed via felling

4) transported part of stem (percent); this is the percent of cut down stem that is removed from the site after intervention

5) transported part of leaf (percent); this is the fraction of leaf on cut down trees that is removed from the site during thinning

```
DATE           THNrate_w(%)    THNrate_nw(%)   transPART_w(%)  transPART_nw(%)
2001.01.31     15              15              90              90
```

MOWING file

If the third management section in the MGM file is activated, MOWING file is used by the model. This management type is associated with grass related simulations. MOWING file

[1] See https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex81/$file/100_22-1.pdf

should begin with a header (e.g. with the name and unit of the parameters). MOWING file has the following 3 columns:

1) date of mowing (e.g. 2001.04.20)

2) the value of LAI after mowing in m^2 m^{-2}

3) 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).

```
DATE          afterLAI(m2/m2)       transPART(%)
2007.06.06    0.5                   90
```

GRAZING file

If the fourth management section in the MGM file is activated, external GRAZING file is used by the model. This management type is associated with pastures related simulations. 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). GRAZING file should begin with a header (e.g. with the name and unit of the parameters). GRAZING file has the following 15 columns:

1) date of first day of the grazing period. Continuous grazing is assumed between the first and last grazing days defined here. The first number defines the start of the first grazing period, and the second defines the start of the second grazing period.

2) date of last day of the grazing period. The grazing periods should not overlap.

3) weight equivalent of an averaged animal (live stock unit) in kilograms; this is the average weight of the livestock

4) animal stocking rate regarding a unit area (number of LSU per hectare)

5) 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)

6) trampling effect coefficient. It defines the increase of senescence (mortality) coefficient 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.

7) proportion of ingested dry matter which turns into excrement (percent of consumed grass)

8) proportion of excrement returning to litter (percent of excrement)

9) carbon content of dry matter (percent; 40-45% is a realistic estimate)

10) nitrogen content of excrement (percent)

11) carbon content of excrement (percent)

12) manure emission factor for direct N_2O emissions from manure management in kgN_2O-N:kgN (IPCC, 2006); we suggest to use the value defined below in the example

13) 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 E.

14) 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 E.

15) fermentation emission factor for CH_4 emission in kg CH_4 LSU-1 year^{-1} (IPCC, 2006; T10.11); we suggest to use the value defined in the example management file in Appendix E.

```
DATEstart  DATEend    wLSU SR   inDM Treff inDM2ex ex2lit DMC manN manC NexcRATE  EFmanN2O EFmanCH4 EFfermCH4
2012.04.10 2012.06.27 381 0.66 8.6  1.5   50      100    43  2    40   0.35      0.005    6        58
```

HARVESTING file

If the fifth management section in the MGM file is activated, external HARVESTING file is used by the model. 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. HARVESTING file should begin with a header (e.g. with the name and unit of the parameters). HARVESTING file has the following 6 columns:

1) date of harvest (e.g. 2001.04.20)

2) percent of removed soft stem carbon content compared to total soft stem

3) percent of removed root carbon content compared to total root (this parameter is not zero for crops where the useful part is the root (e.g. sugar beet))

4) percent of harvested leaves that is removed from the field

5) percent of harvested stem that is removed from the field

6) percent of harvested yield that is removed from the field

Note that in previous versions of BBGCMuSo only the percent of harvested leaves removed from the field could be set by the User. It was assumed that percent of removed carbon is related to leaves and stem. The former logic assumed that yield is always transported away from the field after harvest. Additionally, it was implicit that fine roots are always left at the field. Now this logic is more flexible and applicable to all type of crops. Parameters regarding to percent of harvested plant material controls the lateral carbon flux caused by harvest which has significant implications on NBP.

```
DATE        CUT/TOTstem[%] CUT/TOTrot ratioTRANSleaf%   ratioTRANSstem[%]   ratioTRANSyield[%]
2014.07.29  90             0          0                 0                   100
```

PLOUGHING file

If the sixth management section in the MGM file is activated, PLOUGHING file is used by the model. This management type is applicable for croplands and grasslands, but it can also be used in other biome types. The number of the lines in the PLOUGHING file is the function of the number of the management actions defined by the User. PLOUGHING file has the following 2 columns:

1) date of ploughing (e.g. 2001.04.21)

2) ploughing depth in meter

```
DATE           DEPTH(m)
2013.10.04     0.1
```

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 SOI file.

Note that ploughing causes burial of litter that is usually supposed to reside on the soil surface. To handle this process, BBGCMuSo 7.0 and onwards differentiates between aboveground and belowground litter pools.

FERTILIZING file

If the seventh management section in the MGM file is activated, FERTILIZING file is used by the model. This management type is typically applicable for croplands and grasslands, but it can also be used in other biome types if needed. FERTILIZING file has the following 13 columns:

1) date of fertilizing (e.g. 2001.03.20.)

2) type of fertilizer (e.g. "ammnit", "NPK6_20_30") – a custom name (text) specified by the User; it is only used for identification of fertilizer types (it does not affect the model result). PLEASE BE CAREFUL AND AVOID ANY BLANK SPACE WITHIN THE NAME AS IT CAN CAUSE ERROR IN THE MODEL RUN! For example, "ammnit" is fine, but "amm nit" is not allowed as it contains a space.

3) total amount of fertilizer per hectare per day (kg fertilizer/ha/day)

4) depth of fertilizing in meter

5) dry matter (DM) content of fertilizer in percent of fertilizer

6) nitrate-N fraction of the dry matter in percent of DM

7) ammonium-N fraction of the dry matter in percent of DM

8) urea content of fertilizer in kgN/kg fertilizer (**note: this is an inactive variable which means that it does not affect the simulation results; forthcoming model versions will use this parameter**)

9) organic nitrogen content of fertilizer dry matter content in case of organic manure in percent of DM

10) organic carbon content of fertilizer dry matter content in case of organic manure in percent of DM unit

11) labile carbon fraction of fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)

12) cellulose fraction of the carbon content within the fertilizer organic DM (%) (only applicable if organic content of fertilizer is greater than zero)

13) emission factor of N additions from mineral fertilizers in kg N_2O–N $(kgN)^{-1}$. This parameter is used to estimate an additional emission of N_2O that is independent of the internally calculated N_2O emission (that is estimated with the nitrification/denitrification scheme). It can be considered as the N_2O cost of mineral fertilizer application.

IRRIGATING file

If the eighth management section in the MGM file is activated, IRRIGATING file is used by the model. From version 7.0 the above-canopy, below-canopy, and subsurface irrigation types are differentiated. IRRIGATING file has the following 3 columns:

1) date of irrigation (e.g. 2001.03.20.)

2) amount of water from irrigation in kg m^{-2} day^{-1} (equivalent with mm of precipitation)

3) the height of the irrigation (if positive – applied above the surface; if negative – applied below the surface).

```
DATE          AMOUNT(kgH2O/m2/day)       HEIGHT(m)
2013.07.21    40                         0.5
```

MULCHING file

Starting with BBGCMuSo 7.0 a new management option is available: application of soil cover or mulching in order to protect the soil from drying, and from the effect of extreme temperature conditions. If the ninth management section in the MGM file is activated, MULCHING file is used by the model. MULCHING file has the following 4 columns:

1) date of mulching (e.g. 2001.03.20.)

2) amount of non-woody type of mulch in kgC m^{-2}

3) C:N ratio of non-woody mulch (proportion)

3) amount of non-woody type of mulch in kgC m^{-2}

3) C:N ratio of woody mulch (proportion)

```
DATE         non-woodyMUL_C[kgC/m2] non-woodyMUL_CN[prop] woodyMUL_C[kgC/m2] woodyMUL_CN[prop]
1961.05.15     3                     50                    30                    80
```

CWD-EXTRACT file

In BBGCMuSo 7.0 and onwards a new management option is available: the coarse-woody debris extraction from forest ecosystems. If the tenth management section in the MGM file is activated, *CWD-EXTRACT* file is used by the model. *CWD-EXTRACT* file has the following 2 columns:

1) date of CWD-extract (e.g. 2001.03.20.)

2) rate of extraction in %

```
DATE           CWErate[%]
1962.05.16     50
```

3.6 Restart file

Restart file provides all the information required to start one simulation from the endpoint of a previous simulation. This option is typically used in conjunction with the spinup mode (described above) to initialize the soil carbon, water 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. The restart (or endpoint) file consists of double precision floating point data without header, which means that it is a flat binary file. It can be checked or edited with some programming language.

3.7 Optional input files

3.7.1 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. Starting from Biome-BGCMuSo 7.0 the model uses the year information for the simulation (**this was not the case in earlier Biome-BGC and Biome-BGCMuSo versions!**). It means that the User might create a long CO_2 data file covering many years and the model will use the appropriate years if model run is initiated for a subset of years. This is also the case for N deposition.

3.7.2 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 (WPM), and from version 7.0 annually varying fire mortality (FM) to BBGCMuSo. It is also possible to set maximum stomatal conductance in an annually varying fashion. During the spinup, transient and the normal phase of the simulation the model can either use constant mortality (whole plant and fire) and stomatal conductance, or it can read annually varying mortality and/or conductance defined by a text file (WPM_spinup, WPM_transient.txt, WPM_normal.txt, FM_spinup, FM_transient.txt, FM_normal.txt, conductance_spinup, conductance_transient.txt, conductance_normal.txt – the filenames are fixed) which is/are supposed to be present next to the model executable. During spinup phase mortality and conductance data file will be recycled enough times to establish steady-state conditions (such as the meteorological data). The structure of these files is similar to the structure of the annually varying CO_2 concentration file or the annually varying N deposition file. Note that (like CO_2 and Ndep file) the current model version (from 7.0) considers the year field in the mortality.txt and conductance.txt file. If external file(s) are provided by the User, the settings of whole plant mortality and/or maximum stomatal conductance within the EPC file is the default value of whole plant mortality and/or maximum stomatal conductance if no data is available for the given period.

3.7.3 Groundwater file

Poorly drained forests (e.g. in boreal regions) or croplands in lowland areas are special ecosystems where groundwater can 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 and movement of capillary zone) effect on the ecosystems in BBGCMuSo we implemented an option to supply external information about the depth of the water table, and from BBGCMuSo v7 the nutrient content of water from groundwater table (ammonium, nitrate and dissolved organic matter) can be defined as well.

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 transient or normal phase of the simulation the model can read daily groundwater information defined by another external text file (groundwater_transient.txt or 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 cannot be represented at all, or can be represented only in transient run, only in normal run, or in both phases if both txt files are present).

The structure of groundwater_normal.txt and groundwater_transient.txt is simple (it is similar to the structure of the management files). The User should check whether the groundwater file is continuous and available from the first to the last simulation day. Note that from this new version the groundwater file has 12 columns:

- date [yyyy.mm.dd]
- groundwater depth [m]
- ammonium content [NH_4; ppm]
- nitrate content [NH_3; ppm]
- dissolved nitrogen content of fast microbial recycling soil organic pool [DON1; ppm]
- dissolved nitrogen content of medium microbial recycling soil organic pool [DON2; ppm]
- dissolved nitrogen content of slow microbial recycling soil organic pool [DON3; ppm]
- dissolved nitrogen content of stable soil organic pool [DON4; ppm]
- dissolved nitrogen content of fast microbial recycling soil organic pool [DOC1; ppm]
- dissolved nitrogen content of medium microbial recycling soil organic pool [DOC2; ppm]
- dissolved nitrogen content of slow microbial recycling soil organic pool [DOC3; ppm]
- dissolved nitrogen content of stable soil organic pool [DOC4; ppm]

NH_4, NH_3, DON and DOC are optional input data; if the User has no information about it (set -9999), the model uses the NH_4, NH_3, DON and DOC concentration of the groundwater layer.

The handling of the externally supplied groundwater information is the following. The depth of the groundwater can affect hydrological processes if its level is closer than the depth of the capillary zone (estimated by the model using input data from SOI file (line 99). Due to the proximity of a saturated zone, the water balance changes: the field capacity rises, the layer starts to charge, while the holding capacity decreases. The methodology is quite complex. The authors can provide you the theoretical basis upon request.

3.7.4 Flooding file

The periodic flooding (i.e. the presence of water thanks to natural river dynamics) can play important role in the functioning of the ecosystems close to large rivers. From version 7.0 the model can use optional flooding file in order to simulate the effect of flooding rivers.

Flooding file contains the initial and end date of flooding (e.g. 2023.06.05 2023.06.08), the period in which "pond water" is assumed on the area. Third column is the height of the pond water (from flooding). From the fourth to the seventh column optional input data can be found: NH_4, NO_3 and DOC-content of flooding water. If the User has no information about it, set them to -9999; the model uses predefined values (NH_4 - 0.2 ppm, NO_3 - 10 ppm, DOC - 2 ppm).

3.7.5 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 first line of the SIMULATION_CONTROL block of the INI file to 0 means that the User provides onday and offday in lines 9 and 10 within the EPC file, which will be the same in each simulation year. This new model feature overrides this restriction.

During the spinup, 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_spinup, onday_transient.txt, onday_normal.txt, offday_spinup, 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 onday and offday data file will be recycled enough times to establish steady-state conditions (such as the meteorological data).

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 (similar to conductance and mortality files): 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 types of output produced by BBGCMuSo. 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 includes simple formatted text files: the log file and the so-called *econout* file. The log file contains annual summary information for each simulation year, and it is produced for all non-spinup simulations, and uses a fixed list of output variables. The econout file is simple formatted text file that contains crop management information produced only for crop simulation (it is created when harvest is set in the management file).

These two output types are described in greater detail below.

4.1 Binary and ASCII output files, or option to send the model output to the screen

In BBGCMuSo the User can select the format of the output files. In BBGCMuSo 7.0 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). If the text file option is selected, the User should acknowledge that he/she has to provide a string in the INI file after definition of the daily output variable (see above). This string is used as the header of the ASCII output and is used to distinguish between the variables.

Binary file creation is still possible for backward compatibility and efficiency, but the User has to acknowledge 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, Delphi, IDL, Python, R and other programming languages. They can also be read by many commercially available software packages.

In this model version the User can choose the "*sending output to screen*" option, which means that the results are written to the standard output (typically the computer screen) thus no output file is created.

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 (especially if they are not provided by the uses; see the SOI file section), 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 success 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 simple 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 F contains an example for the log file.

4.4 Econout file

In BBGCMuSo arable crop simulation is possible with different management types. The most important management information is summarized in the econout file for each simulation year in order to facilitate the identification of the most important settings:

- type of the plant
- the amount of crop production [namely grain yield; tC/ha]
- the amount of byproduct production [namely leaf and tC/ha]
- the water amount used during conditional irrigation
- the type of the conditional irrigation (0: no conditional irrigation, 1: conditional irrigation based on SWC, 2: conditional irrigation based on SMSI)

The following plants are recognized by the model (the name of the plant should be in the first line of the EPC file):

1: maize
2: winter_wheat
3: winter_barley
4: sunflower
5: canola
6: spring_wheat
7: spring_barley
8: alfalfa
9: sugarbeet
10: bean
11: pea
12: potato
13: oat
14: rye
15: sugarcane
16: rice
17: cotton
18: crop_notSpec
19: vegetable_notSpec

Appendix G contains an example for the econout file.

5. Code History

The BBGCMuSo biogeochemical 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 preceding the current version BBGCMuSo 7.0.

Biome-BGCMuSo v6.2, Dóra Hidy, 2021 (C/C++)
Biome-BGCMuSo v6.1, Dóra Hidy, 2021 (C/C++)
Biome-BGCMuSo v6.0, Dóra Hidy, 2019 (C/C++)
Biome-BGCMuSo v5.0, Dóra Hidy, 2018 (C/C++)
Biome-BGCMuSo v4.1, Dóra Hidy, 2016 (C/C++)
Biome-BGCMuSo v4.0, Dóra Hidy, 2015 (C/C++)
Biome-BGCMuSo 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, Zoltán Barcza, Emese Bottyán, Roland Hollós, Nándor Fodor, Tamás Ács, Katarína Merganičová, Tibor Filep, Dóra Zacháry.

Please contact the authors for the source code of the model or check the website of the model at http://nimbus.elte.hu/bbgc/. See also https://github.com/bpbond/Biome-BGC for useful information.

You might be interested in the so-called RBBGCMuso R tool that covers a wide functionality to support the application of Biome-BGCMuSo including sensitivity analysis, parameter estimation (i.e. calibration), visualization and others (https://github.com/hollorol/RBBGCMuso). The newly implemented tuneMuso function provides a Graphical User Interface (GUI) to easily handle the model.

.

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Appendix A

EXAMPLE INI FILE FOR BBGCMUSO 7.0

```
BBGCMuSo INI file for Bugac grassland site (HU-Bug FluxNet site)

MET_INPUT
WTH/bugac.wth                                                       (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 = dont read restart
0                                                     (flag) 1 = write restart; 0 = dont write restart
RSTRT/bugac_MuSo6.rst                                        (filename) name of the input restart file
RSTRT/bugac_MuSo6.rst                                       (filename) name of the output restart file

TIME_DEFINE
13                                                                 (int) number of simulation years
2003                                                                    (int) first simulation year
0                                                               (flag) 1 = spinup run; 0 = normal run
500                                                             (int) maximum number of spinup years

CO2_CONTROL
1                                                                 (flag) 0=constant; 1=vary with file
395.0                                                   (ppm) constant atmospheric CO2 concentration
CO2/CO2.txt                                                             (filename) name of the CO2 file

NDEP_CONTROL
1                                                                 (flag) 0=constant; 1=vary with file
0.001400                                           (kgN/m2/yr) wet+dry atmospheric deposition of N
NDEP/Ndep.txt                                                        (filename)  name of the N-dep file

SITE
111.4                                                                               (m)  site elevation
46.69                                                          (degrees) site latitude (- for S.Hem.)

SOI_FILE
SOI/bugac_ MuSo6.soil                                                           (filename) SOI filename

EPC_FILE
EPC/c3grass_ MuSo6.epc                                                          (filename) EPC filename

MGM_FILE
MGM/bugac_MuSo6.mgm                                                (filename) MGM filename (or "none")

SIMULATION_CONTROL
1                                 (flag) phenology flag (1 = MODEL PHENOLOGY 0 = USER-SPECIFIED PHENOLOGY)
1                           (flag) vegper calculation method if MODEL PHENOLOGY is used (0: original, 1: GSI)
0                            (flag) transferGDD flag (1= transfer calc. from GDD 0 = transfer calc. from EPC)
1                                (flag) q10 flag (1 = temperature dependent q10 value; 0= constant q10 value)
1                              (flag) acclimation flag of photosynthesis (1 = acclimation 0 = no acclimation)
1                                 (flag) acclimation flag of respiration (1 = acclimation 0 = no acclimation)
1                                         (flag) CO2 conductance reduction flag (0: no effect, 1: multiplier)
0                                             (flag) soil temperature calculation method (0: Zheng, 1: DSSAT)
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 based on (Jiang et al. 20005), 2: Rn from SWnet and LWnet)
0                          (flag) soilstress calculation method (0: based on VWC, 1: based on transp. demand)
0                            (flag) interception calculation method (0: based on allLAI, 1: based on projLAI)
0         (flag) MR-deficit calculation method (0:non-sep.MRdef, 1:organ-sep.MRdef, 2:w-nw sep.MRdef, 3:Cpool-deficit)
0                (flag) Ksat-estimation method (0: exp. function of soil content, 1: power function of soil content)

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

CN_STATE
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 pool
0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0        (kgC/m2)  litter carbon, unshielded cellulose pool
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 pool
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 pool
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 microbial recycling pool
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 microbial recycling pool
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 microbial recycling pool
0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0         (kgC/m2)  soil carbon, stable SOM (slowest)
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 nitrogen, NH4 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 nitrogen, NO3 pool

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

CONDITIONAL_MANAGEMENT_STRATEGIES
0                                                          (flag) conditional mowing ? 0 - no, 1 - yes
```

```
0.0                                              (m2/m2) fixed value of the LAI before MOWING
0.0                                               (m2/m2) fixed value of the LAI after MOWING
0.0                                           (%) transported part of plant material after MOWING
0                                                 (flag) conditional irrigation? 0 - no, 1 - yes
0.0                                     (prop) SMSI before cond. IRRIGATION (-9999: SWCratio is used)
0.0                               (prop) SWCratio of rootzone before cond. IRRIGATION (-9999: SMSI is used)
0.0                                          (prop) SWCratio of rootzone after cond. IRRIGATION
0.0                                               (kgH2O/m2) maximum amount of irrigated water

OUTPUT_CONTROL
OUT/bugac_ MuSo6                                                         (filename) output prefix
1                              (flag)  writing daily output (0 = no; 1 = binary; 2 = ascii; 3 = on-screen)
0                   (flag)  writing monthly average of daily output (0 = no; 1 = binary; 2 = ascii; 3 = on-screen)
0                    (flag)  writing annual average of daily output (0 = no; 1 = binary; 2 = ascii; 3 = on-screen)
0                             (flag)  writing annual output (0 = no; 1 = binary; 2 = ascii; 3 = on-screen)
1                                                     (flag)  for on-screen progress indicator

DAILY_OUTPUT
12                                                      number of daily output variables
2504                                                                           n_actphen
2605                                                                          vwc00-03cm
2606                                                                          vwc03-10cm
2607                                                                          vwc10-30cm
75                                                                                   GDD
2638                                                                       rooting_depth
2718                                                                        m_soilstress
671                                                                        m_vegc_to_SNSC
171                                                                          evapotransp
3009                                                                           daily_gpp
3014                                                                            daily_tr
2522                                                                            proj_lai

ANNUAL_OUTPUT
16                                                     number of annual output variables
3000                                                                             annprcp
3001                                                                             anntavg
3002                                                                           annrunoff
3003                                                                          annoutflow
2736                                                                         annmax_lai
3031                                                                       cum_Closs_MGM
3032                                                                       cum_Cplus_MGM
3045                                                                      cum_Closs_SNSC
3046                                                                      cum_Cplus_STDB
3058                                                                                vegc
3064                                                                              totalc
3066                                                                         SOM_C_top30
3070                                                                        SOM_C_30to60
3071                                                                        SOM_C_60to90
3068                                                                          NH4_top30
3069                                                                          NO3_top30

END_INIT
```

Appendix B

Example for EPC file (BBGCMuSo 7.0, 142 lines)

```
ECOPHYS FILE - C3 grass  Biome-BGC Muso  based on White et al. 2000 and parameter analysis
---------------------------------------------------------------------------------------
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)
---------------------------------------------------------------------------------------
PLANT FUNCTIONING PARAMETERS
0         (yday)              yearday to start new growth (when phenology flag = 0)
364       (yday)              yearday to end litterfall (when phenology flag = 0)
1.0       (prop.)             transfer growth period as fraction of growing season (when transferGDD_flag = 0)
-9999     (Celsius)           minimum  temperature for growth displayed on current day (-9999: no T-dependence of allocation)
-9999     (Celsius)           optimal1 temperature for growth displayed on current day (-9999: no T-dependence of allocation)
-9999     (Celsius)           optimal2 temperature for growth displayed on current day (-9999: no T-dependence of allocation)
-9999     (Celsius)           maxmimum temperature for growth displayed on current day (-9999: no T-dependence of allocation)
-9999     (Celsius)           minimum  temperature for carbon assimilation displayed on current day (-9999: no limitation)
-9999     (Celsius)           optimal1 temperature for carbon assimilation displayed on current day (-9999: no limitation)
-9999     (Celsius)           optimal2 temperature for carbon assimilation displayed on current day (-9999: no limitation)
-9999     (Celsius)           maxmimum temperature for carbon assimilation displayed on current day (-9999: no limitation)
-9999     (Celsius)           threshold temperature for ET-calculation of PT-method (-9999: no data - only PM-method in INI)
1.0       (1/yr)              annual leaf and fine root turnover fraction     ---> 1.0 (White et al., 2000)
0.00      (1/yr)              annual live wood turnover fraction               ---> 0.0 (White et al., 2000)
0.0       (1/yr)              annual fire mortality fraction              ---> 0.05 (White et al., 2000)
0.02      (1/vegper)          whole-plant mortality fraction in vegetation period  ---> 0.1 (White et al., 2000)
0.2       (prop)              dead stem biomass combustion proportion
0.3       (prop)              coarse woody biomass combustion proportion
21.0      (kgC/kgN)           C:N of leaves                               ---> 25.0 (White et al., 2000)
45.0      (kgC/kgN)           C:N of leaf litter, after retranslocation  ---> 45.0 (White et al., 2000)
50.0      (kgC/kgN)           C:N of fine roots                           ---> 50.0 (White et al., 2000)
21.0      (kgC/kgN)           C:N of fruit      , usually we set same as C:N of leaves
21.0      (kgC/kgN)           C:N of soft stem  , usually we set same as C:N of leaves
0.0       (kgC/kgN)           C:N of live wood
0.0       (kgC/kgN)           C:N of dead wood
0.4       (kgC/kgDM)          dry matter carbon content of leaves
0.4       (kgC/kgDM)          dry matter carbon content of leaf litter
0.4       (kgC/kgDM)          dry matter carbon content of fine roots
0.4       (kgC/kgDM)          dry matter carbon content of fruit
0.4       (kgC/kgDM)          dry matter carbon content of soft stem
0.4       (kgC/kgDM)          dry matter carbon content of live wood
0.4       (kgC/kgDM)          dry matter carbon content of dead wood
0.68      (DIM)               leaf litter labile proportion                  ---> 0.680 (White et al., 2000)
0.23      (DIM)               leaf litter cellulose proportion               ---> 0.230 (White et al., 2000)
0.222     (DIM)               fine root labile proportion                    ---> 0.222 (White et al., 2000)
0.531     (DIM)               fine root cellulose proportion                 ---> 0.531 (White et al., 2000)
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
0.75      (DIM)               dead wood cellulose proportion      , no woody component, does not matter
0.022     (1/LAI/d)           canopy water interception coefficient    ---> 0.022 (White et al., 2000)
0.48      (DIM)               canopy light extinction coefficient      ---> 0.48 (White et al., 2000)
2.0       (g/MJ)              potential radiation use efficiency
0.781     (DIM)               radiation parameter1 (Jiang et al.2015)
-13.596   (DIM)               radiation parameter2 (Jiang et al.2015)
2.0       (DIM)               all-sided to projected leaf area ratio    ---> 2.0 (White et al., 2000)
2.0       (DIM)               ratio of shaded SLA:sunlit SLA            ---> 2.0 (White et al., 2000)
0.28      (DIM)               fraction of leaf N in Rubisco             ---> 0.21 (White et al., 2000)
0.03      (DIM)               fraction of leaf N in PEP Carboxylase
0.006     (m/s)               maximum stomatal conductance (projected area basis)   ---> 0.006 (White et al., 2000)
0.00006   (m/s)               cuticular conductance (projected area basis)           --> 0.00006 (White et al., 2000)
0.04      (m/s)               boundary layer conductance (projected area basis)   ---> 0.04 (White et al., 2000)
1.0       (m)                 maximum height of plant
0.2       (kgC)               stem weight corresponding to maximum height
1.0       (dimless)           plant height function shape parameter (slope)
1.3       (m)                 maximum depth of rooting zone
1.13      (DIM)               root distribution parameter
0.69      (kgC)               root weight corresponding to max root depth
1.3       (dimless)           root depth function shape parameter (slope)
1000      (m/kg)              root weight to root length conversion factor
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
0.0047    (kgN/m2/yr)         symbiotic+asymbiotic fixation of N
0         (day)               time delay for temperature in photosynthesis acclimation
---------------------------------------------------------------------------------------
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 VWCratio (prop. to FC-WP) in germination
0         (DIM)               number of phenophase of photoperiodic slowing effect (from 1 to 7; 0: NO effect)
20        (hour)              critical photoslow daylength
0.005     (DIM)               slope of relative photoslow development rate
0         (DIM)               number of phenophase of vernalization (from 1 to 7; 0: NO effect)
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)
0         (DIM)               number of flowering phenophase (from 1 to 7;0: NO effect)
35        (Celsius)           critical flowering heat stress temperature 1
40        (Celsius)           critical flowering heat stress temperature 2
0.5       (prop.)             theoretical maximum of flowering thermal stress mortality parameter
```

```
----------------------------------------------------------------------------------------
STRESS AND SENESCENCE PARAMETERS
0.5       (prop)             VWC ratio to calc. soil moisture limit 1 (prop. to FC-WP)
0.99      (prop)             VWC ratio to calc. soil moisture limit 2 (prop. to SAT-FC)
30      (prop)               critical length (days) of full water stress leading to complete plant mortality
1000      (Pa)               vapor pressure deficit: start of conductance reduction
5000      (Pa)               vapor pressure deficit: complete conductance reduction
0.0006    (prop.)            maximum water stress mortality coefficient of leaf
0.0003     prop.)            maximum water stress mortality coefficient of softsem and fine root
0.1       (prop.)            multiplier for water stress mortality calculation of non-structured plant material
30        (Celsius)          lower limit extreme high temperature effect on senescence mortality
40        (Celsius)          upper limit extreme high temperature effect on senescence mortality
0.05      (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        (nday)             critical value of water stress length leading to excess mortality (see Manual)
0.2       (dimless)          effect of soilstress factor on photosynthesis (1: full effect, 0: no effect)
----------------------------------------------------------------------------------------
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)
----------------------------------------------------------------------------------------
PHENOLOGICAL (ALLOCATION) PARAMETERS (7 phenological phases)
phase1    phase2    phase3    phase4    phase5    phase6    phase7             (text) name of the phenophase
150       750       700       1500      2000      2000      2000               (Celsius) length of phenophase (GDD)
0.5       0.40      0.30      0.00      0.00      0.1         0.1              (ratio) leaf ALLOCATION
0.5       0.40      0.30      0.20      0.20      0.30        0.30             (ratio) fine root ALLOCATION
0.0       0.00      0.0       0.60      0.60      0.30        0.30             (ratio) fruit ALLOCATION
0.        0.20      0.40      0.20      0.20      0.30        0.30             (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
60        60        43        43        43        43          43               (m2/kgC) canopy average specific leaf area
0.4       0.4       0.56      0.56      0.56      0.56        0.56             (prop.)  current growth proportion
1000      1500      1500      1000      1000      1000        1000             (Celsiusd) maximal lifetime of plant tissue
```

Appendix C

Example for SOI file (BBGCMuSo 7.0, 101 lines)

```
SOILPROP FILE -   muso7.0
-------------------------------------------------------------------------------------
SOIL GENERIC PARAMETERS
3         (m)                 depth of soil
10        (kgC/kgN)           C:N ratio of labile soil pool (soil1)
15        (kgC/kgN)           C:N ratio of medium soil pool (soil2)
20        (kgC/kgN)           C:N ratio of slow soil pool   (soil3)
12        (kgC/kgN)           C:N ratio of stable soil pool (soil4)
10        (kgC/m2)            total soil organic carbon content (for length of spinup run)
0.1       (prop.)             NH4 mobilen proportion
107       (s/m)               aerodynamic resistance (Wallace and Holwill, 1997)
-------------------------------------------------------------------------------------
DECOMPOSITION, NITRIFICATION AND DENITRIFICATION PARAMETERS
1.75      (dimless)           parameter 1 for tscalar function of decomposition
17        (dimless)           parameter 2 for tscalar function of decomposition
2.6       (dimless)           parameter 3 for tscalar function of decomposition
40        (dimless)           parameter 4 for tscalar function of decomposition
-10       (Celsius)           minimum soil temperature for decomposition
10        (m)                 e-folding depth of decomposition rate depth scalar
0.2       (prop.)             net mineralization proportion of nitrification
0.1       (1/day)             maximum nitrification rate
0.02      (prop.)             coefficient of N2O emission of nitrification
0.15      (dimless)           parameter 1 for pHscalar function of nitrification
1         (dimless)           parameter 2 for pHscalar function of nitrification
5.2       (dimless)           parameter 3 for pHscalar function of nitrification
0.55      (dimless)           parameter 4 for pHscalar function of nitrification
1         (dimless)           parameter 1 for tscalar function of nitrification
12        (dimless)           parameter 2 for tscalar function of nitrification
2.6       (dimless)           parameter 3 for tscalar function of nitrification
30        (dimless)           parameter 4 for tscalar function of nitrification
0.1       (prop.)             minimum WFPS for scalar of nitrification calculation
0.45      (prop.)             lower optimum WFPS for scalar of nitrification calculation
0.55      (prop.)             higher optimum WFPS for scalar of nitrification calculation
0.2       (prop.)             minimum value for saturated WFPS scalar of nitrification calculation
0.05      (1/gCO2)            soil respiration related denitrification rate
2         (dimless)           denitrification related N2/N2O ratio multiplier
0.55      (prop)              critical WFPS value for denitrification
-------------------------------------------------------------------------------------
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       (1/day)             rate constant scalar of  labile litter pool
0.07      (1/day)             rate constant scalar of cellulose litter pool
0.014     (1/day)             rate constant scalar of lignin litter pool
0.07      (1/day)             rate constant scalar of  fast microbial recycling pool
0.014     (1/day)             rate constant scalar of  medium microbial recycling pool
0.0014    (1/day)             rate constant scalar of  slow microbial recycling pool
0.0001    (1/day)             rate constant scalar of  recalcitrant SOM (humus) pool
0.001     (1/day)             rate constant scalar of  physical fragmentation of coarse woody debris
0.000     (1/day)             fraction of direct decomposition of labile litter pool
0.000     (1/day)             fraction of direct decomposition of cellulose litter pool
0.000     (1/day)             fraction of direct decomposition of lignin litter pool
-----------------------------------------------------------------------------------------
SOIL MOISTURE PARAMETERS
6         (mm)                limit of first stage evaporation
0.4       (dimless)           coefficient of soil evaporation calculations (EVPlim)
3.5       (dimless)           coefficient of soil evaporation calculations (EVPcum)
10        (mm)                maximum height of pond water
1         (dimless)           curvature of soil stress function
0         (dimless)           runoff curve number (0: no runoff, -9999: model estimation)
0.002     (prop.)             fraction of dissolved part of SOIL1 organic matter
0.002     (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
2         (dimless)           mulch parameter: layer effect
10        (kgC/m2)            mulch parameter: critical amount
100       (dimless)           parameter 1 for mulch function
0.75      (dimless)           parameter 2 for mulch function
0.75      (dimless)           parameter 3 for mulch function
1.0       (dimless)           mulch parameter: evaporation reduction
-------------------------------------------------------------------------------------
CH4 PARAMETERS
212.5     (DIM)               soil CH4 emission bulk density dependence parameter1
1.81      (DIM)               soil CH4 emission bulk density dependence parameter2
-1.353    (DIM)               soil CH4 emission soil water content dependence parameter1
0.2       (DIM)               soil CH4 emission soil water content dependence parameter2
1.781     (DIM)               soil CH4 emission soil water content dependence parameter3
6.786     (DIM)               soil CH4 emission soil water content dependence parameter4
0.010     (DIM)               soil CH4 emission soil temperature dependence parameter1
-------------------------------------------------------------------------------------
SOIL COMPOSITION AND CHARACTERISTIC VALUES (-9999: no measured data)
78.5   78.5 78.5   84.7  92.7  92.7  92.7  92.7  92.7  92.7              (%) sand percentage by volume in rock-free soil
8.6    8.6  8.6    6.0   2.9   2.9   2.9   2.9   2.9   2.9               (%) silt percentage by volume in rock-free soi
7.0    7.0  7.0    7.0   7.0   7.0   7.0   7.0   7.0   7.0               (dimless) soil pH
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999              (dimless) soilB
-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 saturation
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999              (m3/m3) SWC at field capacity
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999              (m3/m3) SWC at wilting point
```

```
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (m3/m3) SWC at hygroscopic water content
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (dimless) drainage coefficient
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (cm/day) hydraulic conductivity at saturation
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (cm) capillary fringe
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (dimless) parameter 1 for diffusion calculation
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (dimless) parameter 2 for diffusion calculation
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (cm2/day) limit of assumed diffusivity
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999          (cm2/day) limit of assumed diffusivity
```

Appendix D

Example for MGM file (BBGCMuSo 7.0)

```
MANAGEMENT_INFORMATION MuSo7
---------------------------------------------------------------------------------------------------------------------
PLANTING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
THINNING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
MOWING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
GRAZING
1                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
MGM/grazing/bugac.grz
---------------------------------------------------------------------------------------------------------------------
HARVESTING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
PLOUGHING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
FERTILIZING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
IRRIGATING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
MULCHING
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
---------------------------------------------------------------------------------------------------------------------
CWD-EXTRACT
0                               (flag) flag of management action: 0 - no MGM, 1 - MGM information from file below
none
```

Appendix E

Examples for ancillary management files defined in MGM file (BBGCMuSo 7.0)

Ancillary file for annually varying planting

DATE	GERMDEPTH(m)	SEEDNUM(n/m2)	1000seedWEIGHT(g)	seedC(%)	CROP(file)
2013.04.21	0.06	7	300	40	epc/maize_apriori_MuSo6.epc
2014.04.18	0.06	7	300	40	epc/maize_apriori_MuSo6.epc
2015.04.24	0.06	7	300	40	epc/maize_apriori_MuSo6.epc
2016.04.21	0.06	7	300	40	epc/maize_apriori_MuSo6.epc

Ancillary file for annually varying thinning

DATE	THNrate_w(%)	THNrate_nw(%)	transPART_w(%)	transPART_nw(%)
1903.04.01	15	15	90	90
1913.01.31	15	15	90	90
1923.01.31	15	15	90	90
1933.01.31	15	15	90	90
1943.01.31	15	15	90	90
1953.01.31	15	15	90	90
1963.01.31	15	15	90	90
1973.01.31	15	15	90	90
1979.01.31	15	15	90	90
1989.01.31	15	15	90	90
1999.01.31	15	15	90	90
2007.01.31	15	15	90	90

Ancillary file for annually varying mowing

DATE	afterLAI(m2/m2)	transPART(%)
2007.06.06	0.5	90
2007.08.20	0.4	80
2008.06.06	0.5	90
2008.08.20	0.4	80
2009.06.06	0.5	90
2009.08.20	0.4	80
2010.06.06	0.5	90
2010.08.20	0.4	80

Ancillary file for annually varying grazing

DATEstart	DATEend	wLSU(kg/LSU)	SR(LSU/ha)	inDM(kgDM/LSU)	TReff(prop)	inDM2exc(%)	exc2lit(%)	DMC(%)	manN(%)	manC(%)	EFmanN2O(kgN2O-N:kgN)	NexcRATE(kgN/1000kgANIMAL/day)	EFmanCH4(kgCH4/LSU/yr)	EFfermCH4
2003.05.01	2003.11.01	381	1.4	8.6	1.5	25	90	43	2	40	0.01	0.35	8	58
2004.05.01	2004.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2005.05.01	2005.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2006.05.01	2006.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2007.05.01	2007.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2008.05.01	2008.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2009.05.01	2009.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2010.05.01	2010.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2011.05.01	2011.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2012.05.01	2012.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2013.05.01	2013.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2014.05.01	2014.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58
2015.05.01	2015.11.01	381	1.4	8.6	1.5	25	100	43	2	40	0.01	0.35	8	58

Ancillary file for annually varying harvesting

DATE	CUT/TOTstem[%]	CUT/TOTroot[%]	ratioTRANSleaf[%]	ratioTRANSstem[%]	ratioTRANSyield[%]
1951.10.10	95	0	100	100	100
1952.10.10	95	0	100	100	100
1953.10.10	95	0	100	100	100
1954.10.10	95	0	100	100	100

Ancillary file for annually varying ploughing

DATE	DEPTH(m)
2013.10.04	0.1
2014.10.02	0.1
2015.10.07	0.1
2016.10.02	0.1

Ancillary file for annually varying fertilizing

DATE	TYPE	AMOUNT(kg/ha)	DPTH(m)	DM(%FRT)	NO3(%DM)	NH4(%DM)	UREA(kgN/kgFRT)	orgN(%DM)	orgC(%DM)	Lfr(%)	Cfr(%)	EMFAC
2013.04.10	ammnit	500	0.25	100	17	17	0	0	0	0	0	0.01
2014.04.10	ammnit	500	0.25	100	17	17	0	0	0	0	0	0.01
2015.05.10	ammnit	500	0.25	100	17	17	0	0	0	0	0	0.01
2016.05.10	ammnit	500	0.25	100	17	17	0	0	0	0	0	0.01

Ancillary file for annually varying irrigation

DATE	AMOUNT(kgH2O/m2)	DEPTH[m]
2013.07.21	40	0.5
2015.07.24	60	-0.1

Ancillary file for annually varying mulching

DATE	non-woodyMUL_C[kgC/m2]	non-woodyMUL_CN[prop]	woodyMUL_C[kgC/m2]	woodyMUL_CN[prop]
2012.05.15	3	50	30	80

Ancillary file for annually varying CWD-extract

DATE	CWErate[%]
2012.05.16	50

Appendix F

Examples for optional groundwater and flooding files (BBGCMuSo 7.0)

Optional input file for daily varying groundwater information

DATE	DEPTH[m]	NH4[ppm]	NO3[ppm]	DOC[ppm]
2012.05.01	10	0.2	10	2
2012.05.02	9	0.2	10	2
2012.05.03	8	0.2	10	2

Optional input file for flooding information

DATE_start	DATE_end	HEIGHT[mm]	NH4[ppm]	NO3[ppm]	DOC[ppm]
2012.05.01	2012.05.20	10	0.2	10	2
2013.06.02	2013.06.15	9	0.2	10	2
2014.04.13	2014.05.03	8	0.2	10	2

Appendix G
EXAMPLE LOG FILE created by BBGCMuSo 7.0

```
NORMAL RUN

VEGETATION TYPE
biome type           - NON-WOODY
woody type           - DECIDUOUS
photosyn.type        - C3 PSN

CALCULATION METHODS
hydrology            - tipping (with diffusion)
temperature          - MuSo
photosynthesis       - Farquhar
evapotranspiration   - Penman-Monteith
radiation            - based on SWabs
soilstress           - based on VWC
interception         - original based on allLAI
transfer period      - EPC
q10 value            - temperature dependent
photosyn. acclim.    - yes
respiration acclim.  - yes
CO2 conduct. effect  - reduction
Decomposition Tresp. - Bell function
Nitrification Tresp. - Bell function

DATA SOURCES
SGS data - model estimation (with GSI method)
EGS data - model estimation (with GSI method)
WPM data - constant
MSC data - constant
management  - YES
groundwater – NO
flooding - NO

SOIL PROPERTIES FOR 10 SOIL LAYERS (POTENTIALLY) ESTIMATED BY THE MODEL
Soiltype (based on sand/silt content):  sand  sand  sand  sand  sand  sand  sand  sand  sand  sand
Clapp-Hornberger b parameter [dimless]: 3.450 3.450 3.450 3.450 3.450 3.450 3.450 3.450 3.450 3.450
bulk density [g/cm3]:                   1.600 1.600 1.600 1.600 1.600 1.600 1.600 1.600 1.600 1.600
VWC at saturation [m3/m3]:              0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
VWC at field capacity [m3/m3]:          0.155 0.155 0.155 0.155 0.155 0.155 0.155 0.155 0.155 0.155
VWC at wilting point [m3/m3]:           0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030
VWC at hygroscopic water [m3/m3]:       0.003 0.003 0.003 0.003 0.002 0.002 0.002 0.002 0.002 0.002
PSI at saturation [MPa]:               -0.001-0.001-0.001-0.000-0.000-0.000-0.000-0.000-0.000-0.000
PSI at field capacity [MPa]:           -0.012-0.012-0.012-0.011-0.011-0.010-0.010-0.010-0.010-0.010
PSI at wilting point [MPa]:             -7506 -7506 -7506 -6633 -6730 -6349 -6349 -6349 -6349 -6349
drainage coefficient [prop]:            0.602 0.602 0.602 0.633 0.637 0.666 0.666 0.666 0.666 0.666
hydr. conduct. at saturation [m/day]:   1.418 1.418 1.418 1.646 1.675 1.912 1.912 1.912 1.912 1.912
capillary fringe [m]:                   0.051 0.051 0.051 0.045 0.045 0.043 0.043 0.043 0.043 0.043

CRITICAL VALUES OF VWC and PSI FOR LIMITATION OF WATER IN 10 SOIL LAYERS (-9999: no limitation
defined by the User)
VWC [m3/m3] at start of drought limit.:  0.092 0.092 0.092 0.092 0.092 0.092 0.092 0.092 0.092 0.092
PSI [MPa]   at start of drought limit.: -0.079-0.079-0.079-0.079-0.071-0.067-0.067-0.067-0.067-0.067
VWC [m3/m3] at start of anoxic  limit.:  0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400 0.400
PSI [MPa]   at start of anoxic  limit.: -0.001-0.001-0.001-0.000-0.000-0.000-0.000-0.000-0.000-0.000

INFORMATION ABOUT SGS AND EGS VALUES (yday of onday and offday)
SGS value (min and max):      9     78
EGS value (min and max):    320    351

SOME IMPORTANT ANNUAL OUTPUTS FROM LAST SIMULATION YEAR
Cumulative sum of GPP [gC/m2/year]:                            1459.3
Cumulative sum of TER [gC/m2/year]:                            1725.9
Cumulative sum of NEE [gC/m2/year]:                             265.8
Cumulative sum of ET  [kgH2O/m2/year]:                          536.8
Cumulative sum of soil evaporation [kgH2O/m2/year]:             247.9
Cumulative sum of transpiration [kgH2O/m2/year]:                288.9
Cumulative sum of N2O flux [gN/m2/year]:                         0.03
Maximum projected LAI [m2/m2]:                                   3.15
Maximum rooting depth [m2/m2]:                                   0.69
Aboveground litter carbon content [kgC/m2/year]:                 0.02
Aboveground CWD carbon content [kgC/m2/year]:                    0.00
Soil carbon content (in 0-30 cm soil layer) [%]:                 1.20
Total litter carbon content [kgC/m2/year]:                       0.07
Total soil carbon content [kgC/m2/year]:                         6.92
Total stable soil carbon content [kgC/m2/year]:                  5.58
Averaged available soil ammonium content (0-30 cm) [ppm]:        0.00
Averaged available soil nitrate content (0-30 cm) [ppm]:         0.00
Averaged soil water content  [m3/m3]:                            0.15
```

```
10-base logarithm of the maximum carbon balance diff.:          -14.0
10-base logarithm of the maximum nitrogen balance diff.:        -15.3
10-base logarithm of the maximum water balance diff.:           -11.3
10-base logarithm of the C-N calc. numbering error:             -13.7

WARNINGS
Limited transpiration due to dry soil
Limited evaporation due to dry soil
Limited leaching
Pond water on soil surface

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

Appendix H

EXAMPLE ECONOUT FILE created by BBGCMuSo 7.0

```
year        planttype primaryProd[tC/ha] secondaryProd[tC/ha] condIRGamunt condIRGtype
2013            1       9.8285            3.5274              150.0000        1
2014           25       0.0000            0.1464                0.0000        1
2014            1       8.4615            4.6705                0.0000        1
2015            2       5.0340            4.7868              150.0000        1
2015           25       0.0000            1.0272                0.0000        1
2016            2       5.0177            4.0939              100.0000        1
2016            1       0.0517            2.9721                0.0000        1
```

Abbreviations

SWC: soil water content
PSI: soil water potential
SGS, EGS: start and end of growing season
HSGSI: 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
DOC: dissolved organic content
NH_4: ammonium
NO_3: nitrate
C: carbon
N: nitrogen

References

Bond-Lamberty, B., Gower, S.T., Ahl, D.E., 2007. Improved simulation of poorly drained forests using Biome-BGC. Tree Physiology 27, 703-715.

Di Vittorio, A.V., Anderson, R.S., White J.D., Miller, N.L., Running, S.W., 2010. Development and optimization of an Agro-BGC ecosystem model for C4 perennial grasses. Ecological Modelling 221, 2038-2053. doi:10.1016/j.ecolmodel.2010.05.013

Farquhar, G.D., von Caemmerer, S., Berry, J.A., 1980. A bio-chemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. Planta 149, 78-90.

Franks, P.J., Adams, M.A., Amthor, J.S., Barbour, M.M., Berry, J.A., Ellsworth, D.S., Farquhar, G.D., Ghannoum, O., Lloyd, J., McDowell, N., Norby, R.J., Tissue, D.T. and von Caemmerer, S., 2013. Sensitivity of plants to changing atmospheric CO_2 concentration: from the geological past to the next century. New Phytologist 197, 1077-1094. doi:10.1111/nph.12104

Hashimoto, S., Morishita, T., Sakata, T., Ishizuka, S., Kaneko, S., Takahashi, M., 2011. Simple models for soil CO_2, CH_4, and N_2O fluxes calibrated using a Bayesian approach and multi-site data. Ecological Modelling 222, 1283–1292. doi:10.1016/j.ecolmodel.2011.01.013

Hidy, D., Barcza, Z., Haszpra, L., Churkina, G., Pintér, K., Nagy, Z., 2012. Development of the Biome-BGC model for simulation of managed herbaceous ecosystems. Ecological Modelling 226, 99-119. doi:10.1016/j.ecolmodel.2011.11.008

Hidy, D., Barcza, Z., Marjanović, H., Ostrogović Sever, M. Z., Dobor, L., Gelybó, G., Fodor, N., Pintér, K., Churkina, G., Running, S., Thornton, P., Bellocchi, G., Haszpra, L., Horváth, F., Suyker, A., Nagy, Z., 2016. Terrestrial Ecosystem Process Model Biome-BGCMuSo v4.0: Summary of improvements and new modeling possibilities. Geoscientific Model Development, 9, 4405-4437. doi:10.5194/gmd-9-4405-2016

Hidy, D., Barcza, Z., Hollós, R., Dobor, L., Ács, T., Zacháry, D., Filep, T., Pásztor, L., Incze, D., Dencső, M., Tóth, E., Merganičová, K., Thornton, P., Running, S., Fodor, N., 2022. Soil-related developments of the Biome-BGCMuSo v6.2 terrestrial ecosystem model. Geoscientific Model Development, 15, 2157–2181. doi:10.5194/gmd-15-2157-2022

IEEE, 2008. Standard for Floating-Point Arithmetic. *IEEE Std 754-2008*, august, 1–70. https://doi.org/10.1109/IEEESTD.2008.4610935.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Jarvis, N.J., 1989. A simple empirical model of root water uptake. Journal of Hydrology 107, 57–72.

Jiang, B., Yi Zhang, Shunlin Liang, Georg Wohlfahrt, Altaf Arain, Alessandro Cescatti, Teodoro Georgiadis, Kun Jia, Gerard Kiely, Magnus Lund, Leonardo Montagnani, Vincenzo

Magliulo, Penelope Serrano Ortiz, Walter Oechel, Francesco Primo Vaccari, Yunjun Yao, Xiaotong Z., 2015. Empirical estimation of daytime net radiation from shortwave radiation and ancillary information, Agricultural and Forest Meteorology, 211–212, 23–36

Kattge, J., Knorr, W., 2007. Temperature acclimation in a biochemical model of photosynthesis: a reanalysis of data from 36 species. Plant Cell and Environment 30, 1176-1190.

Kattge, J., Díaz, S., Lavorel, S., Prentice, I.C., Leadley, P., Bönisch, G., Garnier, E., Westoby, M., Reich, P.B., Wright, I.J., Cornelissen, J.H.C., Violle, C., Harrison, S.P., Van Bodegom, P.M., Reichstein, M., Enquist, B.J., Soudzilovskaia, N. A., Ackerly, D.D., Anand, M., Atkin, O., Bahn, M., Baker, T.R., Baldocchi, D., Bekker, R., Blanco, C.C., Blonder, B., Bond, W.J., Bradstock, R., Bunker, D.E., Casanoves, F., Cavender-Bares, J., Chambers, J.Q., Chapin, F.S., Chave, J., Coomes, D., Cornwell, W.K., Craine, J.M., Dobrin, B.H., Duarte, L., Durka, W., Elser, J., Esser, G., Estiarte, M., Fagan, W.F., Fang, J., Fernández-Méndez, F., Fidelis, A., Finegan, B., Flores, O., Ford, H., Frank, D., Freschet, G.T., Fyllas, N.M., Gallagher, R. V., Green, W. A., Gutierrez, A. G., Hickler, T., Higgins, S.I., Hodgson, J.G., Jalili, A., Jansen, S., Joly, C. A., Kerkhoff, A. J., Kirkup, D., Kitajima, K., Kleyer, M., Klotz, S., Knops, J.M.H., Kramer, K., Kühn, I., Kurokawa, H., Laughlin, D., Lee, T.D., Leishman, M., Lens, F., Lenz, T., Lewis, S.L., Lloyd, J., Llusia, J., Louault, F., Ma, S., Mahecha, M.D., Manning, P., Massad, T., Medlyn, B.E., Messier, J., Moles, A. T., Müller, S.C., Nadrowski, K., Naeem, S., Niinemets, Ü., Nöllert, S., Nüske, A., Ogaya, R., Oleksyn, J., Onipchenko, V.G., Onoda, Y., Ordonez, J., Overbeck, G., Ozinga, W. A., Patino, S., Paula, S., Pausas, J.G., Penuelas, J., Phillips, O.L., Pillar, V., Poorter, H., Poorter, L., Poschlod, P., Prinzing, A., Proulx, R., Rammig, A., Reinsch, S., Reu, B., Sack, L., Salgado-Negret, B., Sardans, J., Shiodera, S., Shipley, B., Siefert, A., Sosinski, E., Soussana, J.F., Swaine, E., Swenson, N., Thompson, K., Thornton, P., Waldram, M., Weiher, E., White, M., White, S., Wright, S.J., Yguel, B., Zaehle, S., Zanne, A. E., Wirth, C., 2011. TRY - a global database of plant traits. Global Change Biology 17, 2905–2935. doi:10.1111/j.1365-2487.0011.02451.x

Koven, C.D., Riley, W.J., Subin, Z.M., Tang, J.Y., Torn, M.S., Collins, W.D., Bonan, G.B., Lawrence, D.M., and Swenson, S.C., 2013. The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4. Biogeosciences, 10, 7109-7131. doi:10.5194/bg-10-7109-2013

Lloyd, J. and Taylor, J.A., 1994. On the Temperature Dependence of Soil Respiration. Functional Ecology, 8, 315-323.

Ma, S., Churkina, G., Wieland, R., Gessler, A., 2011. Optimization and evaluation of the ANTHRO-BGC model for winter crops in Europe. Ecological Modelling 222, 3662-3679. doi:10.1016/j.ecolmodel.2011.08.025

Martínez-Vilalta, J., Sala, A., Asensio, D., Galiano, L., Hoch, G., Palacio, S., Piper, F.I. and Lloret, F., 2016. Dynamics of non-structural carbohydrates in terrestrial plants: a global synthesis. Ecological Monographs 86, 495-516. doi:10.1002/ecm.1231

Parton, W.J., Holland, E., Del Grosso, S., Hartman, M., Martin, R., Mosier, A.R., Ojima, D., Schimel, D., 2001. Generalized model for NO_x and N_2O emissions from soils. Journal of Geophysical Research - Atmospheres, 106, 17403–17419.

Pietsch, S.A., Hasenauer, H., Kucera, J., Cermák, J., 2003. Modeling effects of hydrological changes on the carbon and nitrogen balance of oak in floodplains. Tree Physiology 23, 735–746.

Rawls, W.J., Onstad, C.A., & Richardson, H.H., 1980. Residue and tillage effects on SCS runoff curve numbers. Transactions of the ASAE, 23(2), 357-361.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8, 1204- 1213. doi:10.1029/WR008i005p01204.

Rogers, A., Medlyn, B.E. and Dukes, J.S., 2014. Improving representation of photosynthesis in Earth System Models. New Phytologist 204, 12–14. doi: 10.1111/nph.12972

Running, S.W., Coughlan, J.C., 1988. A general model of forest ecosystem processes for regional applications I. Hydrological balance, canopy gas exchange and primary production processes. Ecological Modelling 42, 125-154.

Running, S.W., Gower, S.T., 1991. A general model of forest ecosystem processes for regional applications II. Dynamic carbon allocation and nitrogen budgets. Tree Physiology 9, 147-160.

Running, S.W., Hunt, E.R.J., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: Scaling Physiological Processes: Leaf to Globe (ed.: Ehleringer, J. R., Field, C.B.). San Diego, Academic Press, 141-158.

Sándor, R., Fodor, N., 2012. Simulation of Soil Temperature Dynamics with Models Using Different Concepts. The Scientific World Journal, vol. 2012, 1-8. doi:10.1100/2012/590287

Smith, N.G., Dukes, J.S., 2013. Plant respiration and photosynthesis in global-scale models: Incorporating acclimation to temperature and CO_2. Global Change Biology 19, 45–63. doi:10.1111/j.1365-2487.0012.02797.x

Thornton, P.E., 1998. Regional ecosystem simulation: combining surface- and satellite-based observations to study linkages between terrestrial energy and mass budgets. Ph.D. dissertation. School of Forestry, University of Montana, Missoula MT, 280 pp.

Thornton, P.E., 2000. User's Guide for Biome-BGC, Version 4.1.1. Available online at ftp://daac.ornl.gov/data/model_archive/BIOME_BGC/biome_bgc_4.1.1/comp/bgc_users_guide_411.pdf.

Thornton, P.E., Running, S.W., 2002. User's Guide for Biome-BGC, Version 4.1.2. Available online at http://www.ntsg.umt.edu/sites/ntsg.umt.edu/files/project/biome-bgc/bgc_users_guide_412.PDF

Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., Goldstein, A.H., Monson, R.K., Hollinger, D., Falk, M., Chen, J., Sparks, J.P., 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agricultural and Forest Meteorology 113, 185-222.

Thornton, P.E., Rosenbloom, N.A., 2005. Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model. Ecological Modelling 189, 25–48. doi:10.1016/j.ecolmodel.2005.04.008

Tjoelker, M.G., Oleksyn, J., Reich, P.B., 2001. Modelling respiration of vegetation: evidence for a general temperature-dependent Q10. Global Change Biology 7, 223-230.

Trusilova, K., Trembath, J., Churkina, G., 2009. Parameter estimation and validation of the terrestrial ecosystem model Biome-BGC using eddy-covariance flux measurements. Max-Planck-Institut für Biogeochemie, Technical Reports 16, 1-60.

White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and sensitivity analysis of the Biome-BGC terrestrial ecosystem model: net primary production controls. Earth Interactions 4, 1-85.

Wullschleger, S.D., 1993. Biochemical limitations to carbon assimilation in C3 plants - a retrospective analysis of the A/Ci curves from 109 species. Journal of Experimental Botany 44, 907–920.

Zheng, D., Raymond, H., Running, S.W., 1993. A daily soil temperature model based on air temperature and precipitation for continental applications. Climate Research 2, 183-191.