CNR - ISAFOM

3D-CMCC-FEM

(Coupled Model Carbon Cycle)

BioGeoChemical and Biophysical Forest Ecosystem Model

User's Guide (v.5.5-ISIMIP, v.5.6)

Forest Modelling Lab.

National Research Council of Italy

website: www.forest-modelling-lab.com

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1. Code availability

The **3D-CMCC-FEM** ("*Three **D**imensional - **C**oupled **M**odel **C**arbon **C**ycle - **F**orest **E**cosystem **M**odel*") is a computer model and is primarily a research tool, and many versions have been developed for specific purposes. The National Research Council of Italy and University of Tuscia maintain benchmark code versions for public release and update these benchmark versions periodically as new knowledge is gained on the research front. The code and executables accompanying this file represent the most recent benchmark version. The **3D-CMCC-FEM** code (any version) is copyrighted.

The 3D-CMCC-FEM is freely available only for non-commercial use. We have developed the 3D-CMCC-FEM code relying solely on open source components, in order to facilitate its use and further development by others. The 3D-CMCC-FEM is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. The 3D-CMCC-FEM code is released under the GNU General Public Licence (GPL) at: https://github.com/Forest-Modelling-Lab/3D-CMCC-FEM. See the GNU General Public License for more details. You should have received a copy of the GNU General Public License along with this program. If not, see http://www.gnu.org/licenses/gpl.html.

The model has been developed and is maintained by the Forest Modelling Laboratory at the National Research Council of Italy, Institute for Agricultural and Forestry Systems in the Mediterranean (CNR-ISAFOM), Perugia. All source code and documents are subject to copyright © by the CNR. In case you have copied and/or modified the 3D-CMCC-FEM code overall, even in small parts of it, you may not publish data from it using the name 3D-CMCC-FEM or any 3D-CMCC-FEM variants unless you have either coordinated your usage and their changes with the developers listed below, or publish enough details about your changes so that they could be replicated.

The 3D-CMCC-FEM has been developed by: Alessio Collalti, Daniela Dalmonech and Gina Marano who are part of (or associated to) the Forest Ecology Laboratory at the National Research Council of Italy (CNR), Institute for Agricultural and Forestry Systems in the Mediterranean (ISAFOM), Via della Madonna Alta, 128, 06128 - Perugia (PG), Italy. CNR accepts no responsibility for the use of the 3D-CMCC-FEM in the form supplied or as subsequently modified by third parties. CNR disclaims liability for all losses, damages and costs incurred by any person as a result of relying on this software. Use of this software assumes agreement to this condition of use. Removal of this statement violates the spirit in which 3D-CMCC-FEM was released by CNR. The 3D-CMCC-FEM (both versions: Light Use Efficiency and the fully BioGeoChemical version). Versions 5.5.x code is open. You can get a free copy of the code online from: (GitHub Repository) https://github.com/Forest-Modelling-Lab/3D-CMCC-FEM.

2. Model description

The 3D-CMCC-FEM is biogeochemical, biophysical forest model that simulates the dynamics occurring in homogeneous and heterogeneous forests with different plant species, for different age, diameter and height classes. The model can reproduce forests from simple up to forests with a complex canopy structure (i.e. constituted by cohorts competing for light and water resources). The 3D-CMCC-FEM simulates carbon fluxes, in terms of gross and net primary productivity (GPP and NPP, respectively), partitioning and allocation in the main plant compartments (stem, branch, leaf, fruit, fine and coarse root, non-structural carbon) and water fluxes in terms of leaf and canopy transpiration, canopy and soil evaporation and the overall forest water balance. In the recent versions, nitrogen fluxes and allocation, in the same carbon pools, are also reproduced. The 3D-CMCC-FEM also takes into account management practices, as thinning and harvest, to predict their effects on forest growth and carbon sequestration. The 3D-CMCC-FEM is written in C-programming language and divided into several subroutines. To run the model, some input data are required. The meteorological forcing variables, on a daily time step, are represented by average, minimum and maximum air temperature, shortwave solar radiation, precipitation, vapor pressure deficit (or relative humidity). The model also needs some basic information about soil, such as soil depth and texture (clay, silt and sand fractions), as well as the forest stand information referred to plant species, ages, diameters, heights and stand density. An additional input is represented by species-specific eco-physiological data for the model parameterization.

3. Referencing the model

If you use 3D-CMCC-FEM in your research, based on the version used, please include the following acknowledgments in the relevant manuscript:

"3D-CMCC-FEM, Version 5.x.x was provided by Alessio Collalti and Daniela Dalmonech, or others, from Forest Modelling Lab. | National Research Council of Italy, Institute for Agricultural and Forestry Systems in the Mediterranean (CNR–ISAFOM);

Please also reference the following citation(s) as the most recent and complete description of the current model versions:

v.4.0 (not more in use)

- "Sviluppo di un modello dinamico ecologico-forestale per foreste a struttura complessa". A. Collalti, 2011. *University of Tuscia,* ***Ph.D. Thesis***, Ph.D. Advisor: Riccardo Valentini. http://dspace.unitus.it/bitstream/2067/2398/1/acollalti_tesid.pdf, (in Italian)

- "A process-based model to simulate growth and dynamics in forests with complex structure: evaluation and use of 3D-CMCC Forest Ecosystem Model in a deciduous forest in Central Italy". A. Collalti, L. Perugini, T. Chiti, A. Nolè, G. Matteucci, R. Valentini. ***Ecological Modelling*** 2014. https://doi.org/10.1016/j.ecolmodel.2013.09.016.

v.5.1.1 (not more in use)

- "Validation of 3D-CMCC Forest Ecosystem Model (v.5.1) against eddy covariance data for 10 European forest sites". A. Collalti, S. Marconi, A. Ibrom, C. Trotta, A. Anav, E. D'Andrea, G. Matteucci, L. Montagnani, B. Gielen, I. Mammarella, T. Grünwald, A. Knohl, F. Berninger, Y. Zhao, R. Valentini and M. Santini, ***Geoscientific Model Development***, 2016. https://doi.org/10.5194/gmd-9-479-2016.

v.PSM (not more in use)

- "Assessing NEE and Carbon Dynamics among 5 European Forest types: Development and Validation of a new Phenology and Soil Carbon routines within the process oriented 3D-CMCC-Forest-Ecosystem Model", S. Marconi, Jan 2013, *University of Tuscia,* ***M.Sc. Thesis***, M.Sc. Advisors: R. Valentini, T. Chiti, A. Collalti.

- "The Role of Respiration in Estimation of Net Carbon Cycle: Coupling Soil Carbon Dynamics and Canopy Turnover in a Novel Version of 3D-CMCC Forest Ecosystem Model". S. Marconi, T. Chiti, A. Nolè, R. Valentini and A. Collalti. ***Forests*** 2017. https://doi.org/10.3390/f8060220.

v.5.3.3-ISIMIP

- "Thinning can reduce losses in carbon use efficiency and carbon stocks in managed forests under warmer climate". Collalti A., Trotta C., Keenan T.F., Ibrom A., Lamberty B.B., Gröte R., Vicca S., Reyer C.P.O., Migliavacca M., Veroustraete F., Anav A., Campioli M., Scoccimarro E., Šigut L., Grieco E., Cescatti A., and Matteucci G., ***Journal of Advances in Modelling Earth System*** 2018. https://doi.org/10.1029/2018MS001275.

- "Climate change mitigation by forests: a case study on the role of management on carbon dynamics of a pine forest in South Italy". Pellicone G., August 2018, *University of Tuscia,* ***Ph.D. Thesis***, Ph.D. Advisors: G. Scarascia-Mugnozza, G. Matteucci, A. Collalti.

v.5.3

- "The sensitivity of the forest carbon budget shifts across processes along with stand development and climate change". Collalti A., Thornton P.E., Cescatti A., Rita A., Borghetti M., Nolè A., Trotta C., Ciais P., Matteucci G. ***Ecological Applications*** 2018. https://doi.org/10.1002/eap.1837.

v.5.5 (and v.5.5–ISIMIP)

- "Plant respiration: Controlled by photosynthesis or biomass?" Collalti A., Tjoelker M.G., Hoch G., Mäkelä A., Guidolotti G., Heskel M., Petit G., Ryan M.G., Battipaglia G., Matteucci G., Prentice I.C. ***Global Change Biology*** 2020, https://doi.org/10.1111/gcb.14857

- "Simulating the effects of thinning and species mixing on stands of oak (Quercus petrea (Matt.) Liebl. / Quercus robur L.) and pine (Pinus sylvestris L.) across Europe", Engel M., VVospernik S., Toigo M., Morin X., Tomao A., Trotta C., Steckel M., Barbati A., Nothdurft A. Pretzsch H., del Rio M., Skrzyszewski J., Ponette Q., Lof M., Jansons A., Brazaitis G., ***Ecological Modelling***, 2021, https://doi.org/10.1016/j.ecolmodel.2020.109406

- "Accuracy, realism and general applicability of European forest models" Mahnken, M., Cailleret M., Collalti A., Trotta C., Biondo C., D'Andrea E., Dalmonech D., Marano G., Mäkelä A., ..., Reyer C.P.O., ***Global Change Biology***, 2022, https://doi.org/10.1111/gcb.16384

- "Feasibility of enhancing carbon sequestration and stock capacity in temperate and boreal European forests via changes to forest management", Dalmonech D., Marano G., Amthor J., Cescatti A., Lindner M., Trotta C., Collalti A., ***Agricultural and Forest Meteorology***, 2022 https://doi.org/10.1016/j.agrformet.2022.109203

v.5.6

- "Simulating diverse forest management in a changing climate on a Pinus nigra subsp. Laricio plantation in Southern Italy", Testolin R., Dalmonech D., Marano G., D'Andrea E., Matteucci G., Noce S., Collalti A., ***Science of the Total Environment***, 2023 https://doi.org/10.1016/j.scitotenv.2022.159361

If you have made any significant modifications to the code, please mention them in your manuscript.

This User's Guide is the only documentation released with 3D-CMCC-FEM.
The code itself contains extensive internal documentation, and users with specific questions about the algorithms used to estimate particular processes should read the comments in the appropriate source code files.

The file **`treemodel.c`** contains references to all the core science routines and is a good starting point for this kind of inquiry. The files **`matrix.c`** defines the data structures that are used to pass information between the process modules and includes both a short text description and the units for each internal variable.

Shall you have questions about the code, appropriate model applications, possible programming errors, etc., please read this entire guide first, and then feel free to contact us.

4. Run the model

4.1 Model inputs

The 3D-CMCC-FEM model uses at least seven input files which are mandatory when not expressly defined as optional. These files must be necessarily provided to run the model:

- *"setting"* file*;*
- *"stand"* file*;*
- *"species"* file*;*
- *"meteo"* file*;*
- *"soil"* file*;*
- *"topo"* file*;*
- *"CO2"* file*;*
- *"management" file (optional);*
- *"Ndep"* file (optional);

A brief description of all files is given first, followed by detailed discussions of each file.
In the version 5.5-ISIMIP and 5.6 the input and output files are .txt ASCII files. The possibility to read/write a netcdf file is however in the code but this has been deactivated, so to provide the code .exe for both unix and windows environment.

Be sure to set the right arguments passed to the project and go into bin directory:

- cd bin

Example of run executable (e.g. in Bash Shell) with default parameters:

```
./3D-CMCC-Forest-Model -i input -o output -p parameterization -d sitename_stand.txt -m sitename_meteo_firstyear.txt -s sitename_soil.txt -t sitename_topo.txt -c sitename_settings.txt -k CO2_hist.txt > log.txt
```

4.2 Stand initialization file

```
/home/alessio/git/3D-CMCC-FEM/softwa
File  Modifica  Cerca  Visualizza  Documento  Aiuto
Year,x,y,Age,Species,Management,N,Stool,AvDBH,Height,Wf,Wrc,Wrf,Ws,Wbb,Wres,Lai
1944,0,0,23,Fagussylvatica,T,1767,0,3.619168081,6.666049802,0,0,0,0,0,0,0
1945,0,0,24,Fagussylvatica,T,1525,0,4.041901639,7.031160656,0,0,0,0,0,0,0
1946,0,0,25,Fagussylvatica,T,1525,0,4.459383607,7.391298361,0,0,0,0,0,0,0
1947,0,0,26,Fagussylvatica,T,1525,0,4.817278689,7.747770492,0,0,0,0,0,0,0
1948,0,0,27,Fagussylvatica,T,1326,0,5.128280543,8.105067873,0,0,0,0,0,0,0
1949,0,0,28,Fagussylvatica,T,1326,0,5.535475113,8.460180995,0,0,0,0,0,0,0
1950,0,0,29,Fagussylvatica,T,1326,0,5.961357466,8.814479638,0,0,0,0,0,0,0
1951,0,0,30,Fagussylvatica,T,1162,0,6.397521515,9.167340792,0,0,0,0,0,0,0
1952,0,0,31,Fagussylvatica,T,1162,0,6.784535284,9.516583477,0,0,0,0,0,0,0
1953,0,0,32,Fagussylvatica,T,1162,0,7.173580034,9.859578313,0,0,0,0,0,0,0
1954,0,0,33,Fagussylvatica,T,1023,0,7.552385142,10.20050831,0,0,0,0,0,0,0
1955,0,0,34,Fagussylvatica,T,1023,0,7.9271261,10.54035191,0,0,0,0,0,0,0
1956,0,0,35,Fagussylvatica,T,1023,0,8.232072336,10.87387097,0,0,0,0,0,0,0
1957,0,0,36,Fagussylvatica,T,906,0,8.591523179,11.20501104,0,0,0,0,0,0,0
1958,0,0,37,Fagussylvatica,T,906,0,8.940905077,11.530883,0,0,0,0,0,0,0
1959,0,0,38,Fagussylvatica,T,906,0,9.270640177,11.85339956,0,0,0,0,0,0,0
1960,0,0,39,Fagussylvatica,T,806,0,9.61235732,12.17648883,0,0,0,0,0,0,0
```

Figure 1 | Example of stand file

The first required input file is called the "**sitename_stand.txt**". It provides information about the stand conditions, i.e. initial condition or stands characteristics across time.
Example for a cell resolution of 100 x 100 meters cell X = 0, Y = 0 and with a monolayer and mono-specie structure ("average tree" concept):

```
Year,x,y,Age,Species,Management,N,Stool,AvDBH,Height,Wf,Wrc,Wrf,Ws,Wbb,Wres,Lai
1944,0,0,23,Fagussylvatica,T,1767,0,3.619168081,6.666049802,0,0,0,0,0,0,0
1945,0,0,24,Fagussylvatica,T,1525,0,4.041901639,7.031160656,0,0,0,0,0,0,0
1946,0,0,25,Fagussylvatica,T,1525,0,4.459383607,7.391298361,0,0,0,0,0,0,0
1947,0,0,26,Fagussylvatica,T,1525,0,4.817278689,7.747770492,0,0,0,0,0,0,0
1948,0,0,27,Fagussylvatica,T,1326,0,5.128280543,8.105067873,0,0,0,0,0,0,0
1949,0,0,28,Fagussylvatica,T,1326,0,5.535475113,8.460180995,0,0,0,0,0,0,0
1950,0,0,29,Fagussylvatica,T,1326,0,5.961357466,8.814479638,0,0,0,0,0,0,0
…
```

In the more general forest structure, the text file must be created following this logic architecture:

- for each tree height class define the number of age classes and their values
-- for each height->dbh class
--- for each height->dbh->age class
---- for each height->dbh->age->species class define its state variables:

Comments are allowed in the parameter file. Comments can appear almost anywhere, must begin with two forward slash characters '//', at the end of the line. Example parameter files are provided. Parameter definition and its value must be separated by one-tab character.

IMPORTANT: Values are referred to the SIZECELL dimensions specified in the setting.txt file (e.g. if SIZECELL = 100 meters variable values refer to tC ha^{-1}).

NOTE: the most basic set-up uses the "average tree" concept with one forest class alone, which simplify simulations and analyses (see above).

Year	Reference year for stand data
X,Y	Cell position
Age	Age of tree(s) (in years)
Species	Name of species (as exactly as the name of species file)
Management	Tree habitus (T = timber; C = Coppice, under development)
N	Number of trees (for that class if more than one class) per cell
*Stool	Number of stool per cell
AvDBH	Average diameter at breast height (for that class if more than one class) (in cm)
Height	Tree height (for that class if more than one class) (in m)
*Wf	Foliage biomass (for that class if more than one class) (in tDM ha^{-1})
*Wrc	Coarse root biomass (for that class if more than one class) (in tDM ha^{-1})
*Ws	Stem biomass (for that class if more than one class) (in tDM ha^{-1})

*Wbb	Branch and Bark biomass (for that class if more than one class) (in tDM ha^{-1})
*Wres	Reserve (for that class if more than one class) (in tC ha^{-1})
*LAI	Leaf Area Index (for that class if more than one class) (in m^2 m^{-2})

*Parameters not mandatory, mostly used from developers or in specific model versions under development. Set the values as 0.

4.3 Soil initialization file

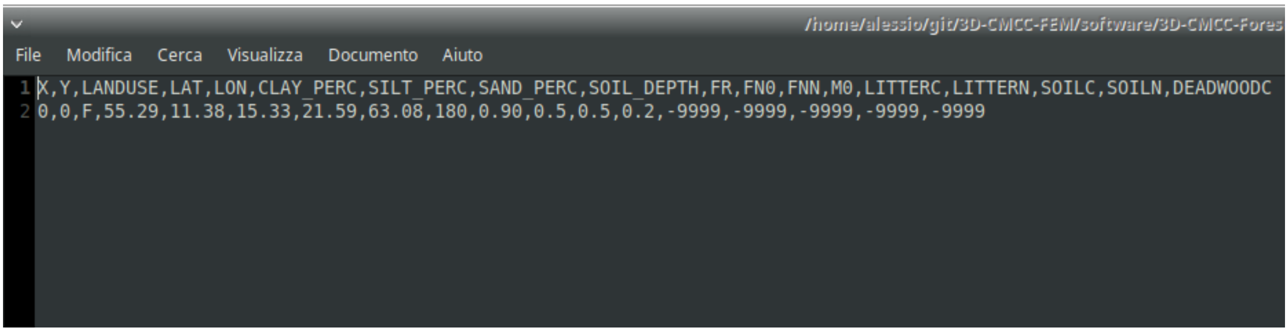


Figure 2| Example of soil characteristic file

The fourth required input file is "***sitename_soil.txt***". It contains information about soil and fertility of the test site.

Comments are allowed in the parameter file. Comments can appear almost anywhere, must begin with two forward slash characters '//', at the end of the line.

It contains the following information:

```
X,Y,LANDUSE,LAT,LON,CLAY_PERC,SILT_PERC,SAND_PERC,SOIL_DEPTH,FR,FN0,FNN,M,LITTER
C, LITTERN,SOILC,SOILN,DEADWOODC
0,0,F,49.3,18.32,20.63,20.63,58.74,80,0.65,0.5,0.5,0.2,-9999,-9999,-9999,-9999,-
9999
```

X,Y	Cell position
LANDUSE	See LANDUSE section
LAT	Latitude (in °)
LONG	Longitude (in °)
CLAY_PERC	Soil clay (in %)
SILT_PERC	Soil silt (in %)
SAND_PERC	Soil sand (in %)
SOIL_DEPTH	Soil depth (in cm), soil depth available to roots
FR	Fertility rating (dim) (only LUE version)
FN0	Value of fertility modifier when FR=0 (dim) (only LUE version)
M0	Value of 'm' when FR=0 (dim) (only LUE version)

*LITTERC	Litter carbon (in tC ha^{-1})
*LITTERN	Litter nitrogen (in tN ha^{-1})
*SOILC	Soil carbon (in tC ha^{-1})
*SOILN	Soil nitrogen (in tN ha^{-1})
*DEADWOODC	Dead wood carbon (in tC ha^{-1})

*Parameters not mandatory, mostly used from developers or in specific model versions under development. Set as -9999. Set the Fertility parameters to 0 If not used.

4.4 Topography initialization file

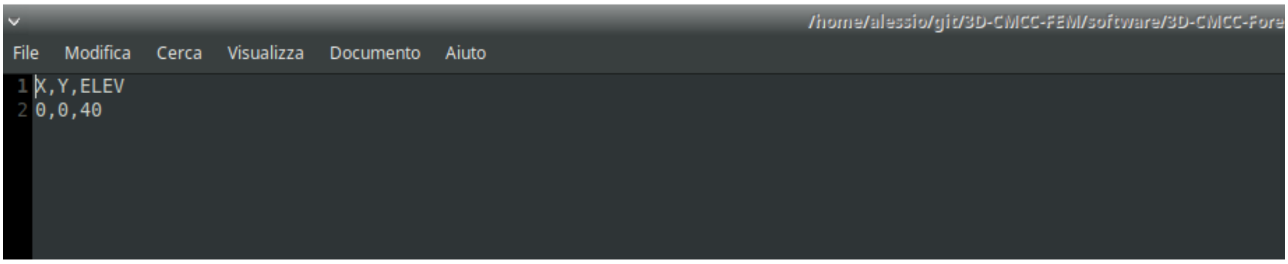


Figure 3| Example of topography file

The fifth required input file is "***sitename_topo.txt***". It contains information about topography of the test site.

Comments are allowed in the parameter file. Comments can appear almost anywhere, must begin with two forward slash characters '//', at the end of the line.

It contains the following information:

```
X,Y,40
```

X,Y	Cell position
ELEV	Elevation (in m)

4.5 Meteorological data file

```
/home/alessio/git/3D-CMCC-FEM/software/3D-CMCC-Forest-Model/input/Soroe/ISIMI
File  Modifica  Cerca  Visualizza  Documento  Aiuto
Year    Month   n_days  Rg_f    Ta_f    Tmax    Tmin    RH_f    Ts_f    Precip  SWC     LAI     ET      WS_f
1950    1       1       0.66079 -3.3303 -2.8258 -3.7631 90.818  -9999   3.3086  -9999   -9999   -9999   9.4395
1950    1       2       0.86905 -2.7728 -1.6239 -3.6495 96.428  -9999   2.7083  -9999   -9999   -9999   6.1997
1950    1       3       0.83663 -2.8126 -1.9484 -3.3205 96.74   -9999   2.319   -9999   -9999   -9999   5.3645
1950    1       4       0.99111 -1.5666 -0.15586        -3.0299 98.398  -9999   0       -9999   -9999   -9999   3.2713
1950    1       5       0.5722  -0.23032        0.81442 -0.85062        99.265  -9999   1.6465  -9999   -9999   -9999   2.919
1950    1       6       0.60553 0.25094 0.81915 -0.45472        98.878  -9999   1.4674  -9999   -9999   -9999   3.0447
1950    1       7       0.76504 0.080499        0.863   -1.4387 98.465  -9999   1.5422  -9999   -9999   -9999   3.3145
1950    1       8       1.4118  -2.1528 -0.50483        -3.2434 100.73  -9999   0       -9999   -9999   -9999   2.6675
1950    1       9       0.77171 -2.2033 -0.80207        -3.246  99.393  -9999   0       -9999   -9999   -9999   3.7197
1950    1       10      1.0098  -2.0168 -0.51813        -3.17   99.493  -9999   0       -9999   -9999   -9999   0.70707
1950    1       11      1.0416  -2.3873 -1.1976 -3.3213 96.823  -9999   0       -9999   -9999   -9999   3.6825
1950    1       12      1.6242  -4.6921 -2.6279 -6.7933 98.563  -9999   0       -9999   -9999   -9999   4.7061
1950    1       13      1.2623  -6.2513 -3.359  -7.7293 98.922  -9999   0       -9999   -9999   -9999   4.3768
1950    1       14      0.47107 -0.159  2.6675  -4.3082 96.418  -9999   2.4672  -9999   -9999   -9999   6.361
1950    1       15      0.56819 0.84741 1.7511  0.044092        98.038  -9999   5.4604  -9999   -9999   -9999   1.4197
1950    1       16      0.62422 0.72564 1.7128  -0.053473       88.423  -9999   4.4559  -9999   -9999   -9999   8.1887
1950    1       17      0.40307 0.86648 1.5948  0.35574 93.298  -9999   1.909   -9999   -9999   -9999   3.8607
1950    1       18      0.90507 1.555   3.038   0.71676 91.267  -9999   1.6136  -9999   -9999   -9999   6.745
1950    1       19      1.4716  -0.8953 1.4544  -3.1815 90.04   -9999   0       -9999   -9999   -9999   2.0056
1950    1       20      2.6245  -4.4482 -1.8488 -5.9832 82.325  -9999   0       -9999   -9999   -9999   4.4033
1950    1       21      1.908   -4.7044 -2.2712 -6.7642 74.18   -9999   0       -9999   -9999   -9999   7.1648
1950    1       22      0.60109 -1.6078 0.86532 -3.3136 94.263  -9999   2.6142  -9999   -9999   -9999   5.9298
1950    1       23      1.1118  -0.32758        0.40042 -0.81354        95.205  -9999   2.5775  -9999   -9999   -9999   5.958
1950    1       24      0.67123 -0.65574        0.18493 -1.5411 96.903  -9999   3.2684  -9999   -9999   -9999   5.9651
1950    1       25      1.1188  -3.6888 -0.97327        -5.3197 92.365  -9999   0       -9999   -9999   -9999   10.245
1950    1       26      2.0437  -5.5667 -4.4261 -6.3314 92.88   -9999   0       -9999   -9999   -9999   10.107
1950    1       27      0.84743 -5.9633 -5.2672 -6.3753 93.6    -9999   2.7738  -9999   -9999   -9999   8.8028
1950    1       28      1.2803  -5.1195 -3.8685 -5.9358 96.718  -9999   3.1565  -9999   -9999   -9999   4.8892
1950    1       29      1.2476  -3.5845 -2.0745 -4.5709 94.952  -9999   2.4422  -9999   -9999   -9999   7.9852
1950    1       30      0.85406 -4.4348 -3.343  -5.0812 93.765  -9999   3.6135  -9999   -9999   -9999   9.9116
1950    1       31      0.46056 -5.3064 -4.6268 -5.616  92.578  -9999   4.7849  -9999   -9999   -9999   11.841
1950    2       1       1.6123  -6.5576 -6.0981 -6.8333 90.423  -9999   2.3175  -9999   -9999   -9999   9.8185
1950    2       2       2.438   -6.3829 -5.4406 -6.8169 92.85   -9999   0       -9999   -9999   -9999   8.1005
1950    2       3       2.0056  -6.39   -5.0542 -7.6904 94.38   -9999   0       -9999   -9999   -9999   6.2946
```

Figure 4| Example of meteorological forcing file

The second required input file is the meteorological data file, which is named using the start year of simulation (e.g. "***sitename_meteo.txt***"), containing the daily meteorological data.

Years of simulation depends on the first and last year of simulation reported in the setting file. All the simulation years have to be included in the met file.

Some met data are mandatory: temperature, precipitation, vapour pressure deficit (or relative humidity) and short-wave solar radiation, whereas others are optional.

If the model runs in "spatial version" daily or monthly LAI values are mandatory otherwise they are not considered in processes (older model version than the 5.5-ISIMIP).
Each variable must be separated by one-tab character. Model considers leap years, so 29th of February has to be included.

Example for year 2007-2xxx in daily version:

Year	Month	n_days	Rg_f	Ta_f	Tmax	Tmin	VPD_f	Ts_f	Precip	SW	LAI	ET	WS_f
2007	1	1	6.1	-9999*	10.4	5.8	0.2	6.3	0.2	0.27	-9999*	-9999*	125.3
2007	1	2	6.2	-9999*	9.9	3.1	0.3	3.3	0	0.39	-9999*	-9999*	126.6
2007	1	3	5.8	-9999*	10	1.9	0.1	0.5	0	0.2	-9999*	-9999*	124.4
...													

*NO DATA = -9999

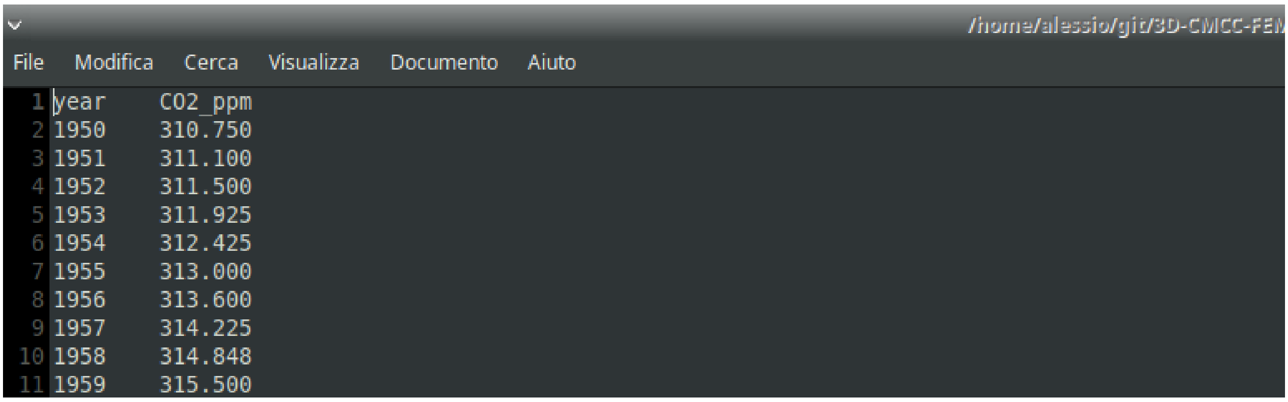
It contains the following variables:

Rg_f	Mean daily global radiation (MJ m^{-2} day^{-1}) , i.e. *downward* shortwave radiation
Ta_f	Daily Average temperature (°C)
Tmax	Daily Maximum temperature (°C)
Tmin	Daily Minimum temperature (°C)
VPD_f or RH_f	Daily Vapour Pressure Deficit (mbar-hPa) **or** Relative Humidity (%)
Ts_f	Daily Soil temperature (°C)
Precip	Cumulated daily precipitation (mm day^{-1})
*SWC	Soil Water Content (mm m^{-2})
*LAI	Leaf Area Index (m^2 m^{-2}) (Only in spatial version)
*ET	Evapotranspiration (mm m^{-2} day^{-1})
*WS_f	Windspeed (m sec^{-1})

*Parameters not mandatory, mostly used from developers or in specific model versions under development

NOTE: missing data (-9999) in mandatory variables may lead the model to interrupt execution.

4.6 CO2 atmospheric concentration file




```
year	CO2_ppm
1950	310.750
1951	311.100
1952	311.500
1953	311.925
1954	312.425
1955	313.000
1956	313.600
1957	314.225
1958	314.848
1959	315.500
```

Figure 5| Example of atmospheric CO_2 concentration forcing file

Average annual data have to be provided for the expected simulation years.

4.7 Management file

See directly section 5 MANAGEMENT.

4.8 Species-Parameterization file

/home/alessio/git/3D-CMCC-FEM/software/3D-CMCC-Forest-Model/i

File Modifica Cerca Visualizza Documento Aiuto

```
//Fagus_sylvatica parameterization file
LIGHT_TOL            1      //4 = very shade intolerant (cc = 90%), 3 = shade intolerant (cc = 100%), 2 = shade tolera
PHENOLOGY            0.1    //PHENOLOGY 0.1 = deciduous broadleaf, 0.2 = deciduous needle leaf, 1.1 = broad leaf everg
ALPHA                0.057  //Canopy quantum efficiency (molC/molPAR) (0.057) Peltionemi et al., 2012, (0.05) from Wil
EPSILONgCMJ          0.69   //Light Use Efficiency  (gC/MJ)(used if ALPHA is not available) Peltionemi et al., 2012,
GAMMA_LIGHT          0      //Empirical parameter for Light modifiers
K                    0.5    //Extinction coefficient for absorption of PAR by canopy 0.71 for F. sylvatica Vitale et a
ALBEDO               0.15   //Albedo, 0.15 (varying from 0.13-0.17) from OTTO et al., BGS 2014
INT_COEFF            0.3    //precip interception coefficient for F. sylvatica fom Tatarinov
SLA_AVG0             40     //Average Specific Leaf Area m^2/KgDM (juvenile) sunlit/shaded leaves for Fagus s. 45 Rötz
SLA_AVG1             20     //Average Specific Leaf Area m^2/KgDM (mature) sunlit/shaded leaves for Fagus s. 9 Rötzer
TSLA                 35     //Age at which SLA_AVG = (SLA_AVG1 + SLA_AVG0 )/2 for 35 Fagus s. Forrester et al., 2017
SLA_RATIO            2.3    //(DIM) ratio of shaded to sunlit projected SLA  for F. sylvatyica from Mollicone et al.,
LAI_RATIO            2      //(DIM) all-sided to projected leaf area ratio for F. sylvatyica from Mollicone et al., 20
FRACBB0              0.20   //Branch and Bark fraction at age 0
FRACBB1              0.125  //Branch and Bark fraction for mature stands (0.125 from Damesin et al., 2003)(0.1 from Ho
TBB                  20     //Age at which fracBB = (FRACBB0 + FRACBB1 )/ 2
RHO0                 0.64   //Minimum Basic Density for young Trees tDM/m^3 0.72 Bouriaud et al., 2004, 0.64 ettore, 0
RHO1                 0.64   //Maximum Basic Density for young Trees tDM/m^3 0.79 Bouriaud et al., 2004, 0.64 ettore, 0
TRHO                 100    //Age at which rho = (RHOMIN + RHOMAX )/2
FORM_FACTOR          0.433  //Form factor Seidl et al., 2012
COEFFCOND            0.08   //Define stomatal responsee to VPD in mbar see Pietsch et al., 2005, 0.057 Forrester et al
BLCOND               0.01   //Canopy Boundary Layer conductance see 0.01 for stomatal Pietsch et al., 2005
MAXCOND              0.003  //Maximum Stomatal Conductance in m/sec 0,005 for Tatarinov et al., 2006, 0.006 Pietsch, 0
CUTCOND              6e-05  //Cuticular conductance in m/sec for F sylvatica 0.000006 Tatarinov et al., 2006
MAXAGE               400    //Determines rate of "physiological decline" of forest
RAGE                 0.95   //Relative Age to give fAGE = 0.5
NAGE                 10     //Power of relative Age in function for Age
GROWTHTMIN           0      //Minimum temperature for growth 5  Rasse et al 2001 0 from Williams 1996, -2 Hoffmann 199
GROWTHTMAX           40     //Maximum temperature for growth 40 from Williams 1996
GROWTHTOPT           20     //Optimum temperature for growth 19.4 Rasse et al 2001, 20 from Lyr & Garbe, 1994, 22 Hoff
GROWTHSTART          60     //(5 °C)average temperature or (GDD) thermic sum for starting growth in °C 130 ettore with
MINDAYLENGTH         12     //minimum day length for fagus from ettore, 12 through satellite images
SWPOPEN              -0.34  //Leaf water potential: start of reduction for Fagus sylvatica -0.6 Mollicone et al., 2002
SWPCLOSE             -2.2   //Leaf water potential: complete reduction for Fagus sylvatica -2.3 Mollicone et al., 2002
OMEGA_CTEM           0.8    //ALLOCATION PARAMETER control the sensitivity of allocation to changes in water and light
```

Figure 6|Example of species–specific parameterization file

The parameterization file is the species eco-physiological constants file, named with specie to simulate (e.g."***Fagussylvatica.txt***").

Comments are allowed in the parameter file. Comments can appear almost anywhere, must begin with two forward slash characters '//', at the end of the line.

Example parameter files are provided. Parameter definition and its value must be separated by one-tab character.

It contains the following species-specific parameters:

LIGHT_TOL	Light Tolerance: 4 = very shade intolerant (max canopy coverage = 90%), 3 = shade intolerant (max canopy coverage 100%), 2 = shade tolerant (max canopy coverage = 110%), 1 = very shade tolerant (max canopy coverage = 120%)
PHENOLOGY	0.1 = deciduous broadleaf, 0.2 = deciduous needle leaf, 1.1 = broad leaf evergreen, 1.2 = needle leaf evergreen
ALPHA	Canopy quantum efficiency (molC molPAR^{-1}) (LUE version)
EPSILONgCMJ	Light Use Efficiency (gC MJ^{-1}) (used if ALPHA is not available)
GAMMA_LIGHT	Empirical parameter for Light modifiers (LUE version)

K	Extinction coefficient for absorption of PAR by canopy
ALBEDO	Canopy albedo
INT_COEFF	Precipitation interception coefficient
SLA_AVG0	Average Specific Leaf Area m^2 KgC^{-1} for sunlit/shaded leaves (juvenile)
SLA_AVG1	Average Specific Leaf Area m^2 KgC^{-1} for sunlit/shaded leaves (mature)
TSLA	Age at which SLA_AVG = (SLA_AVG1 + SLA_AVG0)/2
SLA_RATIO	(DIM) ratio of shaded to sunlit projected SLA
LAI_RATIO	(DIM) all-sided to projected leaf area ratio
FRACBB0	Branch and Bark fraction at age 0 (m^2 Kg^{-1})
FRACBB1	Branch and Bark fraction for mature stands (m^2 Kg^{-1})
TBB	Age at which fracBB = (FRACBB0 + FRACBB1)/2
RHO0	Minimum Basic Density for young Trees (tDM m^{-3})
RHO1	Maximum Basic Density for mature Trees (tDM m^{-3})
TRHO	Age at which rho = (RHOMIN + RHOMAX)/2
FORM_FACTOR	Stem form factor (adim)
COEFFCOND	Define stomatal response to VPD in m sec^{-1}
BLCOND	Canopy Boundary Layer conductance m sec^{-1}
MAXCOND	Maximum Leaf Conductance in m sec^{-1}
CUTCOND	Cuticular conductance in m sec^{-1}
MAXAGE	expected tree lifespan (years)
RAGE	Relative Age to give fAGE = 0.5
NAGE	Power of relative Age in function for Age
GROWTHTMIN	Minimum temperature for growth °C
GROWTHTMAX	Maximum temperature for growth °C
GROWTHTOPT	Optimum temperature for growth °C
GROWTHSTART	Thermic sum value for starting growth in °C
MINDAYLENGTH	Minimum day length for phenology (days)
SWPOPEN	Soil water potential at which stomata are open (MPa)
SWPCLOSE	Soil water potential at which stomata close (MPa)
OMEGA_CTEM	Allocation parameter control the sensitivity of allocation to changes in water and light availability
S0CTEM	Parameter controlling allocation to stem

R0CTEM	Parameter controlling allocation to root
F0CTEM	Parameter controlling allocation to foliage
FRUIT_PERC	% of NPP to fruit
CONES_LIFE_SPAN	Life span for cones (years)
FINE_ROOT_LEAF	Allocation new fine root C:new leaf (ratio)
*STEM_LEAF	Allocation new stem C:new leaf (ratio)
COARSE_ROOT_STEM	Allocation new coarse root C:new stem (ratio)
LIVE_TOTAL_WOOD	Allocation new live wood C:new total wood C (ratio)
N_RUBISCO	Fraction of leaf N in Rubisco (ratio)
CN_LEAVES	CN of leaves ($kgC\ kgN^{-1}$)
*CN_FALLING_LEAVES	CN of leaf litter ($kgC\ kgN^{-1}$)
CN_FINE_ROOTS	CN of fine roots ($kgC\ kgN^{-1}$)
CN_LIVEWOODS	CN of live woods ($kgC\ kgN^{-1}$)
CN_DEADWOOD	CN of dead woods ($kgC\ kgN^{-1}$)
*LEAF_LITT_LAB_FRAC	leaf litter labile fraction (dimension lees)
*LEAF_LITT_CEL_FRAC	leaf litter cellulose fraction (dimension lees)
*LEAF_LITT_LIGN_FRAC	leaf litter lignin fraction (dimension lees)
*FROOT_LITT_LAB_FRAC	fine root litter labile fraction (dimension lees)
*FROOT_LITT_CEL_FRAC	fine root litter cellulose fraction (dimension lees)
*FROOT_LITT_LIGN_FRAC	fine root litter lignin fraction (dimension lees)
*DEADWOOD_CEL_FRAC	dead wood litter cellulose fraction (dimension lees)
*DEADWOOD_LIGN_FRAC	dead wood litter lignin fraction (dimension lees)
BUD_BURST	Days of bud burst at the beginning of growing season (only for deciduous) (days)
LEAF_FALL_FRAC_GROWING	Proportions of the growing season of leaf fall
LEAF_FINEROOT_TURNOVER	Average yearly leaves and fine root turnover rate
LIVEWOOD_TURNOVER	Annual yearly live wood turnover rate
SAPWOOD_TURNOVER	Annual yearly sapwood turnover rate
*DBHDCMAX	Maximum dbh crown diameter relationship when minimum density
DBHDCMIN	Minimum dbh crown diameter relationship when maximum density
SAP_A	Scaling coefficient in sapwood area to DBH relationship (dimensionless)
SAP_B	Scaling coefficient in sapwood area to DBH relationship (exp) (dimensionless)

SAP_LEAF	Sapwood/max leaf area ratio in pipe model (m^2 m^{-2})
SAP_WRES	Sapwood-Reserve biomass ratio used if no Wres data are available
STEMCONST_P	Constant in the stem mass vs. diameter relationship
STEMPOWER_P	Power in the stem mass vs. diameter relationship
CRA	Chapman-Richards a parameter (maximum height, meter)
CRB	Chapman-Richards b parameter
CRC	Chapman-Richards c parameter
*HDMAX_A	A parameter for Height (m) to Base diameter (m) ratio MAX
*HDMAX_B	B parameter for Height (m) to Base diameter (m) ratio MAX
*HDMIN_A	A parameter for Height (m) to Base diameter (m) ratio MIN
*HDMIN_B	B parameter for Height (m) to Base diameter (m) ratio MIN
*CROWN_FORM_FACTOR	Crown form factor (0 = cylinder, 1 = cone, 2 = sphere, 3 = ellipsoid)
*CROWN_A	Crown a parameter
*CROWN_B	Crown b parameter
*MAXSEED	Maximum seeds number (see TREEMIG)
*MASTSEED	Masting year (see TREEMIG)
*WEIGHTSEED	Single fruit weight in g
*SEXAGE	Age for sexual maturity
*GERMCAPACITY	Germinability rate (%)
ROTATION	Rotation for final harvest (based on tree age)
THINNING	Thinning regime, frequency (based on year simulation)
THINNING_REGIME	Thinning regime (0 = above, 1 = below)
THINNING_INTENSITY	Thinning intensity (% of N-tree to remove for each specie-class)

*Parameters not mandatory, mostly used from developers or in specific model versions under development.

ADDITIONAL COMMENTS:

GAMMA_LIGHT: usually set to 0 if the BGC version is used.

SLA : a rough estimate of this value is sufficient.

FRACBB0, FRACBB1: as reference see Forrester et al.2016 Dataset.

RHO0 and RHO1: are used only if the parameters STEMCONST_P and STEMPOWER_P are not provided. See also the database of Zanne et al. 2009 - Global wood density database. If data at different age are not available, simply set the same value of wood density.

TRH0: a rough estimate of this value is sufficient.

FORM_FACTOR: is used to estimate the volume of the stem as function of DBH and height. See Seidl et al., 2012.

COEFFCOND : currently simply kept as 0.5 for all the species.

MAXAGE: it controls the rate of physiological decline of forest.

OMEGA_CTEM, SOCTEM,ROCTEM and FOC_TEM: see Arora and Boer al.2005.

CONES_LIFE_SPAN: for evergreen trees which do not have cones, set this parameter to 1.

BUD_BURST: in the model the phonological module assumes that within this period both the bud burst and the fully leaf development occur.

DBHDCMAX: in the version 5.5-ISIMP and 5.6 this parameter is computed in the code

DBHDCMIN: it determines when self-thinning should occur.

SAP_A and SAP_B: for some references see 'Sapwood biomass carbon in northern boreal and temperate forests' Thurner et al.2019 , Wullschleger et al.2001

STEMCONST_P, STEMPOWER_P, CRA, CRB, CRC: where possible, to be estimated from site data.

ROTATION: harvesting is intended clear cut/removal of the entire forest class. It follows a replanting which can be used to mimic the natural regeneration.

Rotation, thinning interval and intensity parameters are used only if the setting MANAGEMENT = ON.

THINNING_REGIME: this variable is currently set in the setting_file.

For more details see section 5 MANAGEMENT.

4.9 Settings file

```
/home/alessio/git/3D-CMCC-FEM/software/3D-CMCC-Forest-Model/input/Soroe/ISIMIP/FT/Soroe_settings_ISIMIP_
File  Modifica  Cerca  Visualizza  Documento  Aiuto
SITENAME Soroe
VERSION f                            //Must be 'f' for FEM version or 'b', for BGC version for FOREST LANDUSE
SPATIAL u                            //Must be 's' or 'u', spatial or unspatial
TIME d                               //Must be 'm' or 'd', monthly or daily
SPINUP off                           //Must be 'on' or 'off'
SPINUP_YEARS 6000                    //Number of years for spinup
SCREEN_OUTPUT off                    //Must be 'on' or 'off'
DEBUG_OUTPUT off                     //Must be 'on' or 'off'
DAILY_OUTPUT on                      //Must be 'on' or 'off'
MONTHLY_OUTPUT off                   //Must be 'on' or 'off'
ANNUAL_OUTPUT on                     //Must be 'on' or 'off'
SOIL_OUTPUT off                      //Must be 'on' or 'off'
NETCDF_OUTPUT off                    //Must be 'on' or 'off'
YEAR_START 1950                      //Starting year simulation
YEAR_END 2099                        //Ending year simulation
YEAR_RESTART off                     //Year to restart
PSN_mod 0                            //Must be '0' (FvCB) or '1' (LUE) for photosynthesis approach
CO2_trans on                         //Must be 'on' or 'off'
YEAR_START_CO2_FIXED -9999           //When Co2_trans = var, year at which fix [CO2]
Ndep_fixed on                        //Must be 'on' or 'off'
Photo_accl on                        //Photosynthesis temperature acclimation Must be 'on' or 'off'
Resp_accl on                         //Q10 temperature acclimatation Must be 'on' or 'off'
regeneration off                     //Must be 'on' or 'off'
management var                       //Must be 'on' or 'off'
YEAR_START_MANAGEMENT 2020           //First year of management
Progn_Aut_Resp on                    //Prognostic autotrophic respiration, Must be 'on' or 'off', if off Y values are used
SIZECELL 100                         //Its value must be within 10 and 100 (unity measure is meter: 10 = 10x10 = 100m^2)
Y 0.48                               //Fixed_Aut_Resp_rate Assimilate use efficiency-Respiration rate-GPP/NPP
CO2CONC 368.865                      //CO2 concentration refers to 2000 as ISIMIP PROTOCOL
CO2_INCR 0.01                        //1% increment
INIT_FRAC_MAXASW 1                   //0.1 Minimum fraction of asw based on maxasw (wilting point) (unchanged)
TREE_LAYER_LIMIT 3                   //define differences among tree heights in meters classes to define number of layers in unspatial version
SOIL_LAYER 1                         //define soil layer/s to consider
MAX_LAYER_COVER 1.2
THINNING_REGIME  Above               // thinning regime (Above or Below)
REPLANTED_SPECIES Fagussylvatica     // species name of replanted trees (mandatory)
REPLANTED_MANAGEMENT T               // (T) management of replanted trees (should be only T)(mandatory)
REPLANTED_TREE 6000                  // number of replanted trees (mandatory)
REPLANTED_AGE 4                      // (yr) age of replanted trees (mandatory)
REPLANTED_AVDBH 1                    // (cm) average dbh of replanted trees (mandatory)
REPLANTED_LAI 0                      // (m2/m2) lai for replanted trees (mandatory for evergreen, useless for deciduous)
REPLANTED_HEIGHT 1.3                 // (m) height of replanted trees (mandatory)
REPLANTED_WS 0                       // (tDM/ha) stem biomass of replanted trees (optional)
REPLANTED_WCR 0                      // (tDM/ha) coarse root biomass of replanted trees (optional)
REPLANTED_WFR 0                      // (tDM/ha) fine root biomass of replanted trees (optional)
REPLANTED_WL 0                       // (tDM/ha) leaf biomass of replanted trees (optional for evergreen if LAI!= 0, otherwise useless)
REPLANTED_WBB 0                      // (tDM/ha) branch biomass of replanted trees (optional)
```

Figure 7 | Examples of settings file

It contains the following setting parameters:

SITENAME	Name of site
VERSION	Must be 'f' for FEM version (other versions under development)
SPATIAL	Must be 's' or 'u', spatial or un-spatial
TIME	Must be 'm' or 'd', monthly or daily
SPINUP	Must be 'on' or 'off' (under development , set as 'off')
SPINUP_YEARS	Number of years for spin-up (under development, set as 'off')
SCREEN_OUTPUT	Must be 'on' or 'off'
DEBUG_OUTPUT	Must be 'on' or 'off'
DAILY_OUTPUT	Must be 'on' or 'off'
MONTHLY_OUTPUT	Must be 'on' or 'off'
ANNUAL_OUTPUT	Must be 'on' or 'off'
SOIL_OUTPUT	Must be 'on' or 'off' (under development, set as 'off')
NETCDF_OUTPUT	Must be 'off' (currently not used)
YEAR_START	Starting year simulation
YEAR_END	Ending year simulation
YEAR_RESTART	Year to restart. Must be 'off' (currently not used)
PSN_mod	Must be '0' (FvCB version) or '1' (LUE version) for photosynthesis approach
CO2_trans	Must be 'on' , 'off', or 'var'
YEAR_START_CO2_FIXED	-9999 . When Co2_trans = var, year at which fix [CO2]
*Ndep_fixed	Must be 'on' or 'off' (under development, set as 'off')
Photo_accl	Photosynthesis temperature acclimation Must be 'on' or 'off'
Resp_accl	Q_{10} temperature acclimation. Must be 'on' or 'off'
regeneration	Must be 'on' or 'off'
management	Must be 'on', 'off', or 'var'
YEAR_START_MANAGEMENT	First year of management
Progn_Aut_Resp	Prognostic autotrophic respiration. Must be 'on' or 'off', if off Y values are used
SIZECELL	Length of the side of a square cell in meters. Its value must be within 10 and 100 (is meter: 10 = 10x10 = 100m^2)

Y	Assimilate use efficiency-Respiration rate-NPP/GPP (if Progn_Aut_Resp = off)
CO2CONC	CO_2 concentration refers to year 2000
CO2_INCR	1% increment in [CO_2]
INIT_FRAC_MAXASW	Percentage of water content in soil compared to maximum at the beginning of simulation, i.e. 1 January (1 = 100%) .
TREE_LAYER_LIMIT	Define differences among tree heights in meters classes to define a new layer
*SOIL_LAYER	Define soil layer(s) to consider
MAX_LAYER_COVER	Maximum overlap between tree crowns (1.2 = 120%)
THINNING_REGIME	Thinning regime (Above or Below)
REPLANTED_SPECIES	Species name of replanted trees (mandatory)
REPLANTED_MANAGEMENT	(T) management of replanted trees (should be only T) (mandatory)
REPLANTED_TREE	Number of replanted trees (mandatory)
REPLANTED_AGE	(yr) age of replanted trees (mandatory)
REPLANTED_AVDBH	(cm) average dbh of replanted trees (mandatory)
*REPLANTED_LAI	(m^2m^{-2}) LAI for replanted trees (mandatory for evergreen useless for deciduous).
REPLANTED_HEIGHT	(m) height of replanted trees (mandatory)
*REPLANTED_WS	(tDM ha^{-1}) stem biomass of replanted trees (optional)
*REPLANTED_WCR	(tDM ha^{-1}) coarse root biomass of replanted trees (optional)
*REPLANTED_WFR	(tDM ha^{-1}) fine root biomass of replanted trees (optional)
*REPLANTED_WL	(tDM ha^{-1}) leaf biomass of replanted trees (optional for evergreen if LAI!= 0, otherwise useless)
*REPLANTED_WBB	(tDM ha^{-1}) branch biomass of replanted trees (optional)
REGENERATION_SPECIES	Species name of regenerated trees (mandatory)
REGENERATION_MANAGEMENT	(T) management of replanted trees (should be only T) (mandatory)
REGENERATION_N_TREE	number of replanted trees (mandatory)
REGENERATION_AGE	(yr) age of regeneration trees (mandatory)
REGENERATION_AVDBH	(cm) average dbh of regeneration trees (mandatory)
*REGENERATION_LAI	(m^2m^{-2}) LAI for regeneration trees (mandatory for evergreen, useless for deciduous)
REGENERATION_HEIGHT	(m) height of regenerated trees (mandatory)
*REGENERATION_WS	(tDM ha^{-1}) stem biomass of regeneration trees (optional)

*REGENERATION_WCR	(tDM ha^{-1}) coarse root biomass of regeneration trees (optional)
*REGENERATION_WFR	(tDM ha^{-1}) fine root biomass of regeneration trees (optional)
*REGENERATION_WL	(tDM ha^{-1}) leaf biomass of regeneration trees (optional for evergreen if LAI!= 0, otherwise useless)
*REGENERATION_WBB	(tDM ha^{-1}) branch biomass of regeneration trees (optional)
*PRUNING	Must be 'on' or 'off' (currently not used, set to 'off')
*IRRIGATION	Must be 'on' or 'off' (currently not used, set to 'off')

*Parameters not mandatory, mostly used from developers or in specific model versions under development

ADDITIONAL COMMENTS:

SPATIAL: version 5.5-ISIMIP and 5.6 have been tested for the unspatial version only.

TIME: version 5.5-ISIMIP and 5.6 run on a daily time step only.

CO2_TRANS: if set to 'off', [CO2] is fixed at the value defined by CO2CONC for the whole time frame of the simulation. If set to 'on', the data from the external [CO2] file are used. If set to 'var' , the code considers the [CO2] data from the external [CO2] file up to the year YEAR_START_CO2_FIXED and then a yearly increase of CO2_INCR is considered.

YEAR_START_MANAGEMENT: it is used only if MAN = ON. The difference between YEAR_START_MANAGEMENT and YEAR_START has to be lower than the parameter value THINNING (see species parameter file).

SIZECELL: length of the side of a square cell in meters. This is the cell/area considered for the simulation and the output at class and cell level. Hence the stand data have to be provided accordingly, e.g. stand density has to refer to SIZECELLxSIZECELL area.

INIT_FRAC_MAXASW: the model is not particularly sensitive to this value.

REPLANTED_TREE, REPLANTED_AGE, REPLANTED_AVDBH, REPLANTED_HEIGHT only used if MAN= 'on' or MAN ='var'.

REGENERATION _TREE, REGENERATION _AGE, REGENERATION _AVDBH, REGENERATION _HEIGHT only used if MAN ='var' and regeneration='on'.

For specific details about replanting and regeneration-related parameters, see the section 5 MANAGEMENT.

4.10 **Model outputs**

For each simulation the 3D-CMCC-FEM creates *ex–novo* or rewrites into the output folder a file named "output.txt".

In this folder 4 other subfolders based on time-scale and settings choices should created. These files contain every result for debug (if necessary) daily, monthly and annual time-step simulations. It is also useful to check which model functions have been used. These results can be obtained at stand level or for each type of class level (layer, dbh, age or species class) on Unix like platforms, if you need to extrapolate a variable it is advised to use the "grep" tool.

E.g. open a terminal into the output folder and for the variable NPP type:

"`cat output.txt | grep 'Stand NPP'` " if you want to see grep output into terminal;
"`cat output.txt | grep 'Stand NPP' > NPP.txt`" if you want to redirect grep output into an NPP file inside the output folder

<u>IMPORTANT: be sure to use the correct declaration of the output as grep parameter</u>.

The Model provides outputs at class, canopy level or at cell level (by summing up or averaging across the classes). It is assumed that the cell is covered by vegetation. The entire cell can be then completely or partially covered by the canopy. Values at class and canopy level refer to m2 of cell-area. Please be aware that LAI is computed as m2/m2 of canopy-covered area. This means that in order to have the average value at cell level it has to be multiplied by the canopy cover fraction. This could be important if the value is compared to a remote-sensing based value.
Output variables for the nitrogen pools/fluxes and soil are provided. However, the version with the full nitrogen cycle and the soil is still under development.

When the model is applied on a multi-specie or multi-layer forest, the output for each class is reported for every time step, in separated rows. Currently the model still prints the cell-level information for each class, which is redundant. In the next version, the cell-level data will be saved in a separated file.

4.10.1 Annual Outputs

<u>At class level:</u>

YEAR	Year of simulation
LAYER	Layer of tree class
HEIGHT	Average height of a species (m)
DBH	Average diameter at breast height of a species (cm)
AGE	Age of trees (years)
SPECIES	Tree Species
MANAGEMENT	T = Timber
GPP	Yearly Gross Primary Production (gC m^{-2} $year^{-1}$)
GPP_SUN:GPP	Yearly Gross Primary Production for sun leaves (gC m^{-2} $year^{-1}$)
GPP_SHADE:GPP	Yearly Gross Primary Production for shaded leaves (gC m^{-2} $year^{-1}$)
v_SUN:A_SUN	Carboxylation rate/Final assimilation rate ratio for sun leaves
Aj_SUN:A_SUN	RuBP regeneration/Final assimilation rate ratio for sun leaves
Av_SHADE:A_SHADE	Carboxylation rate/Final assimilation rate ratio for shaded leaves
Aj_SHADE:A_SHADE	RuBP regeneration/Final assimilation rate ratio for shaded leaves
Av_TOT:A_TOT	Carboxylation rate/Final assimilation rate ratio

Aj_TOT:A_TOT	RuBP regeneration/Final assimilation rate ratio
GR	Growth respiration (gC m^{-2} $year^{-1}$)
MR	Maintenance Respiration (gC m^{-2} $year^{-1}$)
RA	Autotrophic respiration (gC m^{-2} $year^{-1}$)
NPP	Net Primary Production (gC m^{-2} $year^{-1}$)
BP	Yearly Biomass Production (gC m^{-2} $year^{-1}$)
reser_as_diff	-
ResAlloc	Annual reserve allocated (gC m^{-2} $year^{-1}$)
ResDeple	Annual reserve depleted (gC m^{-2} $year^{-1}$)
ResUsage	Annual reserve used (gC m^{-2} $year^{-1}$)
BP/NPP	Biomass productivity vs. Net Primary Production
ResAlloc/NPP	Annual reserve allocated vs. Net Primary Production
ResAlloc/BP	Annual reserve allocated vs. Biomass productivity
ResDeple/NPP	Annual reserve depleted vs. Net Primary Production
ResDeple/BP	Annual reserve depleted vs. Biomass productivity
ResUsage/NPP	Annual reserve used vs. Net Primary Production
ResUsage/BP	Annual reserve used vs. Biomass productivity
CUE	Annual Carbon Use Efficiency (gC NPP gC GPP^{-1})
BPE	Biomass Production Efficiency (gC BP gC GPP^{-1})
diffCUE-BPE	CUE - BPE
Y(PERC)	RA/GPP * 100
MAX_NSC_CONC	Annual max value of NSC concentration (RESERVE/SAPWOOD)
MIN_NSC_CONC	Annual min value of NSC concentration (RESERVE/SAPWOOD)
PeakLAI	Peak LAI (maximum attainable LAI) ($m^2 m^{-2}$)
MaxLAI	Maximum of LAI (maximum reached LAI) ($m^2 m^{-2}$)
SLA	Specific Leaf Area ($m^2 Kg^{-1}$)
SAPWOOD_AREA	Tree sapwood area (cm^2)
CC-Proj	Projected Canopy Cover (frac of the cell)
DBHDC	DBH/Crown diameter ratio
CROWN_DIAMETER	Crown Projected Diameter (m)
CROWN_HEIGHT	Crown Height (m)
CROWN_AREA_PROJ	Crown Projected Area (at zenith angle) (m^2)
APAR	Absorbed Photosynthetically Active Radiation (molPAR$m^{-2}$$year^{-1}$)
LIVETREE	Number of live trees (ntree $cell^{-1}$)
DEADTREE	Number of dead trees (ntree $cell^{-1}$)
THINNEDTREE	Number of thinned trees (ntree $cell^{-1}$)
VEG_D	Annual number of vegetative days (days $year^{-1}$)
FIRST_VEG_DAY	First annual day of vegetative period (DIM)
CTRANSP	Canopy Transpiration (mm $year^{-1}$)
CINT	Canopy Interception (mm $year^{-1}$)
CLE	Canopy Latent Heat (W $m^{-2}$$year^{-1}$) (NB: summed value)
WUE	Annual Water Use Efficiency (DIM)
MAX_ANN_RESERVE_	Annual maximum reserve carbon pool (tC $cell^{-1}$)
MIN_ANN_RESERVE_C	Annual minimum reserve carbon pool (tC $cell^{-1}$)
TREE_MAX_ANN_RESERVE_C	Annual maximum tree reserve carbon pool (tC $tree^{-1}$)
TREE_MIN_ANN_RESERVE_C	Annual minimum tree reserve carbon pool (tC $tree^{-1}$)
MIN_RESERVE_C	Current Minimum reserve carbon pool (tC $cell^{-1}$)

RESERVE_C	Current Reserve carbon pool (tC cell^{-1})
STEM_C	Current Stem carbon pool (tC cell^{-1})
STEMSAP_C	Current Stem sapwood carbon pool (tC cell^{-1})
STEMHEART_C	Current Stem heartwood carbon pool (tC cell^{-1})
STEMSAP_PERC	Stem Sapwood vs. Total Stem (%age)
STEMLIVE_C	Current Stem live wood carbon pool (tC cell^{-1})
STEMDEAD_C	Current Stem dead wood carbon pool (tC cell^{-1})
STEMLIVE_PERC	Live stem vs. Total stem (%age)
MAX_LEAF_C	Maximum Current Leaf carbon pool (tC cell $^{-1}$year^{-1})
MAX_FROOT_C	Maximum Current Fine Root carbon pool (tC cell $^{-1}$year^{-1})
CROOT_C	Current Coarse Root carbon pool (tC cell^{-1})
CROOTLIVE_C	Current Coarse root live wood carbon pool (tC cell^{-1})
CROOTDEAD_C	Current Coarse root dead wood carbon pool (tC cell^{-1})
CROOTLIVE_PERC	Live Coarse Root vs. Total stem (%age)
BRANCH_C	Current Branch carbon pool (tC cell^{-1})
BRANCHLIVE_C	Current Branch live wood carbon pool (tC cell^{-1})
BRANCHDEAD_C	Current Branch dead wood carbon pool (tC cell^{-1})
BRANCHLIVE_PERC	Live Branch vs. Total stem (%age)
FRUIT_C	Current Fruit carbon pool (tC cell^{-1})
MAX_FRUIT_C	Annual Fruit carbon pool (tC cell^{-1}year^{-1})
RESERVE_N	Current Reserve nitrogen pool (tC cell^{-1})
STEM_N	Current Stem nitrogen pool (tC cell^{-1})
STEMLIVE_N	Current Live Stem nitrogen pool (tN cell^{-1})
STEMDEAD_N	Current Dead Stem nitrogen pool (tN cell^{-1})
CROOT_N	Current Coarse Root nitrogen pool (tN cell^{-1})
CROOTLIVE_N	Current Coarse root live wood nitrogen pool (tN cell^{-1})
CROOTDEAD_N	Current Coarse root dead wood nitrogen pool (tN cell^{-1})
BRANCH_N	Current Branch nitrogen pool (tN cell^{-1})
BRANCHLIVE_N	Current Branch live wood nitrogen pool (tN cell^{-1})
BRANCHDEAD_N	Current Branch dead wood nitrogen pool (tN cell^{-1})
FRUIT_N	Current Fruit nitrogen pool (tN cell^{-1})
STANDING_WOOD	Standing wood carbon (tC cell^{-1})
DELTA_WOOD	Annual wood increment (tC cell^{-1}year^{-1})
CUM_DELTA_WOOD	Cumulated annual wood increment (tC cell^{-1}year^{1})
BASAL_AREA	Individual basal area (m^{2}ha^{-1})
TREE_CAI	Single Tree Current Annual Volume Increment (m^{3}tree^{-1}year^{1})
TREE_MAI	Single Tree Mean Annual Volume Increment (m^{3}tree^{-1}year^{1})
CAI	Current Annual Volume Increment (m^{3}class^{-1}year^{-1})
MAI	Mean Annual Volume Increment (m^{3}class^{-1}year^{-1})
VOLUME	Stem volume (m^{3}class^{-1})
TREE_VOLUME	Single tree volume (m^{3}tree^{-1})
DELTA_TREE_VOL (perc)	Tree volume increment (%)
DELTA_AGB	Aboveground biomass increment (tC cell^{-1}year^{-1})
DELTA_BGB	Belowground biomass increment (tC cell^{-1}year^{-1})
AGB	Aboveground Biomass pool (tC cell^{-1})
BGB	Belowground Biomass pool (tC cell^{-1})
BGB.AGB	BGB/AGB
DELTA_TREE_AGB	Aboveground biomass increment (tC cell^{-1}year^{-1})
DELTA_TREE_BGB	Belowground biomass increment (tC cell^{-1}year^{-1})

C_HWP	Annual harvested woody products removed from (tC cell^{-1}year^{-1})
VOLUME_HWP	Annual volume harvested woody products removed (m^{3}cell^{-1}year^{-1})
STEM_RA	Stem autotrophic respiration (gC m^{-2}year^{-1})
LEAF_RA	Leaf autotrophic respiration (gC m^{-2}year^{-1})
FROOT_RA	Fine root autotrophic respiration (gC m^{-2}year^{-1})
CROOT_RA	Coarse root autotrophic respiration (gC m^{-2}year^{-1})
BRANCH_RA	Branch autotrophic respiration (gC m^{-2}year^{-1})

*variables may change across the different model versions

4.10.2 At cell level:

gpp	Gross Primary Production (gC m^{-2}year^{-1})
npp	Net Primary Production (gC m^{-2}year^{-1})
ar	Autotrophic respiration (gC m^{-2}year^{-1})
hr	Heterotrophic Respiration (gC m^{-2}year^{-1})
rsoil	Soil respiration flux (gC m^{-2}year^{-1})
rsoilCO2	Soil respiration flux (gC m^{-2}year^{-1})
reco	Annual ecosystem respiration (gC m^{-2}year^{-1})
nee	Annual net ecosystem exchange (gC m^{-2}year^{-1})
nep	Annual net ecosystem production (gC m^{-2}year^{-1})
et	Annual evapotranspiration (mm year^{-1})
le	Latent heat flux (W m^{-2}year^{-1}) (NB: this is a yearly sum)
soil.evapo	Annual soil evaporation (mm year^{-1})
asw	annual average available soil water (mm volume^{-1})
iWue	Annual intrinsic Water Use Efficiency (DIM)
vol	Current volume (m^{-3}cell)
cum_vol	Cumulated volume (m^{-3}cell)
run_off	Current amount of water outflow (runoff) (mm m^{-2}year^{-1})
litrC	Litter carbon (gC m^{-2})
litr1C	Litter labile carbon (gC m^{-2})
litr2C	Litter unshielded carbon (gC m^{-2})
litr3C	Litter shielded carbon (gC m^{-2})
litr4C	Litter lignin carbon (gC m^{-2})
cwd_C	Cwd carbon (gC m^{-2})
cwd_2C	Cwd unshielded (gC m^{-2})
cwd_3C	Cwd shielded (gC m^{-2})
cwd_4C	Cwd lignin (gC m^{-2})
soilC	Soil carbon (gC m^{-2})
soil1C	Microbial recycling pool carbon (fast) (gC m^{-2})
soil2C	Microbial recycling pool carbon (medium) (gC m^{-2})
soil3C	Microbial recycling pool carbon (slow) (gC m^{-2})
soil4C	Recalcitrant SOM carbon (humus, slowest) (gC m^{-2})
litterN	Litter nitrogen (gN m^{-2})
litter1N	Litter labile nitrogen (gN m^{-2})
litter2N	Litter unshielded cellulose nitrogen (gN m^{-2})
litter3N	Litter shielded cellulose nitrogen (gN m^{-2})
litter4N	Litter lignin nitrogen (gN m^{-2})
cwd_N	Cwd nitrogen (gN m^{-2})
cwd_2N	Cwd unshielded nitrogen (gN m^{-2})

cwd_3N	Cwd shielded nitrogen (gN m^{-2})
cwd_4N	Cwd lignin nitrogen (gN m^{-2})
soilN	Soil nitrogen (gN m^{-2})
soil1N	Microbial recycling pool nitrogen (fast) (gN m^{-2})
soil2N	Microbial recycling pool nitrogen (medium) (gN m^{-2})
soil3N	Microbial recycling pool nitrogen (slow) (gN m^{-2})
soil4N	Recalcitrant SOM nitrogen (humus, slowest) (gN m^{-2})
solar_rad	Incoming short-wave radiation (MJ $m^{-2}year^{-1}$)

*variables may change across the different model versions

4.10.3 Monthly Outputs

At class level:

YEAR	Year of simulation
MONTH	Month of simulation
LAYER	Layer of tree class
HEIGHT	Average height of a species (m)
DBH	Average diameter at breast height of a species (cm)
AGE	Age of trees (years)
SPECIES	Tree species
MANAGEMENT	T = Timber
GPP	Gross Primary Production (gC m^{-2} $month^{-1}$)
NET_ASS	Monthly net assimilation (gC m^{-2} $month^{-1}$)
RA	Autotrophic Respiration (gC m^{-2} $month^{-1}$)
NPP	Net Primary Production (gC m^{-2} $month^{-1}$)
CUE	Monthly Carbon Use Efficiency (0→1) (gC_{NPP} gC_{GPP}^{-1})
CTRANSP	Canopy Transpiration (mm $month^{-1}$)
CET	Canopy Evapotranspiration (mm $month^{-1}$)
CLE	Canopy Latent Heat (W $m^{-2}month^{-1}$) (NB:this is a summed value)
LAI	Average monthly LAI
CC	Canopy Cover
DBHDC	DBH/Crown diameter relationship
HD_EFF	Effective Height/Diameter ratio (DIM)
HDMAX	Height (m) to Base diameter (m) ratio MAX (DIM)
HDMIN	Height (m) to Base diameter (m) ratio MIN (DIM)
N_TREE	Number of trees (n tree $cell^{-1}$)
WUE	Monthly Water Use Efficiency (DIM)
Wres	Reserve carbon pool (tC $cell^{-1}$)
WS	Stem carbon pool (tC $cell^{-1}$)
WSL	Stem live wood pool (tC $cell^{-1}$)
WSD	Stem dead wood (tC $cell^{-1}$)
PWL	Maximum leaf wood (tC $cell^{-1}$)
PWFR	Maximum fine root wood (tC $cell^{-1}$)
WCR	Coarse root biomass (tC $cell^{-1}$)
WCRL	Coarse root live wood biomass (tC $cell^{-1}$)
WCRD	Coarse root deadwood biomass (tC $cell^{-1}$)
WBB	Branch biomass (tC $cell^{-1}$)
WBBL	Branch live wood biomass (tC $cell^{-1}$)
WBBD	Branch dead wood biomass (tC $cell^{-1}$)

*variables may change across the different model versions

At cell level:

gpp	Gross Primary Production (gC $m^{-2}month^{-1}$)
npp	Net Primary Production (gC $m^{-2}month^{-1}$)
ar	Autotrophic respiration (gC $m^{-2}month^{-1}$)
et	Monthly evapotranspiration (mm $month^{-1}$)
le	Latent heat flux (W m^{-2}) (NB: this is a summed value)
asw	Available soil water (mm $volume^{-1}$)
iWue	Intrinsic Water Use Efficiency

*variables may change across the different model versions

4.10.4 Daily Outputs

At class level:

YEAR	Year of simulation
MONTH	Month of simulation
DAY	Day of simulation
LAYER	Layer of forest structure
HEIGHT	Average height of a specie (m)
DBH	Average diameter at breast height of a specie (cm)
AGE	Age of trees (years)
SPECIES	Tree species
MANAGEMENT	T = Timber
GPP	Gross Primary Production (gC $m^{-2}day^{-1}$)
Av_TOT	Carboxylation rate for limited assimilation (µmol $m^{-2}s^{-1}$)
Aj_TOT	RuBP regeneration limited assimilation (µmol $m^{-2}s^{-1}$)
A_TOT	Final assimilation rate (µmol $m^{-2}s^{-1}$)
RG	Growth respiration (gC $m^{-2}day^{-1}$)
RM	Maintenance Respiration (gC $m^{-2}day^{-1}$)
RA	Autotrophic respiration (gC $m^{-2}day^{-1}$)
NPP	Net Primary Production (gC $m^{-2}day^{-1}$)
BP	Daily biomass production (gC $m^{-2}day^{-1}$)
CUE	Daily carbon Use Efficiency (gC_{NPP} gC_{GPP}^{-1})
BPE	Daily biomass production efficiency (gC $m^{-2}day^{-1}$)
LAI_PROJ	LAI for Projected Area overed (at zenith angle) (m^2 m^{-2})
PEAK-LAI_PROJ	Peak Projected LAI (maximum attainable LAI) (m^2 m^{-2})
LAI_EXP	LAI for Exposed Area covered (m^2 m^{-2})
D-CC_P	Projected Canopy Cover (frac of the cell)
DBHDC	DBH/Crown diameter relationship
CROWN_AREA_PROJ	Crown Projected Area (at zenith angle) (m^2)
PAR	Photosynthetically Active Radiation (molPAR $m^{-2}day^{-1}$)
APAR	Absorbed Photosynthetically Active Radiation (molPAR m^2day^{-1})
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation (unitless)
NTREE	Number of trees
VEG_D	Day of vegetative period for class (Days/Year)
INT	Canopy Interception (mm day^{-1})
WAT	Canopy Water stored (mm day^{-1})
EVA	Canopy Evaporation (mm day^{-1})
TRA	Canopy Transpiration (mm day^{-1})

ET	Canopy Evapotranspiration (mm day^{-1})
LE	Canopy Latent Heat (W m^{-2})
WUE	Water Use Efficiency (DIM)
RESERVE_C	Current Reserve carbon pool (tC $cell^{-1}$)
STEM_C	Current Stem carbon pool (tC $cell^{-1}$)
STEMSAP_C	Current Stem sapwood carbon pool (tC $cell^{-1}$)
STEMLIVE_C	Current Stem live wood carbon pool (tC $cell^{-1}$)
STEMDEAD_C	Current Stem dead wood carbon pool (tC $cell^{-1}$)
LEAF_C	Current Leaf carbon pool (tC $cell^{-1}$)
FROOT_C	Current Fine root carbon pool (tC $cell^{-1}$)
CROOT_C	Current Coarse root carbon pool (tC $cell^{-1}$)
CROOTSAP_C	Current Coarse root sapwood carbon pool (tC $cell^{-1}$)
CROOTLIVE_C	Current Coarse root live wood carbon pool (tC $cell^{-1}$)
CROOTDEAD_C	Current Coarse root dead wood carbon pool (tC $cell^{-1}$)
BRANCH_C	Current Branch carbon pool (tC $cell^{-1}$)
BRANCHSAP_C	Current Branch sapwood carbon pool (tC $cell^{-1}$)
BRANCHLIVE_C	Current Branch live wood carbon pool (tC $cell^{-1}$)
BRANCHDEAD_C	Current Branch dead wood carbon pool (tC $cell^{-1}$)
FRUIT_C	Current Fruit carbon pool ((tC $cell^{-1}$)
DELTARESERVE_C	Daily allocation to reserve (tC $cell^{-1}day^{-1}$)
DELTA_STEM_C	Daily allocation to stem (tC $cell^{-1}day^{-1}$)
DELTA_LEAF_C	Daily allocation to leaf (tC $cell^{-1}day^{-1}$)
DELTA_FROOT_C	Daily allocation to fine root (tC $cell^{-1}day^{-1}$)
DELTA_CROOT_C	Daily allocation to coarse root (tC $cell^{-1}day^{-1}$)
DELTA_BRANCH_C	Daily allocation to branch (tC $cell^{-1}day^{-1}$)
DELTA_FRUIT_C	Daily allocation to fruit (tC $cell^{-1}day^{-1}$)
RESERVE_N	Current reserve nitrogen pool (tN $cell^{-1}$)
STEM_N	Current stem nitrogen pool (tN $cell^{-1}$)
STEMLIVE_N	Current Live Stem nitrogen pool (tN $cell^{-1}$)
STEMDEAD_N	Current Dead Stem nitrogen pool (tN $cell^{-1}$)
LEAF_N	Current leaf nitrogen pool (tN $cell^{-1}$)
FROOT_N	Current Fine Root nitrogen pool (tN $cell^{-1}$)
CROOT_N	Current Coarse Root nitrogen pool (tN $cell^{-1}$)
CROOTLIVE_N	Current Coarse root live wood nitrogen pool (tN $cell^{-1}$)
CROOTDEAD_N	Current Coarse root dead wood nitrogen pool (tN $cell^{-1}$)
BRANCH_N	Current Branch nitrogen pool (tN $cell^{-1}$)
BRANCHLIVE_N	Current Branch live wood nitrogen pool (tN $cell^{-1}$)
BRANCHDEAD_N	Current Branch dead wood nitrogen pool (tN $cell^{-1}$)
FRUIT_N	Current Fruit nitrogen pool (tN $cell^{-1}$)
DELTARESERVE_N	Daily allocation to reserve (tN $cell^{-1}day^{-1}$)
DELTA_STEM_N	Daily allocation to stem (tN $cell^{-1}day^{-1}$)
DELTA_LEAF_N	Daily allocation to leaf ((tN $cell^{-1}day^{-1}$)
DELTA_FROOT_N	Daily allocation to fine root (tN $cell^{-1}day^{-1}$)
DELTA_CROOT_N	Daily allocation to coarse root (tN $cell^{-1}day^{-1}$)
DELTA_BRANCH_N	Daily allocation to branch (tN $cell^{-1}day^{-1}$)
DELTA_FRUIT_N	Daily allocation to fruit (tN $cell^{-1}day^{-1}$)
STEM_AR	Stem autotrophic respiration (gC $m^{-2}day^{-1}$)
LEAL_AR	Leaves autotrophic respiration (gC $m^{-2}day^{-1}$)
FROOT_AR	Fine Roots autotrophic respiration (gC $m^{-2}day^{-1}$)

CROOT_AR	Coarse Roots autotrophic respiration (gC $m^{-2}day^{-1}$)
BRANCH_AR	Branch autotrophic respiration (gC $m^{-2}day^{-1}$)
F_CO2	CO2 fertilization effect (DIM) (as choiced in script)
F_CO2_VER	CO2 fertilization effect (DIM) (Veroustraete's version)
F_CO2_FRA	CO2 fertilization effect (DIM) (Franks et al.'s version)
FCO2_TR	CO2 fertilization effect (DIM) (for stomatal conductance)
FLIGHT	Light modifier
FAGE	Age modifier (0→1)
FT	Air temperature modifier (0→1)
FVPD	VPD modifier (0→1)
FN	Soil nutrient modifier (0→1)
FSW	Soil water modifier (0→1)
LITR_C	Current Litter Carbon Pool (tC $cell^{-1}$)
CWD_C	Coarse Woody Debris Carbon (tC $cell^{-1}$)

*variables may change across the different model versions

<u>At cell level</u>:

gpp	Gross Primary Production (gC $m^{-2}day^{-1}$)
npp	Net Primary Productivity (gC $m^{-2}day^{-1}$)
ar	Autotrophic respiration (gC $m^{-2}day^{-1}$)
hr	Heterotrophic respiration (gC $m^{-2}day^{-1}$)
rsoil	Soil respiration flux (gC $m^{-2}year^{-1}$)
reco	Daily ecosystem respiration (gC $m^{-2}day^{-1}$)
nee	Daily net ecosystem exchange (gC $m^{-2}day^{-1}$)
nep	Daily net ecosystem production (gC $m^{-2}day^{-1}$)
et	Daily evapotranspiration (mm day^{-1})
le	Daily latent heat flux (W m^{-2})
soil_evapo	Daily soil evaporation (mm day^{-1})
snow_pack	Current Amount of Snow (Kg m^{-2})
asw	Current available soil water (mm $volume^{-1}$)
moist_ratio	Soil moisture ratio (DIM)
iWue	Daily intrinsic Water Use Efficiency (DIM)
litrC	Litter carbon (gC m^{-2})
litr1C	Litter labile carbon (gC m^{-2})
litr2C	Litter unshielded carbon (gC m^{-2})
litr3C	Litter shielded carbon (gC m^{-2})
litr4C	Litter lignin carbon (gC m^{-2})
cwd_C	Cwd carbon (gC m^{-2})
cwd_2C	Cwd unshielded (gC m^{-2})
cwd_3C	Cwd shielded (gC m^{-2})
cwd_4C	Cwd lignin (gC m^{-2})
soilC	Soil carbon (gC m^{-2})
soil1C	Microbial recycling pool carbon (fast) (gC m^{-2})
soil2C	Microbial recycling pool carbon (medium) (gC m^{-2})
soil3C	Microbial recycling pool carbon (slow) (gC m^{-2})
soil4C	Recalcitrant SOM carbon (humus, slowest) (gC m^{-2})
litterN	Litter Nitrogen (gN m^{-2})
litter1N	Litter labile Nitrogen (gN m^{-2})
litter2N	Litter unshielded cellulose Nitrogen (gN m^{-2})
litter3N	Litter shielded cellulose Nitrogen (gN m^{-2})
litter4N	Litter lignin Nitrogen (gN m^{-2})

cwd_N	Cwd Nitrogen (gN m^{-2})
cwd_2N	Cwd unshielded Nitrogen (gN m^{-2})
cwd_3N	Cwd shielded Nitrogen (gN m^{-2})
cwd_4N	Cwd lignin Nitrogen (gN m^{-2})
soilN	Soil Nitrogen (gN m^{-2})
soil1N	Microbial recycling pool Nitrogen (fast) (gN m^{-2})
soil2N	Microbial recycling pool Nitrogen (medium) (gN m^{-2})
soil3N	Microbial recycling pool Nitrogen (slow) (gN m^{-2})
soil4N	Recalcitrant SOM Nitrogen (humus, slowest) (gN m^{-2})
tsoil	Soil Temperature (°C)
daylenght	Day length

*variables may change across the different model versions

5. Management

The model simulates the most common management practices on high stands, while coppice management is still under development. The management schemes are based on thinning (intensity and frequency), rotation, replanting, prescribed regeneration.

There are three main settings for management type ('management' parameter in the setting file):

- "***man off***": no management will be applied.

- "***man on***": the model will simulate the management as set in the *species.txt* file (e.g. Fagus_sylvatica.txt), for example the thinning.

  Thinning frequency is the number of years between removals. Thinning intensity is modelled as % of tree to remove. Rotation is based on tree age.

  If the stand is mono-species, thinning, clear-cut and replanting can be applied to both mono and multi-layered forest. It is possible to change species after the first clear cut, setting the name of the new species in the setting file (REPLANTED_SPECIES parameter).

  Currently there is no difference between THINNING_REGIME= 'from above' or THINNING_REGIME='from below' in the setting file. This means that in the case of multi-layered, mono-species stand, the same % of trees is removed from each layer/class.

  If only thinning is applied, it is possible to run the model for multi-species and -layers. Otherwise after the clear cut, all the species are substituted with the species indicated in the setting file.

- "***man var***": stand density and management are prescribed from external files.

  Option 1) The model simulates the observed management as mirrored by the measured stand density. The stand density data are read from the file "sitename_stand.txt" after the first year of simulation. Please note that only stand density data are used, however in the stand file all the variables need to be provided. While density is prescribed, the mortality is deactivated. Removed trees are considered thinned. If the management file is not provided, no management is applied. If the stand is multi-layer or multi-species, density data have to be provided for each class.

  If the management file is provided, the model will apply the indicated interventions. However, this option has been tested for mono-species and mono-layered forest only.

  It is advisable to provide stand density data at high frequency (5 year or less).

Option 2) Version 5.6 only: the model uses the stand density data of the first year of simulation (in the stand file no other yearly data are provided after the first year) and applies the management scheme as reported in the management file. This option has been tested for mono-species and mono-layered forest. Change of specie after the clear-cut is possible.

Option 3) Version 5.6 only, shelterwood option: "*man= var*" and "*regeneration=on*".

As option 1) or option 2), in the management file the year of regeneration is provided. Regeneration is prescribed as a new class of established saplings (as in LPJ-GUESS). This option has been tested for a mono-layered forest only. When the new established forest layer is inserted, management is only applied to the dominant layer. When the old layer is removed *via* clear-cut, management is applied to the new layer.

In the **management file**, comments are allowed and must begin with two forward slash characters '//', at the end of the line.
The file can contain the following information: 'Thinning' (year of thinning), 'Harvesting' (year of prescribed clear cut),'Thinning_int' (thinning intensity as % of biomass removed, i.e. % of tree removed) and 'regeneration' (year of prescribed regeneration), followed by the year of intervention and separated by comma as in this example:

Thinning,2027,2035

Harvesting,2043,2174

Thinning_int,70,20

Regeneration,2026

It is possible to set the following combinations and provide the data for:

- Thinning,
- Thinning + Harvesting,
- Harvesting,
- Thinning + Thinning_int,
- Thinning + Harvesting + regeneration,
- Thinning + Thinning_int + Harvesting + regeneration.

The last three combinations are available for the v.5.6 only.

If the data for Thinning_int is not provided, thinning intensity is read from the species file.

If option 3) applies, the year for the regeneration must be provided.

6. 3D-CMCC-FEM Usage

3D-CMCC-FEM is a command line program, and its behaviour is controlled by several command line options:

-i input path	i.e.: -i c:\input\directory\
-o output path	i.e.: -o c:\output\directory\
-p parameterization directory	i.e.: -i c:\parameterization\directory\
-d dataset filename stored into input directory	i.e.: -d input.txt
-m met filename list stored into input directory	i.e.: -m meteo.txt or meteo.nc
-s soil filename stored into input directory	i.e.: -s soil.txt or soil.nc
-t topo filename stored into input directory	i.e.: -t topo.txt or topo.nc
-c settings filename stored into input directory	i.e.: -c settings.txt
-k CO_2 atmospheric concentration file	i.e.: -k co2_conc.txt
-q management setting file	i.e. –q management.txt
-n ndep file	i.e.: -n ndep.txt
-r output vars list	i.e.: -r output_vars.lst
-u benchmark path	*(for model developers)*
-h	print this help

More specifically:

-i	This is **not** a mandatory parameter. if not used, input files will be searched where program is.
-o	This is **not** a mandatory parameter. If not used, output files will be created where program is.
-p	This is **not** a mandatory parameter. If not used, parameterization file will be searched where program is.
-d "*stand*"	This file will be searched in input path, if specified. It can be an ASCII or NETCDF file. You can use '//' for comment it. ASCII file must have following header, separated by a comma: Mandatory parameters: `"Year, x, y, Age, Species, Management, N, Stool, AvDBH, Height"` NOTE: Please see **[SPECIES]*** section and **[MANAGEMENT]**** section to check allowed values. Same columns name applies to variables name in NETCDF version of file.
-m "*meteo*"	This file will be searched in input path, if specified. It can be an ASCII or NETCDF file. You can specify a .lst (list) file if you have separated values. List file must contain the name of NETCDF files to import, one row for variable e.g.:

6_WS_f_2000_2001_123_456.nc

6_TOT_PREC_2000_2001_123_456.nc

6_SWC_2000_2001_123_456.nc

6_TMAX_2M_2000_2001_123_456.nc

6_TMIN_2M_2000_2001_123_456.nc

6_TSOIL_2000_2001_123_456.nc

6_VPD_2000_2001_123_456.nc

6_ET_2000_2001_123_456.nc

6_LAI_2000_2001_123_456.nc

6_RADS_2000_2001_123_456.nc

ASCII file must have following header, separated by a tab (/t) :

Mandatory parameters: "`Year, Month, n_days, Rg_f, Ta_f, Tmax, Tmin, Rh_f, Ts_f, Precip, SWC, LAI, ET, WS_f`"

Same columns name applies to variables name in NETCDF version of file.

-s "*soil*" This file will be searched in input path, if specified.

It can be an ASCII or NETCDF file. ASCII file must have following header, separated by a comma:

Mandatory parameters: "`X, Y, LANDUSE, LAT, LON, CLAY_PERC, SILT_PERC, SAND_PERC, SOIL_DEPTH, SOIL_DEPTH, FR, FN0, FNN, M0, LITTERC, LITTERN, SOILC, SOILN, DEADWOODC`"

Please see [LANDUSE] section to check allowed values. Same columns name applies to variables name in NETCDF version of file.

-t "*topography*" This file will be searched in input path, if specified.

It can be an ASCII or NETCDF file.

ASCII file must have following header, separated by a comma

Mandatory parameters: "`X, Y, ELEV`"

Same columns name applies to variables name in NETCDF version of file.

-c "*model setting*" This file will be searched in input path, if specified.

It must be an ASCII file. You can put comment using '//' token;

NOTE: the file must contain the rows described in the "*Settings file*" section.

-k "[*CO2*]" This file will be searched in input path, if specified.

It must be an ASCII file and must have following header, separated by a tab (/t):

Mandatory parameters: "`year (/t)    CO2_ppm`"

<u>NOTE: mandatory parameter only if "**CO2_trans**" in settings file is set on '*on*' or '*var*'</u>

-q "management"

This file will be searched in input path, if specified.

ASCII file with the following information, as row names: 'Thinning' (year of thinning),'Harvesting'(year of clear cut),'Thinning_int' (thinning intensity as % of biomass removed, i.e. number of trees to remove) and 'regeneration' (year of prescribed regeneration), followed by the year of intervention, separated by comma, as in the example:

Thinning,2027,2035

Harvesting,2043,2174

Thinning_int,70,20

regeneration,2026

-n "*N deposition*"

This file will be searched in input path, if specified.
It must be an ASCII file and must have following header, separated by a tab (/t):

Mandatory parameters: ""`year (/t)   ndep`"

<u>NOTE: mandatory parameter only if "**Ndep_fixed**" in settings file is set on '*off*'</u>

-r

this is **not** a mandatory parameter. Use it if you want export variables values inside a NETCDF file.

You can specify more variables per row using a comma as delimiter. Each variable must

have "**daily_**", "**monthly_**" or "**annual_**" prefix. i.e.:

daily_gpp, annual_GPP, daily_ar, monthly_ar, annual_npp

In previous example, daily values for GPP and AR are exported. Monthly values for AR are exported and annual values for GPP and NPP are exported. Files will be created in output path if any or where program is.

[SPECIES]*

Currently, the following species have been parameterized:

0,*Fagussylvatica*
1,*Castaneasativa*
2,*Larixdecidua*
3,*Piceaabies*
4,*Pinussylvestris*
5,*Quercuscerris*
6,*Quercusilex*
7,*Quercusrobur*
8,Pinushalepensis
9,Pinusnigra

	The species can be used on relative column inside an ASCII dataset (without indexes) NOTE: if you use a NETCDF file you must use their indexes. The name of species in the stand file has to be exactly as the name of species file.
[MANAGEMENT]**	Following type of management can be used on relative column inside as ASCII dataset (without indexes). NOTE: if you use a NETCDF file you must use their indexes. T is for timber C is for Coppice (under development) 0,T 1,C
[LANDUSE]***	Following type of landuse can be used on relative column inside as ASCII dataset (without indexes). Please note that you must use their indexes if you use a NETCDF file. F is for Forest Z is for Crop (currently not implemented) 0,F 1,Z

7. How to run and develop the 3D-CMCC-FEM

7.1 Code Characteristics

3D-CMCC-FEM was primarily developed on UNIX-Linux with Eclipse IDE Platforms and is compiled using GNU GCC 4.7.2.

IMPORTANT: Be sure to execute 3D-CMCC-FEM on a Linux machine with architecture X86_64 (64 bit), otherwise you firstly need to rebuild code to obtain the object files needed for runs.

7.2 Eclipse usage instruction (for developers)

To Run or to modify (develop the model we suggest using Eclipse CDT simply following these steps (be sure if you choose to use Eclipse, to have installed Git and Egit and to have an internet connection):

1) Save the 3D-CMCC-FEM Model (https://github.com/Forest-Modelling-Lab/3D- CMCC-FEM) directory in the path you are going to use as Eclipse Workspace;

2) If you are planning to use/develop the I/O with netcdf, first in the main.c file, uncomment the line #define NC_USE. To prevent error from NETCDF libraries, open terminal and type:

- `$ sudo apt-get install netcdf-bin`
- `$ sudo apt-get install libnetcdf-dev`

3) To make the model work under Eclipse CDT (any version) using Git follow these steps:

- download from terminal Git and build-essential
  - `$ sudo apt-get install build-essential`
  - `$ sudo apt-get install git`
- download from Ubuntu software center jre 7-8 or jdk (if not installed)
  - `$ sudo apt-get install default-jdk`

4) Download from Eclipse site the most recent version of Eclipse IDE for C/C++ Developers (https://www.eclipse.org/downloads/packages/)
5) Open Eclipse and set your Workspace as the same path in which you've placed the Model's folder - to do so click on File, then "switch Workspace" and click on "Other..."; here input your current path;
6) File -> Import -> Git -> Projects from Git -> Clone Url and in URL please paste the code version you find over the GitHub https://github.com/Forest-Modelling-Lab/3D-CMCC-FEM

For NETCDF file you need to add libraries within eclipse through:

Project->Properties->C/C++ Build->Settings->Cross G++ Linker->Libraries-> in Libraries (-l) add "netcdf"->OK

How to increase Eclipse available heap size (optional)

Some JVMs put restrictions on the total amount of memory available on the heap. If you are getting *OutOfMemoryErrors* while running Eclipse, the VM can be told to let the heap grow to a larger amount by passing the -vmargs command to the Eclipse launcher (http://wiki.eclipse.org/FAQ_How_do_I_increase_the_heap_size_available_to_Eclipse%3F).

Here follows a short how to:

1) Search for the location of your *eclipse.ini* file (usually *usr/lib/eclipse*);
2) Open eclipse.ini using gedit command from terminal as super user (*sudo gedit eclipse.ini*);

BE EXTREMELY CAREFUL TO FOLLOW ECLIPSE DEVELOPERS RULES

Each option and each argument to an option must be on its own line.
All lines after -vmargs are passed as arguments to the JVM, so all arguments and options for eclipse must be specified before -vmargs (just like when you use arguments on the command- line).
Any use of -vmargs on the command-line replaces all -vmargs settings in the .ini file unless – launcher .appendVmargs is specified either in the .ini file or on the command-line. (doc):

in line 12 change -Xms40m into -Xms512m (just replace 40 with 512 without changing the rest of the line).

in line 13 change -Xmx256m into -Xmx1024m (just replace 256 with 11024 without changing the rest of the line)

save eclipse.ini and restart eclipse.

How to work on Eclipse for bash scripts (optional)

To work in Bash Shell scripts within the Eclipse IDE you need to install ShellED eclipse package through the web.

7.3 Bash launch (for UNIX users and developers)

If you are interested only in running the 3D-CMCC-FEM with no interest in developing the model code you can either run the model code in the terminal (i.e. Bash) once check that you have the executable (e.g. in Debug or Release folder) build for your OS (be careful that it fits with your architecture: i.e. 36 or 64 bit) through the command line:

```
./3D-CMCC-Forest-Model -i input -o output -p parameterization -d sitename_stand.txt -m sitename_meteo_firstyear.txt -s sitename_soil.txt -t sitename_topo.txt -c sitename_settings.txt -k CO2_hist.txt
```

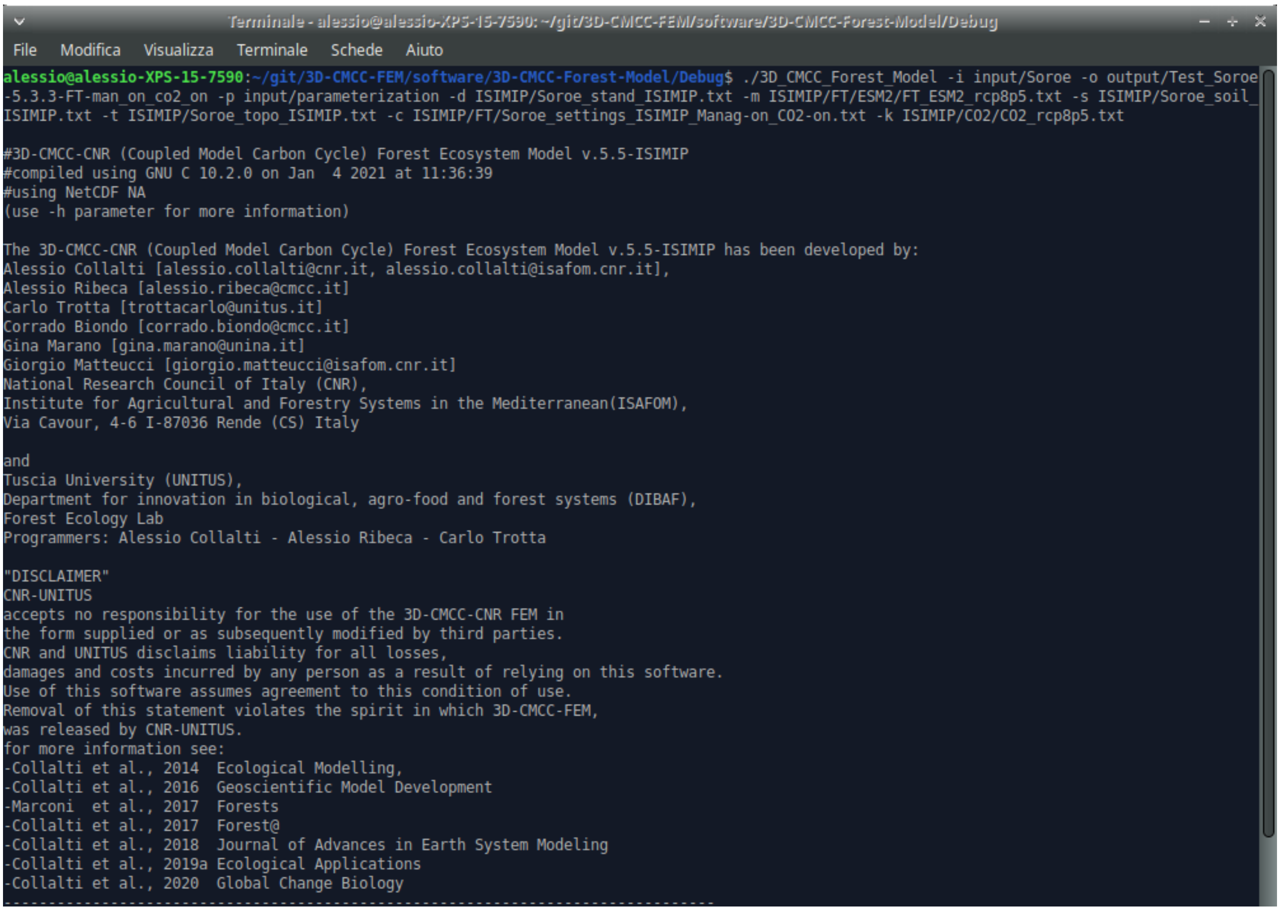


Figure 8|Launching the model in Bash

If you are already used to develop and config/compile your codes in the *unix* environment and *via* command line, in the repository (in the folders /3D-CMCC-Forest-Model and /src) you will find the make-files and config-files. As different compilers might handle errors differently, please let us know any error signalled when using your compiler.

7.4 The R-Wrapper (UNIX and Windows users)

If you are interested only in running the 3D-CMCC-FEM with no interest in developing the model code and you are particularly familiar with R, an R-wrapper is available on the repository. The wrapper has been developed to easily run simulations over a list of sites, climate scenarios and management schemes (no-management and the thinning+harvest+replanting scheme). In the repository a manual is also provided.

Briefly: the organization is user-friendly with folders containing the model executable (for both Windows and Linux), R code scripts which do not have to be modified, a pre-compiled launcher script and example files. The input file folders structure is also indicated. The 'launch_3DCMCCFEM.R' file will start an R Studio session where you can modify the wrapper arguments to define your simulations. The launcher has three blocks of arguments, which can be easily filled. There are three type of arguments: mandatory (e.g. site, climate, time span, management type etc), conditional, and optional (e.g. atmospheric CO_2).

To run the simulation it is only needed to press Ctrl + Enter.

8. Questions or comments

Shall you have issues with the code or for any suggestions, please let us know. For any questions on how to parameterize or run the code, please read this file first.

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