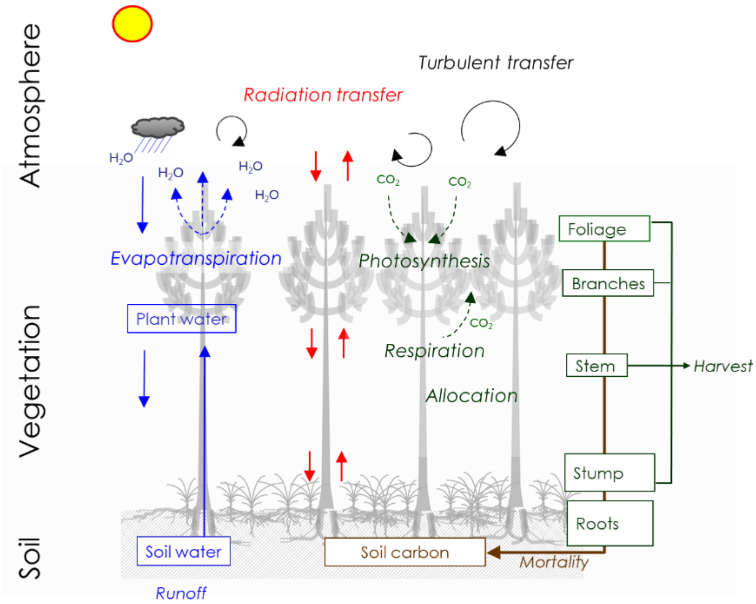
User manual

GO+ version 3.0

2020-02-10.



Denis Loustau, Christophe Moisy, Alexandre Bosc, Soisick Figuères, Simon Martel, Virginie Moreaux, Delphine Picart-Deshors.

INRAE, UMR ISPA, Villenave d'Ornon, 33140, France.

Contact. Denis.Loustau@inrae.fr

Contents

1. Introduction

The Python 3.0 code documented in this manual is the GO+ v3.0 model. The first version of the model was developed during Annabel Porté's Ph. D. Thesis (1999) and within the *Carbofor* project (2001-2003, French Ministers of Ecology and Agriculture, Loustau et al. 2005, 2010). A second version including management and incorporating the soil carbon Roth-C model was developed by Virginie Moreaux during her PhD thesis research (2011) and further enhanced by David Achat, Delphine Picart-Deshors, Raphaël Aussenac and Simon Martel. Among others addition and complements, a nutrient module was added. GO+ versions were adapted to broadleaved species and Douglas fir (Achat et al. 2018, within the framework of projects supported by the French national agency of research (ANR projects ORACLE and MACCAC of the programs CEPS and *AgroBiosphère* respectively), CNRS (project Forever), ADEME (project *Evafora*), and Agriculture and Forest French Minister (Roux et al. 2018).

The version 3.0 merges these "branch" species-specific versions into a single "master" code where all species and management options are implemented. The GO+ model is still being developed within projects supported by ADEME (project *BIOSYLVE*, program *GRAINE*) and the French Ministry of Agriculture and Alimentation (project *Forêts-21*, program "*Investissement pour l'amont forestier"*). This code is therefore expected to be maintained at least until 2024.

This manual is documenting the version3.0 as delivered in the associated package. This version of GO+ code is not degraded and includes calculations performed at the tree level: living fraction of biomass parts, respiration, growth. Simplified versions may be used when upscaling GO+ at large scale.

2. General organisation of the GO+ model code (Python 3.2).

The model elements are located under the *goplus* folder. Other folders contain the parameters files of species and site (*Parameters files\)*, meteorological data sets (*Met files*) initial values of the individual tree diameter (*Parameters files**Tree stand)*. Some examples of output files are provided in the *output files* folder. The *Scripts* folder includes examples of the scripts that are short python codes launching a simulation.

Three folders are located under *goplus*:

- *goBases*
- *goTools*
- *goModel*

where *goBases* and *goTools* are including mathematical functions, integration functions and definitions of elements that are used in the main model. The third, *goModel*, is organising the different component describing the biological and physical processes included in GO+.

The GO+ model is launched using scripts. Some examples are provided in the *Scripts* folder. These examples can be used for simulating the data shown in Moreaux et al 2020 GMD manuscript table 2 or figures 13 and 14 respectively.

The script file instantiates the model. It defines the list of output variables (section 5) and specifies the path of the parameters, site, initialisation and meteorological files required by the model. The files needed are comma separated csv files including forcing variables and parameters as follows:

- meteorological data set (ex. *Met_FR-LBr_1984-2011.csv*)
- species-specific parameters data set (*Ppinaster.csv*, *Fsylvativa.csv*, *DouglasFir*.csv etc.)
- a site-specific data set *DK-Sor.csv, DE-Sol.csv etc.*
- a file including list of tree stem diameter(cm) used for initiating the tree stand , such as *FR-Hes_dbh_1998* and *FR-LBr_dbh_1987.csv.* A simulation may also be launched without such data: *Goplus* creates a tree stand from the mean and standard deviation of the stem diameter at time t=0 (see an example in the *DF_BC49_1998-2010.py* script).
- Optionally, a list of output variables (“varToIntegrate”)

3. Installation

- GO+ runs with P*ython3* and *numpy* library
- Linux :
  - install *python3* and *python3-numpy* packages
  - from a terminal, run : *python3 Validation_Ppinaster_Bray.py*
- Windows :
  - install Anaconda distribution (https://www.anaconda.com/distribution/#download-section)
  - from windows Start menu, select Anaconda3 and Anaconda Prompt
  - navigate to GO+ Applications directory : cd goplus/Scripts
  - enter the path of the python executable and of the goplus application to run, e.g. *c:\ProgramData\Anaconda3\python.exe Validation_Ppinaster_Bray.py*

To run GO+, you need to extract the source code, keeping its tree directory. Navigate to *Scripts* directory and run one of the program, for example :

python3 Checking_Ppinaster.py

Once the program is started, you will start to see the outputs of the model :

1998 Age: 75.0 , nb: 328 , HEIGHT: 29.880109057009467 , DBH: 24.91856707317075 IStress: 0.0 LAI 3.0803941144628815

Other examples are as follows. All files but the scripts are in csv format.

Script (.py)	Site	Species	Meteorological data	Initial Tree Stand DBH	Output file
Fs_DK-Sor_1998-2012	DK-Sor	Fsylvatica	Met_DK-Sor_1998-2013	DK-Sor_dbh_1998	DK-Sor 1998-2012_d
Pp_FR-LBr_1987-2010	FR-LBr	Ppinaster	Met_FR-LBr_1984-2011	FR-LBr_dbh_1986	FR-LBr_1987-2011_d
Fs_FR-Hes_1998-2010	FR-Hes	Fsylvatica	Met_FR-Hes_1998-2010	FR-Hes_dbh_1998	FR-Hes_1998-2010_d
DF_BC49_1998-2010	BC-DF49	Douglas fir	Met_BC-DF49_1998-2010	Generated	BC_DF49_1998-2010_d

4. GO+ model elements (folder \goplus\goModel)

4.1. Clock and climate elements

i) LocTime (mdlLocTIme.py)

It provides a clock, *locTime,* and some temporal milestones (start and end of the day and year) allowing to trigger, start or terminate specific model processes.

ii) Climate (mdlClimate.py)

This element reads the meteorological data file, calculates the atmospheric pressure at ground level, diffuse – direct fractions of the incident shortwave radiation and atmospheric CO_2 concentration. The CO_2 concentration can be prescribed according to the following scenarios.

- historical data based on the *Mauna Loa* observatory time series since 1950 (scenario 0).
- RCP 2.6, 4.5, 6.0 and 8.5 scenarios (Moss et al. 2010) as proposed by the *ISIMIP* platform (scenario 3, 4, 6 and 8 respectively).
- *SRES A2* scenario (scenario 2)
- Constant and fixed at 500 ppm (scenario 1), this value can be changed.

iii) MicroClimate (mdlMicroClimate.py)

It calculates :

- Air specific humidity, air vapour saturation partial pressure and saturation deficit at reference level from the data obtained from the meteorological data set.
- Temperature dependent air properties: dry air density, specific heat of air, psychrometric constant.

iv) SunLocal (mdlSunLocal.py)

From the site latitude and altitude, the *SunLocal* module provides the sun azimuth and elevation at any time of year. In the version 3.0 as provided, the effects of slope and exposure of the site are not activated.

4.2. Forest element (ForestElements\mdlForest.py).

Forest is an integrative element grouping the two vegetation layers, soil layer, and microclimates associated with each layer. Forest executes two tasks:

- it calls the processes solved, starting from the top (tree layer) to the bottom (soil layer) and manages exchanges of variables or values between components, such as passing micrometeorological variables values among canopy layers.
- from the elementary processes implemented in each vegetation and soil layer, *Forest* calculates the values of main variables integrated over the entire ecosystem.

Rnet	*= var('net radiation calculate as the ecosystem radiative balance (W m-2_soil)')*
H	*= var('sensible heat flux (W m-2_soil)')*
LE	*= var('latent heat flux (W m-2_soil)')*
ETR	*= var('actual Evapotranspiration (kg_H2O m-2_soil hr-1)')*
T	*= var('Global Transpiration (kg_H2O m-2_soil hr-1)')*
NEE	*= var('Carbon-CO_2 Net Ecosystem Exchange (g_C m-2_soil hr-1)')*
NPP	*= var('Ecosystem Net Primary Production (gC m-2_soil hr-1)')*

GPP = *var('Ecosystem Gross Primary Production (gC m-2_soil hr-1)')*
Reco = *var('ecosystem respiration (gC m-2_soil hr-1)')*
RAuto = *var('Autotrophic ecosystem respiration (gC m-2_soil hr-1)')*
RUNOFF = *var('Runoff (kg_H2O m-2_soil hr-1)')*
SoilCarbon = *var('Soil organic carbon = sum of DPM, RPM, HUM and BIO (gC m-2_soil)')*
BiomCarbon = *var('Biomass Carbon stock (trees + understorey (gC m-2_soil)')*

4.3. TreeStand element (mdlTreeStand.py)

This class includes the main canopy processes: phenology, carbon allocation, growth, respiration, hydraulics, senescence. These are solved for the entire canopy and tree stand apart from the respiration that is calculated for each individual tree. The parameters needed in each section are provided in corresponding subsections of the species parameter file:

- Phenology, growth structure (5)
- Tree hydraulics (6)
- Respiration of the tree parts (7)
- Carbon Allocation among tree parts (8)

TreeStand simulates also the tree mortality and manages the tree stand installation. Finally, it calculates the statistics related to tree height, diameter, basal area and biomass. *TreeStand* calls three daughter classes: canopy processes, cohort lifecycle and tree growth.

i) Canopy processes (Canopy\mdlCanopy.py)

The *Canopy* class is called by the *TreeStand* and *Understorey* classes using layer specific set of parameters listed in the *ParamSpecies.csv* file. It describes the exchanges of energy and mass between the tree canopy as a whole, and the atmosphere. The group of parameters associated are as follows (+ section number of the species parameter file):

– Stomatal model (1)
– Radiation transfer and energy balance (2)
– Rainfall interception (3)
– Photosynthesis (4)

ii) Leaf Cohort (mdlLeavesCohort.py, parameters file section 5)

This class describes at daily resolution the life cycle of leaf –or needle- cohort(s) of the tree layer. It includes the phenological stages from budburst to leaf expansion and shedding. Depending on the species, the number of cohort may vary from one (broadleaved species) up to six and more (coniferous and evergreen species).

The module uses the name of the species declared in the species parameter file (heading lines) and the value of the current year cohort biomass calculated from the allocation of the primary production among tree parts. This module is not used in the calculation of understorey leaf area or biomass (see section 4. *Understorey* below).

iii) Tree growth (mdlTreeSizes.py, parameters file section 8)

In this element, the individual tree growth is calculated annually using species-specific allometry equations. The tree layer annual assimilation is allocated to individual trees based on their individual leaf weight. The individual net increment in biomass named *Wproducted* (kg dm) is then derived after subtracting the maintenance and growth respiration from photosynthesis. *Wproducted* is first partitioned among below- and aboveground parts and then among tree organs. When the annual carbon balance of a given tree is negative, one tree among two is assumed dead and removed from the tree population.

4.4. Understorey element (mdlUnderStorey.py).

Just like *TreeStand*, *Understorey* organises as series of internal and external processes describing phenology, radiation transfer, energy balance, transpiration, rainfall interception, photosynthesis mortality, respiration and growth of the understorey vegetation. The understorey model has the following specificities:

- unlike the tree layer, the understorey vegetation is generic and does not identify specific species or individual plants.
- the understorey vegetation includes three parts, the foliage, roots and perennial part (can be either stem, seeds, rhizome).
- the growth of each plant part is resolved at a daily resolution whereas, apart from the foliage, tree growth is calculated only once a year.

The processes implemented in the *Canopy* module for the understorey are identical than for trees. They are included in the *Canopy* class that is called by *Understorey*. In this version, the group of parameters associated are included in the tree Species parameter file. It might be separated in the future as a understorey parameter file. The species parameters sections related to the understorey are as follows:

– Stomatal model	(9)
– Radiation transfer and energy balance	(10)
– Plant hydraulics	(11)
– Rainfall interception	(12)
– Photosynthesis	(13)

The phenology, respiration, plant hydraulics, growth and mortality are internal functions of *Understorey*, defined and coded within.

4.5. Soil element (in \SoilElements).

i) Surface processes (mdlSoilSurface.py)

The soil surface-atmosphere exchanges of energy and water are calculated hourly. The soil surface water balance is described first separating the dry and wet fractions of soil surface and then calculating the evaporation. The dry surface resistance is empirical and assumes the resistance increases linearly with soil moisture deficit.

ii) Soil waterCycle (mdlSoilWaterCycle.py)

The soil water retention characteristics are the water content at saturation, field capacity, wilting point and residual. They are either prescribed as such or calculated dynamically using pedotransfer functions, the soil texture and organic matter content (*pcs_Hydro_parameters*). The Van Genuchten parameters can be also prescribed as such or calculated from the soil texture, basic density and organic matter content (*pcs_VG-parameters*). The parameters needed, such as the soil texture, basic density and initial value of soil water and carbon are provided in the *Site.csv* file.

WaterCycle calculates the water balance of the soil. The soil is modelled as three component bucket cascading system. It includes three dynamic layers : dry surface layer, *A*, has a water content below field capacity, unsaturated layer, *B,* has a water content between field capacity and saturation and the deeper layer, *C*, is saturated (flooded).

From the values of the water content and depth of layers *A, B* and *C*, the groundwater discharge and the root zone mean water content are calculated (*pcs_discharge, pcs_layersDepthUpdate, pcs_WaterStatusInRootsLayer*) and the water potential and hydraulic resistance of the soil matrix in the root zone are modelled using Van Genuchten equations.

iii) Soil CarbonCycle (mdlSoilCarbonCycle.py)

This is a *Python* adaptation of the *Roth-C* model running at a daily time step. Organic matter input into the soil is provided by litterfall and mortality of canopy layers and roots. The requested parameters of the soil are provided in the *Site.csv* file and those related to the vegetation, *e.g.* the DPM/RPM ratio and age of plant parts, in the *species.csv* file section 17.

The only change of the Roth-C model in GO+ is the introduction of a "plowing" effect. It is modelled by multiplying the decomposition and mineralisation of the soil carbon fraction affected by a factor whose value is prescribed in the *Site.csv* file. This effect has a halftime duration also specified in the *Site* file.

4.6. Manager elements (goplus\goModel\ManagerElements)

The management plans available in the GO+ v3.0 code are defined as lists of successive forest operations triggered either at a specified time or according to tree or stand size criteria. The plan itself is a function of the *mdlManager.Manager* class. The forest operations available are defined as functions of the *mdlMngt_Operations* class.

i) Management operations

The module *mdlMngt_Operations* is a catalogue describing each of the forest operations commonly performed in European forestry, from the plantation or seeding to pre-commercial and commercial thinnings, understorey control, coppicing, clearcutting and logging.

Thinnings. Thinning operations are removing trees from the stand using criteria based upon tree individual diameter, age, basal area or competition index. The selection of trees to be thinned can be set from above (thicker trees), from below (thinner trees) or random, using a value of the power of the diameter rank normalised in [0, 1], named *Thin_Factor*. A Thin-Factor value below 1.0 select thicker trees, and conversely thinner trees when >1.0. Trees are drawn randomly until the thinning target value (basal area, competition index or number of trees) is reached.

Example 1. Script used to test the model against historical observations.

The historical management of the Beech stand at the FR-Hes site includes a plantation in 1966 and successive natural or artificial thinnings in 1998, 1999, 2000, 2001, 2004, 2009. For each of them the number of trees removed, their ranking and the part of tree exported out of the site is specified in the first part of the script named *Fs_FR-Hes_1998-2010.py* as explained below.

- L5 - L72 list the variables to be output.
- L90 - 97 creates a dictionary listing the management events and set up their parameters.
- L105 - L123 initialise the values of management variables.
- L128 – L145 specify the management operations to be implemented, here a plantation in 1966 and thinnings based on the stem density criteria.

```
90 INTERVENTIONS = {
91         1966 : ('PLANTATION',5000, 2, 3.0, 1.0),
92         1998 : ('THINNING',3364,0.8, True),
93         1999 : ('THINNING',3297, 0.5, True),
94         2000 : ('THINNING',3194, 1, True),
95         2001 : ('THINNING',3186, 1, True),
96         2004 : ('THINNING',2633, 0.15, True),
97         2009 : ('THINNING',2310, 0.20, True),
98         }
99 
100 class Hesse_Manager(mdlMngt_Operations.Manager):
101 
102     def update(self):
103 
104         #Management variables initialisation
105 
106         self.harvest_WStem      = 0.
107         self.harvest_WBranch    = 0.
108         self.harvest_WTapRoot   = 0.
109         self.harvest_WFoliage   = 0.
110         self.NbCutTrees         = 0.
111         self.harvest_DBHmean    = 0.
112         self.harvest_DBHsd      = 0.
113         self.harvest_DBHquadratic = 0.
114         self.harvest_HEIGHTmean = 0.
115         self.harvest_HEIGHTsd   = 0.
116         self.harvest_basalArea  = 0.
117 
118         del self.Cut_Trees [:]
119 
120         if self.locTime.isSimulBeginning:
121             self.lastThinningYear    = self.locTime.Y - 10
122             self.thinnings           = 0
123             self.seedingCutYear      = self.locTime.Y - self.forest.treeStand.Age - 5
124             self.FirstThinning       = False
125 
126         # Specifications of the Plantation and thinnings operations
127 
128         for interventionYear, interventionParameters in INTERVENTIONS.items():
129             if  self.locTime.isYearEnd and self.locTime.Y == interventionYear   :
130 
131                 if  interventionParameters[0] == 'PLANTATION' :
132                     self.do_plow(areaFractionPlowed = 0.2,soilCarbonFractionAffected = 0.2)
133                     self.do_NewTrees(interventionParameters[2], interventionParameters[1], interventionParameters[3], interventionParameters[4])
134 
135                 if  interventionParameters[0] == 'THINNING' :
136                     self.do_Density_Thinning(
137                             ThinFactor      = interventionParameters[2],
138                             densityObjective = interventionParameters[1],
139                             )
140                     self.do_Logging(
141                             harvestStem = interventionParameters[3],
142                             harvestBranchWood = False,
143                             harvestTapRoot = False,
144                             harvestStump=False,
145                             harvestFoliage = False,
146                             )
147                     self.lastThinningYear= self.locTime.Y
148 
149                 self.forest.treeStand.pcs_SetSizes() #update the stand characteristics after management operations
150 
```

The 'PLANTATION' includes a soil preparation affecting 20% of area and 20% of soil carbon (L132) and the plantation of 5000 2-year old seedlings. The code of the stand regeneration itself is listed in the *mdlMngt_Operations* module as the *do_New_Trees* function that includes the four parameters, age of trees, stem number per hectare and the mean and standard deviation of the tree DBH. From those, it created a tree stand having a Gaussian distribution of DBH with a mean of 0.03 m and standard deviation = 0.01 m prescribed at L91.

The 'THINNING' includes two distinct operations, the selection of trees to be cut as *do_Density_Thinning (L136)* and stem logging, instantiated in the *do_Logging* function (L140). Until the density objective is reached, the successive thinnings remove larger trees e.g. in 1998 (ThinFactor = 0.8) or randomly selected trees in 2000 (ThinFactor = 1). For each thinning only the stem is harvested, other tree parts are left over on site. Additional thinning operations (do*_RDI_thinning* and *do_BA_Thinning*) based on competition or basal area are also available as functions of the *mdlMngt_Operations* class.

Logging

The *do_Logging* object manages the left over parts of the trees cut and update the remaining tree stand. It calculates the main statistics of the trees harvested. The part of the tree harvested can be the stemwood, branches, taproot or foliage biomass. The understorey is not harvested. The biomass leftover is input into the soil organic matter. A logging operation with no part harvested corresponds to a “thinning out” or “non-commercial harvest”.

CAUTION: the *do_Logging* function must be called following each thinning or clearcutting operation.

Clearcutting

The *do_Clearcut* is actually similar to a thinning operation for which all trees would be removed but has been coded as a separate function.

Soil and understorey operation. The soil can be plowed, stripped, moulded of disked. These operations are all defined in the generic “*do_Plow*” function. The user must specify :

- the fraction of the soil organic carbon affected, as a percentage (gC gC-1),
- the fraction of area concerned (m2 m-2).

Do_PLow is managing the effect of the soil carbon cycle and the understorey, incorporating plant parts killed into the soil. In this version, the operation is not supposed to mix the soil organic matter of the root layer with deeper soil. The root and soil depths are not supposed to be changed either. The understorey vegetation is killed by the soil operation in proportion of the area fraction for the aboveground biomass and the fraction of soil organic carbon times the area fraction for the underground parts.

Example 2. A soil tillage of the entire area until a depth of 0.5m --where all the organic carbon is included-- should be specified as:

self.do_Plow(areaFractionPlowed = 1.0 ,soilCarbonFractionAffected =1.0)

In this case, the understorey foliage, roots and perennial parts are entirely destroyed and put into the soil.

Example 3. A light soil surface disking made between tree rows in a pine plantation as fire preventing measure and affecting 75 pct of the plot area and the top 10cm --where 15 pct of the soil organic carbon is present-- will be defined as:

self.do_Plow(areaFractionPlowed = 0.75 ,   soilCarbonFractionAffected =0.15)

The understorey foliage will reduced by 75pct and the belowground part (roots and perennial) by 0.75 x 0.15=0.1125 pct.

Example 4. The removal of all understorey aboveground parts is prescribed by:

self.do_Plow(areaFractionPlowed = 1.0 ,   soilCarbonFractionAffected =0.0)

Tree regeneration (*do_NewTrees*).

After clearcutting, or following a putative mortality of 100% of the trees, a new stand can be regenerated using the function *do_NewTrees.* This function includes four parameters and generate a list of trees with the DBH distributed according to a Gaussian distribution with specified values of the mean and standard deviation of DBH.

ii) How can a management plan be coded for GO+ ?

The management of the forest stand itself is a combination of forest operations and rules triggering each specific operation. The operations detailed previously and coded in the *mdlMngt_operations* are the basic generic forest operations that can be combined in multiple ways in a management plan starting from an initial state and going through an entire forest life cycle. This manual provides one example below.

Example 5. (script *Fs_FR-MTR_2006-2100_managed* and – *unmanaged*). In a recent Master's research (Figuères, 2019), the model was applied to simulate old-growth beech forest close from the Pyrenean mounts. Specifically a standard management plan was compared to an unmanaged forest reservation plan with no management. We provide the scripts and the files requested to run a 140 year-old beech stand from 2006 to 2100 according to the two management alternatives. The management plans are both included in the *Manager* module.

- The management plan (*manager.practicesType* == 0) is the standard management performed by the French national forest Office. It includes successive thinnings allowing to harvest timber in the young phase and to subsequently thin the tree stand in order to regenerate a new stand. The plan ends with a clearcut. The thinnings are all based on target values of the basal area and dominant height. The script to be used is *Fs_FR-MTR_2006-2100_managed*.

- The self thinning rule based upon the Relative Density Index (RDI) is applied to the forest reserve (*manager.practicesType == 2*). It is based upon the Reineke (1933) competition index, RDI, adapted by Le Moguedec and Dhôte (2002). When RDI exceeds 0.95, mortality is triggered until RDI comes back below the value 0.85. In this particular case, RDI threshold is not reached, tree mortality is being provoked instead by a negative carbon balance. The script to be used is *Fs_FR-MTR_2006-2100_unmanaged*.

5. Files required

The files used in GO+ and provided as examples are self-explanatory since including the description and unit of all variables together with default values.

- **Site.** Ex: *ParamSite_FR_LBr.csv.* This file includes 29 parameters that are describing the leap year accounting method, altitude, latitude, slope, exposure, reference level of the meteorological data, area of the plot and soil texture and depth. The following rules must be observed when completing this file:
  - sum of the percentages of texture classes must be 100;
  - initial depth of layer B should be equal or lesser than the root depth;
  - The area must be the area of the plot where the tree stand inventoried in the *treedbh.csv* file is present. It can be anything from 10 to 10^6 m² (the computation time is however depending upon the number of trees and the plot area).
  - The reference level corresponding to the meteorological variables data set must be either 2 or 10m.

- **Meteorological.** The meteorological file must include a complete time series of hourly values of meteorological variables, air temperature, horizontal wind speed, air water vapour pressure, bulk precipitations, diffuse and direct incident shortwave radiations and incident longwave radiation. The values must correspond to either *z* = 2m or *z* = 10m above ground. These variables always need to be sorted in the same way. When leap years are present, the first parameter of the *Param_Site* file must be set to 1, zero otherwise.

- **Species specific parameters.** This file includes 238 parameters together with their description and default values. It is organised by layers (trees, understorey and soil) among 17 sections related to specific processes. The parameters description corresponds to the table S1 of the supplementary material of the Moreaux et al. manuscript. Three species are documented so far, European beech, Douglas Fir and Maritime pine and other species (*Eucalyptus Gunnii, Pinus sylvestris, Quercus robur)* are to be added.

- **Tree stand inventory.** The file includes a list of the diameter at 1.30 m height of the individual trees present in the plot at time t=0 (cm). it is used for running the model from a given initial stand. Alternatively, GO+ can also be run from a stand created using a prescribed distribution assumed normal with four parameters (number of trees per hectare, tree age, mean and standard deviation of the DBH).

6. Output files

- **Output variables declaration.** The Python GO+ code provides a range of options for selecting output variables and statistics associated. The output files are typically a continuous time series of values of the statistics of variables selected by the user.
  - The time step at which GO+ resolves its variables can be either hour, day or year and is declared in the script file. Only one time resolution can be chosen in each run.
  - Any number of variables can be obtained (but be parsimonious because the writing process slows down the execution of the program). The list of the main variables provided at the ecosystem level is provided in section 7.
  - Optionally, some code lines put as comments in the *forest.treeStand* class allow for creating a file containing the standing –or dead- tree inventory. Similarly, some optional code lines are actionable in the *LeafCohorts* class, allowing to create a file containing the leaf cohort characteristics in order to check their phenology and life cycle.

- **Statistics.** The following statistics can be calculated over the time span chosen: min, max, last, mean, sum.

  At the hourly time step, these statistics produce of course the same value. The list of variables available together with their stats must be declared in a string "*varsToIntegrate*" heading the script file. Alternatively, they can also be listed in a file and called by the script. For instance, to obtain a csv file including year, day of year, sum of Rain, shortwave direct and diffuse radiation, ecosystem GPP and ETR the following lines must be inserted:

varsToIntegrate =’’’
Last: mdl.locTime.Y
Last: mdl.locTime.DOY
Sum: mdl.climate.microclim.Rain

Sum: mdl.climate.microclim.SWDir
Sum: mdl.climate.microclim.SWDif
Sum: mdl.forest.LE (or mdl.forest.ETR)
Sum: mdl.forest.GPP
’’’

- **Variable names**

The data values simulated and requested are output in a csv.file headed by the variables names coded at the end of the script file. The names are composed according to the following:

SSSS:mdl.folder.(subfolder).class.(subclass).XXXX

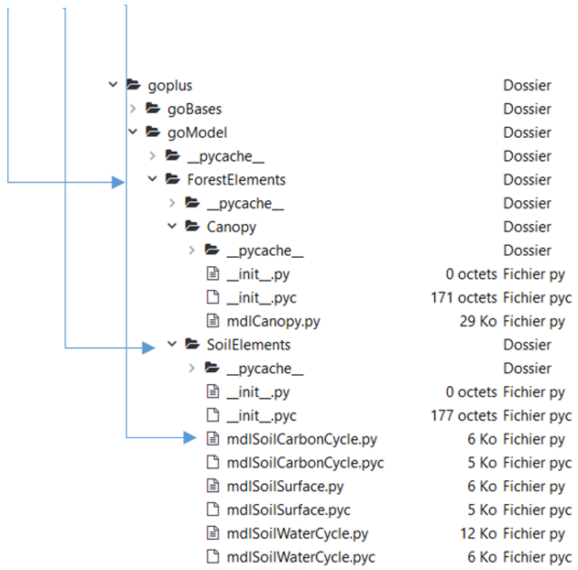
where:

- *SSSS* is the stat requested (Last, Mean, Sum, Min or Max)
- “*Folder*” may be “*forest*” or “*manager*” that stand for *ForestELements* and *ManagerElements* respectively. This item is not needed for the clock and climate variables since the related objects, *locTIme, SunLocal, Climate* and *Microclimate* are directly under the main *goplus* folder.
- “*Subfolder*” is the below level folder when present.
- “*Class*” is the main class where the variables are instantiated.
- “*Subclass*” names a class called by the Class above.
- *XXXX* is the variable name.

The main variable names in the code are listed in the *GO+ 3.0 variable name.pdf* file together with the corresponding symbols, unis and definitions. The symbols refer to the Moreaux et al. manuscript submitted at *GeoScientific Model Development*.

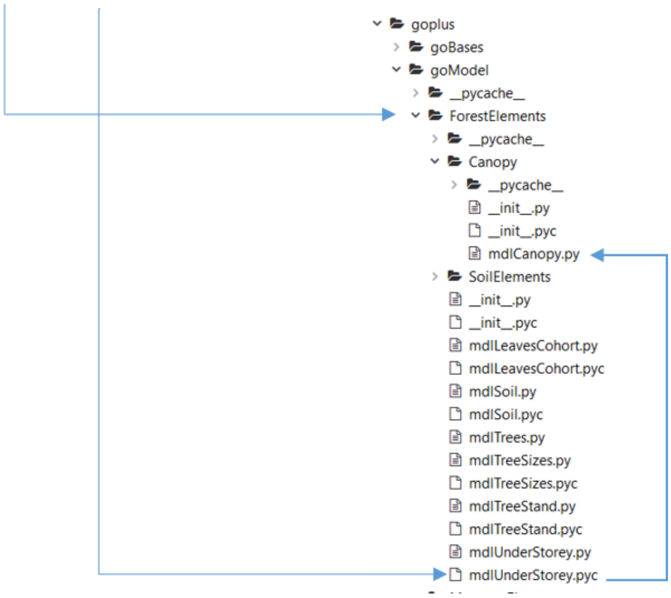
The diagram below provides the branching structure of GO+ *Python* files. For obtaining the stock of carbon if the humified compartment, the corresponding variable is:

Last: mdl.forest.soil.carbonCycle.HUM



A second example is for obtaining a time series of hourly values of the understorey carbon assimilation in gC m^{-2} $hour^{-1}$. Since the "Canopy" object is called first by the understorey class, the variable name should read:

Last: mdl.forest.underStorey.canopy.Assimilation



7. List and mapping of the variables calculated by the GO+ v3.0 code

The list provided in a separate file, *GO+ v3 variables list.pdf.* It includes the main variables simulated by the GO+ code. In this list, the variable name and unit shown is for a hourly resolution and is only for the tree layer. Obtaining the corresponding variables for the understorey layer would need to substitute *treesStand* by *UnderStorey*. The stats name and the prefix "mdl." are omitted. Some variables have not been explicitly described in the Moreaux et al. 2020 manuscript but are mentioned in *GO+ v3 variables list.pdf*, and can be obtained when needed.

8. References

Achat, D. L., Martel, S., Picart, D., Moisy, C., Augusto, L., Bakker, M. R., and Loustau, D.: Modelling the nutrient cost of biomass harvesting under different silvicultural and climate scenarios in production forests, For Ecol Manag, 429, 642-653, 2018.

Figuères S., 2019.Assessment of the carbon storage potential in old-growth pyrenean forests. Masters Degree Diss.ENSAT Toulouse 2019, INRAE, UMR ISPA. Spécialisation Qualité de l'Environnement et Gestion des Ressources, 84p.

Le Moguédec, Dhôte, 2012. Fagacées: a tree centered growth and yield model for sessile oak (Quercus petraea L.) and common beech (Fagus sylvatica L.). Ann. For. Sci. 69, 257–269.

Loustau, D., Bosc, A., Colin, A., Ogee, J., Davi, H., Francois, C., Dufrene, E., Deque, M., Cloppet, E., Arrouays, D., Le Bas, C., Saby, N., Pignard, G., Hamza, N., Granier, A., Breda, N., Ciais, P., Viovy, N., and Delage, F.: Modeling climate change effects on the potential production of French plains forests at the sub-regional level, Tree Physiol, 25, 813-823, 2005.

Loustau, D.: Forests, carbon cycle and climate change. QUAE, Versailles, 2010.

Moreaux, V.: Observation et modélisation des échanges d'énergie et de masse de jeunes peuplements forestiers du Sud-Ouest de la France., Ph. D.thesis., Ecole Doctorale 304 "Sciences et Environnements", Thématique "Physique de l'Environnement", Université de Bordeaux-1, Bordeaux, 262 pages pp., 2012.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P. et al. The next generation of scenarios for climate change research and assessment. Nature, 463 (7282), 747-756.2010.

Porté, A.: Modélisation des effets du bilan hydrique sur la production primaire et la croissance d'un couvert de Pin maritime (Pinus pinaster Ait.) en lande humide., 1999.Thèse de Doctorat, Paris XI, Orsay, 160 pp., 1999.

Reineke, L.H., 1933. Perfecting a stand density index for even-agedstands. J. Agric. Res. 46, 627±638.

Roux A., Dhôte J.-F. (Coordinateurs), Achat D., Bastick C., Colin A., Bailly A., Bastien J.-C., Berthelot A., Bréda N., Caurla S., Carnus J.-M., Gardiner B., Jactel H., Leban J.-M., Lobianco, A., Loustau D., Meredieu C., Marçais B., Martel S., Moisy C., Pâques L., Picart-Deshors D., Rigolot E., Saint-André L., Schmitt B. (2017). Quel rôle pour les forêts et la filière forêt-bois françaises dans l’atténuation du changement climatique? Une étude des freins et leviers forestiers à l’horizon 2050. Rapport d’étude pour le Ministère de l’agriculture et de l’alimentation, INRA et IGN, 101 p. + 230 p. (annexes).