HETEROFOR 1.0
User Manual

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2. Introductory remarks

HETEROFOR is a tree-level model developed according to a spatially-explicit process-based approach to explore the response of structurally-complex stands (uneven-aged, mixed) to changing environmental conditions. Since 2012, HETEROFOR has been progressively elaborated through the integration of various modules (light interception, phenology, water balance, photosynthesis and respiration, carbon allocation, mineral nutrition and nutrient cycling) within CAPSIS, a collaborative modelling platform dedicated to tree growth and stand dynamics (Dufour-Kowalski *et al.*, 2012). A general overview of the model functioning and a detailed description of the carbon-related processes of HETEROFOR (photosynthesis, respiration, carbon allocation and tree dimensional growth) can be found in Jonard *et al.* (submitted to GMD). For the light interception, HETEROFOR is coupled to the SAMSARALIGHT library first developped by Courbaud *et al.* (2003) and further adapted by Ligot *et al.* (2014) and André *et al.* (in prep). The phenology and water balance module of HETEROFOR are presented in de Wergifosse *et al.* (submitted to GMD) while the mineral nutrition and nutrient cycling module must still be improved and will be published later.

HETEROFOR was designed to be particularly suitable for the level II plots of ICP Forests. The processes were described at a scale that facilitates the comparison between model predictions and observations. Many data collected in these plots can be used to initialize and run the model or to calibrate and evaluate it. HETEROFOR can also be seen as a tool for integrating forest monitoring data and quantifying non-measured processes.

3. Installation of HETEROFOR under CAPSIS

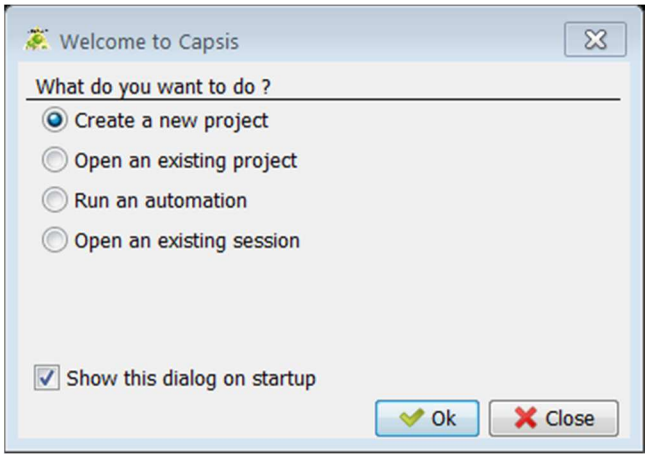
The source code of CAPSIS and HETEROFOR is accessible to all the members of the CAPSIS co-development community. Those who want to join this community are welcome but must contact François de Coligny (coligny@cirad.fr) or Nicolas Beudez (nicolas.beudez@inra.fr) and sign the CAPSIS charter (http://capsis.cirad.fr/capsis/charter). This charter grants access on all the models to the modellers of the CAPSIS community but only to them. The modellers may distribute the CAPSIS platform with their own model but not with the models of the others without their agreement. CAPSIS4 is a free software (LGPL licence) which includes the kernel, the generic pilots, the extensions and the libraries. HETEROFOR is basically not free and belongs to its authors who decided to distribute it as an installer containing the CAPSIS4 kernel and the latest version (or any previous one) of HETEROFOR upon request from Mathieu Jonard (mathieu.jonard@uclouvain.be).

The source code for the modules published in Geoscientific Model Development (Jonard *et al.,* submitted*;* de Wergifosse *et al.*, submitted) can be downloaded from the CAPSIS website (http://amap-dev.cirad.fr/projects/capsis/files) or obtained by contacting directly Mathieu Jonard.

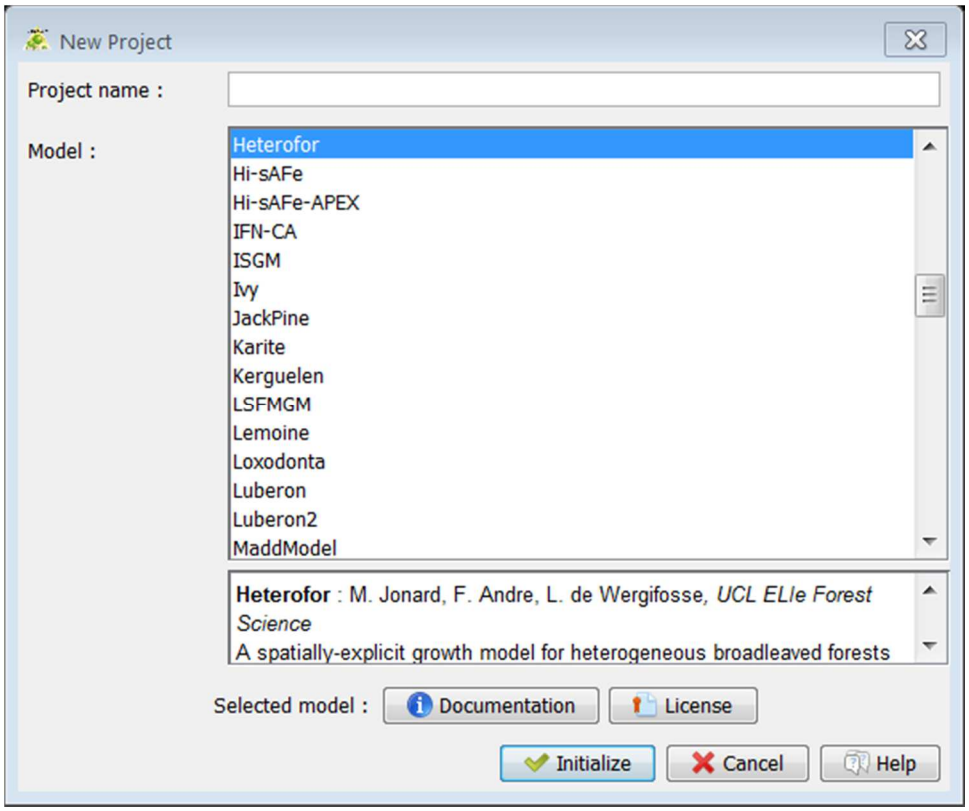
The end-users who do not need access to the source code can install CAPSIS from an installer containing only the HETEROFOR model while the modellers who signed the CAPSIS charter can have access the complete version of CAPSIS with all the models. Depending on your status (end-user vs modeller or developer), the instructions to install CAPSIS are given on the CAPSIS website (http://capsis.cirad.fr/capsis/documentation).

4. Initialization of HETEROFOR

When CAPSIS is started, a first window appears and one can create a new project or open an existing one. The user can also open an existing session containing several projects.



If “Create a new project” is chosen, a second window opens from which the HETEROFOR model can be selected among the list of models available in CAPSIS. When an installer is used, only a subset of models are available. To launch the model initialization, click on the Initialize button.



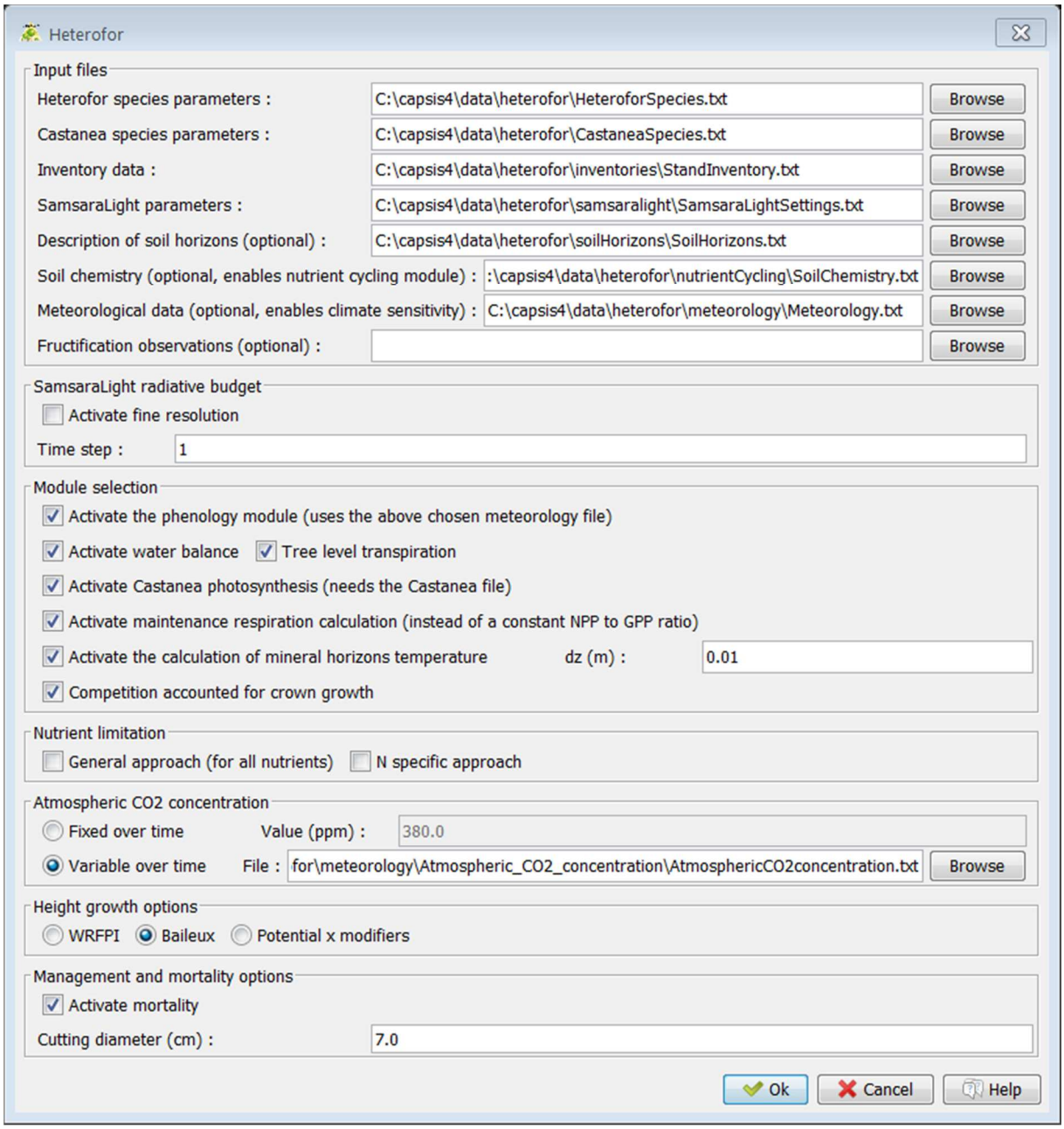
Initializing HETEROFOR requires a series of information provided by loading files and selecting model options. When HETEROFOR is run with the default mode, the vegetation period is defined based on the budburst and the leaf shedding dates provided in the setting file of SAMSARALIGHT; no water balance is achieved; the gross primary production (gpp) of each tree is calculated with a radiation use efficiency approach; the net primary production (npp) is determined based on a fixed proportion of

gpp and a distance-independent routine is used to describe crown extension. The initial dialog allows the user to activate (i) the phenology module, (ii) the water balance module with a possibility to calculate transpiration at the tree-level (recommended), (iii) the coupling with CASTANEA for the photosynthesis calculation, (iv) the temperature-dependent routine to determine maintenance respiration, (v) the soil heat transfer module (spatial resolution must be provided) and (vi) the distance-dependent approach to describe crown extension. The user can also define the time step at which the radiative budget must be performed and whether the detailed approach must be used. The model can account for the nutrient limitation of tree growth with the possibility to select an approach particularly adapted to nitrogen. These nutritional aspects being still under testing, we recommend not using this option for the moment. For the photosynthesis estimated with CATANEA, the model can either consider a fixed atmospheric CO_2 concentration or load a file describing its temporal change according to various IPCC scenarios (yearly time step). Several approaches were tested to estimate the height growth. We recommend to select the "Baileux" option which has been described in Jonard *et al.* (submitted to GMD). Finally, one can choose to activate the mortality routine and select the branch and trunk diameter under which the wood is not harvested and left in the forest (which has implications for the nutrient budget).

Besides this selection of options, three parameter/setting files must be provided since two CAPSIS libraries (SAMSARALIGHT for light interception and CASTANEA for photosynthesis) are used in addition to HETEROFOR. For HETEROFOR and CASTENEA, the parameters are mostly species specific; they are defined in Jonard *et al.* (submitted to GMD) and de Wergifosse *et al.* (submitted to GMD) regarding HETEROFOR and in Dufrêne *et al.* (2005) for CASTANEA. The setting parameter needed to initialize SAMSARALIGHT as well as the description of the functioning of this library are presented on the CAPSIS website at http://capsis.cirad.fr/capsis/help_en/samsaralight.

Then, the user must provide an inventory file containing the relative position (*x, y, z*) and the main dimensions of each tree: girth at breast height (*gbh* in cm), height (*h* in m), height of maximum crown extension (*hlce* in m), height to crown base (*hcb* in m) and crown radii in the four cardinal directions (*cr* in m). This file also specifies the starting date, the cell size for the radiation transfer module, the maximum leaf area index for the whole ecosystem, the foliar nutrient concentrations, the latitude, longitude and slope of the site (in degrees) and the clockwise angle between North and the x axis (in degrees). When data on fruit litterfall are available, a file providing the amount of fruit litterfall per year and per tree species can be loaded and used to adapt the allometric equations predicting fruit production at the individual level.

When the water balance module is activated, two additional files must be loaded: a file describing soil horizon properties and another one for the meteorology. For each horizon, the following properties are provided: upper and lower horizon limits (m), coarse fraction ($m^3.m^{-3}$), bulk density ($kg.m^{-3}$), sand, silt and clay content ($g.g^{-1}$), organic carbon ($mg.g^{-1}$), mean, wilting point and saturated water content ($m^{-3}.m^{-3}$), soil solution pH, log pCO_2 (with pCO_2 in atm), fine root proportion (%) and tortuosity factor ($m.m^{-1}$). The meteorological data are read by a loader and stored in hourly meteo line objects containing the date split in four (year, month, day, hour) and seven meteorological variables: radiation ($W.m^{-2}$), air temperature (°C), soil surface temperature (°C), rainfall ($l.m^{-2}$ or mm), relative humidity (% or hPa / 100 hPa), wind speed ($m.s^{-1}$) and wind direction (degrees).



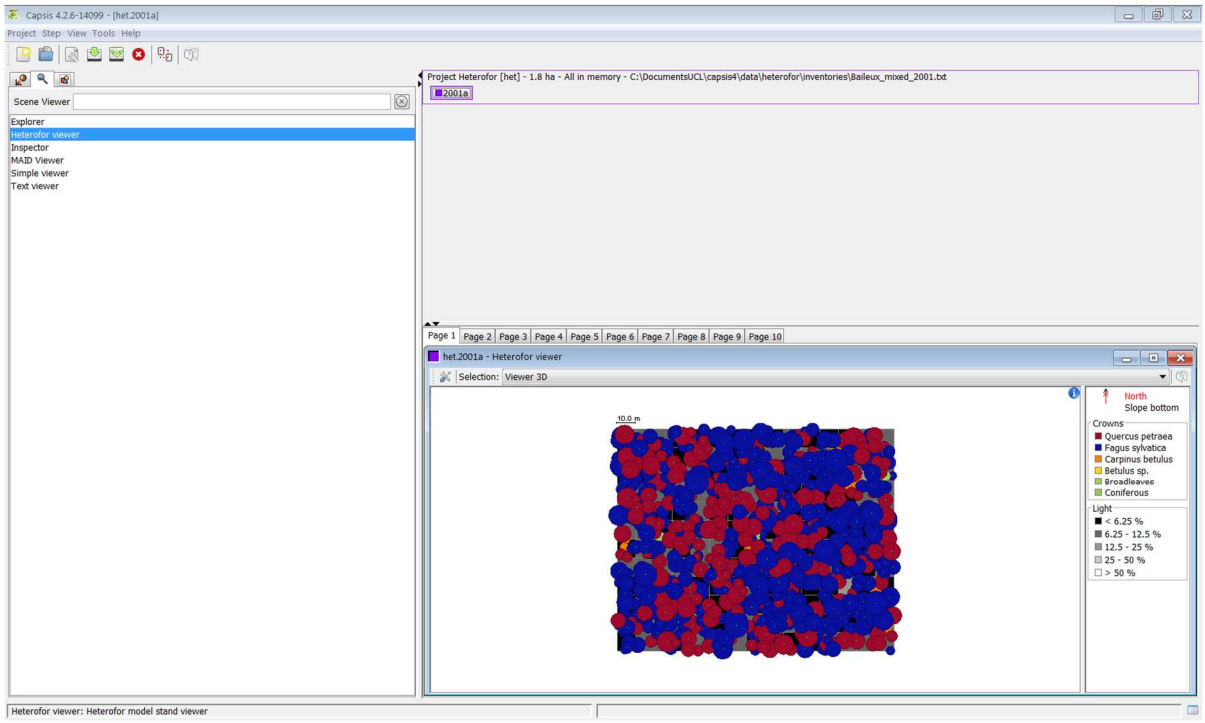
Finally, the soil chemistry input file must be provided when the nutritional limitation is considered. This file contains 6 parts:

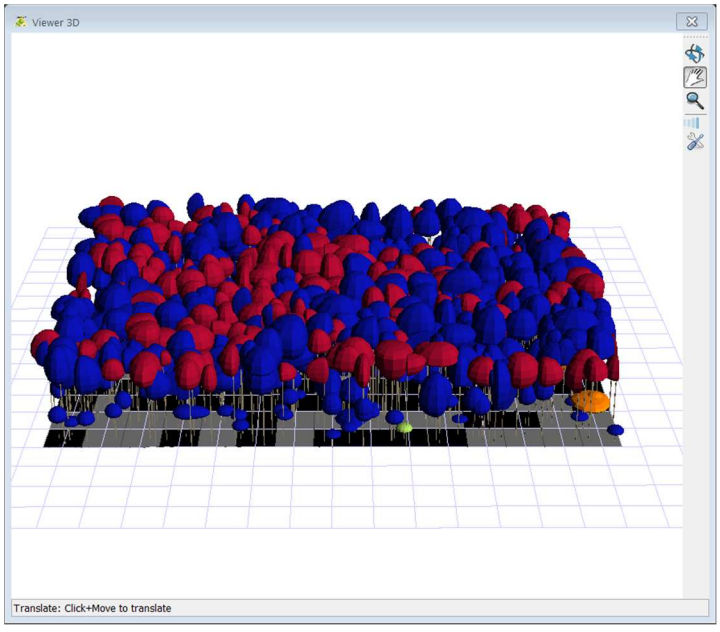
- a list with all the chemical elements, their charge and atomic mass,
- the element concentrations in the soil solution for each soil horizon (K, Ca, Mg, Na, Nam, Al, Mn(2), Fe(3), Cl, Nnit, S(6), P, Si, Cit, C(4) in $mg.l^{-1}$),
- the exchangeable cation concentrations for each cation exchanger (Xo, Xm, Xs) and soil horizon (e.g. HXo, KXo, CaXo2, MgXo2, NaXo, NamH4Xo, AlXo3, MnXo2, FeXo3, HXm, KXm, CaXm2, MgXm2, NaXm, NamH4Xm, AlXm3, MnXm2, FeXm3, HXs, KXs, CaXs2, MgXs2, NaXs, NamH4Xs, AlXs3, MnXs2, FeXs3 in $cmole.kg^{-1}$),
- the exchangeable anion concentrations for each anion exchanger (Ya) and soil horizon (e.g. YaCl, YaNnitO3, Ya2SO4, YaH2PO4, YaH3SiO4, Ya3Cit, YaHCO3, YaOH in $cmole.kg^{-1}$),
- the mineral properties: mineral type (e.g., quartz, K-feldspar, K-mica, illite, albite, anorthite, chlorite(14A), Vrm, kaolinite, variscite, Ca-Montmorillonite, manganite, Fe(OH)3(a)), concentration in mole/kg, weathering type (1 for equilibrium and 2 for kinetics), target

saturation index as log(IAP/Ks) with IAP: ion activity product and Ks: solubility product of the mineral (all dimensionless), reaction type (d for dissolution, p for precipitation and b for both), kinetics parameters depending on the formula mentioned in the PHREEQC database,

- the atmospheric deposition (in kg.ha^{-1}.year^{-1}).

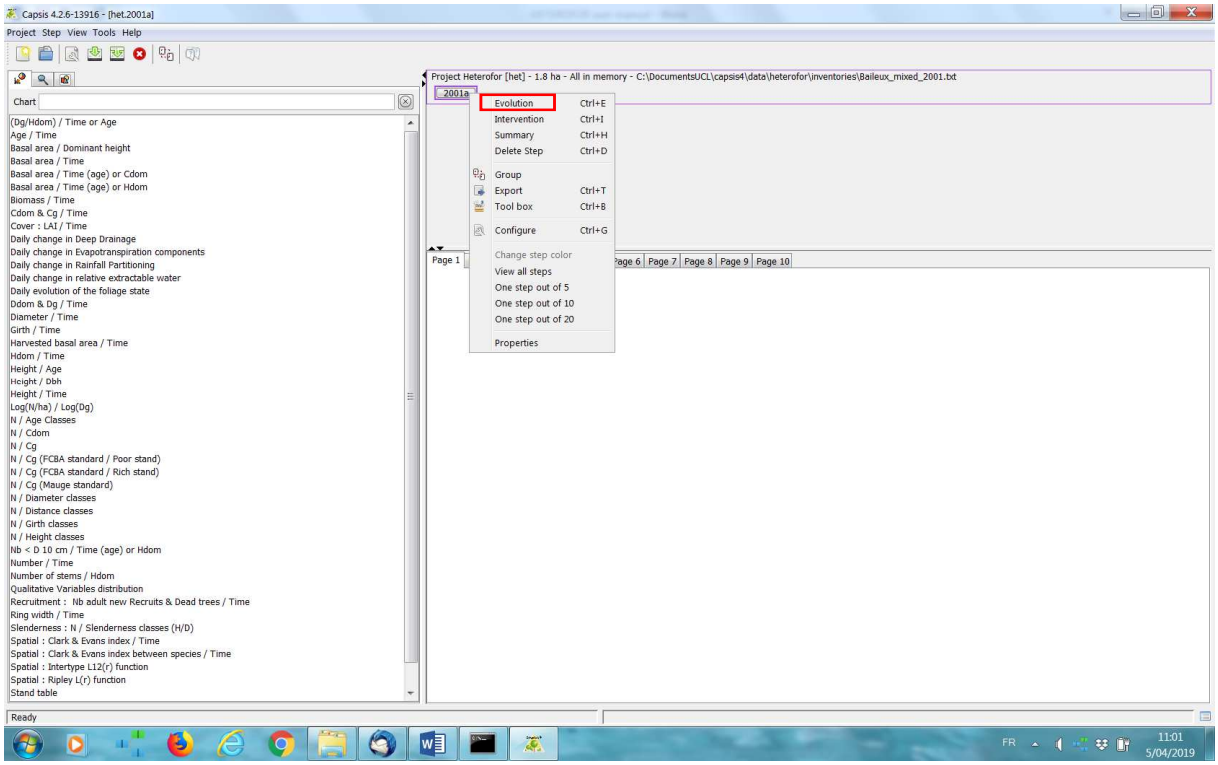
After selecting the desired options and specifying the paths to the input files, the initialization can be launched by pressing on the “Ok” button. The model creates then a new project with only the initial step corresponding to the state of the forest stand at the starting date mentioned in the inventory file. The stand can be visualize in 2D by selecting the “scene viewer” tab (choose Heterofor viewer) on the left panel. This viewer shows the tree crowns and the relative light transmitted to the ground cells. To obtain a 3D representation of the stand, the user must choose the 3D viewer in the lower right panel and select the trees with the mouse (right click).



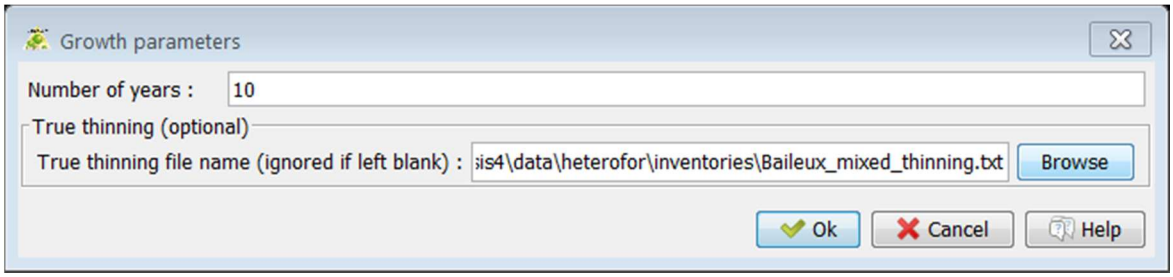


5. Launching an evolution and planning silvicultural interventions

Right-click on the initial step and select “Evolution” in the drop-down menu to launch a simulation.



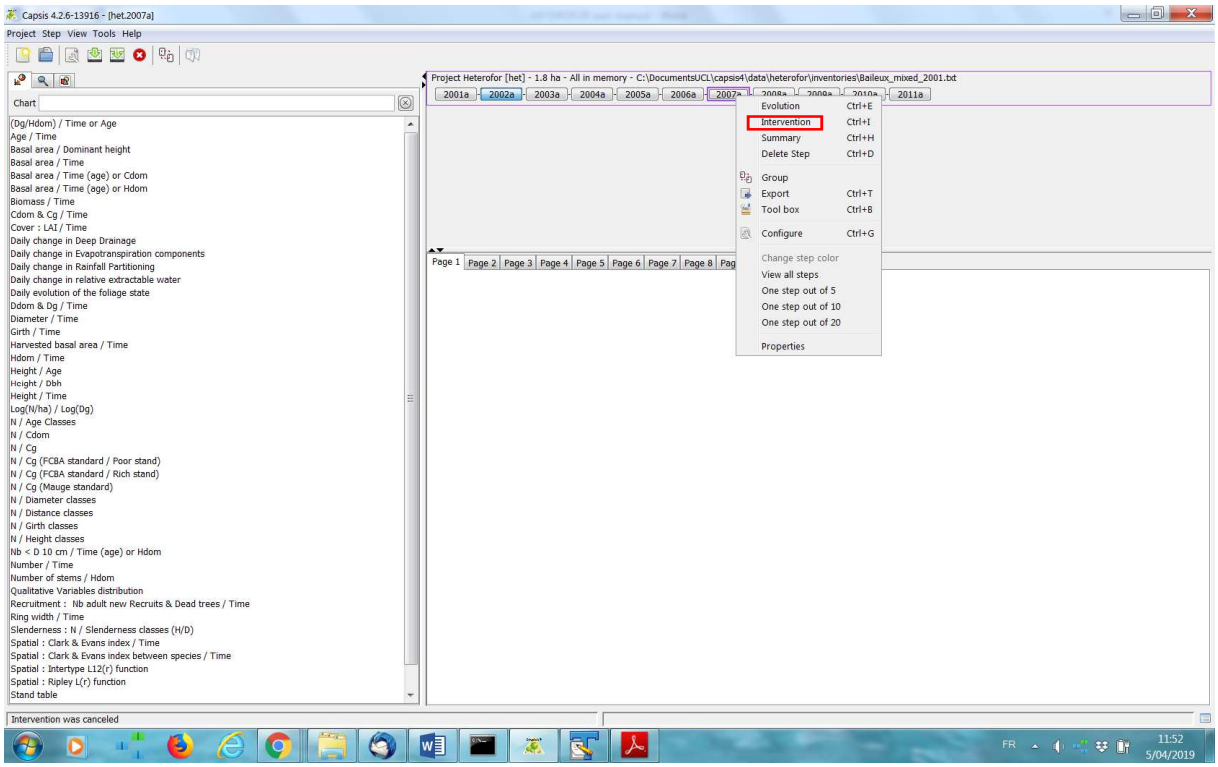
A window appears and allows the user to specify the length of the simulation and to load a file listing the trees to be thinned and their last year of presence in the stand.

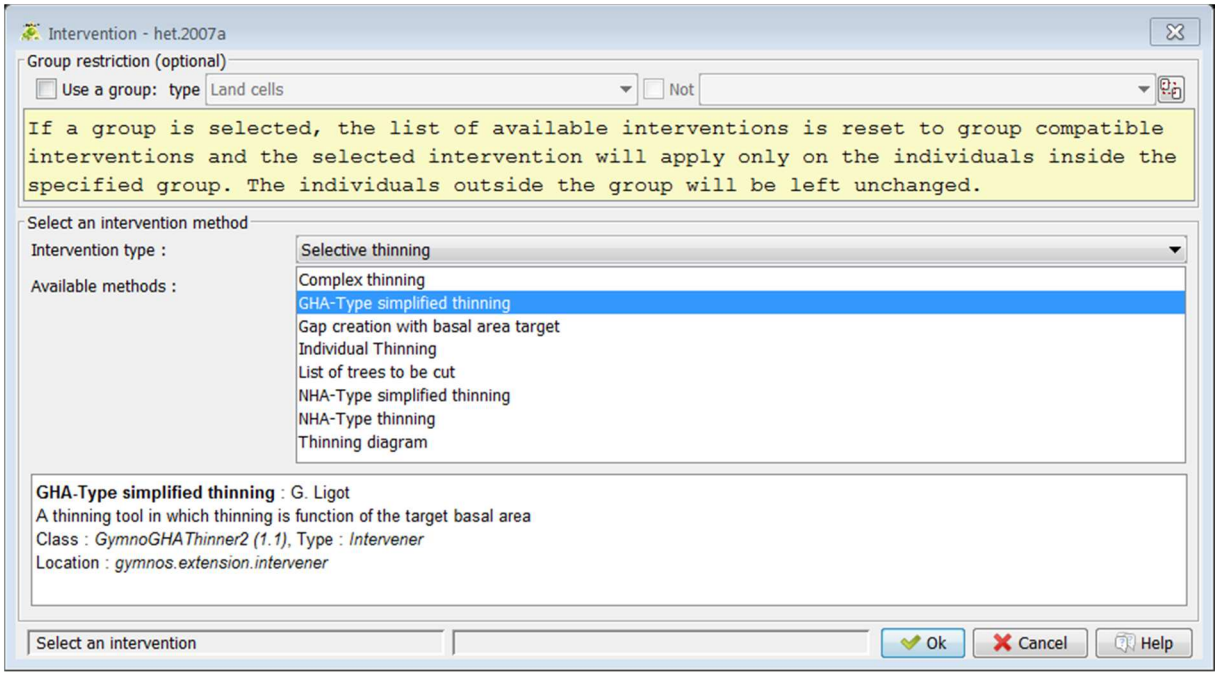


The simulation can take several minutes depending on its length. When the evolution is finished, the project is composed of as many steps as years in the evolution. Each step correponds to a year and contains the state of the stand at the end of this year (after the vegetation period).

The thinning file is optional and thinning can be achieved by right clicking on the step after which the thinning must be done and selecting “Intervention” in the drop-down menu. In the window that appeared, choose “Selective thinning” in the intervention type. You will then have access to all the routines created in CAPSIS to achieve a thinning as far as they are compatible with HETEROFOR. The

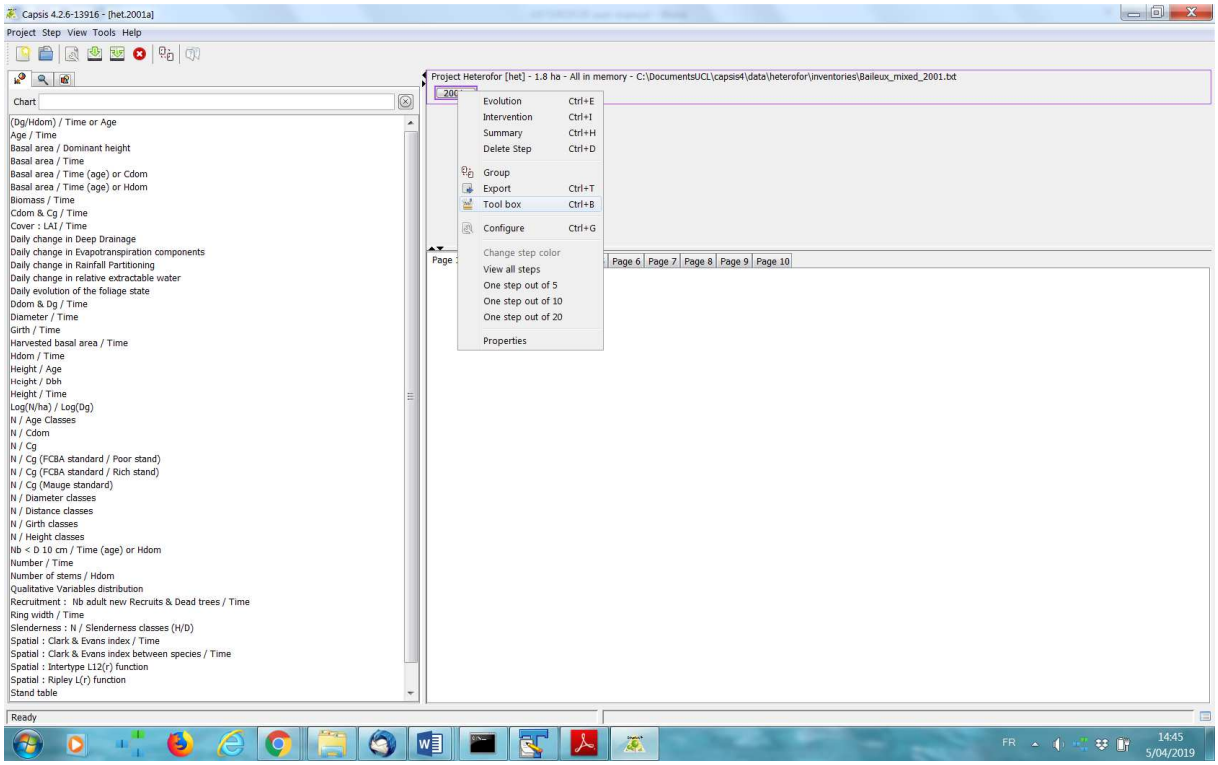
user is referred to the documentation of CAPSIS for a detailed description of these thinning routines called interveners (http://capsis.cirad.fr/capsis/documentation/interventions).

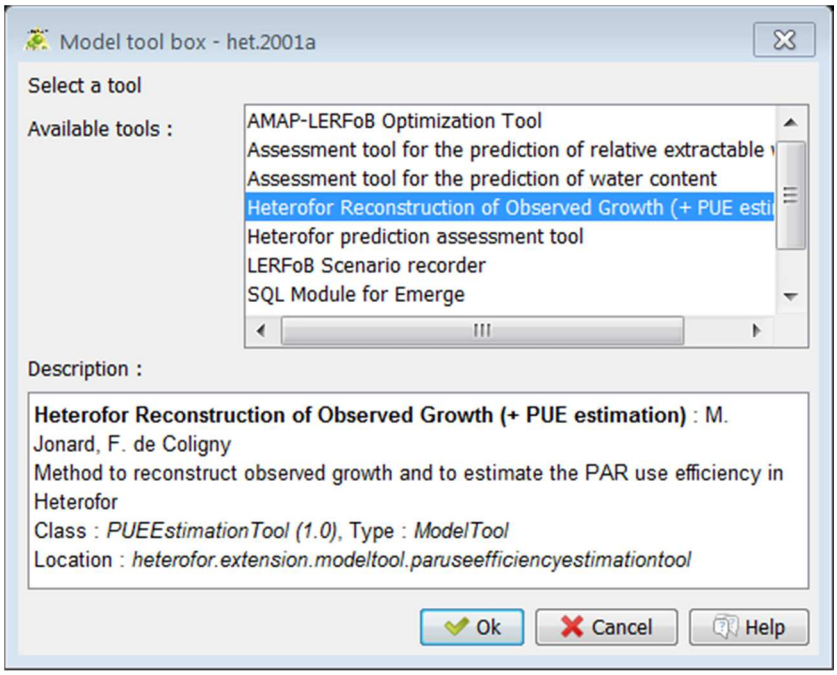


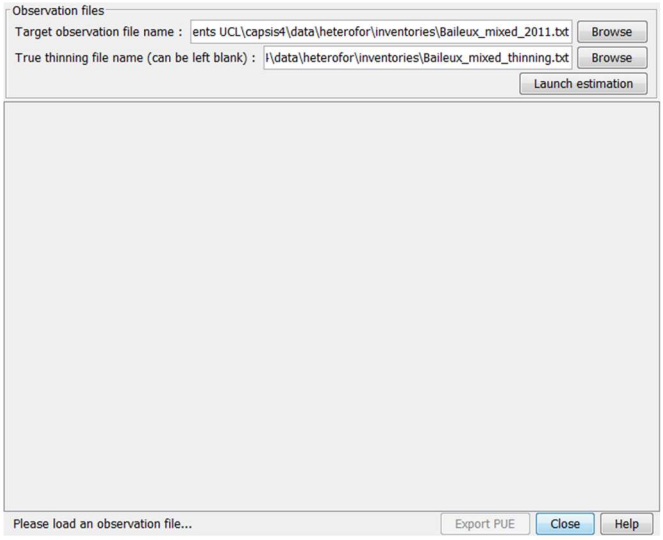


6. Launching a reconstruction

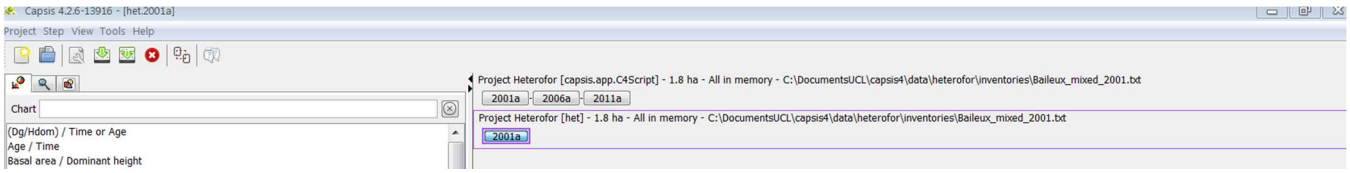
HETEROFOR was adapted to allow the user to run it in reverse mode starting from the known increments in girth and height to reconstruct individual tree growth using exactly the same parameters and equations as in the normal mode. To achieve a reconstruction, an inventory file with tree measurements must be loaded to create the initial step (see sect. 5.). The reconstruction tools can be launched by right-clicking on the initial step and select “Tool box” in the drop-down menu. Then, the user must choose the reconstruction tool (Heterofor Reconstruction of Observed Growth) and provide an inventory file with tree measurements achieved one or several years later as well as the thinning file. Based on these files, HETEROFOR calculates the mean girth and height increments for each tree and use the model equations to reconstruct each step. Do not forget to click on the “Launch estimation” button.





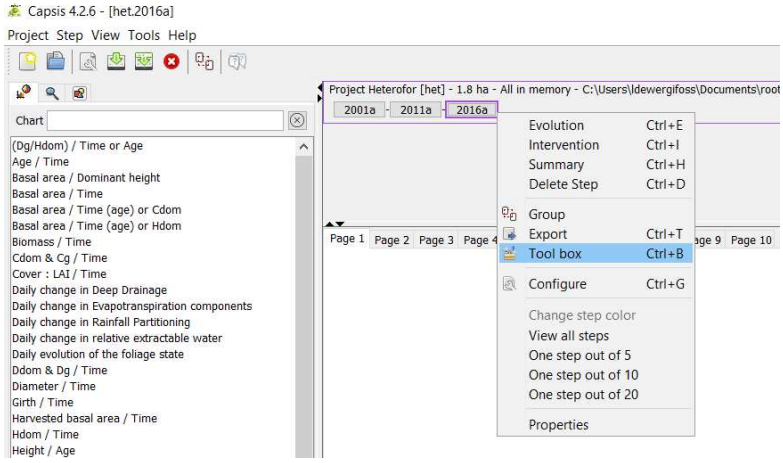


After a while, a graph showing the PAR use efficicency as a function of the light competition index will appear. The project corresponding to the growth reconstruction will appear after clicking on the initial step.

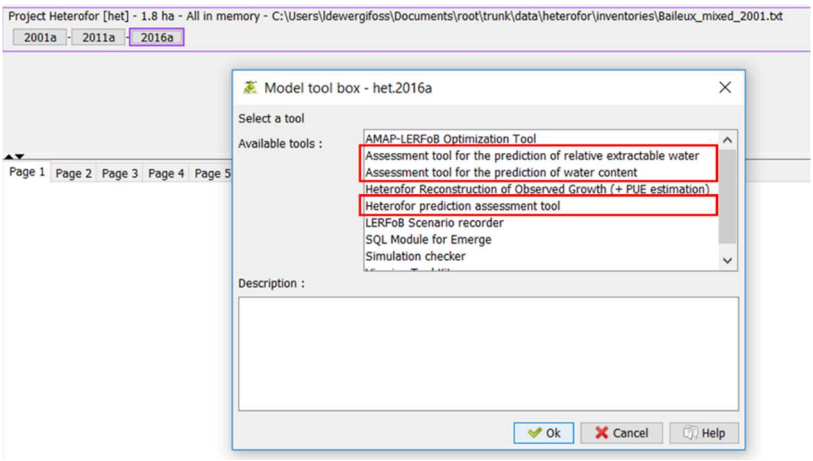


7. Evaluation tools

Different evaluation tools can be used in HETEROFOR to compare the model predictions with the observations. A visual comparison is proposed by default but a txt file and a table with the corresponding predictions and observations can be created and opened, respectively. The visualisation tools can be access with a right-click on the step for which or until which observations are available and by selecting “Tool box” (Ctrl+B).



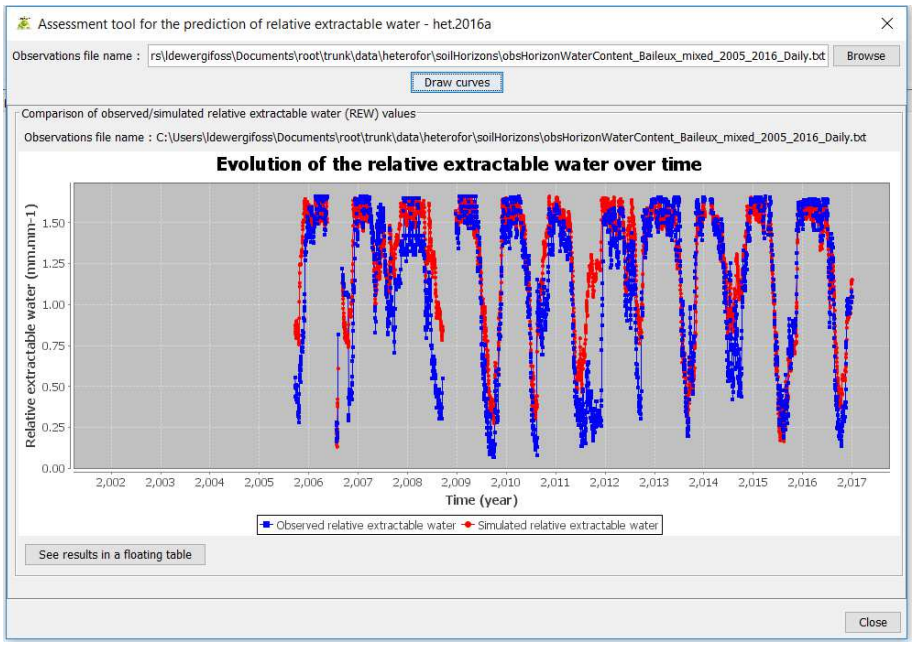
Different toolboxes are available but only three are evaluation tools: the assessment tool for the prediction of relative extractable water (REW), the assessment tool for the prediction of water content and and the HETEROFOR prediction assessment tool which is dedicated to the evaluation of tree dimensional growth.



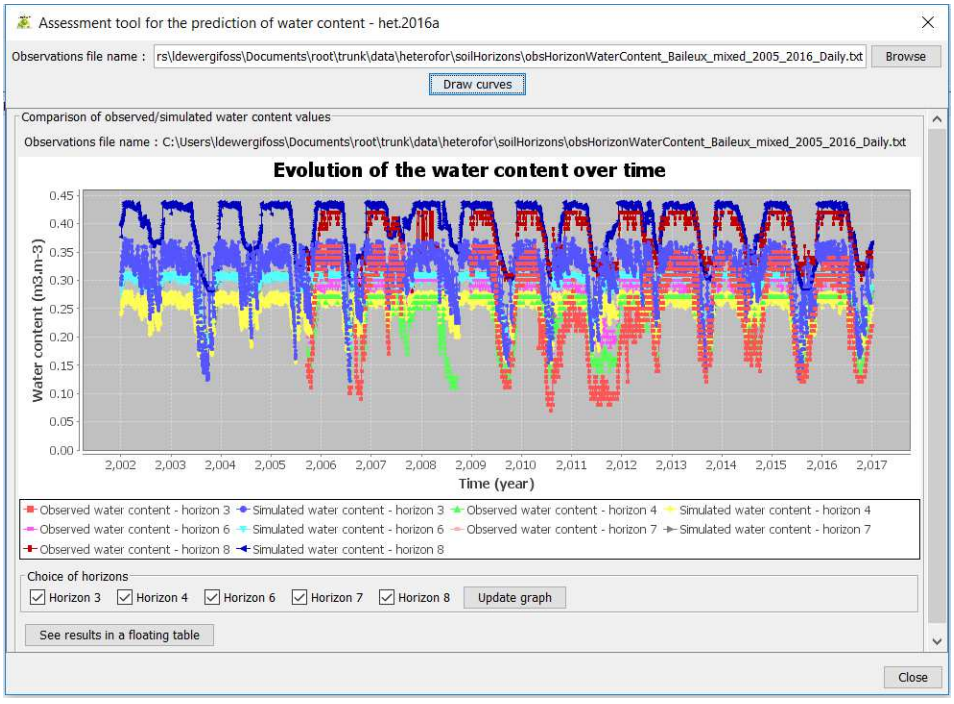
Evaluation based on soil water content data

Both evaluation tools for REW and water content predictions require the same observational file. This file is a table providing the water content (in $m^3.m^{-3}$) per soil horizon for each day or hour. The date is indicated based on three or four fields: Year, Month, Day, Hour.

For the REW evaluation tool, the resulting graph displays the temporal evolution of the predicted and observed REW. The REW is calculated according to de Wergifosse *et al.* (submitted to GMD) by considering only the horizons for which water content data are available. Missing data do not prevent the evaluation tool to run but it will generate discontinuities in the graph.



The second tool displays the temporal variability of predicted and observed water content per soil horizon. The superposition of the different lines can make it difficult to read. It is therefore recommended to select one horizon at a time.



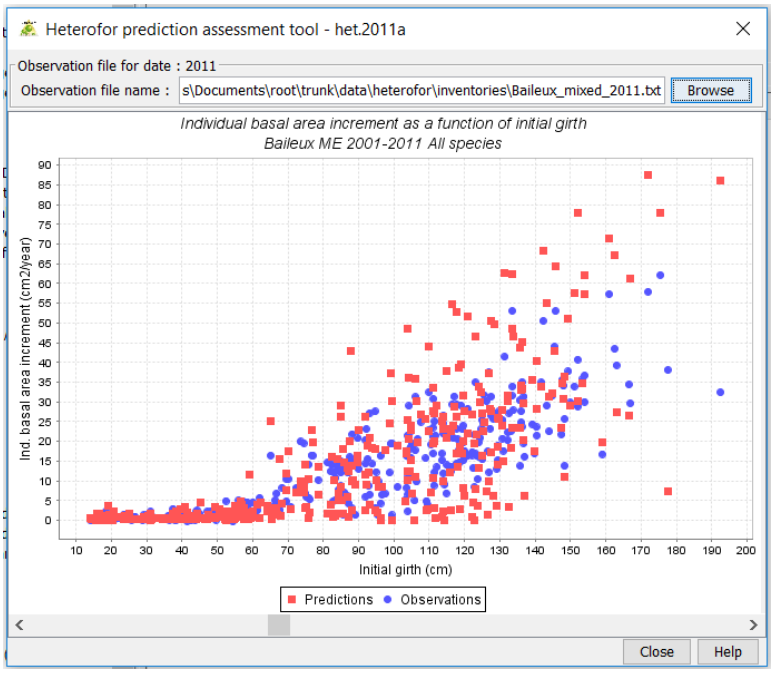
For both evaluation tools, the data can be visualize in a table by clicking on “See results in a floating table”.

Evaluation based on tree growth data

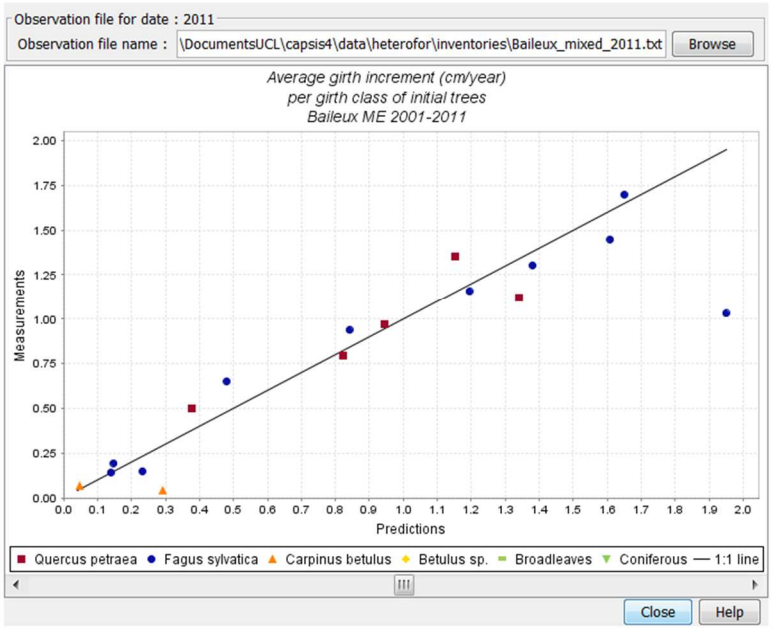
The tool to assess tree growth requires an inventory file similar to the one used for the initialization but for a later date in order to calculate the increments in girth, height and crown dimensions. The user must select the step for which a repeated inventory is available and load the corresponding file.

A large amount of graphs is displayed after a short calculation time. The data corresponding to these graphs can be obtained by right-clicking on them and select “extract in a table”.

Three types of evaluation graphs are proposed. First, bar charts compare mean predictions and observations for the various tree species (see previous figure). Such graphs are available for the girth increment ($cm.yr^{-1}$), basal area increment ($cm^2.yr^{-1}$), height increment ($m.yr^{-1}$), crown base height increment ($m.yr^{-1}$), largest crown extension increment ($m.yr^{-1}$) and the quadratic crown radius increment. Second, scatter plots compare predicted *vs* observed size-growth relationships. Two types of relationships are available: the height increment ($m.yr^{-1}$) as a function of initial height (m) and the basal area increment ($cm^2.yr^{-1}$) as a function of initial girth (cm).

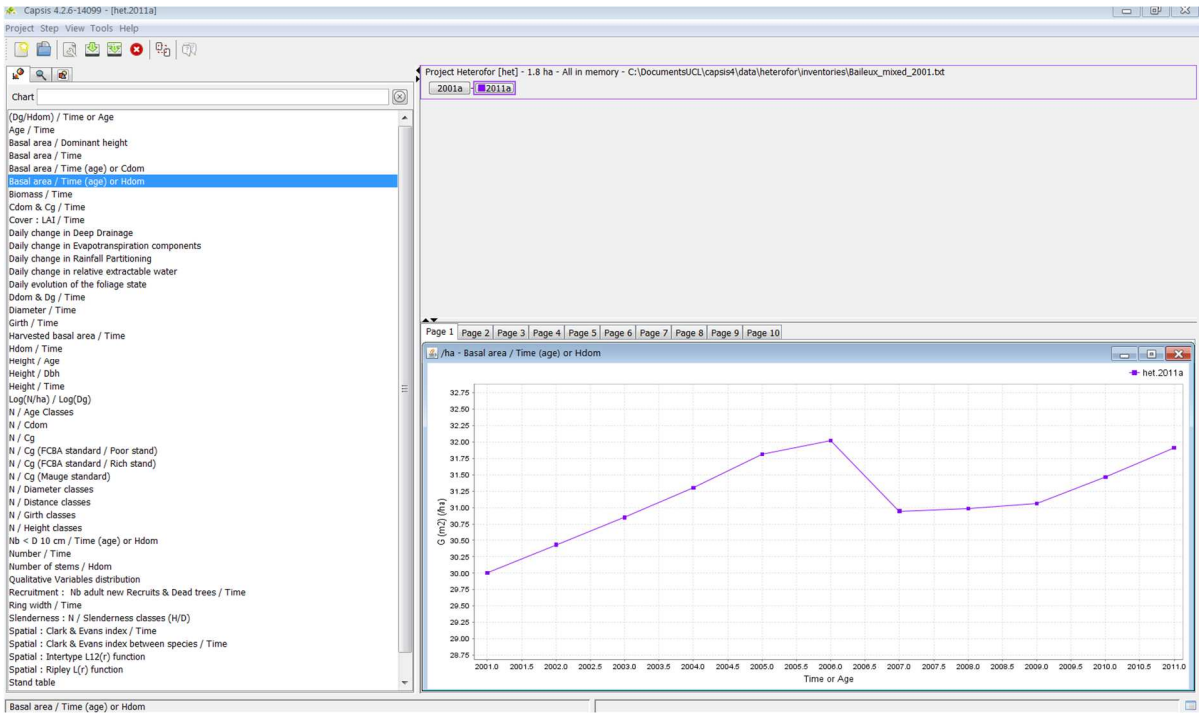


Third, scatter plots comparing observations with predictions enable to assess the quality of the predictions (with reference to the 1:1 line) and detect some eventual biases. For some graphs, trees are grouped per girth class while, for others, the observations and predictions correspond to individual trees. Such graphs are available for the girth increment ($cm.yr^{-1}$), the basal area increment ($cm^2.yr^{-1}$), the height increment ($m.yr^{-1}$), the crown base height increment ($m.yr^{-1}$), the largest crown extension increment ($m.yr^{-1}$) and the crown radius increments in the four cardinal directions (with and without log transformation).



8. Model outputs (graphs and tables)

The user has at his disposal a whole series of graphs created for all individual-based models in CAPSIS. These graphs are listed on the left panel when the “Chart” tab is selected. For creating a graph for a given simulation, select the corresponding project in the upper right panel and double-click on the graph name in the list. It will then appear in the lower right panel. For example, a graph shows the temporal trend in basal area or its evolution with dominant height. This graph can be modify by right-clicking on it and selecting “Configure”. For the basal area graphs, one can choose the unit for the basal area (in m^2 or in $m^2.ha^{-1}$) or the variable of the X axis (Time or Dominant height).

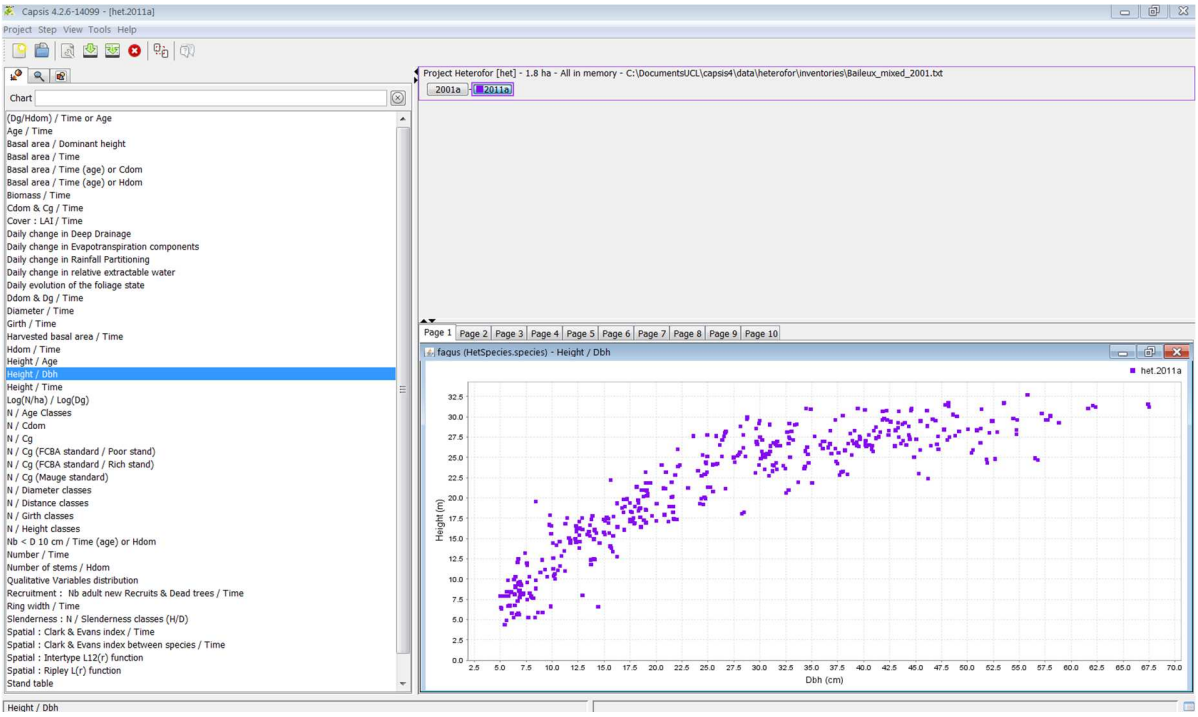


Graphs displaying temporal trends can also be obtained for other variables: geometric mean or dominant girth/dbh, girth/dbh of selected trees (right-click on the graph and choose “Configure” to select the trees of interest), LAI and dominant height. Some graphs are present in the list but do not appear correctly when selected. This happens for the graphs showing an evolution with tree age because tree age is not considered in HETEROFOR. Other graphs are showing relationships between tree dimensions (e.g., height *vs* dbh) or between stand variables (e.g., log N vs log mean dbh). One can also create tables with stand characteristics or histograms showing the distribution of trees per size class.

Besides these default graphs available for all individual-based models of CAPSIS, some charts are specific to HETEROFOR. Among them, a graph shows the daily evolution in the foliage state for each tree species. The state of the foliage is characterized by two variables:

- ladProp: the proportion [0-1] of leaf with reference to the maximum leaf amount when the full leaf development is reached,
- greenProp: the proportion of green leaves with reference to maximum leaf amount.

One can zoom on the graph with the left-click. The data used to create the graph can be obtained by right-clicking on the graph and selecting “open in a floating table”.


Capsis 4.2.6-14099 - [het.2011a]
Project Step View Tools Help
Project Heterofor [het] - 1.8 ha - All in memory - C:\DocumentsUCL\capsis4\data\heterofor\inventories\Baileux_mixed_2001.txt
2001a
2011a
Chart
(Dg/Hdom) / Time or Age
Age / Time
Basal area / Dominant height
Basal area / Time
Basal area / Time (age) or Cdom
Basal area / Time (age) or Hdom
Biomass / Time
Cdom & Cg / Time
Cover : LAI / Time
Daily change in Deep Drainage
Daily change in Evapotranspiration components
Daily change in Rainfall Partitioning
Daily change in relative extractable water
Daily evolution of the foliage state
Ddom & Dg / Time
Diameter / Time
Girth / Time
Harvested basal area / Time
Hdom / Time
Height / Age
Height / Dbh
Height / Time
Log(N/ha) / Log(Dg)
N / Age Classes
N / Cdom
N / Cg
N / Cg (FCBA standard / Poor stand)
N / Cg (FCBA standard / Rich stand)
N / Cg (Mauge standard)
N / Diameter classes
N / Distance classes
N / Girth classes
N / Height classes
Nb < D 10 cm / Time (age) or Hdom
Number / Time
Number of stems / Hdom
Qualitative Variables distribution
Recruitment : Nb adult new Recruits & Dead trees / Time
Ring width / Time
Slenderness : N / Slenderness classes (H/D)
Spatial : Clark & Evans index / Time
Spatial : Clark & Evans index between species / Time
Spatial : Intertype L12(r) function
Spatial : Ripley L(r) function
Stand table
Page 1
Page 2
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Page 4
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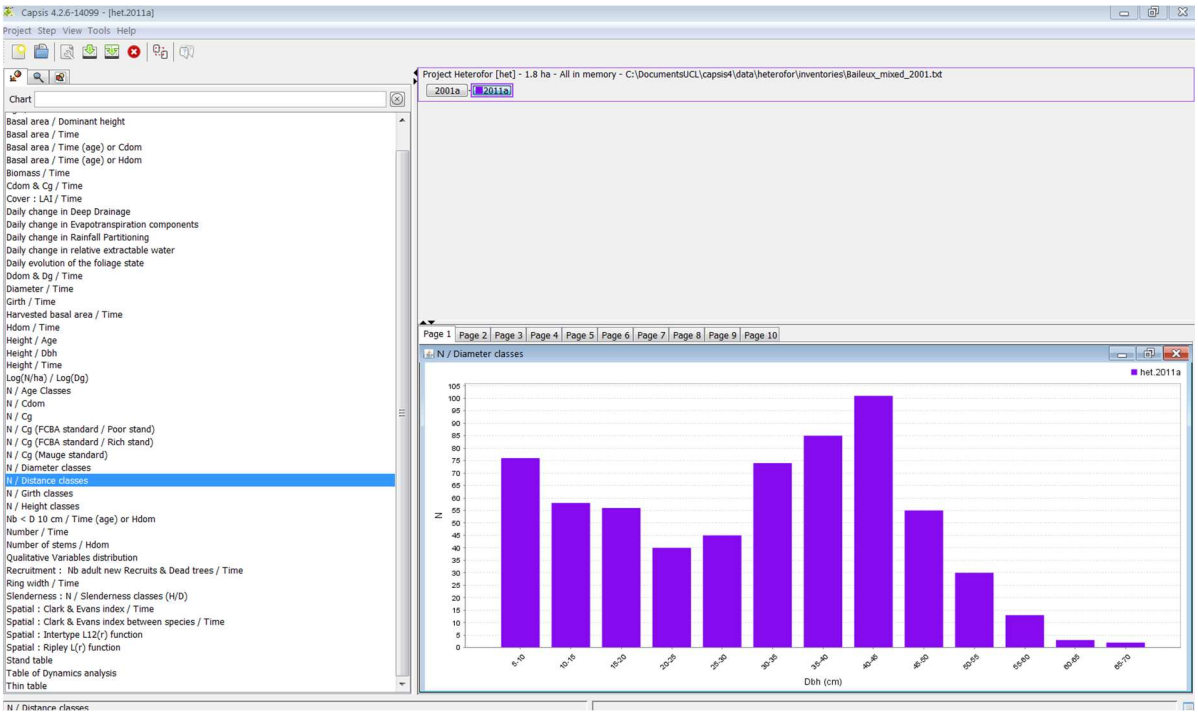
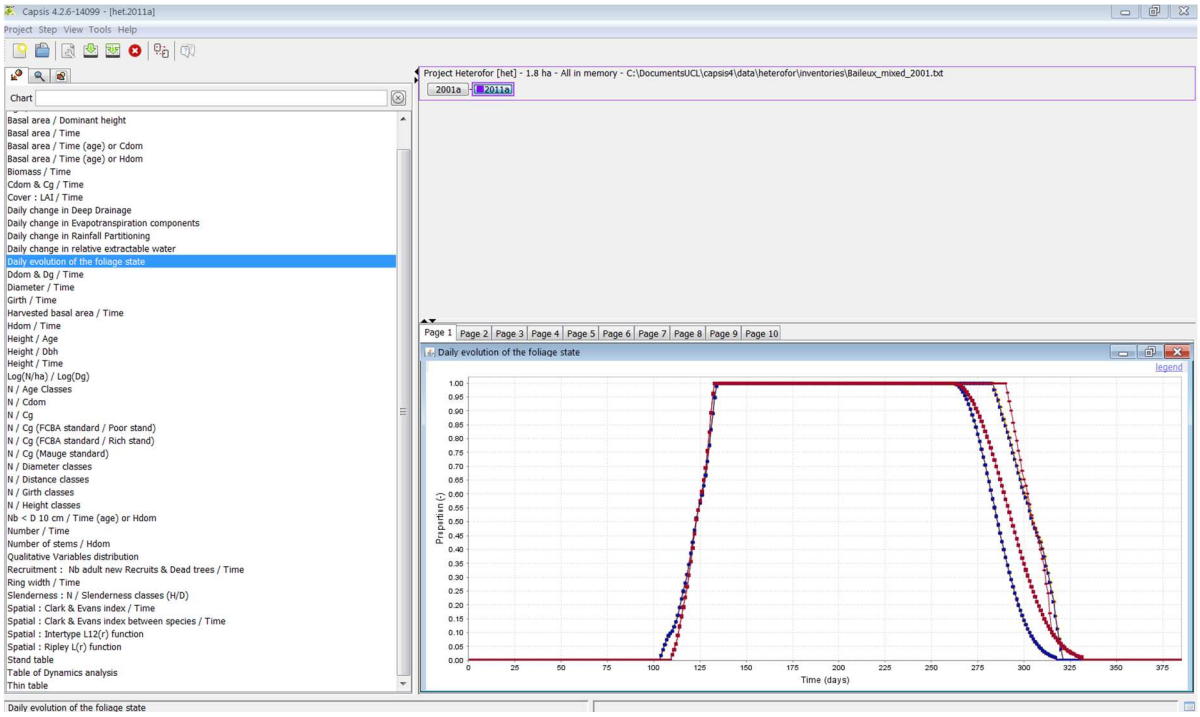
Page 7
Page 8
Page 9
Page 10
fagus (HetSpecies.species) - Height / Dbh
het.2011a
Height (m)
Dbh (cm)
Height / Dbh


Capsis 4.2.6-14099 - [het.2011a]
Project Step View Tools Help
Project Heterofor [het] - 1.8 ha - All in memory - C:\DocumentsUCL\capsis4\data\heterofor\inventories\Baileux_mixed_2001.txt
2001a
2011a
Chart
Basal area / Dominant height
Basal area / Time
Basal area / Time (age) or Cdom
Basal area / Time (age) or Hdom
Biomass / Time
Cdom & Cg / Time
Cover : LAI / Time
Daily change in Deep Drainage
Daily change in Evapotranspiration components
Daily change in Rainfall Partitioning
Daily change in relative extractable water
Daily evolution of the foliage state
Ddom & Dg / Time
Diameter / Time
Girth / Time
Harvested basal area / Time
Hdom / Time
Height / Age
Height / Dbh
Height / Time
Log(N/ha) / Log(Dg)
N / Age Classes
N / Cdom
N / Cg
N / Cg (FCBA standard / Poor stand)
N / Cg (FCBA standard / Rich stand)
N / Cg (Mauge standard)
N / Diameter classes
N / Distance classes
N / Girth classes
N / Height classes
Nb < D 10 cm / Time (age) or Hdom
Number / Time
Number of stems / Hdom
Qualitative Variables distribution
Recruitment : Nb adult new Recruits & Dead trees / Time
Ring width / Time
Slenderness : N / Slenderness classes (H/D)
Spatial : Clark & Evans index / Time
Spatial : Clark & Evans index between species / Time
Spatial : Intertype L12(r) function
Spatial : Ripley L(r) function
Stand table
Table of Dynamics analysis
Thin table
Page 1
Page 2
Page 3
Page 4
Page 5
Page 6
Page 7
Page 8
Page 9
Page 10
N / Diameter classes
het.2011a
N
Dbh (cm)
N / Distance classes


Capsis 4.2.6-14099 - [het.2011a]
Project Step View Tools Help
Chart
Basal area / Dominant height
Basal area / Time
Basal area / Time (age) or Cdom
Basal area / Time (age) or Hdom
Biomass / Time
Cdom & Cg / Time
Cover : LAI / Time
Daily change in Deep Drainage
Daily change in Evapotranspiration components
Daily change in Rainfall Partitioning
Daily change in relative extractable water
Daily evolution of the foliage state
Ddom & Dg / Time
Diameter / Time
Girth / Time
Harvested basal area / Time
Hdom / Time
Height / Age
Height / Dbh
Height / Time
Log(N/ha) / Log(Dg)
N / Age Classes
N / Cdom
N / Cg
N / Cg (FCBA standard / Poor stand)
N / Cg (FCBA standard / Rich stand)
N / Cg (Mauge standard)
N / Diameter classes
N / Distance classes
N / Girth classes
N / Height classes
Nb < D 10 cm / Time (age) or Hdom
Number / Time
Number of stems / Hdom
Qualitative Variables distribution
Recruitment : Nb adult new Recruits & Dead trees / Time
Ring width / Time
Slenderness : N / Slenderness classes (H/D)
Spatial : Clark & Evans index / Time
Spatial : Clark & Evans index between species / Time
Spatial : Intertype L12(r) function
Spatial : Ripley L(r) function
Stand table
Table of Dynamics analysis
Thin table
Project Heterofor [het] - 1.8 ha - All in memory - C:\DocumentsUCL\capsis4\data\heterofor\inventories\Baileux_mixed_2001.txt
2001a
2011a
Page 1
Page 2
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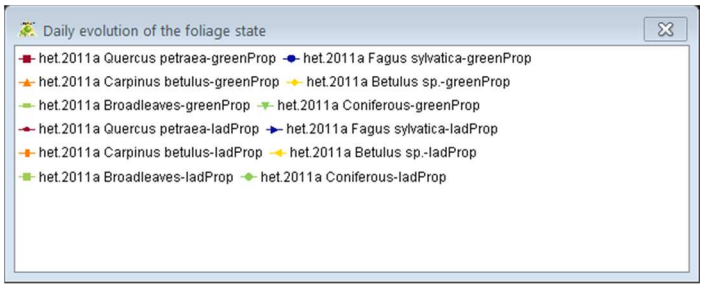
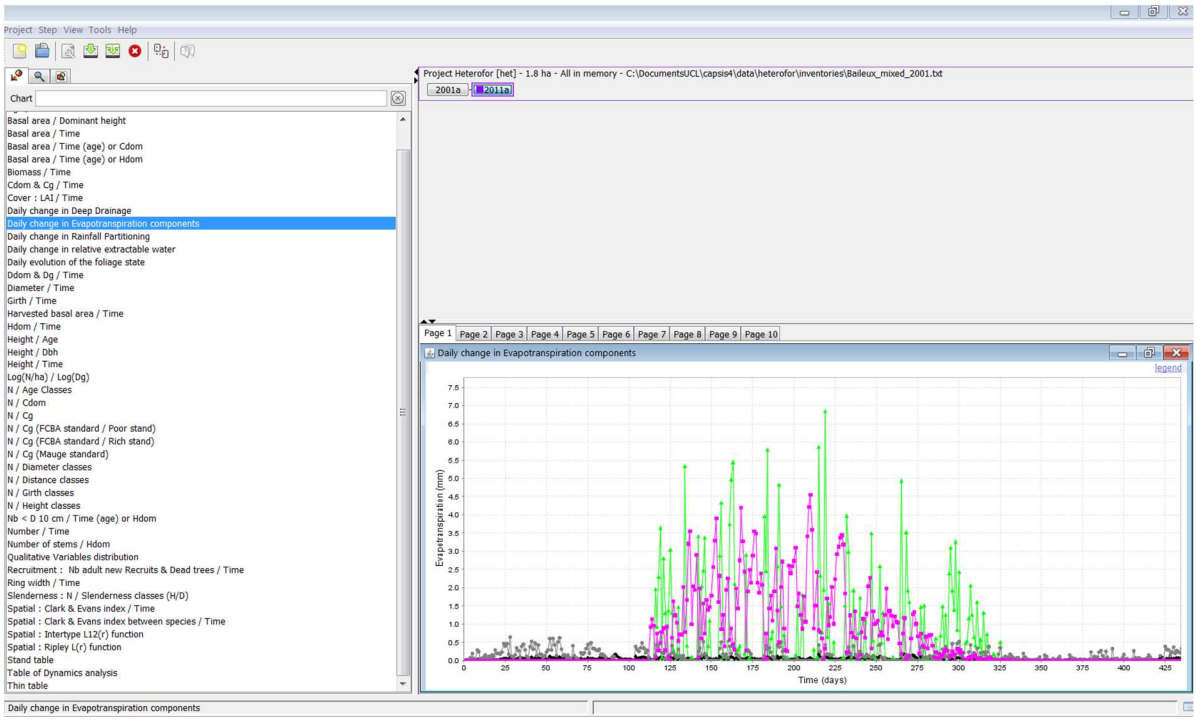
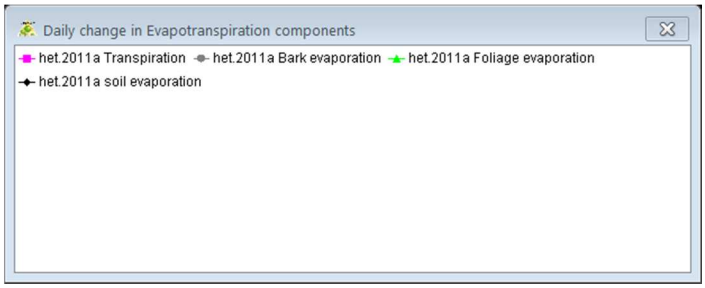
Page 10
Daily evolution of the foliage state
legend
Prpartun (-)
Time (days)
Daily evolution of the foliage state

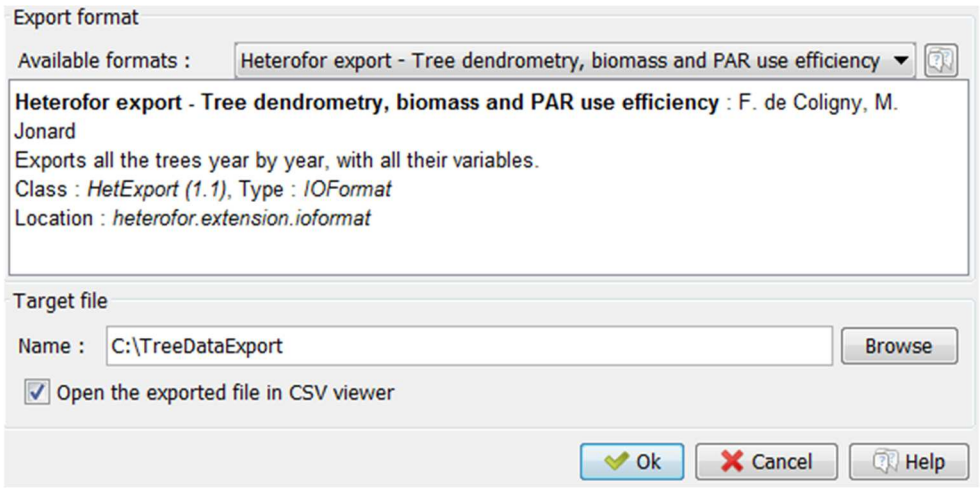

Daily evolution of the foliage state
het.2011a Quercus petraea-greenProp
het.2011a Fagus sylvatica-greenProp
het.2011a Carpinus betulus-greenProp
het.2011a Betulus sp.-greenProp
het.2011a Broadleaves-greenProp
het.2011a Coniferous-greenProp
het.2011a Quercus petraea-ladProp
het.2011a Fagus sylvatica-ladProp
het.2011a Carpinus betulus-ladProp
het.2011a Betulus sp.-ladProp
het.2011a Broadleaves-ladProp
het.2011a Coniferous-ladProp

Similar graphs show the daily change in rainfall partitioning, evapotranspiration components, deep drainage and relative extractable water.





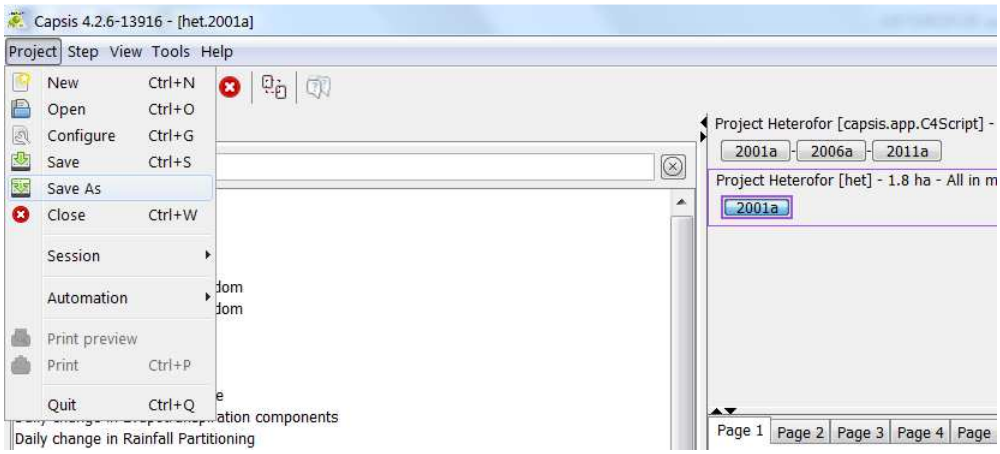
In addition to these graphs, the state variables of HETEOFOR can be visualized in table and exported in txt files. To generate an export, right-click on the final step of a project and select “Export”. You will have access to a list of exports through the window here below and have to specify where the txt file must be stored.



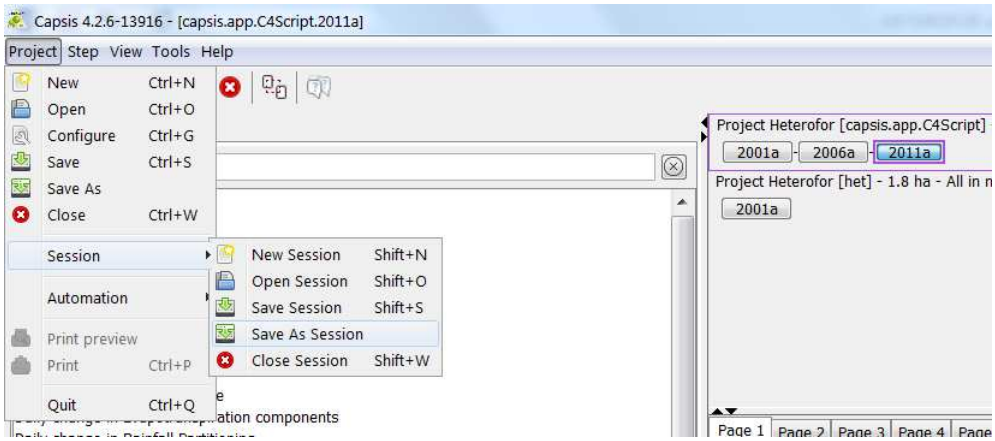
Many variables can be exported and concerns the foliage state (see above), the phenological dates corresponding to the main phenological events, the tree characteristics, the hourly soil temperature, the water fluxes and contents at yearly, monthly, daily or hourly time step, the nutrient fluxes and stocks (in the tree an in the soil) and the soil chemistry.

9. Saving the project or the session

The project can be save by selecting it and then choose “save” or “save as” in drop-down menu under “Project”.



Similarly, the session containing all the projects can be saved.



10. Script mode

CAPSIS is generally used in interactive mode which allows the users to work in a graphical environment with menus and dialogs as described above. Alternatively, the script mode can also be very useful to execute long and repetitive simulations. The results of these simulations are saved in files that can be analysed later in Capsis or with other analysis or statistical tools. The script mode is also very interesting to call CAPSIS from another software (such as R) in order to, for example, perform a calibration of the model parameters. All the information needed to create a script is available at http://capsis.cirad.fr/capsis/documentation/script_mode

11. References

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Dufour-Kowalski, S., Courbaud, B., Dreyfus, P., Meredieu, C., de Coligny, F. 2012. Capsis: an open software framework and community for forest growth modelling. *Annals of Forest Science*, 69, 221–233.

Dufrêne, E., Davi, H., François, C., Le Maire, G., Le Dantec, V., Granier, A. 2005. Modelling carbon and water cycles in a beech forest: Part I: Model description and uncertainty analysis on modelled NEE. *Ecological Modelling*, 185, 407-436.

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Ligot, G., Balandier, P., Courbaud, B., Jonard, M., Kneeshaw, D. 2014. Managing understory light to maintain a mixture of species with different shade tolerance. *Forest Ecology and Management*, 327, 189-200.