Handbook DSS
"CAFE"

The project LIFE RESILIENT FORESTS – Coupling water, fire and climate resilience with biomass production from forestry to adapt watersheds to climate change is co-funded by the LIFE Programme of the European Union under contract number LIFE 17 CCA/ES/000063.

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1. Overview of CAFE

C.A.F.E. (Carbon, Aqua, Fire & Eco-resilience) is a Multi-Objective Decision Support System (MODSS) for forest management stems from the European LIFE project program, entitled "Life Resilient Forest" (https://www.resilientforest.eu/), which to promote a forest management approach at the watershed scale that improves forests resilience to wildfires, water scarcity, environmental degradation and other effects induced by climate change.

This tool determines the optimum silvicultural activities to manage multiple products, goods and services such as biomass production, carbon sequestration, fire risk, water provisioning, climatic resilience or biodiversity, which are simultaneously quantified in time and space for a selected solution. To that end, C.A.F.E. combines eco-hydrological simulation and multi-objectives optimization with evolutionary algorithms. Finishing the execution with an iterative visualization of the results that allows the user to understand and select the most appropriate option. Therefore, the three blocks on which this DSS is structured are: Simulation, optimization and visualization (Fig. 1). The combination and communication of these blocks make it a multipurpose and useful tool for decision making by forest managers.

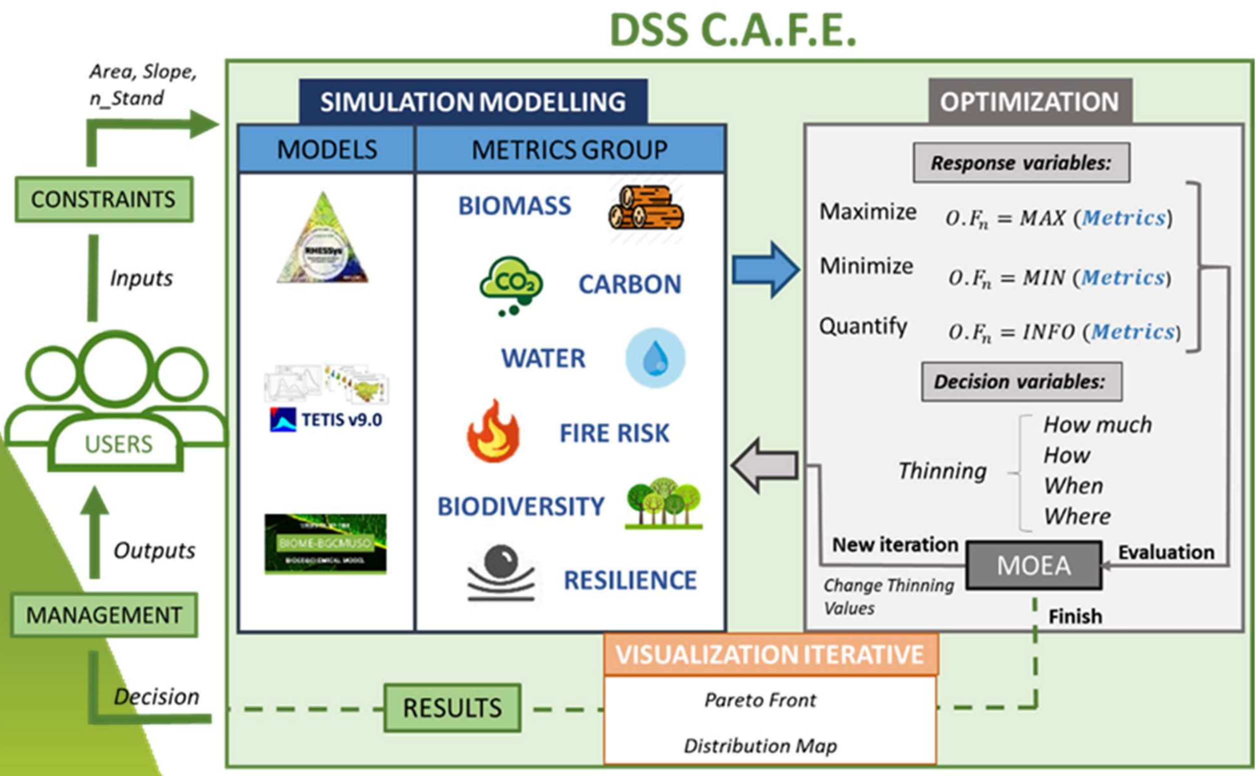

Figure 1. Decision Support System Schematic, C.A.F.E.

Section 1: Simulation

Process-based models (PBM), also known as mechanical or ecosystem models, are the mathematical representation of the functioning of a well-defined biological system (Tanevski et al., 2017). Los PBM pueden ser espacialmente distribuidos o no distribuidos. Los distribuidos son capaces de diferenciar los procesos que ocurren en un área determinada por las características del terreno o de la vegetación, y pueden trabajar a nivel de colina (o píxel) o de cuenca. Por el contrario, los modelos no distribuidos hacen una representación puntual y promediada de las características del terreno y trabajan a nivel de parcela o región de características homogéneas (Fig. 2).
Within this module, the tool has 4 simulation PBM. Being 2 distributed models (Rhessys and Tetis-Veg) and 2 non-distributed (Biome-Bgc and CLM). Both types have been implemented to meet the different needs of managers. They can simulate a whole forest or just a single stand. Distributed models can be interesting when the simulation domain is heterogeneous or the user just wants to spatially differentiate the domain. ON the contrary, if the user works with contemporary stand (productive or not), the non-distributed models can be used. In addition, distributed models are also capable of working like non-distributed models and are therefore applicable to all cases.

-RHESSys is an ecohydrological model designed to simulate the integrated cycling and transport of water, carbon and nitrogen in a spatially variable terrain. The model is structured as a hierarchical and spatially nested representation of the landscape, with a series of hydrological, microclimatic and ecosystem processes associated with specific landscape objects at different levels of the hierarchy. This approach is designed to facilitate environmental analysis that requires an understanding of the processes within the catchment, as well as the aggregate fluxes of water, carbon and nitrogen. RHESSys has been applied in a variety of ecosystem types, including deciduous coniferous forest and grassland regions, alpine and Mediterranean-type ecosystems, and urban areas (Tague y Band, 2004).

-Tetis is a spatially distributed hydrological simulation model by subdividing the catchment into regular cells with physically based parameters (Francés et al., 2007). Tetis allows the coupling of several sub-modules and for this work the vegetation sub-module has been activated (Pasquato et al., 2015; Ruiz-Pérez et al., 2017). The model adequately incorporates the spatial variability of the hydrological cycles and part of the vegetation growth. Its conceptual basis is based on the principle of parsimony, i.e. the model with the smallest number of parameters is selected to obtain similar performance.

-Biome-BGC_MuSo is an ecosystem process model that estimates the storage and flow of energy, carbon, nitrogen and water for vegetation and soil components of terrestrial ecosystems. We call it a process model because its algorithms represent the physical and biological processes that control energy and mass fluxes (Hydi, et al, 2016).

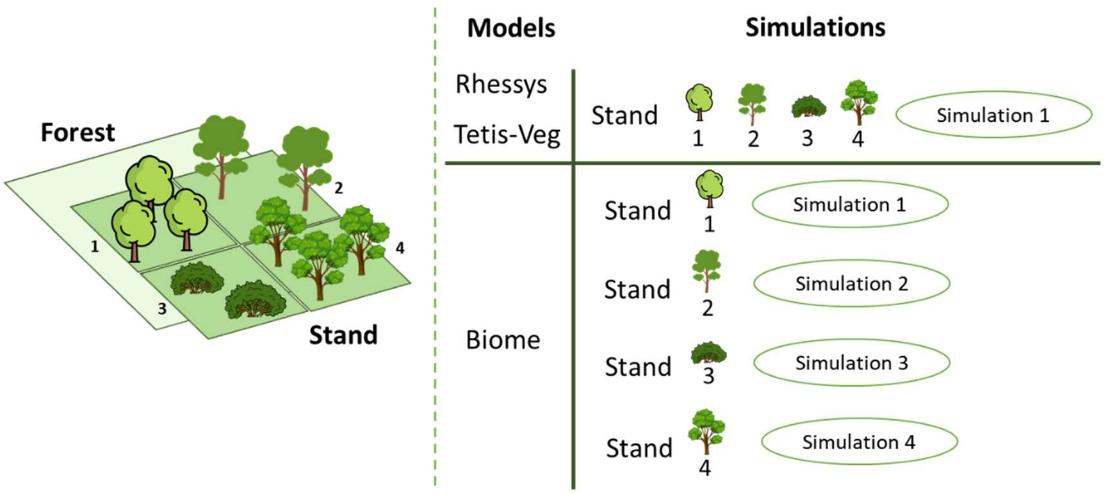

Figure 2. Difference between distributed and non-distributed simulation models.

The metrics that CAFE provides to users (Table 1) can be grouped into the following categories: biomass removed, carbon sequestered, increase in water stored, fire risk reduction, structural biodiversity and forest resilience. To derive these variables, it is necessary to assess the water and carbon cycling provided by the models. As the DSS is not closed, new metrics are being included and the behaviour of the simulated values is being evaluated with field data.

Table 1. Calculated metrics to quantify and optimise.

Metrics	Description	Unit	Model
Biomass extraction	This is the sum of all the stands to which the carbon difference between the day before thinning and the day after thinning is applied, repeated as many times as interventions are carried out during the simulation.	Kg/m^2	All
Carbon Sequestration	Soil and in-flight carbon stocks that are averaged over the simulation period.	Kg/m^2	Rhessys Biome
Soil respiration	Calculated from the CO2 emitted by the soil, which is averaged over the simulation period.	Kg/m^2	Rhessys Biome
Percolation	It is obtained by adding the annual totals for the simulation period and dividing by the simulation years.	mm	All
Baseflow	Calculated from the sum total of surface runoff and percolation over the entire simulation period.	mm	All
Streamflow	Total sum of the flow through the streams during the whole simulation period.	Hm^3	All
KBDI	This is the average value of the KBDI (fire risk index) for the simulation period.	adimensional	Rhessys
Structural Biodiversity	It is the sum of different structural values of the stand such as density, number of strata, diameters, dead wood on the ground and in flight in the stand.	adimensional	Rhessys
Resilience	This is the mean value of the annual average values of the ratio of water used by the plant to wood growth, compared to the baseline situation.	adimensional	Rhessys Biome

Improve baseline	It is the sum of the categorical value given to each of the metrics that exceed the values with forestry performance compared to the reference situation.	dimensionless	All

Section 2: Optimisation

A multiobjective optimization problem (MOP) involves a number of objective functions that are to be either minimized or maximized, subjected to a number of constraints and variable bounds. The objectives often conflict with each other, where the improvement of one objective may lead to the deterioration of another. Thus, a single solution, which can optimize all objectives simultaneously, does not exist. Instead, the best trade-off solutions, called the Pareto optimal solutions, are important to a decision maker (DM). These solutions are the points lying on the non-domination front, where by definition, do not become dominated by any other point in the objective space; hence they are Pareto-optimal Front (PF). It is characteristic that no unique solution exists but a set of mathematically equally good solutions can be identified. Due to their population-based nature, Multi-Objectives evolutionary algorithms (MOEAs) are able to approximate the whole PF of an MOP in a single run and is one of the most widely used heuristic optimization methods in research over the last 20 years (Deb, 2015; Zhou et al., 2011).
To create the optimization module with MOEA in CAFE, the open source python library Rhodium has been used, which allows for robust decision making (RDM), many-objective robust decision making (MORDM), and exploratory modelling. These decision-support frameworks enable the identification of robust strategies for the management of complex environmental systems, by evaluating the trade-offs among candidate strategies, and characterizing their vulnerabilities (Hadjimichael et al., 2020).

MOEAs attempt to optimise or quantify the mathematically formulated variables (metrics) in CAFE. These metrics are considered as the objective functions (OF), which are obtained from the operations with the outputs of the simulation models. The MOEAs have to be told whether each of the OFs should be maximised, minimised or just quantified. Another important section of these algorithms are the decision variables, which are the variables on which the optimisation has to provide their appropriate values to optimise the OFs. In CAFE there are up to 4 decision variables on the thinning to be applied (Where?, When?, How? or How much?) and one on the initial planting density (How much?), which refer to the type of forest management to be applied. All or only some of these can be used. Finally, there are the constraints, which are the limits that the optimisation has on the decision variables or the OFs. In this case, the tool has so far implemented the slope restriction (limiting the intensity of clear-cutting on steep slopes), number of stands or maximum area on which to act.

Section 3: Interactive visualization

The last module implemented in CAFE is the interactive visualisation part. It is divided into three parts, console, interactive graphics and clear distribution maps. The first one is where the values of each iteration are displayed (Metrics-Actuations), and where the optimisation proposes the values of the decision variables ("Where?, When?, How much?, How?"), the proposed changes are applied on the vegetation, and the simulation is launched. Once each simulation is finished, the metrics to be quantified or optimised are calculated, according to the user's selection (each one can be selected as Maximise, Minimise or Info). The value obtained in each of the metrics (FO) is evaluated by the algorithm, it decides whether to store the solution or discard it, and moves on to the next iteration

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making changes in the decision variables to repeat the process until the MOEA finds the FP. When this happens, it moves on to the second part, which is the interactive graphics where the user can visualise the results obtained and filter the solutions by the criteria he/she considers. Here you can see the table with the values of the metrics, the Pareto frontier and the 3D cube. Once the user has selected the preferred solution, the third part opens and gives way to the visualisation of the clear distribution map, provided that the case study uses the distributed simulation models (Fig. 3). In addition, it incorporates access to the J3 application of the Rhodium project that has an interactive visualisation of the data once finished and saves your results on your local disk.

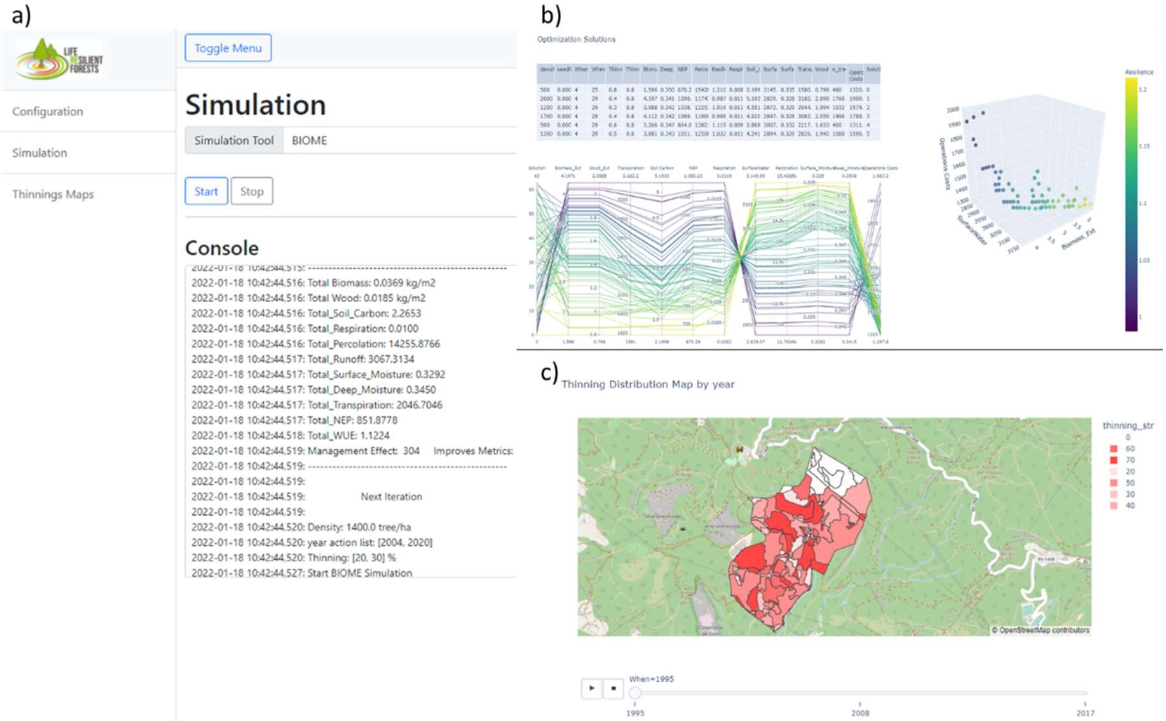

Figure 3. Interactive visualisation of CAFE. a) Console showing iterations, b) Pareto front of the solutions

2. Aim

The DSS CAFE is a free-to-use scientific-technical tool that aims to promote sustainable forest management through multi-objective forest management. It helps managers to quantify and optimise their goods and services derived from forest management.

The Life ResilientForests project assumes no responsibility for its use by third parties, and makes no warranty, express or implied, as to its quality, reliability or any other characteristic of the results generated by the use of this tool. In order to obtain results, the user must have some prior knowledge of the calibration of the models used in the study area, without which the results provided by the DSS have no contrasted value.

3. Scope

This document is intended as a user manual for the CAFE tool. The challenge is to create a guide that allows the installation and use of the DSS by any user. The Life ResilientForests project aims to promote the use of this tool to enable sustainable management of the multiple goods and services of the ecosystem. It is considered completed when the user is able to use their own case studies with the tool.

4. Technical requirements: Hardware and software

The requirements for this tool to be installed and used are the same requirements that are associated with the installation of Docker, which depend on the operating system used and can be specified in the following link (https://docs.docker.com/get-started/). These software limitations correspond to the older versions of each system that are capable of running this program. However, there is also a common limitation for all operating systems concerning the minimum hardware with which Docker is able to run in order to create virtual machines, this limitation corresponds to the minimum RAM of 4GB.

5. Installation

To complete the installation of the CAFE tool, the user must complete the following steps:

1. The user must download the version on the project website (https://www.resilientforest.eu/resources/) and save it on your local disk, in a folder with the name of your choice (Example: C:/DSS_CAFE). A compressed folder "dss_cafe.tar.gz" will be stored in this folder.
2. To complete the CAFE installation, the Docker software must be downloaded and installed (https://www.docker.com/products/docker-desktop/) depending on the computer being used (Mac, Windows or Linux). This tool is capable of executing all the requirements and components that make up CAFE, so that the user does not have to install innumerable parts, thus avoiding version failure in any of them.
3. Once you have Docker and the CAFE version, run the following command in the folder where the DSS is installed in the command console (cmd):

   docker load < dss_app.tar.gz

6. Start DSS

Once CAFE is installed, every time you want to use and run it, you must complete a sequence of steps in cmd:

1. *docker run -e DISPLAY=$DISPLAY -v /tmp/.X11-unix:/tmp/.X11-unix:rw -v %cd%(pwd)/app-data:/app-data -p 5000:5000 --rm -it dss_app /bin/bash*
2. *python app.py*

("Windows" %cd%)("IOs" $)

Finally, to view the graphical interface of the DSS, you have to go to your web browser and type the following address into the url:

Localhost:5000

7. Pre-configuration

Before running a case study in CAFE, you must enter all the inputs of the model you intend to use already calibrated.

7.1 Model input creation and calibration

The most difficult part of using this tool is knowing how to prepare the inputs that all models need to be executed. This is why, prior to using the tool, it is strongly recommended that users complete their training with the models' own manual.

BIOME-BGC_MuSo

This model can be used to simulate one species or the aggregated behaviour of several species within the same area. We recommend the use of this model when you have homogeneous forest stands and/or forest plantations. Here we provide the main guidelines for performing a simulation with the model, but we strongly recommend the user to review the user manual available on the BIOME-BGC_MuSo website and also provided with the CAFE user manual.

The use of the model follows three basic steps: i) construction of the input data; ii) calibration and validation of the model parameters; iii) simulation.

The input data needed for the model are:

- Meteorology (Meteorology.txt): time series of daily values of: Precipitation (cm), Temperature (ºC) (mean, maximum and minimum), Solar radiation (W/m2day), Vapour pressure deficit (Pa) and daylight hours (seconds). The time series must be complete, as no gaps or incomplete years are allowed.

- Soil physical characteristics (Soil.txt): texture, field capacity, saturation point, wilting point and bulk density of the 10 soil layers.

- Site characteristics (.init): Latitude, elevation, albedo and annual temperature range.

- Annual values of CO2 (CO2.txt) and N deposition (Ndep.txt) (ppm).

- Ecophysiological parameters of the species (.epc). This file includes more than 100 parameters that must be calibrated and validated to ensure that they correctly represent the behaviour of the species.

Once the inputs have been constructed, the parameters have to be calibrated and validated (".epc" file). In this step, the user must know whether the simulated forest system is a plantation, which will be simulated from the moment of planting, or whether it is a natural forest. In the case of a forest plantation, the user must provide the C content per plant, and with the tree density of the plantation transform this KgC/tree into KgC/m^2. This quantity will be divided by 6 and the result will be included in the CN_STATE section of the ".ini" file (see figure 4). Subsequently, the user will calibrate the desired ecophysiological parameters by comparing the simulated data with the observed data.

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```
CN_STATE
0.00026                                             (kgC/m2)  first-year maximum leaf carbon
0.00026                                         (kgC/m2)  first-year maximum fine root carbon
0.00026                                            (kgC/m2)  first-year maximum fruit carbon
0.00026                                        (kgC/m2)  first-year maximum softstem carbon
0.00026                                    (kgC/m2)  first-year maximum live woody stem carbon
0.00026                                   (kgC/m2)  first-year maximum live coarse root carbon
```

Figure 4. C pools of the ".ini" file to be modified when simulating a forest plantation.

When working with a natural forest, the user must first run a "spin up" simulation (in other words, auto-initialisation, or equilibrium run), which starts with a very low initial level of soil carbon and nitrogen, and runs until a steady state is reached with the climate in order to estimate the initial values of the state variables (mostly soil carbon and nitrogen stocks, including recalcitrant soil organic matter, the latter being the main source of nitrogen mineralisation in the model). To run a spin up simulation, a flag in the TIME_DEFINE section of the ".ini" file must be set (see Figure 5). Model calibration is usually performed during the normal simulation, where the user must compare the simulated and observed data and modify the parameters accordingly.

```
TIME_DEFINE
36                                                    (int) number of simulation years
2004                                                      (int) first simulation year
0                                                 (flag) 1 = spinup run; 0 = normal run
6000                                               (int) maximum number of spinup years
```

Figure 5. TIME_DEFINE section of the ".ini" file that allows the user to set the number of simulation years, the first simulation year and to switch between normal and spin up simulation.

The comparison of simulated and observed data can be daily, monthly and/or yearly. The user must specify the outputs to be printed by the model and at which time step (see figure 6). This is specified in the ".ini" file, and the number of output variables (first line) at each desired time resolution must be equal to the number of variables selected, otherwise the model will not work. Furthermore, to ensure the connection between CAFE and BIOME, the name of the variables must be the one specified in the model. The variables, their codes and names can be found in the file "output_map_init.C" located in the "src" folder of the model.

```
DAILY_OUTPUT
14      number of daily output variables
3002    outflow
2604    vwc03-10cm
2605    vwc10-30cm
2606    vwc30-60cm
307     leafc
319     livestemc
159     soilw_evap
101     percolation
171     evapotransp
3009    daily_gpp
325     livecrootc
2520    proj_lai
170     transp_SUM
94      preciptiation

ANNUAL_OUTPUT
32      number of annual output variables
3000    annprcp
3001    anntavg
101     anndeeppercolation
3002    annrunoff
3003    leaching_root_zone
3050    annET
2734    annmax_lai
3031    cum_Closs_MGM
3032    cum_Cplus_MGM
3045    cum_Closs_SNSC
3046    cum_Cplus_STDB
3058    vegc
3064    totalc
3066    SOM_C_top30
3070    SOM_C_30to60
3071    SOM_C_60to90
3068    NH4_top30
3069    NO3_top30
3061    Total_Soil_C
3100    Net_greenhouse_gas_balance
3062    Soil_N_Total
3033    cum_Closs_THN_woody
3008    NBP
3023    NEP
3163    LaboveCnsc_nw
3164    LaboveCnsc_w
3159    LDaboveCnsc_nw
3160    LDaboveCnsc_w
3060    litrC
3167    DaboveCnsc_nw
3168    DaboveCnsc_w
3076    frootc_LandD

END_INIT
```

Figure 6. List of output variables in the ".ini" file that will generate the model. Each variable is named with a numerical code (left) and some text (right).

Normally, the model does not care about the text part, but to make the connection to CAFE possible, the text (or name) describing the variable must be the one written in the file "output_map_init.C" located in the "src" folder of the model.

RHESsys

RHESSys is a semi-distributed model that can be used at plot, catchment or semi-basin scale and with different species and vertical strata. We recommend this model when the user wants to include vegetation and/or topographic heterogeneity of the simulation domain. Currently the model does not have a user manual, but usage information can be found at https://github.com/RHESSys/RHESSys/wiki. Here we provide the main guidelines for preparing the necessary inputs and for running the model, but we strongly recommend visiting the website and reviewing all the information.

For the preparation of the input data, RHESSys needs the following inputs:

1.- Worldfile and Flowtable

3.- Def and Header file

4.- Tec file

5.- Climate data

6.- Parameter definition files

They are all txt files that are built in different ways. The first two (worldfile and flowtable) are built using the RHESSysPreprocessing package (https://github.com/RHESSys/RHESSysPreprocessing), while the rest are simply txt files that can be developed manually.

Worldfile y Flowtable

These two files contain important biophysical information of your modelling site. On the one hand, the Worldfile contains the biophysical characteristics (topography, water, C and N status) of the study

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site, which is divided into Catchment, Slope, Zone, Stand and finally Stratum. On the other hand, the Flow Table describes the flow routing between the above elements.

In order to construct both entries an initial DTM is needed. The DTM will be used to develop the following maps (ascii raster):

1. Slope (%): there are many programs that can be used to develop this map: ArcMap, GRASS, QGIS, SAGA or RStudio (library(tmap)).

2. Aspect (degrees): there are many programs that can be used to develop this map: ArcMap, GRASS, QGIS, SAGA or RStudio (library(tmap)).

3. World map: this will represent the entire domain of the study site, and is a raster with value 1 for the domain, and -9999 for outside the simulation domain.

4. Watershed map: this is a raster that defines the simulation watersheds, each watershed must have a unique ID (number). It can be produced using ArcMap, GRASS, QGIS or SAGA.

5. Stream network map. This can be developed using ArcMap, GRASS, QGIS or SAGA. To do this, the stream accumulation map must first be made. Then, the stream map must have value 1 to represent the streams, and 0 for the rest of the domain.

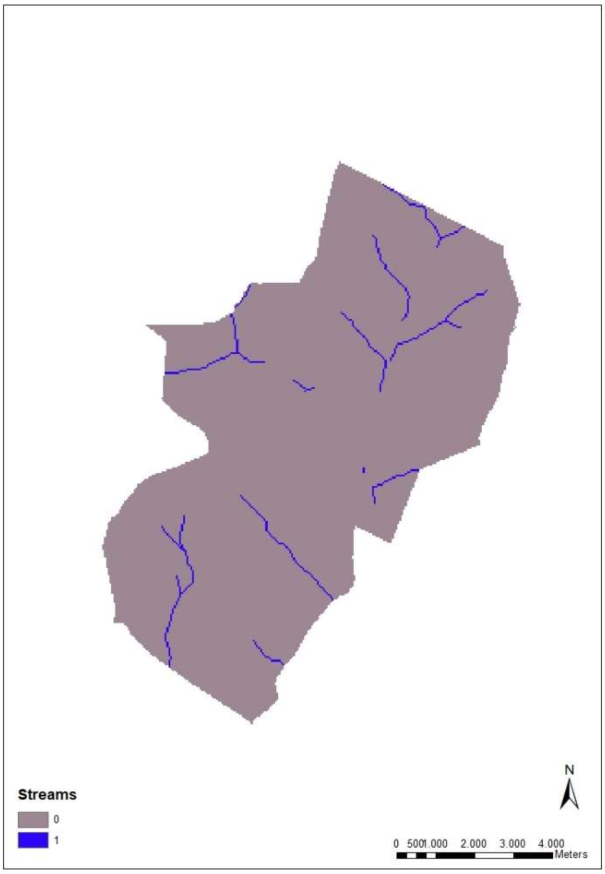

Figure 7. Example of a stream network map

6. Slope map. This is a sub-basin map, and can be developed using ArcMap, GRASS, QGIS or SAGA. It is important that each slope has a unique ID, otherwise the simulation results may be confusing.

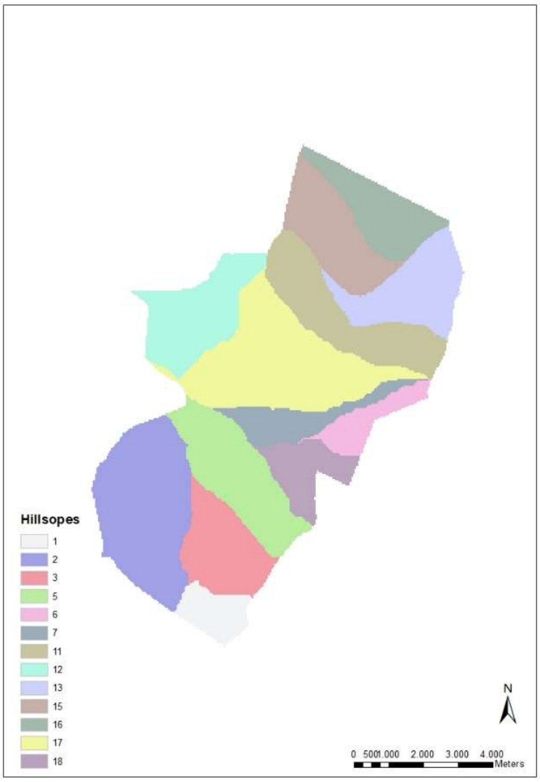

Figure 8. Example of a hillside map.

7. Zone map: defines the different orientations (and thus radiation) and precipitation lapse rates within the simulation domain. The slope map can also be used here as a zone map.

8. Stand map: this map represents the units of forest work to be entered into the DSS tool, and has to be developed by the user. Once made, it has to be combined with the slope map, as when a patch falls on different slopes, RHESSys will divide the patch into as many slopes as it falls on, and will generate this same number of patches, but with the same patch ID. To avoid this confusion, it is important that the initial patch map has a unique ID for each patch. Subsequently, using any raster calculator (ArcMap. QGIS, R, etc.), the user multiplies the slope and patch map, and will obtain a patch map with a unique ID, as the patch falling on different slopes will now be divided by multiplying each part by its corresponding slope.

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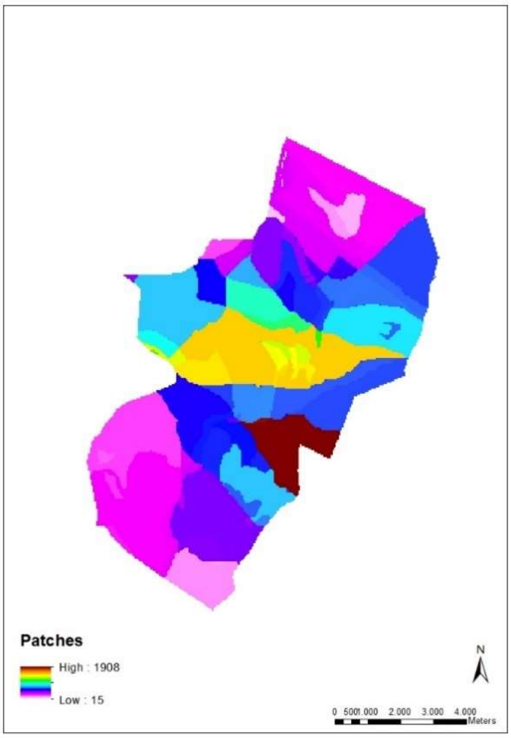

Figure 9. Example of a stand map.

9. East and West horizons: can be developed using the DTM as input in QGIS or GRASS.

10. Number of vertical strata of vegetation that the user wants to simulate.

11. Maps of canopy cover and gap fraction (from 0 to 1) for each stratum. Both values do not necessarily add up to 1.

12. Vegetation map, using numbers as IDs, which will become the IDs in the definition files.

13. Map of soil types, using numbers as IDs, which will become the IDs in the definition files.

All maps must have the same resolution, projection system and dimensions. Once all maps have been developed, both the Worldfile and the Flowtable are built using the RHESSysPreprocessing package. Here is an example of an R script to build both entries:

```
library(RHESSysPreprocessing)
setwd("my directory")
RHESSysPreprocess(
template=" my_watershed.txt",
name="name of your results",
type = "Raster",
typepars="path to the maps",
streams = "name of the stream map",
overwrite = TRUE,
roads = NULL,
impervious = NULL,
roofs = NULL,
header = FALSE,
```

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unique_strata_ID = TRUE,
seq_patch_IDs = TRUE,
output_patch_map = TRUE,
fire_grid_out = FALSE,
parallel = TRUE,
make_stream = 4,
wrapper = TRUE)

As a result, the Worldfile and the Flowtable are generated with the name indicated in: name= " name of your results". More information using this package can be found at: https://github.com/RHESSys/RHESSysPreprocessing.

Def y Header

The Def files are all the files that make up the soil and vegetation parameters. These files are the ones that are later included in the Header file so that the model can use them. This Header file is a txt where the paths to all the Def files must be specified. Here is an example of a header file:

```
1        num_basin_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/basin1.def        basin_default_file
1        num_hillslope_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/hill1.def        hillslope_default_file
1        num_zone_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/zone1.def        zone_default_file
2        num_soil_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/soil/1.def        soil_default_file
/mnt/c/RHESSYS/Serra/Divalterra/defs/soil/2.def        soil_default_file
1        num_landuse_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/lu_ag.def        landuse_default_file
2        num_stratum_default_files
/mnt/c/RHESSYS/Serra/Divalterra/defs/veg_pine_2853.def        stratum_default_file
/mnt/c/RHESSYS/Serra/Divalterra/defs/veg_conifer2.def        stratum_default_file
/mnt/c/RHESSYS/Serra/Divalterra/defs/veg_chap_af.def        stratum_default_file
1        num_base_stations_files
/mnt/c/RHESSYS/Serra/Divalterra/clim/daily.base        basestations_file
```

The user can copy this same text into a txt file and modify it according to the appropriate entries and paths.

Tecfile

This file is used to set actions to occur on different dates:

1- Date to start printing results.
2- Date to print an output Worldfile, which could be used for chained simulations.
3- Date to modify the Worldfile in order to simulate forest management, pests, etc. This modification is done by typing redefine_world. The following example shows a Tecfile where the first five lines correspond to printing the results, lines 6 and 7 represent a modification to the Worldfile, with 7 being forest management, and the last line involves writing a Worldfile.

```
1999 01 20 1 print_daily_on
1999 01 20 2 print_daily_growth_on
1999 01 20 3 print_monthly_on
1999 01 20 4 print_yearly_on
1999 01 20 5 print_yearly_growth_on
2002 01 15 1 redefine_world
```

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2002 01 15 2 redefine_world_thin_remain
2002 01 15 3 output_current_state

Climatic

This entry consists of the climate data plus a .base file with information about the weather station and the path to all climate data. Each climate variable is stored in a single txt file, the first line of which corresponds to the start date of the time series. Here is an example of daily precipitation (m):

```
1999 1 20 1
0.0002
0.0005
0.0011
0.0001
0
0
0
0
0
0.0001
```

RHESSys requires at least daily time series of precipitation and temperature (maximum and minimum). However, the introduction of daily data for solar radiation, vapour pressure deficit and wind speed significantly improves the results.
The .base file defines the station ID (which must be the same as in the Worldfile) among other station variables. Subsequently, the file must contain the climate variables and their paths. The following example shows the format of this file, which can be copied back into a txt file and modified according to the appropriate entries.

```
101	base_station_ID
0	x_coordinate
0	y_coordinate
714	z_coordinate
2.5	effective_lai
2	screen_height
annual	annual_climate_prefix
0	number_non_critical_annual_sequences
monthly	monthly_climate_prefix
0	number_non_critical_monthly_sequences
/mnt/c/RHESSYS/Serra/clim/moncada_daily1	daily_climate_prefix
3	number_non_critical_daily_sequences
vpd	/mnt/c/RHESSYS/Serra/clim/moncada_daily1.vpd
Kdown_direct	/mnt/c/RHESSYS/Serra/clim/moncada_daily1.Kdown_direct
wind	/mnt/c/RHESSYS/Serra/clim/moncada_daily1.wind
hourly	hourly_climate_prefix
0	number_non_critical_hourly_sequences
```

Parameter Definition

The Basin, Hillslope and Zone elements need a definition file. The definition files will establish some of the physical characteristics of these elements. On the other hand, both vegetation and soil also need definition files. There will be one definition file per vegetation type that will establish the ecophysiological characteristics of the species. These characteristics are set as parameters and are subject to calibration until the vegetation dynamics match the observed data. Regarding the soil. There will also be a definition file by soil type that will establish its physical characteristics. Among

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the most influential are saturated hydraulic conductivity, soil porosity (and its decay) and the decay of saturated hydraulic conductivity with saturation deficit. For more information, see https://github.com/RHESSys/RHESSys/wiki/Parameter-Definition-Files#soil-definition-file-parameters.

Once all these inputs are prepared, the user is ready to run RHESSys. The model runs in IOs or Unix environments. So if you run RHESSys from Windows you need to install the WSL system (https://docs.microsoft.com/en-us/windows/wsl/install). However, if you run RHESSys from CAFE you do not need to take any of these considerations into account, as you can use it directly from CAFE in IOs, Windows or Unix environments.

To run the model it is necessary to build a command line to specify where the input files are, the output folder, the start and end time of the simulation and other options. The user can build this command line in a txt file like this one:

```
#!/bin/sh
cd /mnt/c/RHESSYS/Serra/Divalterra/scripts/
/mnt/c//RHESSYS/RHESSys-develop_July_2022/rhessys/rhessys7.4 -w
/mnt/c/RHESSYS/Serra/Divalterra/worldfiles/Serra_grided.txt.WORLD -whdr
/mnt/c/RHESSYS/Serra/Divalterra/hdr/Serra9.hdr -t
/mnt/c/RHESSYS/Serra/Divalterra/tecfiles/tecDIV.REDEF -r
/mnt/c/RHESSYS/Serra/Divalterra/flowtables/Serra_grided.txt.FLOW -st 1999 01 20 1 -ed 2019 01 20 5
-pre /mnt/c/RHESSYS/Serra/Divalterra/out_dev/p_ini -gw 5 0.2 -g -climrepeat
```

This command line can also be built using RStudio (RHESSysIOinR package available on RHESSys Github) or directly in CAFE, where the user will find the appropriate box to indicate where the worldfile, header, tecfile, flowtable and output folder are located. This command line is executed from CAFE, WSL or RStudio to run the model, and the results are txt files with daily, monthly and/or annual variables (time step specified in the tecfile) that can be analysed using RStudio, Excel or any other software the user is comfortable with. The calibration and validation process is similar to that of any other ecohydrological model, it is based on comparing the simulated variables with the observed ones and adjusting the model parameters so that the simulation results are as close as possible to the observed data.

Tetis

This model accurately calculates water and sediment fluxes in a distributed environment, but not C and N fluxes (see Figure 7). Therefore, we recommend the use of TETIS for water quantification and/or optimisation.

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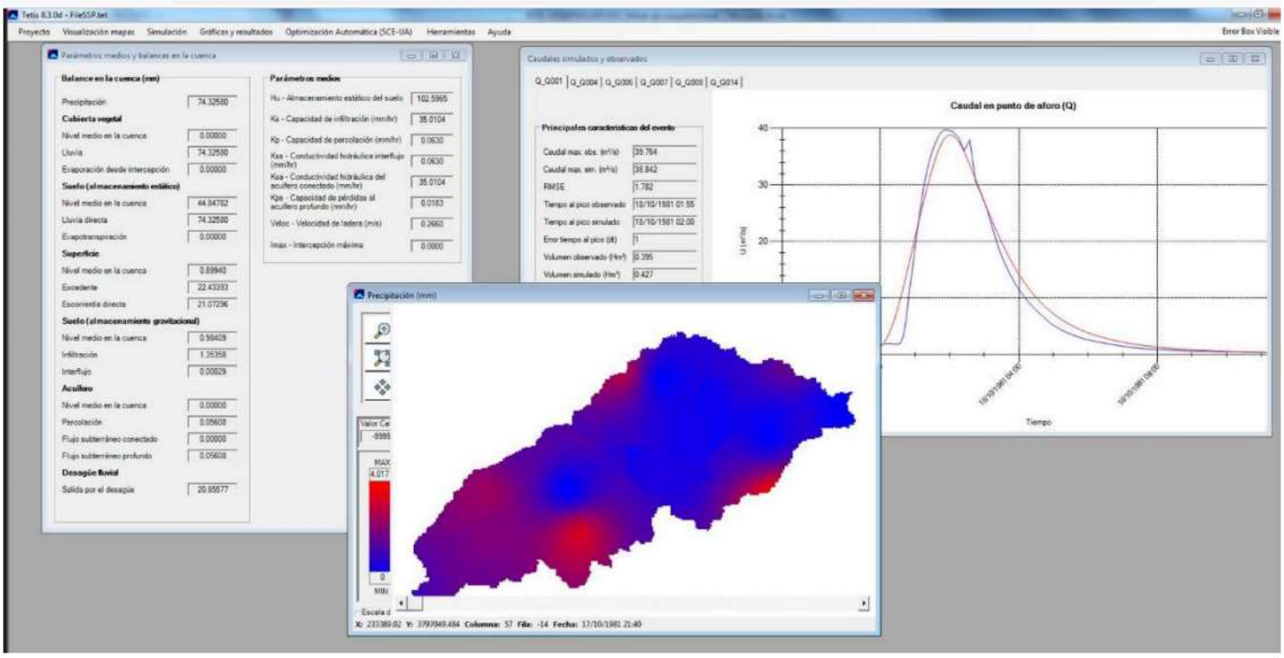

Figure 10. TETIS screenshot of catastrophe balance and avaraged parameters (left), distributed precipitation (left), distributed precipitation (centre) and simulated and observed driver discharge time series (right).

The manual provided explains in great detail how to prepare the model inputs and run the model. According to this manual, the programme is based on the philosophy of creating a project and a set of tools useful for hydrological modelling of a catchment.

The tools on which TETIS v.8.3 is based are:

(i) Creation of a single file with the information specific to each cell with respect to its parameters and state variables. This file is usually called TOPOLCO.SDS.

ii) Generation of an initial state of the initial storages in all tanks of each cell (including the channel). This initial state can be the same for the whole basin or it can be the final state obtained in a period prior to the simulation.

iii) Establish the snow water content in the areas (cells) where snow is present, by interpolation of point values. This model allows to select the area covered by snow at the initial time.

(iv) Cutting off part of the catchment, thus reducing the calculation time and facilitating the use of automatic optimisation algorithms. This reduction of information was included to eliminate upstream reservoir areas that affect downstream results.

v) The simulation of flood events and the simulation of the continuum using the TETIS model. The programme allows manual calibration of parameter correction factors.

vi) Automatic obtaining of the correction factors, the rainfall interpolation factor and the initial state of each reservoir by means of the automatic optimisation technique called SCE-UA.

The necessary files and their formats to run TETIS are summarised in Table 2.

Table 2: Main characteristics of the files used by the TETIS model. In bold the minimum files necessary for the execution of the programme.

FILE NAME	Required for initial implementation (Yes/No)	Generated by TETIS (Yes/No)	Format Type
FILESSP.TET	**Yes**	Yes	Text
FILESVEG.TXT	**Yes**	Yes	Text
PARAMGEO.TXT	**Yes**	Yes	Text
SETTINGS.TXT	**Yes**	Yes	Text
CALIB.TXT	**Yes**	Yes	Text
TOPOLCO.SDS	No	Yes	Cell per row
HANTEC.SDS	No	Yes	Cell per row
FACTORETMES.TXT	**Yes**	Yes	Text
CURVASHV.TXT	Yes(if there are reservoirs)	No	Text
Fichero entrada.txt	**Yes**	No	Col/CEDEX
HANTEC2.SDS	No	Yes	Cell per row
Fichero salida.txt	No	Yes	Col/CEDEX
NIEVE.ASC	Yes(if there is snow)	Yes	Ascii grid
NIEVE2.ASC	No	Yes	Ascii grid
MED.ASC	**Yes**	No	Ascii grid
HU.ASC	**Yes**	No	Ascii grid
KS.ASC	**Yes**	No	Ascii grid
KP.ASC	**Yes**	No	Ascii grid
KSS.ASC	**Yes**	No	Ascii grid
KSA.ASC	**Yes**	No	Ascii grid
KPS.ASC	**Yes**	No	Ascii grid
VEL.ASC	**Yes**	No	Ascii grid
HSTAR.ASC	**Yes**	No	Ascii grid
COBVEG.ASC	Yes (including variable ET)	No	Ascii grid
SLOPE.ASC	**Yes**	No	Ascii grid
DIRFLUJO.ASC	**Yes**	No	Ascii grid
ACUM.ASC	**Yes**	No	Ascii grid
CONTROL.TXT	No	Yes	Text
RECORTA.TXT	Yes (if there are reservoirs)	No	Text
REGHOMOG.ASC	Yes (if there are homogeneous regions)	No	Export. ArcGis
VAR-SCEUA.TXT	No	Yes	Text
RES-SCEUA.TXT	No	Yes	Text
RAD01.ASC	Si (si hay nieve distribuida)	No	Ascii grid
KARST.ASC	Si (si hay karst)	No	Ascii grid
MANANTIALES.TXT	Si (si hay karst)	No	Ascii grid
MULTIPLE.TXT	No	No	Text
MULTICALIB.TXT	No	No	Text
UMBRALESQ.TXT	No	No	Text
MULTIEVENTO.TXT	No	Yes	Col/CEDEX
WARNINGHANTEC.TXT	No	Yes	Text

7.2 Introduce your own cases to CAFE

The way to introduce your own case studies to the CAFE tool must be done by creating a root folder that contains all the information of the model you are using. This folder can be named as the user wishes (Example: Caso_Madrid). This folder must contain the information of the model to be executed. When this folder is complete and with the structure it should have, as will be seen for each model, it must be included in the Docker folder "Own_data", so that these directories can be used in the DSS interface.

Biome case

If you intend to assemble a case study with the BIOME model, the files that need to be in this root folder of the assembled case study are all the files that appear in the .ini file:

```
------------------------------------------------------------------------------------------------------------------------
BBGCMuSo simulation

MET_INPUT
Clim_gen1.txt        (filename) met file name
4                    (int) number of header lines in met file
0                    (int) number of simdays in last simyear (truncated year: <= 365)

RESTART
0                    (flag) 1 = read restart; 0 = dont read restart
1                    (flag) 1 = write restart; 0 = dont write restart
hhs_MuSo4.endpoint   (filename) name of the input restart file
hhs_MuSo5.endpoint   (filename) name of the output restart file

TIME_DEFINE
30                   (int) number of simulation years
2000                 (int) first simulation year
0                    (flag) 1 = spinup run; 0 = normal run
6000                 (int) maximum number of spinup years

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

NDEP_CONTROL
1                    (flag) 0=constant; 1=vary with file
0.000200             (kgN/m2/yr) wet+dry atmospheric deposition of N
Ndep.txt             (filename)  name of the N-dep file

SITE
181.0                (m)  site elevation
43.30                (degrees) site latitude (- for S.Hem.)
0.20                 (DIM) site shortwave albedo
15.00                (Celsius) mean annual air temperature
9.96                 (Celsius) mean annual air temperature range
0.50                 (prop.) proprortion of NH4 flux of N-deposition

SOIL_FILE
hhs.soi              (filename) SOIL filename

EPC_FILE
pira.epc             (filename) EPC filename

MANAGEMENT_FILE
management.txt       (filename) MGM filename (or "none")

SIMULATION_CONTROL
0                    (flag) phenology flag (1 = MODEL PHENOLOGY 0 = USER-SPECIFIED
PHENOLOGY)
1                    (flag) vegper calculation method if MODEL PHENOLOGY is used (0: original, 1: GSI)
0                    (flag) transferGDD flag (1= transfer calc. from GDD 0 = transfer calc. from EPC)
```

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0	(flag) q10 flag (1 = temperature dependent q10 value; 0= constans q10 value)
0	(flag) acclimation flag of photosynthesis (1 = acclimation 0 = no acclimation)
0	(flag) acclimation flag of respiration (1 = acclimation 0 = no acclimation)
0	(flag) CO2 conductance reduction flag (0: no effect, 1: multiplier)
0	(flag) soil temperature calculation method (0: Zheng, 1: DSSAT)
0	(flag) soil hydrological calculation method (0: Richards, 1: tipping DSSAT)
1	(int) discretization level of soil hydr.calc.[Richards-method] (0: low, 1: medium, 2: high)
0	(flag) photosynthesis calculation method (0: Farquhar, 1: DSSAT)
0	(flag) evapotranspiration calculation method (0: Penman-Montieth, 1: Priestly-Taylor)
0	(flag) radiation calculation method (0: SWabs, 1: Rn)
1	(flag) soilstress calculation method (0: based on VWC, 1: based on transp. demand)

W_STATE

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

CN_STATE

0.00003000										(kgC/m2) first-year maximum leaf carbon
0.00003000										(kgC/m2) first-year maximum fine root carbon
0.00003000										(kgC/m2) first-year maximum fruit carbon
0.00003000										(kgC/m2) first-year maximum softstem carbon
0.00003000										(kgC/m2) first-year maximum live woody stem carbon
0.00003000										(kgC/m2) first-year maximum live coarse root carbon
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) coarse woody debris carbon
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) litter carbon, labile pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) litter carbon, unshielded cellulose pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) litter carbon, shielded cellulose pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) litter carbon, lignin pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) soil carbon, fast microbial recycling pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) soil carbon, medium microbial recycling pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) soil carbon, slow microbial recycling pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgC/m2) soil carbon, recalcitrant SOM (slowest)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgN/m2) litter nitrogen, labile pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgN/m2) soil mineralized nitrogen, NH4 pool
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	(kgN/m2) soil mineralized nitrogen, NO3 pool

CLIM_CHANGE

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

CONDITIONAL_MANAGEMENT_STRATEGIES

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

OUTPUT_CONTROL

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

DAILY_OUTPUT	
18	number of daily output variables
3002	outflow
2604	vwc03-10cm
2605	vwc10-30cm
2606	vwc30-60cm
159	soilw_evap
101	percolation
171	evapotransp
3009	daily_gpp
2520	proj_lai
3100	Net_greenhouse_gas_balance
310	frootc
316	softstemc
319	livestemc
325	liverootc
307	leafc
170	transp_SUM
3023	NEP
94	precipitation

ANNUAL_OUTPUT	
28	number of annual output variables
3000	annprcp
3001	anntavg
101	anndeeppercolation
3002	annrunoff
3003	leaching_root_zone
3050	annET
2734	annmax_lai
3031	cum_Closs_MGM
3032	cum_Cplus_MGM
3045	cum_Closs_SNSC
3046	cum_Cplus_STDB
3058	vegc
3064	totalc
3066	SOM_C_top30
3070	SOM_C_30to60
3071	SOM_C_60to90
3068	NH4_top30
3069	NO3_top30
3061	Total_Soil_C
3100	Net_greenhouse_gas_balance
3062	Soil_N_Total
3033	cum_Closs_THN_woody
3008	NBP
3023	NEP
3163	LaboveCnsc_nw

3164 LaboveCnsc_w
3159 LDaboveCnsc_nw
3160 LDaboveCnsc_w

END_INIT

All the files needed for this model are the ones in this file and they have to have the same name and extension as reflected in the .ini file. In addition, the .ini file must be in the same folder as the other files.

Finally, the THINNING.txt file must also be included, which is the one that in the management.txt file specifies the characteristics of the performance and that later the optimisation will modify in each iteration.

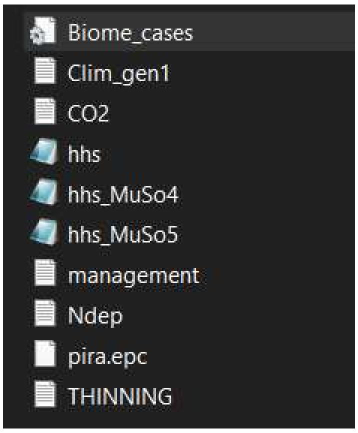

Figure 11. BIOME case structure.

Once in the interface, you only have to give the directory of the case study (e.g. Caso_Madrid), which has an extension .ini:

/Own_Data/Caso_madrid/Biome_cases.ini

With this address and all these files the simulation can be run from CAFE.

RHESsys case

If a case study is to be set up to use the RHESsys model, a root folder must be created with the name of the case study (e.g. Caso_Barcelona), which must contain the structure that the model itself uses to be executed and created. It is recommended that all the files created in the different parts seen in the previous point are stored in folders with the information structured by blocks: clim, defs, flowtables, hdr, out, tecfiles, worldfiles, scripts. This way, you can see that all the information is complete and correct in an easier way.

However, in order to be launched in the interface and subsequently display the stand map and its performances, an extra folder must be created when using the RHESsys model without the use of the DSS CAFE which is the one that hosts the shapefiles. This folder is "maps" and here there must be a .shp vector file and its companions called "patches" and containing an attribute as a column "Stand", where the ID of the stands that appears in the Worldfile must be put in order to subsequently map the intensity of clear-cutting. It is important not to forget that the reference system of this file must be in WGS84 (EPSG:4326).

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Figure 12. RHESsys case structure.

Tetis case

To generate the case study in Tetis, a folder must be created with all the information of the case study as if the simulation model were to be run independently. Subsequently, to run it from the DSS, this folder must be contained in another main folder that also has two ascii files that is the distribution of stands (Forest Working Unit), the folder that contains all the Tetis case study can be named as you wish (example: Secon_folder).

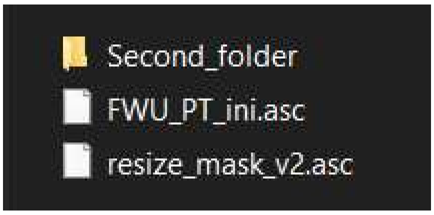

Figure 3. Tetis case structure.

To run Tetis, the executable "Tetis_v2b_DSS" has to be run with the DSS, which is located in the Tetis example folder and has to be copied to the user's own case to be mounted. To do this operation, Linux commands to copy elements between directories must be executed.

** This section is still in progress*

8. Interface

The graphical interface of CAFE is developed in a web environment. This makes the visualisation on all computers easier to display and adjustable to the screen of each one, as it is coded in HTML language. As mentioned in point 6 "Start DSS", once the Docker container has been executed and we have the created image of the tool. Just run the function (python app.py) which launches the

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visual part of the DSS in the virtual machine that has been created. To open and display the interface, just type "localhost:5000" (this is better explained in point 6) in your web browser.

The interface is composed of a main window with two parts, the right side with the Life Resilient Forests logo and a left side with 4 sections (Configuration, Execute, Visualise and Clear Map). Each section opens on the right-hand side (where the logo appears), allowing the user to make the changes they determine to use their case study.

Each of the parts that these sections have will be explained in the following point (Workflow), where you will be able to see each of the parameters that appear and their appearance to be able to be modified with criterion.

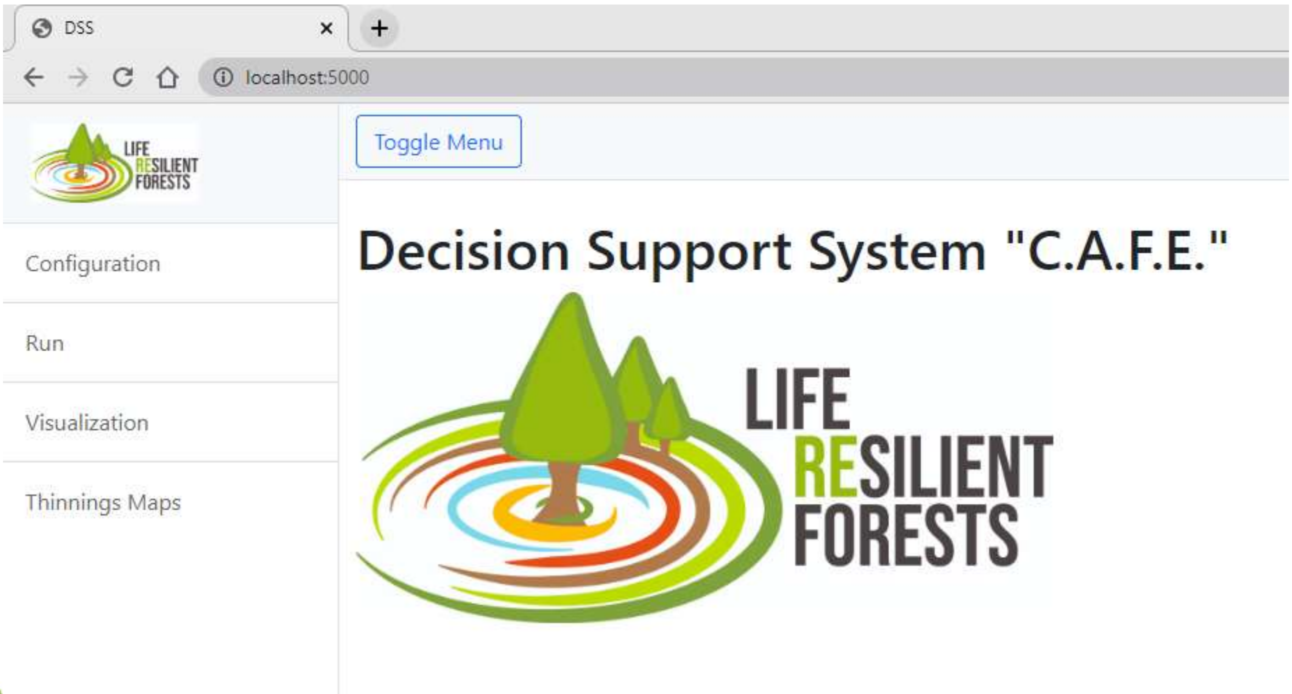


Figure 13. Web interface design

9. Workflow

The use of CAFE involves a series of steps that the user must follow each time. In this section, it is intended to show the workflow that must be used to use an own case study.

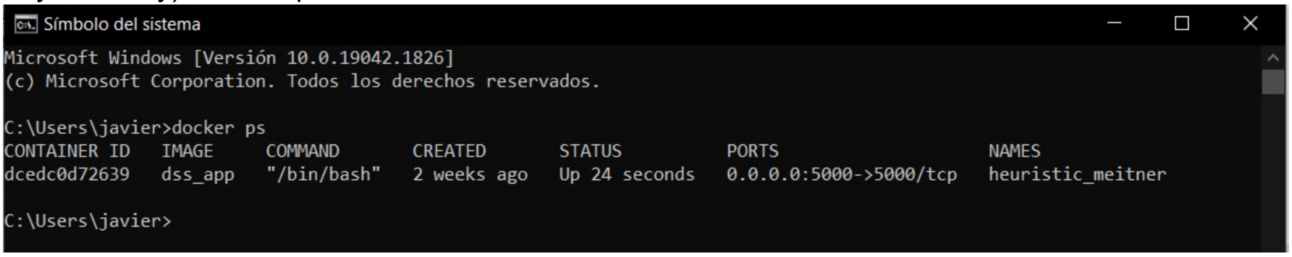
1. Start CAFE

The first step that must be done is to start CAFE, the implementation of this action has been explained in the previous point (point 6 "Starting DSS").

We take advantage of this point to tell some peculiarities of the creation of this tool in the Docker environment and the advantages that this offers. Once you have created your virtual machine in a container, which hosts the image of the CAFE tool, Docker allows the user to open other identical machines in parallel in order to run the CAFE tool at the same time and save time. Below is a series of commands that allow another machine to be started in parallel.

To achieve this, the following steps must be followed:

1- Obtain the ID of the container of the CAFE image created, to do this, type in the cmd (from any directory) "docker ps".



2- Execute the same container to create a clone, this is done by executing the command:

docker exec -it (ID Contenedor) \bin\bash

2. Preparing inputs

2.1. Assembling cases

As seen in Section 7 (7.1 Creation of model inputs and calibration) of this document, creating the case study involves preparing the inputs needed by the model to be used and, therefore, more or less requirements and difficulty. In addition, the calibration of the parameters necessary to obtain correct results. In this way, the values of the study area are in accordance and coherent with reality in a contrasted way.

2.2. Enter in DSS

After the previous step of creating the case study with the inputs that the model needs to be executed and with the parameters well calibrated, it is the turn to introduce these files into the tool. This step was extensively developed in Point 7 (7.2 Introducing own cases to CAFE) where you can see how the case study must be assembled so that the DSS can recognise it and execute it.

3. Configure

Once CAFE has been started and our own case study has been saved, the most important step is to configure the execution of the DSS with the user's criteria, and to do so, two main parts must be configured. The first is the model that you want to use, and depending on which one you want to use, you have to configure different parameters for each one. These are simulation-optimisation options that the user can determine depending on the case study. Each model can be seen in its own tab, which, depending on which one is to be used, must be clicked and configured.

And the second, are the common parameters, which are the same for all models and configure the optimisation options of the metrics that will calculate the simulation that the user has prepared.

Figure 14. Configuration Tabs

3.1. Simulation Models

The configuration of CAFE starts with the introduction of the input files needed by the simulation model to be used, so that the case study can be executed with all the input files it requires to be launched.

Next, the intervention configuration parameters are the options that the user must select to obtain the appropriate silvicultural actions (thinning or planting) and to which the DSS must respond. Depending on the model to be used, more or less forestry action options can be included (Where to act?, When to act?, How much to act?, How to act?) as shown in table 1.

Table 1. *Configuration of interventions according to model.*

Model	Forestry Actions	Actions
RHESSys	Thinning	Where, when, how much and how?
BIOME-BGC_MuSo	Thinning	When and how much?
	Planting	How much?
Tetis	Thinning	Where and how much?

Finally, you can also configure the constraints to be used to derive the management plan. Restrictions are a way of limiting interventions in some cases. In particular, they are currently applied to the intensity of the intervention when the slope of the terrain is very steep and you do not want to have a very steep slope. Therefore, it is made so that the optimisation cannot be applied above a certain threshold that the user determines. This can only be applied to the RHESSys model at the moment.

Once all changes have been made to the model to be used, the "Save configuration" button at the end of the tab must be clicked before leaving the tab.

3.1.1. RHESSys

The configuration of the RHESSys model is divided into the three parts explained above. In addition, there is an extra tab called "Stands" that allows you to filter the area where you want to have the optimisation determine the appropriate forestry actions. This is because the cases that are usually assembled in this model have a large number of stands, so it is easier to have this step in a separate tab.

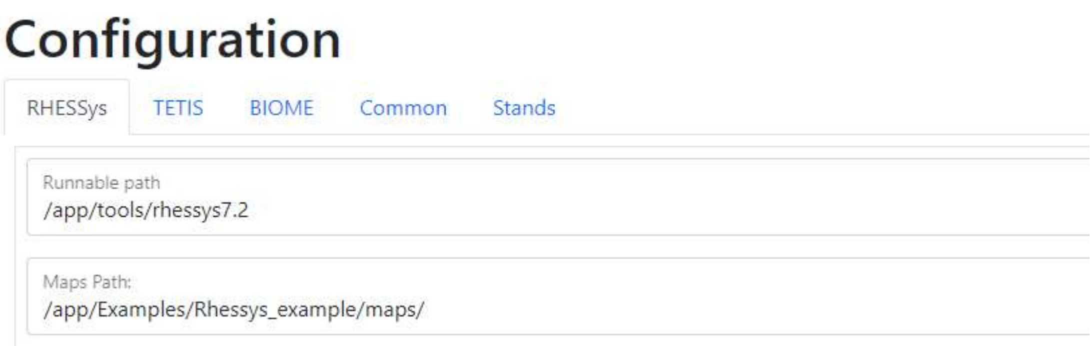


Figure 15. RHESsys model configuration.

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3.1.1.1. Simulation Inputs

This section focuses on creating the command statements to launch RHESSys and the prepared case study. To do this, you need the multitude of directories for each of the input elements you need to start the simulation. The addresses of the example case are automatically displayed, which must be replaced by the address of each item saved in the Own_Data folder.

Table 2. *Commands and description of RHESsys input parameters.*

Comando	Descripción
Runnable path	This is the path of the RHESsys simulation model, automatically the version 7.2 appears, which is the most stable version to obtain the metrics that are calculated with this model. This path should not be substituted.
Maps Path	This address is the folder that contains the shapefile files of the Stands that will allow the visualisation of the stand map with the associated silvicultural actions.
Worldfile (-w)	This is the address of the Worldfile file that defines the representation of the landscape within RHESsys, which is based on a hierarchical structure describing each spatial level containing progressively finer units (watershed, hillside, zone, patch, stratum).
Worldfile header (-whdr)	This is the address of the Worldfile header file containing all soil, climate and vegetation parameter paths.
Tecfile (-t)	This is the address of the Tecfile file which is the temporary event control. Used to specify hourly, daily, monthly and yearly print output options. In addition, it allows to redefine the status variables.
Flowtable (-r)	This is the address of the Flowtable file that defines the hydrological connection between the different spatial elements of the simulation domain.
Start Date: y md h (-st)	Start date of simulations intended to be used and for which climate data are available.
End Date: y md h (-ed)	Final simulation date up to which the model is to be run and the climate series is to be reached.
Path for output (-pre)	Address of output files (model outputs)
Optional parameters	Corrective parameters derived from model calibration. They can be included directly in the soil biophysical description files.
Definition files	Files defining the biophysical parameters of the slope, zone, watershed, vegetation and soil.
Redefine Worldfile	Modification of Worldfile to allow simulation of forest management.
Initial Worldfile	Worldfile with which to start the simulation, i.e. derived from model calibration and validation.
Worldfile path	Address to Worldfile.

3.1.1.2. Forest management configuration

The parameters in this section refer to the silvicultural actions (questions, decision variables) that the user wants to design through the DSS. For this model it is possible to answer up to 4 questions that refer to the clearings at the same time, being the model that offers the most combination possibilities to the user.

***Table 3.** Intervention configuration options in RHESsys*

Command	Description
Act on all stand or only on a certain number of stands? (Where?)	This parameter has two possible values. By default, it is all possible stands "All", so that in the optimisation the where is the whole study area and each of the stands that compose it. If, on the other hand, the value "specific" is selected, it means that the where will be in a specific area/s of stands.
If Specific stands selected, maximum number of stands in which to act	This parameter refers to the maximum number of stands where intervention is possible. It shall only have a value if "Specific" has been selected in the previous parameter.
What range of thinning intensity? (How much?)	Minimum and maximum range of clear percentage (percentage of the mass to be clarified) for the optimisation to explore and find the optimum value. The step between values goes from 10 to 10. The minimum being 10, and the maximum 100.
At what level do you want to intervene? (How?)	This is the type of intervention to be carried out, and can be of two types. At stand level, without distinguishing between the strata of vegetation, or by stratum, which distinguishes the vertical strata (tree, shrub, herbaceous) within the same stand.
Number of interventions? (When?) minimum es 1.	This is the number of clearings to be executed during the simulation period.
Year since start simulation for first thinning	Number of years since the start of the simulation on which the first intervention is applied. If in the previous section the number is "1", only this clear one will be implemented and therefore the "When" is not intended to be obtained in the action plan.
Years of rest between interventions	Number of years of obligatory rest between interventions if there is more than one intervention during the simulation period.

3.1.1.3. Constraints

Constraints are the last configuration section of this model. This constraint is made to avoid solutions that in real life cannot be tackled due to execution risk. Up to now, the only way to limit the exploration space of the optimisation algorithm is by the slope of the terrain where the clear.

***Table 4.** Constraint parameters.*

Command	Description

Slope constraints to reduce thinning value (%)	Maximum slope value to limit the intensity of intervention in stands exceeding that value.
Maximum thinning (%) with slope constraints	Maximum intervention intensity between the values that the optimisation can seek solutions for.

3.1.2. Tetis

The configuration of the Tetis model has only two sections, the first is the input of the address of the files themselves to run the model, as well as a stand filter that allows constraint the area to intervene versus the area to act. The second section is for configuring the interventions to be carried out.

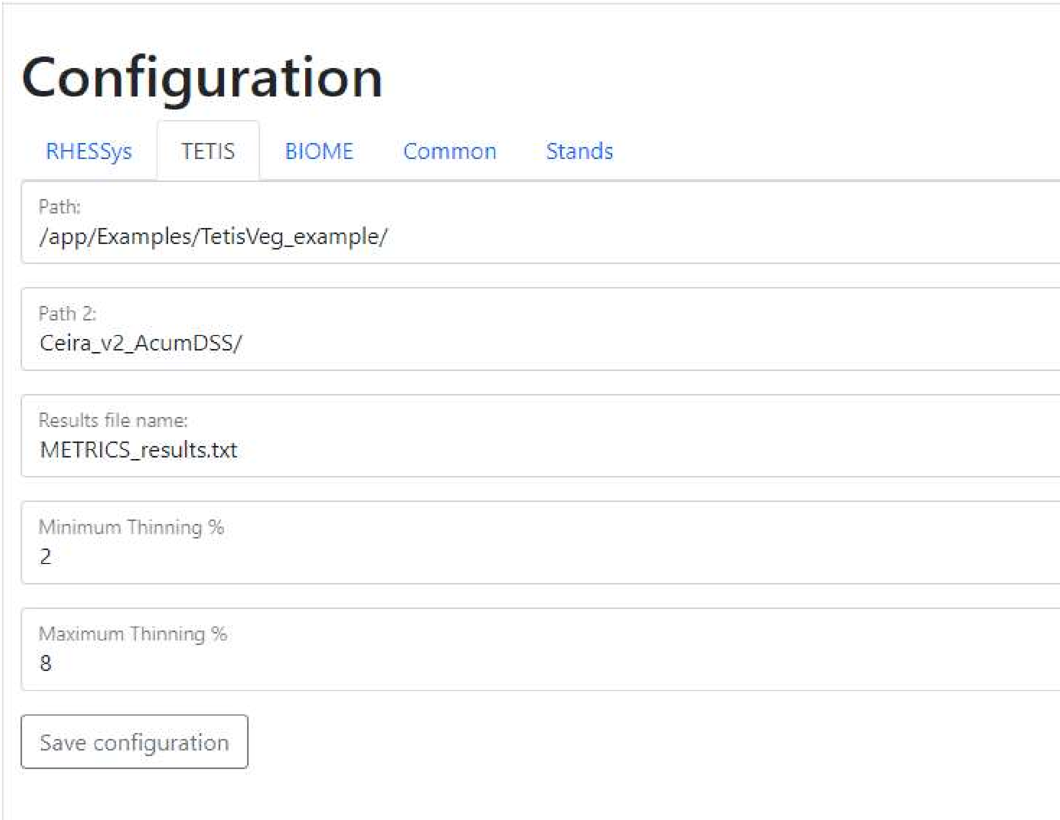

Figure 16. Tetis model configuration.

3.1.2.1. Simulation Inputs

The entries that need to be made in the configuration of this model are reduced. You only need to know the main path of the case study, together with the complementary folder as can be seen in table 5 below. By default, the paths that appear are those of the example case of this model. They must be replaced by the own case that you want to launch and that has been hosted in the "Own_Data" folder.

Table 5. Tetis input parameters.

Command	Description
Path	Main path of the input data to the model, this folder should contain the folder with the hulled

	case to simulate Tetis and the file 'FWU_PT_ini.asc' with the full values of each stand.
Path2	Path to the folder with all the files needed to launch Tetis.
Stand list	List of stands that allows filtering the simulation area. If you do not want to filter you have to enter all stand IDs.
Result file name	File name of the output file of the iterations displayed on the console.

3.1.2.2. Interventions' configuration

Tetis only has the clearings as a silvicultural action, and is able to answer the questions How much? and Where? should be applied. However, the where options do not allow to be limited to some areas only as in the RHESSys model. Instead, all stands to be introduced must be acted upon.

Table 6. Options for the configuration of interventions in Tetis.

Command	Description
What range of thinning intensity? (How much?)	Rango mínimo y máximo de porcentaje de clara (porcentaje de la masa a aclarar) para que la optimización explore y encuentre el valor óptimo. El paso entre valores va de 10 en 10. Siendo el mínimo 10, y el máximo 100.

3.1.3. BIOME-BGC_MuSo

The configuration of this model has like the previous one only two sections. The first one contains the input information to the model and the second one contains the optimisation options.

3.1.3.1. Simulation Inputs

As mentioned above, this model requires the ".ini" start-up file and the files referenced in it. As with the previous models, the default path is that of the example case study provided with this version of the tool. To execute the own case, it must be replaced by the working directory saved in the folder "Own_Data".

Table 7. Biome input parameters.

Command	Description
Biome ini file	Route of the case study to be implemented.

3.1.3.2. Interventions' configuration

BIOME-BGC_MuSo is the only one of the current models of this version that allows not only to design the thinning intensity, but also to design the plantation density. This makes it possible to simulate mature stands and young stands of both productive and protective plantations. Therefore, with this model it is possible to obtain the optimum plantation density together with the necessary silvicultural actions for its entire stage.

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Table 8. Intervention configuration options in Biome.

Command	Description
Management	This parameter can be either protective or productive. The only difference is that if producer is selected, a final cut of 100% of the vegetation is applied at the end of the simulation.
Planting?	Parameter defining whether planting comes into play in forestry operations. If the user wants the optimisation to determine the optimal density, the user must define "yes" and if not "no".
What range of planting density? (How much?)	Minimum and maximum range between the values that the optimisation can explore the values of the plantation. The step between values goes from 100 to 100, with the minimum being 100.
Weight kgC/m^2 of plant	This is the value of the carbon weight per square metre of 1000 plants.
Initial density in mature forests	This is the planting value that a mature stand would have. This parameter would be used for the calculation of the cost of operations.
What range of thinning intensity? (How much?)	Minimum and maximum range of clear percentage (percentage of the mass to be clarified) for the optimisation to explore and find the optimum value. The step between values goes from 10 to 10. The minimum being 10, and the maximum 100.
Number of interventions? (When?) minimum es 1.	This is the number of whites to be executed during the simulation period.
Year since start simulation for first thinning	Number of years since the start of the simulation on which the first intervention is applied. If in the previous section the number is "1", only this clear one will be implemented and therefore the "When" is not intended to be obtained in the action plan.
Years of rest between interventions	Number of years of obligatory rest between interventions, provided that the number is more than one.

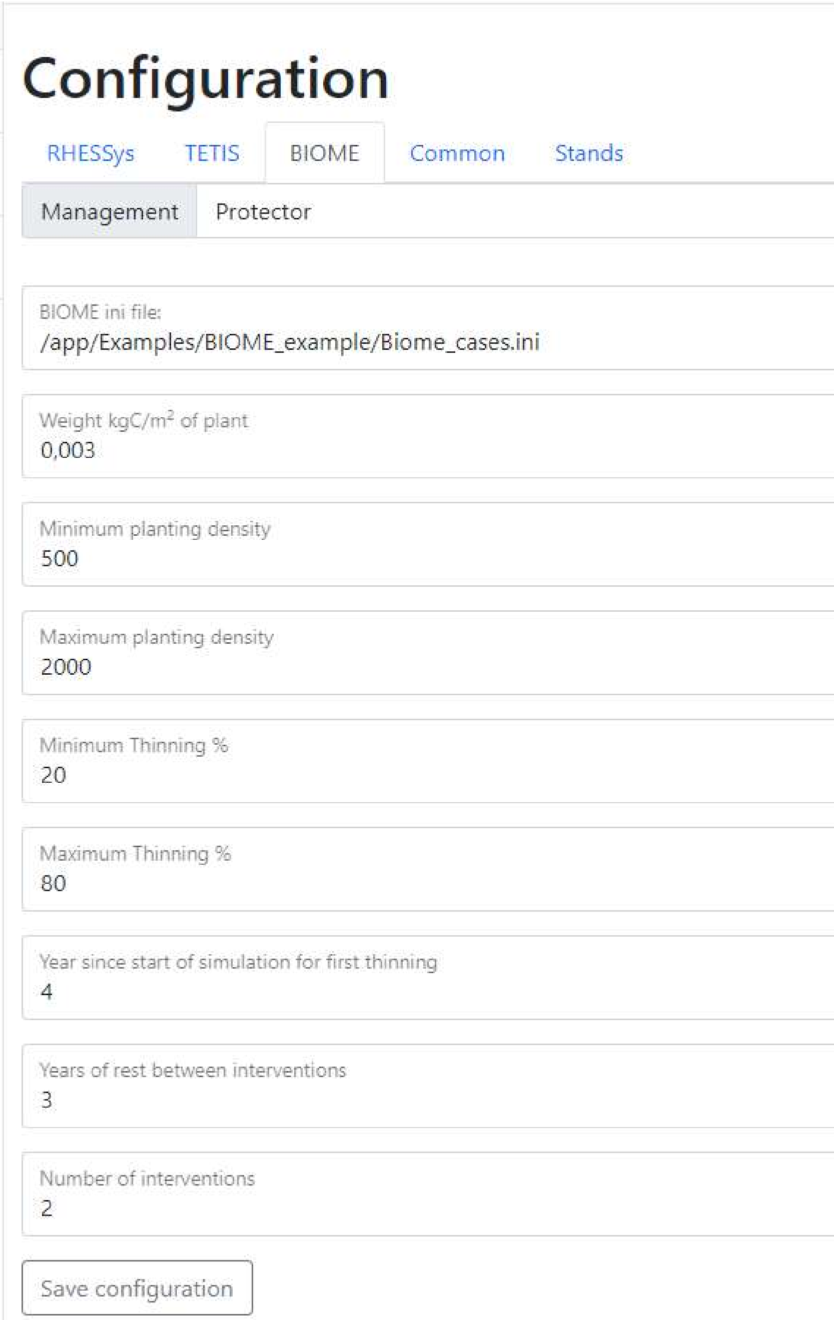

Figure 17. Biome model configuration.

3.2. Common

Once the configuration of the model to be used has been completed, having prepared all the information required in its tab and saved the configuration (important, do not forget), the next step is to configure the common parameters that all models have. These refer to the optimisation part, being the metrics that can be calculated with the selected simulation model. In addition, the optimisation algorithm to be used can be configured, as well as the interactions to be searched for. Finally, the user is allowed to save the results with the name and address of his choice.

3.2.1. Selection of Metrics

The selection of metrics will depend on the simulation model used as not all models can calculate all the values of goods and services that appear in the CAFE tool. The combination of models makes the tool very flexible for the user as he/she can use different options depending on the complexity of each model in the preparation of the input parameters, as well as the calibration of the parameters themselves, as has been shown in the previous points. For this reason, the simplest models to prepare to be launched in CAFE, such as the BIOME-BGC_MuSo or Tetis models, are those that provide a smaller selection of metrics. Therefore, depending on the model that has been configured, it is necessary to select those metrics that can be calculated by the model. That said, all metrics, whatever model they are calculated with, can aim to be maximised, minimised or simply quantified "info". It should be noted that only up to 5 metrics can be maximised or minimised at a time, the rest will be quantified if the user wishes. This is for reasons of reducing computational time and not making the execution of the case study too complex. In addition, there are times when it is impossible to obtain results from these options because we have narrowed down the exploratory space of the optimisation algorithm with this criterion.

To conclude with the selection of metrics and their optimisation, the steps to be followed by the user are as follows:

-See which metrics are calculated by your employed model, which also appear in the third column "Models".

-See what type of optimisation you want for each of the available metrics "maximize", "minimize" or "info".

-Activate or deactivate those that you want or do not want to be part of the final results.

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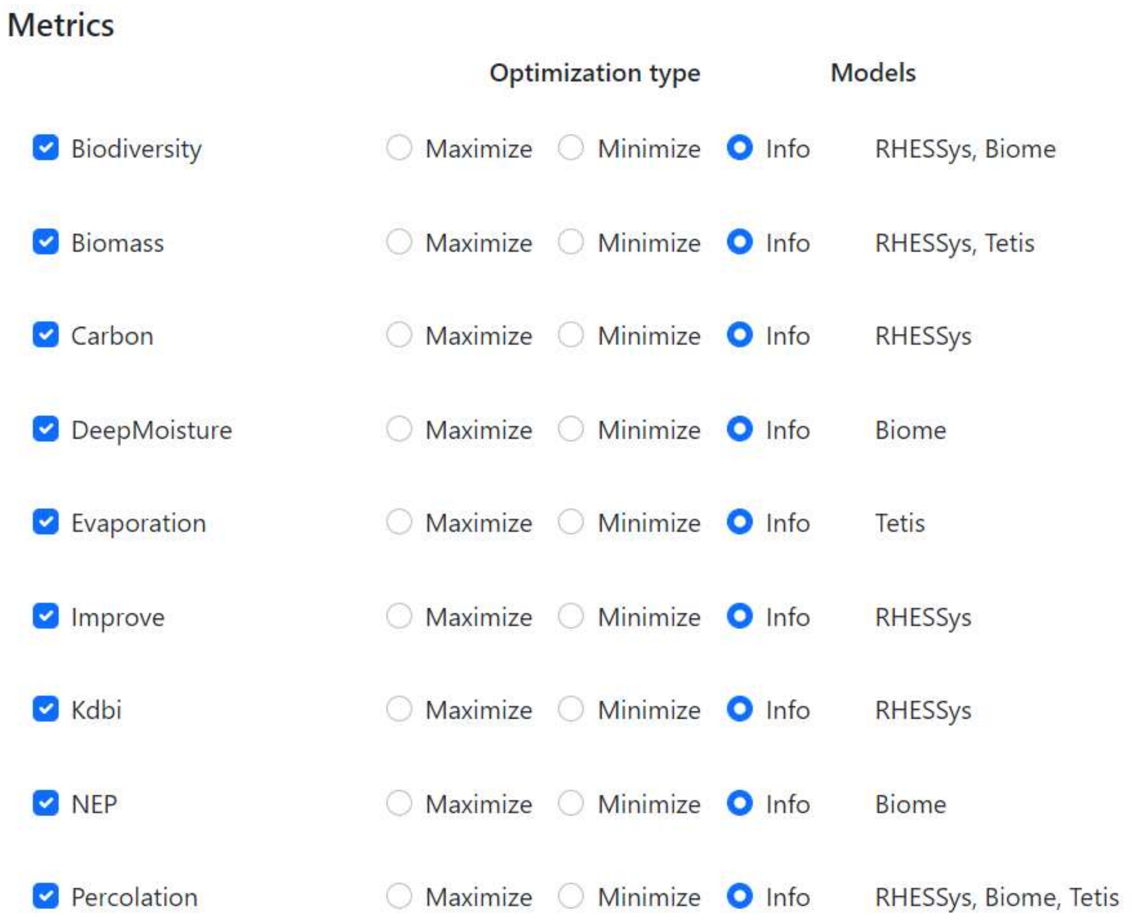

Figure 18. Metrics and type of optimisation per model

Finally, in this section there is a parameter that the user can modify to obtain the approximate value of the operational costs of the forestry actions to be carried out with the optimisation criteria. This metric does not come into play in the optimisation, because if the user decided to minimise it, this would turn the multi-objective tool into a single objective, prioritising money over all goods and services. Therefore, these values are calculated once the optimisation is finished for the possible optimised solutions and for information purposes. In this way, the user can finally include the economic criterion in the multifunctional forest management options.

Figure 19. Parameters for operating costs.

3.2.2. Algorithm Configuration

The second section that can be configured by the user is the section pertaining to the optimisation algorithm used and the possible numbers of solutions in the sample space. This section is intended for scientific users who want to be sure that the solutions they are looking for are robust solutions and that the optimisation has thoroughly explored the sample space and that the solutions obtained by the algorithm are the best without any doubt. It is composed of two parameters, one the algorithm itself that is used within the Multi-Objective Evolutionary Algorithms (MOEA), which by default and because it is the most common one used automatically is the NSGA-II. On the other hand, the number of iterations refers to the final solutions that the optimisation will show to the user and from which the user will finally select one.

After the different tests carried out with synthetic cases of each model, it has been determined that for technical users it is recommended not to change the algorithm used and to have a number of solutions between 100 and 1000. Depending on the processing time to be used. In order to obtain indicative values of how forest management works in the provisioning of goods and services, with a value of 100 solutions, it is possible to be aware and the tool is capable of supporting the decision that the manager has to calculate.

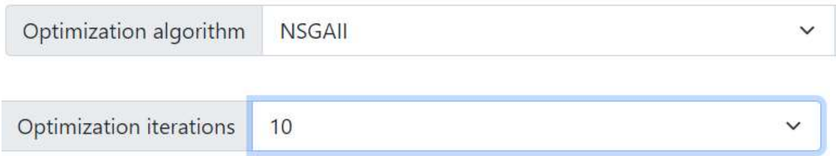

Figure 20. Algorithm configuration

3.2.3. Results Directory

The last section of the common parameters is the address and name where you want the results generated by CAFE to be saved, these files may want to be modified if you intend to use the tool repeatedly to know which result is which. The automatic address is the "Results" folder which can be viewed directly in the local folder on your computer once the DSS has finished its calculations within Docker. This is a vital option if you want to manipulate and interpret them in another tool such as Excel or another visualisation tool such as J3. In addition, this address will also save the clear maps that are calculated in HTML format to be able to share or view them later without having to enter the tool.

3.3. Stands filter

To finish with the configuration, the Stands tab belongs to the RHESsys model as mentioned above and has been made separate to help the user to visualise all stand values well. This is because the case studies assembled in RHESsys are often large areas with a large number of stands and therefore can be well appreciated here. This section allows the user to filter the study area over which the forest management is to be optimised, without limiting the simulation to the whole forest.

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4. Execute tool

Once the configuration of the model and optimisation parameters has been completed, always having saved the changes to verify that the execution of the tool corresponds to the user's criteria. The next step is to launch or run CAFE.

This step is very simple, you only have to select the model you want to use in the drop-down menu and that has been configured as seen in the previous point. Then, press the "Start" button, where immediately in the lower console of this screen the values of the different interactions that are being calculated will start to be printed. In each intervention, the values of the forestry actions that the optimisation has proposed and the value of the metrics obtained once the simulation has finished can be observed. This is repeated until the tool has finished obtaining the optimum possible solutions.

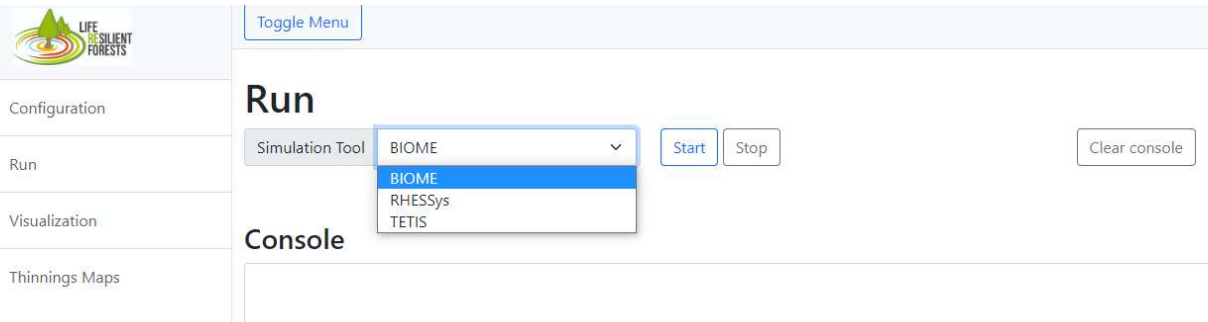


Figure 21. Launch DSS with selected model

5. Visualise results

When CAFE finishes running, it automatically opens the visualisation tab. In this section you see the results provided by the optimisation as the best solutions. There are two parts here, the upper part where the results are configured and the lower section where the Pareto front is displayed.

The visualisation parameters that can be modified are the metrics that you want to use in the 3D cube of the Pareto front, where you can edit 5 options. The 3 axes of the cube (x,y,z), the colour and the size of the points.

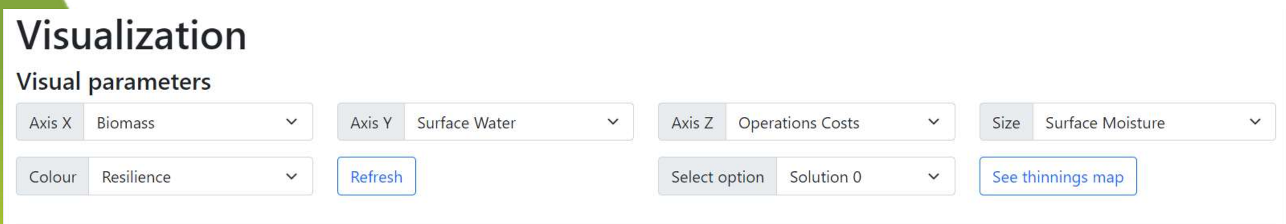


Figure 22. Display parameters

By default, some metrics are displayed for each element, but they can be changed for other metrics and the graph can be redrawn. In this way, the user can update the representation of the results by pressing "Refresh" and be able to better interpret the relationship between metrics and select a solution as the most suitable for his criteria.

In addition, in this section there is a "See thinning map" button that allows you to see the distribution map of the forestry operations in order to obtain the value of the metrics. To do this, the most appropriate solution must be selected in the "Select option" drop-down menu.

5.1. Pareto front

The first result that the DSS provides to the user is the Pareto front, which are the optimal solutions for the criterion previously set by the user and which are composed of 3 parts: Table, parallel coordinates graph (2D) and the 3D cube.

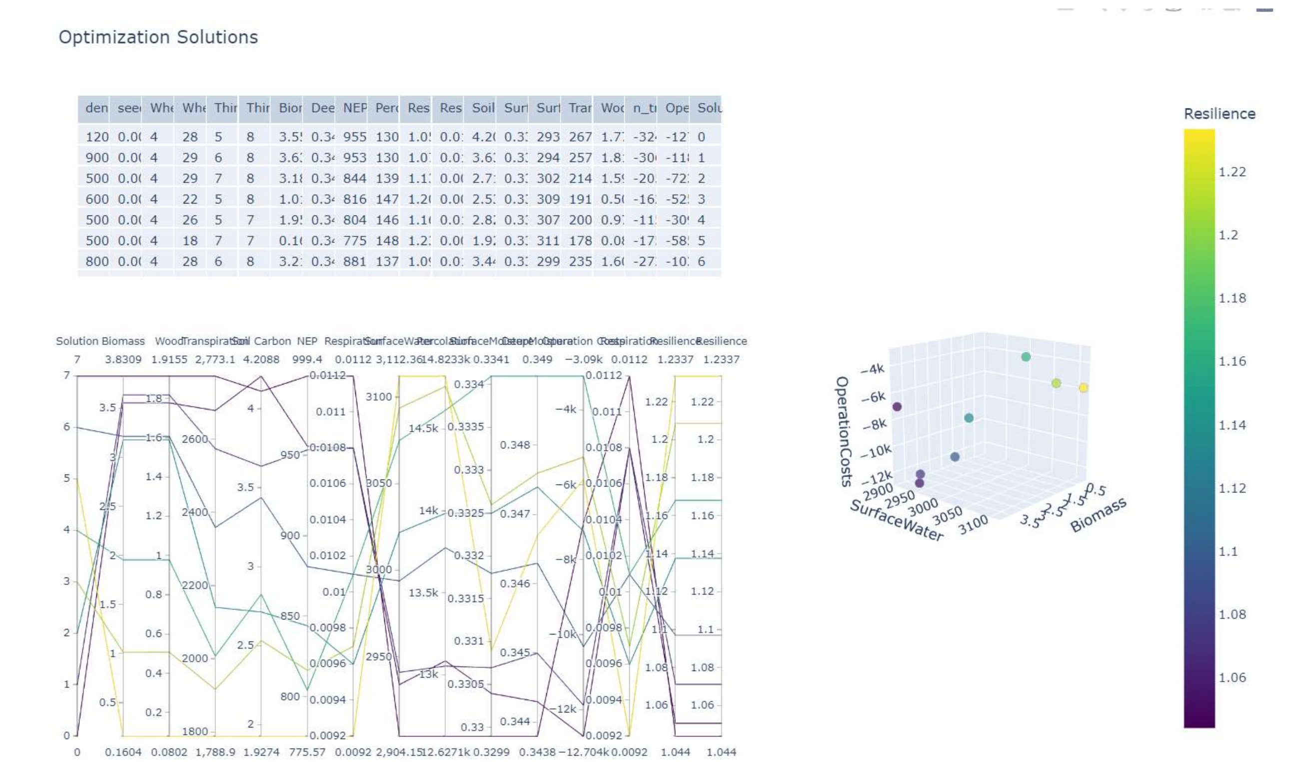
-The table is made up of the values of each metric and each solution, being rows solutions and columns metrics.

-2D parallel coordinate graphs are lines connecting values of the metrics in each solution. That is, each line is a solution and connects all metrics. This graph is editable, being able to move the position of the metrics between them, and it can also be filtered by clicking on a metric and making a specific range.

3D Cube is a three-dimensional graph of the metric values previously configured at the top of the visualisation tab. Where the values can be viewed interactively.

With all this, the user must select a solution to be able to see the clear map if he has used a distributed model or end the use of CAFE.

In any case, the results of the table with all the solutions are saved in the "Result" folder as .csv and the interactive visualisation is stored as .html for later visualisation externally to the DSS or in case you want to share it with other managers.


Optimization Solutions

den	see	Whe	Whe	Thir	Thir	Bior	Dee	NEP	Per	Res	Res	Soil	Surl	Surl	Trar	Woc	n_ti	Ope	Solu
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900	0.0(	4	29	6	8	3.6:	0.34	953	130	1.0:	0.0:	3.6:	0.3:	294	257	1.8:	-30	-11!	1
500	0.0(	4	29	7	8	3.1!	0.34	844	139	1.1:	0.0(	2.7:	0.3:	302	214	1.5!	-20.	-72:	2
600	0.0(	4	22	5	8	1.0:	0.34	816	147	1.2(	0.0(	2.5:	0.3:	309	191	0.5(	-16.	-52!	3
500	0.0(	4	26	5	7	1.9!	0.34	804	146	1.1(	0.0:	2.8:	0.3:	307	200	0.9:	-11.	-30!	4
500	0.0(	4	18	7	7	0.1(	0.34	775	148	1.2:	0.0(	1.9:	0.3:	311	178	0.0!	-17.	-58!	5
800	0.0(	4	28	6	8	3.2:	0.34	881	137	1.0!	0.0:	3.4	0.3:	299	235	1.6(	-27.	-10:	6

Figure 23. Interactive result of the Pareto front.

5.2. Thinning Maps

This result can be viewed in a separate tab and opens automatically when the "See thinning map" button is clicked when the user has chosen a particular solution. As mentioned above, this result can only be seen when using a distributed simulation model (Tetis or RHESsys).

The map shown is the stand layer that the user stored in the "maps" folder and which is in the WGS84 coordinate system. This map shows in the central part, the stands with different colours, in the right part there is a legend where each light intensity has a colour and can even be clicked or unclicked to hide or show those stands with that value. Meanwhile, at the bottom of the screen there is a bar showing the time in which the clear intensity is executed, here you can see the different performances over time if they have been selected by the user.

This result is stored at the same time in the "Results" folder in HTML format so that it can be opened at a later time or shared with another manager.

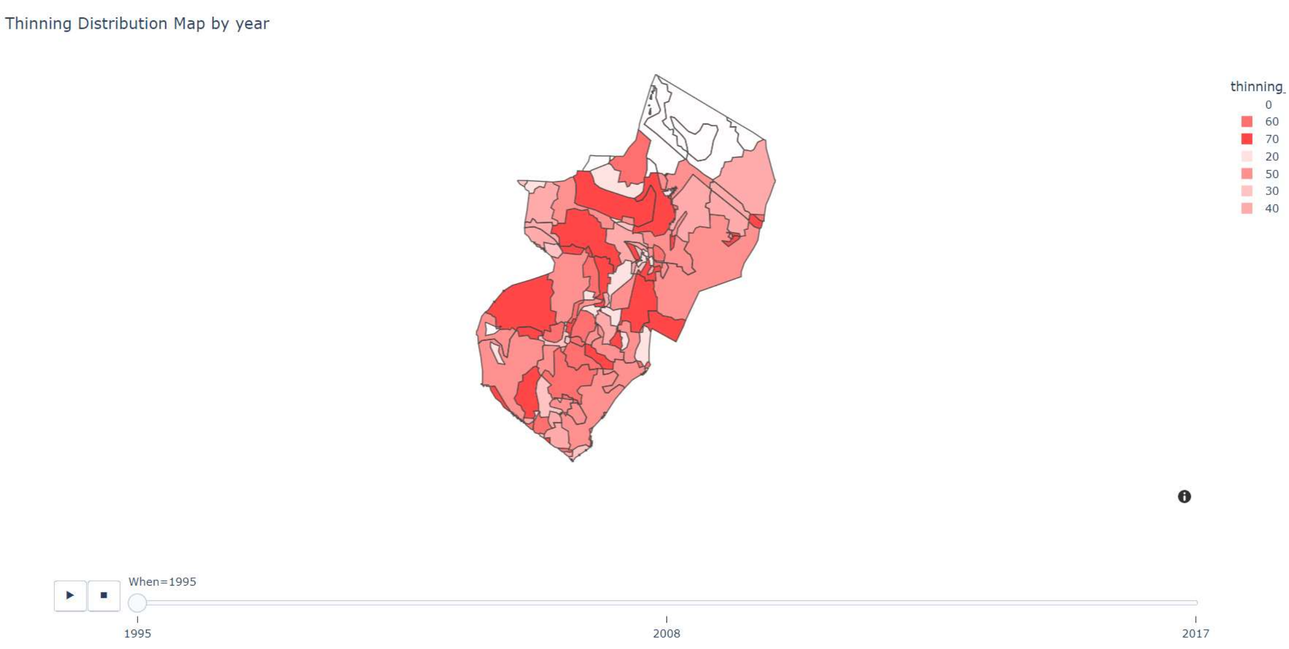

Figure 24. Interactive result of the clearance distribution map.

6. Exporting results

The previously viewed results, as mentioned above, are stored in the "Results" folder. This folder is directly linked to our computer so that everything that is seen inside the image created in the Docker container is seen on our Local Disk. This automatically allows us to access the files that are generated in it on both computers, ours and the one created by Docker. So, we go into the "Results" directory and we can copy and paste the files that have been generated and that we want to save in another directory.

7. Turning off DSS

To pay CAFE, you have two ways to operate. One from the cmd console you have to execute "Ctrl + C" to abort the execution of the DSS on the web page. Whereas, if you want to shut down the created virtual machine, you must then type "Exit" and enter.

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Another way to shut it down completely, is from the Docker application where you can press the stop button "Stop".

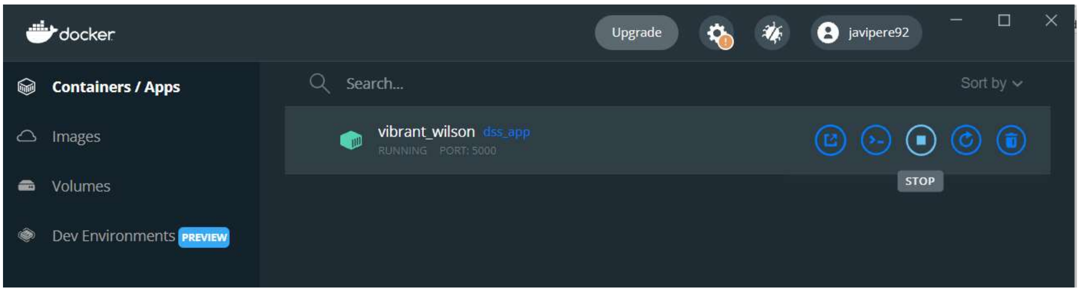

Figure 25. Turn off CAFE from Docker.

10. References

Deb, K., 2015. Multi-Objective Evolutionary Algorithms, in: Kacprzyk, J., Pedrycz, W. (Eds.), Springer Handbook of Computational Intelligence, Springer Handbooks. Springer, Berlin, Heidelberg, pp. 995–1015. https://doi.org/10.1007/978-3-662-43505-2_49

Francés, F., Vélez, J.I., Vélez, J.J., 2007. Split-parameter structure for the automatic calibration of distributed hydrological models. J. Hydrol. 332, 226–240. https://doi.org/10.1016/j.jhydrol.2006.06.032

Hadjimichael, A., Gold, D., Hadka, D., Reed, P., 2020. Rhodium: Python Library for Many-Objective Robust Decision Making and Exploratory Modeling. J. Open Res. Softw. 8, 12. https://doi.org/10.5334/jors.293

Pasquato, M., Medici, C., Friend, A.D., Francés, F., 2015. Comparing two approaches for parsimonious vegetation modelling in semiarid regions using satellite data. Ecohydrology 8, 1024–1036. https://doi.org/10.1002/eco.1559

Ruiz-Pérez, G., Koch, J., Manfreda, S., Caylor, K., Francés, F., 2017. Calibration of a parsimonious distributed ecohydrological daily model in a data-scarce basin by exclusively using the spatio-temporal variation of NDVI. Hydrol. Earth Syst. Sci. 21, 6235–6251. https://doi.org/10.5194/hess-21-6235-2017

Running, S.W., Hunt, E.R., 1993. 8 - Generalization of a Forest Ecosystem Process Model for Other Biomes, BIOME-BGC, and an Application for Global-Scale Models, in: Ehleringer, J.R., Field, C.B. (Eds.), Scaling Physiological Processes, Physiological Ecology. Academic Press, San Diego, pp. 141–158. https://doi.org/10.1016/B978-0-12-233440-5.50014-2

Tague, C.L., Band, L.E., 2004. RHESSys: Regional Hydro-Ecologic Simulation System—An Object-Oriented Approach to Spatially Distributed Modeling of Carbon, Water, and Nutrient Cycling. Earth Interact. 8, 1–42. https://doi.org/10.1175/1087-3562(2004)8<1:RRHSSO>2.0.CO;2

Tanevski, J., Simidjievski, N., Todorovski, L., Džeroski, S., 2017. Process-Based Modeling and Design of Dynamical Systems, in: Altun, Y., Das, K., Mielikäinen, T., Malerba, D., Stefanowski, J., Read, J., Žitnik, M., Ceci, M., Džeroski, S. (Eds.), Machine Learning and Knowledge Discovery in Databases, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 378–382. https://doi.org/10.1007/978-3-319-71273-4_35

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Zhou, A., Qu, B.-Y., Li, H., Zhao, S.-Z., Suganthan, P.N., Zhang, Q., 2011. Multiobjective evolutionary algorithms: A survey of the state of the art. Swarm Evol. Comput. 1, 32–49. https://doi.org/10.1016/j.swevo.2011.03.001

Bond-Lamberty, B., Gower, S. T., & Ahl, D. E. (2007). Improved simulation of poorly drained forests using Biome-BGC. Tree Physiology, 27(5), 703-715.

Chen, B., Liu, Z., He, C., Peng, H., Xia, P., & Nie, Y. (2020). The Regional Hydro-Ecological Simulation System for 30 Years: A Systematic Review. Water, 12(10), 2878.

Chiesi, M., Maselli, F., Moriondo, M., Fibbi, L., Bindi, M., & Running, S. W. (2007). Application of BIOME-BGC to simulate Mediterranean forest processes. Ecological Modelling, 206(1-2), 179-190.

Coughlan, J. C., & Dungan, J. L. (1997). Combining remote sensing and forest ecosystem modeling: an example using the Regional HydroEcological Simulation System (RHESSys). In The use of remote sensing in the modeling of forest productivity (pp. 135-158). Springer, Dordrecht.

Eastaugh, C. S., Pötzelsberger, E., & Hasenauer, H. (2011). Assessing the impacts of climate change and nitrogen deposition on Norway spruce (Picea abies L. Karst) growth in Austria with BIOME-BGC. Tree Physiology, 31(3), 262-274.

Engstrom, R., Hope, A., Kwon, H., Harazono, Y., Mano, M., & Oechel, W. (2006). Modeling evapotranspiration in Arctic coastal plain ecosystems using a modified BIOME-BGC model. Journal of Geophysical Research: Biogeosciences, 111(G2).

Garcia-Prats, A., González-Sanchis, M., Del Campo, A. D., & Lull, C. (2018). Hydrology-oriented forest management trade-offs. A modeling framework coupling field data, simulation results and Bayesian Networks. Science of the Total Environment, 639, 725-741.

González-Sanchis, M., Del Campo, A. D., & Molina, A. J. (2015). Modeling adaptive forest management of a semi-arid Mediterranean Aleppo pine plantation. Ecological Modelling, 308, 34-44.

Li, C., Sun, H., Wu, X., & Han, H. (2020). An approach for improving soil water content for modeling net primary production on the Qinghai-Tibetan Plateau using Biome-BGC model. Catena, 184, 104253.

Liu, K. (2019). Forest Carbon and Water Fluxes Simulation Using Multi-layer Soil Parameters Assimilation. Remote Sensing Technology and Application, 34(5), 950-958.

Nunes, L., Gower, S. T., Peckham, S. D., Magalhaes, M., Lopes, D., & Rego, F. C. (2015). Estimation of productivity in pine and oak forests in northern Portugal using Biome-BGC. Forestry: An International Journal of Forest Research, 88(2), 200-212.

Puertes, C., González-Sanchis, M., Lidón, A., Bautista, I., del Campo, A. D., Lull, C., & Francés, F. (2020). Improving the modelling and understanding of carbon-nitrogen-water interactions in a semiarid Mediterranean oak forest. Ecological Modelling, 420, 108976.

Ruiz-Pérez, G., González-Sanchis, M., Del Campo, A. D., & Francés, F. (2016). Can a parsimonious model implemented with satellite data be used for modelling the vegetation dynamics and water cycle in water-controlled environments?. Ecological modelling, 324, 45-53.

Sanchez-Ruiz, S., Chiesi, M., Fibbi, L., Carrara, A., Maselli, F., & Gilabert, M. A. (2018). Optimized Application of Biome-BGC for Modeling the Daily GPP of Natural Vegetation Over Peninsular Spain. Journal of Geophysical Research: Biogeosciences, 123(2), 531-546.

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Schmid, S., Zierl, B., & Bugmann, H. (2006). Analyzing the carbon dynamics of central European forests: comparison of Biome-BGC simulations with measurements. Regional Environmental Change, 6(4), 167-180.

Shin, H., Park, M., Lee, J., Lim, H., & Kim, S. J. (2019). Evaluation of the effects of climate change on forest watershed hydroecology using the RHESSys model: Seolmacheon catchment. Paddy and Water Environment, 17(4), 581-595.

Tatarinov, F. A., & Cienciala, E. (2006). Application of BIOME-BGC model to managed forests: 1. Sensitivity analysis. Forest Ecology and Management, 237(1-3), 267-279.

Ueyama, M., Ichii, K., Hirata, R., Takagi, K., Asanuma, J., Machimura, T., ... & Hirano, T. (2010). Simulating carbon and water cycles of larch forests in East Asia by the BIOME-BGC model with AsiaFlux data. Biogeosciences, 7(3), 959-977.

The project LIFE RESILIENT FORESTS – Coupling water, fire and climate resilience with biomass production from forestry to adapt watersheds to climate change is co-funded by the LIFE Programme of the European Union under contract number LIFE 17 CCA/ES/000063.