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SOFTWARE

R3DFEM: an R package for running the 3D-CMCC-FEM model

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Abstract

Forest ecosystems account for about one-third of the Earth's land area, and monitoring their structure and dynamics is essential for understanding the land's carbon cycle and its role in the greenhouse gas balance. In this framework, process-based forest models (PBFMs) allow studying, monitoring and predicting forest growth and dynamics, capturing spatial and temporal patterns of carbon fluxes and stocks. The 'Three Dimensional-Coupled Model Carbon Cycle—Forest Ecosystem Module' (3D-CMCC-FEM) is a well-known eco-physiological, biogeochemical, biophysical process-based model, able to simulate energy, carbon, water and nitrogen fluxes and their allocation in homogeneous and heterogenous forest ecosystem. The model is specifically designed to represent forest stands, from simple ones to those with complex structures, involving several cohorts competing for light and other resources in a prognostic way. The model is also designed to simulate current forest management practices commonly applied in Europe. The 3D-CMCC-FEM model is implemented in C-language, which can be challenging for the broad public to use, thus limiting its applications. In this paper, we present the open-source R package 'R3DFEM' which introduces efficient methods for: i) generating and handling input data needed for the model initialization; ii) running model simulations with different setup and exploring input; and iii) plotting output data. The functions in the R-package are designed to be user-friendly and intended for all R users with little to advanced coding skills, who aim to perform simulations using the 3D-CMCC-FEM. Here we present the package and its functionalities using some real case studies and model applications.

Keywords Forest modeling · Carbon cycle · Climate change · R package · Open access

Introduction

Forest ecosystems play an active role in the global carbon cycle, acting as a climate regulator by modulating the exchange of energy, carbon and water fluxes between lands and atmosphere (Huntingford et al. 2009; Collalti et al. 2016). In particular, via the gross primary production (GPP), forests fix atmospheric CO_2 as an organic compound offsetting anthropogenic emission of greenhouse gases. Due to the key role of forests in the climate change context, much progress was achieved in the development of process-based forest models (PBFMs) integrating more and more representation of detailed eco-physiological and population-related processes (Makela et al. 2000). However, most models have limitations in accurately predicting forest photosynthesis, growth and carbon dynamics, particularly for forests that exhibit high structural complexity natural or semi-natural forests, especially in the Mediterranean regions, can be composed of numerous tree species with complex horizontal and vertical structures, resulting from past management and

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disturbance regime. Despite the importance of representing forest complexity, just a few models are able to represent heterogeneous ecosystems (Seidl et al. 2012; Collalti et al. 2014; De Wergifosse et al. 2022), and, at the same time, in a way that is accessible and user-friendly for non-practitioners or those without programming expertise. To address this limitation—which may hinder the broader use of the 3D-CMCC-FEM model, particularly among non-expert users—we introduce the R3DFEM package. This R-based tool is specifically designed to make the application of the 3D-CMCC-FEM model more accessible, user-friendly, and ready to use. By providing a simplified interface and streamlined workflows within the widely used R environment, R3DFEM facilitates model implementation, data handling, and output analysis, thus significantly lowering the technical barriers to using a complex process-based forest model like 3D-CMCC-FEM.

The 3D-CMCC-FEM model

The 3D-CMCC-FEM model is biogeochemical, biophysical process-based model specifically designed to represent forest stands of different dimensions and from simple ones to those with complex structures, involving several cohorts competing for light and other resources. The model is developed with the aim to simulate both fluxes and stocks at different temporal and spatial scales, i.e., from daily to annual (depending on the process to simulate), and, i.e., from stomata to ecosystem level processes (depending on the process but also on the ecological level to simulate) (Collalti et al. 2024).

Main processes

In the 3D-CMCC-FEM photosynthesis is represented via the biogeochemical model of Farquhar et al. (1980) for sun and shaded leaves and parametrized as in Bernacchi et al. (2001). Therefore, any changes in atmospheric CO_2 concentration, the so-called "CO_2 fertilization effect," are already embedded into the biogeochemical photosynthesis model. Temperature acclimation of leaf photosynthesis to increasing temperature is accounted for following Kattge and Knorr (2007). Autotrophic respiration (R_A) is considered the sum of maintenance respiration of already living tissue (R_M) and respiration for growth (R_G) modeled mechanistically. Maintenance respiration is controlled by the amount of nitrogen (stoichiometrically fixed fraction of live tissues) and temperature of the different respiring tree pools (i.e., leaves, branch and bark, stem, coarse and fine roots). Temperature effects on enzyme kinetics are modeled through a standard Arrhenius relationship but acclimated for temperature as described in Collalti et al. (2018). Net primary production (NPP) is computed as gross primary production minus R_A, and its partition and allocation in the main plant compartments (stem, branch, leaf, fruit, fine and coarse root, including non-structural carbon compounds [NSC] i.e. a reserve carbon pool) follows species-specific patterns, described in Merganicova et al. (2019) and Collalti et al. (2016, 2019, 2024). When and if all NSCs are depleted because of metabolism without being replenished through NPP, the model simulates and predicts stand mortality based on the carbon starvation hypothesis (McDowell 2011). In the latest versions (see for example: Collalti et al. 2019, 2020; Dalmonech et al. 2022, 2024; Testolin et al. 2023; Morichetti et al. 2024; Vangi et al. 2024a, 2024b), nitrogen fluxes and allocation, in the same carbon pools, are also considered.

Model initialization

The 3D-CMCC-FEM, as a stand-level model, is initialized by providing the forest structure information, such as species share, average diameter at breast height (DBH) and age class at a certain date (commonly at the first of January). The 3D-CMCC-FEM model also implements past management practices (e.g., thinning and harvest) and can predict their effects on forest growth, carbon sequestration and stock under future climate change scenarios or within a 'what if' scenarios framework. The model has been extensively tested for many European species in monospecific and multispecies stands, both under climate change and management scenarios and compared with other forest models (see e.g. Mahnken et al. 2022; Saponaro et al. 2024; Morichetti et al. 2024). Validation with ground-based measured data, both for fluxes and stocks, is recommended before application with untested species. The model does not simulate natural disturbances that are not represented in the input meteorological data (such as fires, wind damage and pathogens) and does not simulate migration and natural change of species.

The programming language

The 3D-CMCC-FE is written in C-language and divided into several libraries and source files, each describing the main physiological processes, within thousands of line codes (about 30.000 lines). Despite the potential of the model in monitoring and forecasting forest ecosystems in simulating forest growth under different management and climate assumptions, reported extensively in the literature, its applicability still remains for users with a good programming level, limiting the possibilities offered by this tool. Wrapping the model in an R package can ensure a simpler approach for users with less programming experience and a better way to share the knowledge on which the model is based, expanding the user base and simultaneously improving the model itself through the reporting of issues and the experiences of researchers. The first version of the presented *R3DFEM* package was recently used to investigate the impact of stand age on the stability and resilience of forest carbon budget under current and climate change scenarios (Vangi et al. 2024a) and to explore the direct effects of climate change on the total carbon woody stock and mean annual increment across different species and ages cohorts (Vangi et al. 2024b) as well as for the effects of different forest management practices on carbon and water fluxes in a suite of European beech forest stands (Saponaro et al. 2024). The 3D-CMCC-FEM model was heavily tested and evaluated for fluxes and stocks in a multitude of forests across Europe, from the plot level to the regional and national scale, and compared against others PBFM (https://www.forest-modelling-lab.com/publications). More recently, the model has seen its applications out of Europe, in Canada (Puchi et al. 2024) and other non-European applications are ongoing in prep.).

This paper aims to: i) present the *R3DFEM* R package for running the 3D-CMCC-FEM model; and, ii) test the package in different real-case scenarios. First, we provide a detailed description of the functions and features of the package (Sect. 2). Second, we show illustrative examples by applying *R3DFEM* over different forest stands and validate the outputs against field measurement (Sect. 3). Third, we explore the impact of this new package by highlighting the scientific and operative contribution of *R3DFEM* (Sect. 4).

The R3DFEM design and implementation

R3DFEM is an R package written in R 4.2 (R Core team 2017) and compatible with the latest R versions. The package is designed as a wrapper to the main source C-code of the 3D-CMCC-FEM model. Currently, the main source code is compiled in an executable (.exe) file for Windows OS only and the package is guaranteed to be compatible with Windows OS only. The main function performs some basic input checks and builds the system call to the.exe file of the model without impacting the output structure or computational time, which instead can vary depending on the OS. At the installation of the package, all the routines and process, written in C-language are downloaded as a compiled.exe file. The R package follows a simple name convention: all function names start with a verb indicating the function's primary purpose followed by an underscore (i.e. plot_, run_, check_, Table 1). *R3DFEM* uses the *data.table* package (https://r-datatable.com) for the data structure, allowing fast and memory-efficient data aggregation and manipulation. The main function (run_3DFEM) is designed to call the.exe in an easily parallelizable way, exploiting the computational power of the modern PC. The output of the 3D-CMCC-FEM is a simple.txt file that, in addition to the in-built functions in the package, can be read by the most common R packages for data handling and plotting, such as *data.table*, *readxl* and *ggplot2*. *R3DFEM* provides functions for: i) checking and creating input data, ii) running simulations, and iii) plotting input and output data. For each function, we provide detailed information in subsequent sections.

Inputs and outputs

Below we present a schematic description of the input needed by the functions in the R package:

For initialization, the 3D-CMCC-FEM requires as input data:

- The initial stand conditions: species name (since the model is parameterized at specie-level), age, mean tree height, diameter at breast height (DBH), and number of trees per size cell. The initial data are aggregated per classes (height classes, cohorts and species) by a pre-processing activity as follows: (1) the relative values of diameters class is associated for each species, (2) the corresponding value of height class is assigned for each diameter class, and (3) the relative age is assigned for each height class (Collalti et al. 2014; 2024).
- Species-specific parameters, are mostly based on species-specific eco-physiological and allometric characteristics and can be partially derived from forest inventories and

Table 1 Functions within the R3DFEM package, listed in alphabetical order

Function name	Description
check_meteo_3DFEM	Check that the input meteo data meets the model specifications
make_CCS	Create a detrended input meteo file from observed meteo data
make_gif_3DFEM	Create a gif from the annual output of the model
make_stand_INFC	Create an input forest stand file from the Italian NFI tree level data
make_topo	Create the input topographic file that meets the model specification
plot_meteo_3DFEM	Plot time series of climate variables form an input meteo file
plot_output_3DFEM	Plot time series of output variables from the output file of the model
plot_soil_3DFEM	Make a ternary plot from the input soil file of the model
run_3DFEM	Run the 3D-CMCC-FEM model
virtual_stand_generator	Create a forest stand file for a user-defined age from an initial stand file

literature (Collalti et al. 2019). Along with the package comes a suite of already parameterized files for different and most common European tree species, used in many real case studies across Europe.
- Meteorological forcing data: daily maximum (Tmax, °C) and minimum air temperature (Tmin, °C), soil temperature whitin the first meter of depth (Tsoil, °C), vapour pressure deficit (hPa), global solar radiation (MJ m^{-2} day^{-1}) and precipitation amount (mm day^{-1}).
- Annual atmospheric CO_2 concentration (ppm).
- Nitrogen deposition (optional) (Collalti et al. 2018).
- Soil and topographic information: soil depth (in cm), average sand, clay, silt percentages and elevation. These information are static parameters during throughout the simulation.

All input data need to be written into separate.txt files whose structure is fully described in the user manual (https://www.forest-modelling-lab.com/_files/ugd/8a7700_d31451e9a5e64073b50c07f7f007eb71.pdf). Based on the input files and the argument setting, the function wrapping the model (run_3DFEM) creates a setting file in the output directory which is used only by the internal C code; the user does not need to interact with the setting file.

The main output of the 3D-CMCC-FEM (either at daily, monthly or annual scale) are: Gross Primary Productivity (GPP), Net Primary Productivity (NPP), and state variables such as evapotranspiration (ET), Leaf Area Index (LAI) and rain interception (to cite some). Results are obtained either at class-level (species, diameter, height, or age class level), layer-level (as the sum of all tree height classes in the same layer), and grid level (as the sum of all classes in the different layers). The model provides information to support decision-making in forest management planning, such as mean annual volume increment (MAI), current volume increment (CAI), basal area, and DBH.

Since this paper has not the aim to describe the underlying model processes and functionalities, for detailed information about 3D-CMCC-FEM and its applications we strongly encourage to refer to the literature (Collalti et al. 2014, 2016, 2020, 2024; Marconi et al. 2017; Mahnken et al. 2022; Dalmonech et al. 2022, 2024; Testolin et al. 2023; Vangi et al. 2024a, 2024b; Morichetti et al. 2024; Saponaro et al. 2024), and the main web page (https://www.forest-modelling-lab.com/the-3d-cmcc-model, accessed online on 26/09/2024), where the most updated user guide can be found (which include the detailed description of all inputs and outputs, as well as the instruction for launching the model from command line, Eclipse and Bash; Collalti et al. 2022). Throughout the paper and in the description of the functions we will often refer to the user guide and the official web page (Table 2).

Main functions

Below is shown a schematic representation of the main function of the package and their relations with respect to outputs and inputs (Fig. 1).

Initialization and input check

R3DFEM offers functions to check the requirements of input data for the model and some facilities to perform common tasks in modeling applications, such as detrending climate data for creating baseline scenarios in climate change impact studies.

The function *check_meteo_3DFEM* takes as input a path to a.txt meteo file (see the 3D-CMCC-FEM User Guide parag. 4.5 for the specific format and name convention of the meteo file), which consists of daily meteorological observation, covering the entire simulation period. The function checks throughout the simulation period several assumptions to ensure that the input meets the model requirements, such as the consistency of temperature values (Tmin < Tmean < Tmax), the consistency of solar radiation,

Table 2 Package metadata

Code metadata description	
Current code version	v.0.0.1
Operating system and platform	Microsoft Windows 10 and above
Permanent link to code/repository used for this code version	https://github.com/VangiElia/R3DFEM
Legal code license	GNU GPLv3.0
Code versioning system used	git
Software code languages, tools, and services used	R version 4.2.1
Compilation requirements, operating environments, and dependencies	R packages: data.table, dplyr, exactextractr, foreach, magrittr, sf, terra, withr, zoo
If available, link to developer documentation/manual	https://github.com/VangiElia/R3DFEM https://www.forest-modelling-lab.com/the-3d-cmcc-model https://www.forest-modelling-lab.com/_files/ugd/8a7700_d31451e9a5e64073b50c07f7f007eb71.pdf
Support email for questions	elia.vangi@isafom.cnr.it, daniela.dalmonech@cnr.it, alessio.collalti@cnr.it,

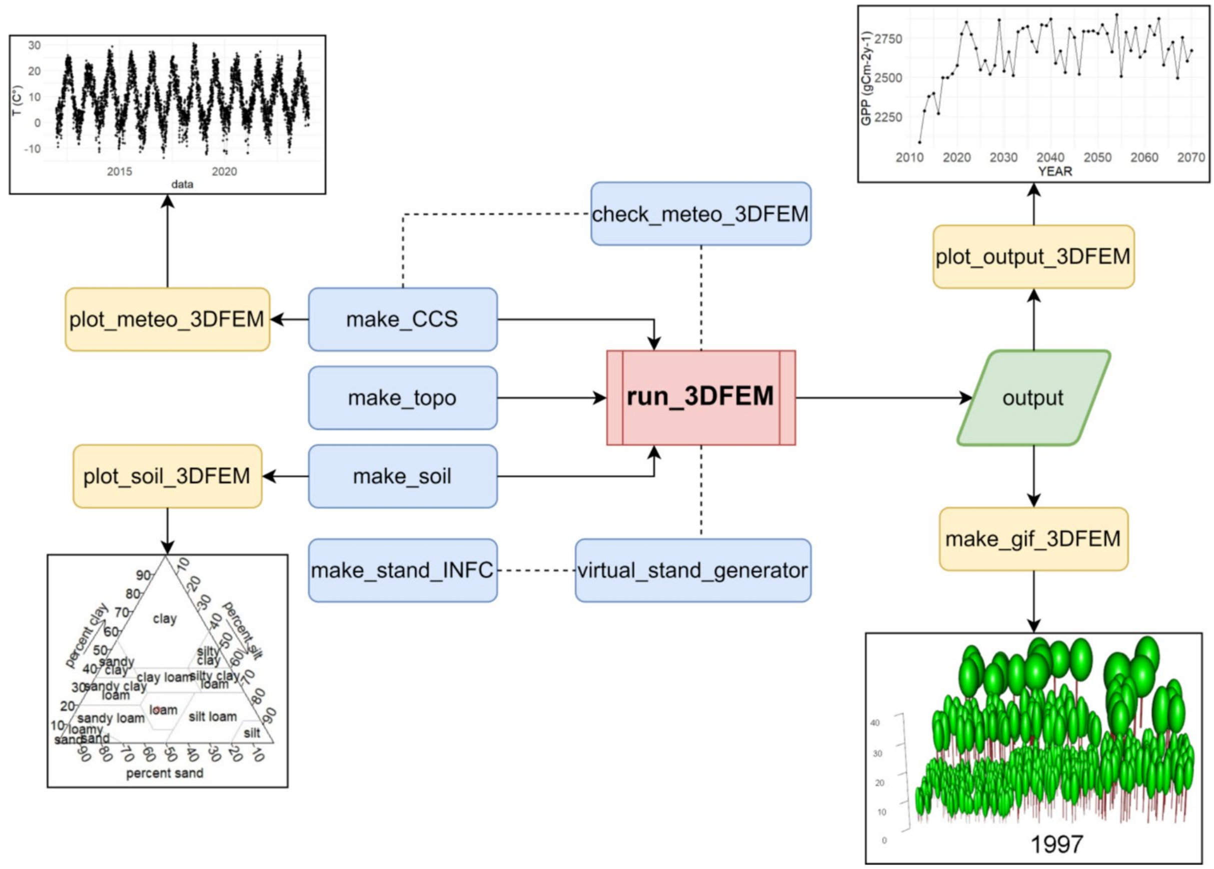

Fig. 1 Flowchart of *R3DFEM* package. In blue, functions for creating/manipulating input data; in red, the main function for running the model; in green, the output; in yellow, functions for plotting inputs and outputs. The arrows represent the pathways of the output of the different functions, while the dashed line represents an optional pathway

precipitation and relative humidity values (values > 0), the correctness of the number of days in each month and years (leap years are also considered), the presence of missing values or wrong column names spelling. The function reports any inconsistency with the model specification and (if specified by the user) tries to fix any errors (when a temperature error is encountered in the input meteo file, the function resolves the temperature inconsistency by exchanging the values between maximum, minimum and average temperature in such a way that the relationship Tmin < Tmean < Tmax is met. Precipitation, radiation and humidity values < 0 are assigned 0 values), saving a new file with corrected data. Daily input meteorological data are adjusted within the whole simulation period.

The function *make_stand_INFC* uses the package in-built tree-level data from the Italian National Forest Inventory (INFC) to create the stand initialization file, meeting the model specification (see the User Guide parag. 4.2 for the format of the stand file). Like all the other input data, this is a.txt file with the stand structural characteristics, such as the age, mean DBH, height, and number of trees for the main species in the plot. This function is intended to create real examples of input files with the structural characteristics of a forest stand. This is not a strictly necessary function for applying the model and the other package functions but can be used to create templates of the input stand file and to test the model on real forests.

The function *virtual_stand_generator* creates "virtual stands" from a real stand file (such as one created by *make_stand_INFC*) by running the model with the real stand information and under a no climate change scenario (usually created by the repeated and detrended cycle of observed climate with the package providing the function *make_CCS* for this purpose) and, usually, with a BAU management. Simulations are run as far as the stand reaches the age needed by the user. From the output the structural attributes at specific ages are extracted (an in-depth description of the rationale is described in Dalmonech et al. 2022 and Vangi et al. 2024a, b). This approach, known as the Composite Forest Matrix (CFM), is designed to generate a set of virtual forest stands that represent a wide range of age classes and their associated structural attributes. The goal is to produce model outputs that are representative of an entire forest rotation period, approximately 140 years, depending on the species and management practices. Simulations are initialized using the current state of the forest and run under a de-trended current climate scenario with business-as-usual (BAU) management. At a specified point, either before or after the end of the rotation period, depending on user requirements, key structural variables such as tree density, age, diameter at breast height (DBH), and tree height are extracted from the simulation outputs. This method enables the characterization of long-term forest dynamics under current climate and management conditions. This function is useful to assess (and to depict) the effect of the age at the beginning of a simulation for the same stand or to create representative forest parcels, without the need to perform new field campaigns or inventory not always performable or available.

The function *make_topo* creates the topographic file following the model specification, starting from the coordinates and elevation of the site (see the User Guide parag. 4.4 for the format and name convention of the topographic file).

The function *make_CCS* creates a "current climate scenario" from a meteo file, by detrending and repeating cycles of observed meteo up to a user-defined time span. The function needs at least two years of meteo data, even if 30 years of observed meteo are usually needed to define a climate regime. This function is useful for creating baseline-scenarios i.e. counterfactual scenarios, against which climate change scenarios and 3D-CMCC-FEM model outputs can be compared (see for an example Collalti et al. 2018). It is important to note that two years of climate data are the minimum requirement for the function to run, but the authors advise against using such a short time series to create a baseline climate scenario. 30 years of observation is usually the number of years considered suitable to define a climate regime.

Running simulations

The main function of the package is *run_3DCMCCFEM* which is a wrapper around the C code compiled in the exe file provided within the package. The function allows to run the model from the R environment. Each argument of the C functions is matched in the wrapper, so that the model can be launched with every possible setting. First, the function performs several checks needed to ensure the consistency of all arguments specified by the user, then the function checks the consistency against the model specifications and finally builds the system call to run the model, translating the R-code to a Bash call. All the inputs needed for the simulation (see the 3D-CMCC-FEM User Guide parag. 4 for a detailed overview of each input file), must be in the same directory, whose path is an input for the function. The output is saved locally following a root path that depends on the simulation setting (i.e. temporal scale of the output, name of the simulated site, whether the simulation has been performed with fixed CO_2 or with active management, etc.) and is managed internally by the C-code. The user needs to specify the working directory where to save the simulation outputs and the function creates the tree path accordingly. The output files, saved by the function, consist of the main output file and contain the model results about the carbon, nitrogen, and water fluxes and stock values for each time step (i.e. day, month, year), each species, age class, dbh class and layer (see the 3D-CMCC-FEM User Guide pararg. 4.10 for the detailed output list), a debug file, where, in case of failed simulation, all the errors of the run and the list of the input file used for the simulation are reported (useful for debugging and sharing).

Plotting

The package implements some functions for a visual assessment of inputs and outputs, which can also be used for publications, reporting and other activities.

The function *plot_soil_3DFEM* creates a soil texture diagram (also known as triangle plot or ternary plot) from the input soil file of the model (see the 3D-CMCC-FEM User Guide parag. 4.3 for detailed information on the soil input file). In a ternary plot, 3D textural coordinates, whose sum is constant, are projected in the 2D space using simple trigonometry rules. Our Package exploits the *triax.plot* function from the *plotrix* R-package (Lemon 2006) to build the soil diagrams.

The function *plot_meteo_3DFEM* creates a time-series plot of climate-forcing variables starting from the path of a meteo file. It is possible to define the period of the time series, and to plot a moving average at a user-defined time window.

The function *plot_output_3DFEM* allows to plot one or more variables from the output file of a simulation run. The function can plot the time series of one or more output variables or a scatterplot of two variables, depending on the number of inputs specified in the function. In particular, the function accepts two arguments, *x* and *y*. If *y* is not specified, the resulting plot will be a time-series plot, or a scatterplot.

For examples of graphs produced by the plot functions, see the next parag 3.

R3DFEM applications

The following section describes the use of the *R3DFEM* package in real-case applications to illustrate the main function's capabilities. In particular, in this section, we will see: i) a validation against Eddy tower fluxes (Pastorello et al. 2020) at the Sorø forest site (Denmark); ii) the creation of virtual forest stands at the Hyytiälä forest site (Finland); iii) a comparison of a climate change scenario against the baseline "current climate" scenario at the Bilý Kříž forest site (Czech Republic).

Study sites

The study was conducted in three even-aged, previously managed European forest stands: i) the Boreal Scots pine (*Pinus sylvestris* L.) forest of Hyytiälä, Finland (FI-Hyy); ii) the wet temperate continental Norway spruce (*Picea abies* (L.) H. Karst) forest of Bílý Krìz in the Czech Republic (CZ-BK1); and iii) the temperate oceanic European beech (*Fagus sylvatica* L.) forest of Sorø, Denmark (DK-Sor). The chosen sites have been selected due to their long monitoring history and the availability of a wide range of data sources for both carbon fluxes and biometric data for model evaluation provided in the PROFOUND database (Reyer et al. 2020), as well as bias-corrected climate scenarios for simulations under climate change scenarios as provided within the ISIMIP initiative (https://www.isimip.org/). For more details about these sites, please refer to Mahnken et al. (2022), Vangi et al. (2024a, b) and Morichetti et al. (2024).

Case 1: validation of GPP at Sorø

This real-case application shown the validation of the main flux (GPP, gC m^{-2} day^{-1}) at the daily temporal scale for the European beech forest of Sorø against the flux data measured by theeddy covariance tower from the FLUXNET database installed at the same site http://fluxnet.org/data/fluxnet2015-dataset/; Pastorello et al. 2020). The sensors installed on the tower continuously measure gas exchange between the land surface (soil and vegetation) and the atmosphere to quantify large-scale net ecosystem carbon exchange from an hourly to yearly time scale.

```r
#Install the package from GitHub
devtools::install_github("VangiElia/R3DFEM")
#load the packages for this exercise
library(R3DFEM)
library(ggplot2)
```

set up the directories

```r
soro <- system.file("extdata","soro",package = "R3DFEM")
#prepare eddy data data
obs_data <- read.csv(list.files(soro,full.names = T,pattern ="validation"))
colnames(obs_data)[2] <- "GPP_obs"
obs_data$date <- as.Date(obs_data$date)
```

Plot soil diagram

Here the function *plot_soil_3DFEM* is used to produce the soil diagram plot of the site, based on the input soil file (Fig. 2).

```r
#plot soil data from the input
plot_soil_3DFEM(list.files(soro, full.names = T,pattern = "soil"),save_plot = F)
```

Run simulations

Here we run a simulation to compare the model output with the measured data from the eddy covariance tower. Since the measured data are provided for the period 1996–2014, and since the available climate data for the site start from 1997, the simulation period is 1997–2014, to cover as much as possible the time window of the observations.

```
base_out <- file.path(tempdir(),"output")
dir.create(base_out,recursive = T)
year_start <- 1997
year_end <- 2014

run_3DCMCCFEM(site="Soroe",
          species = "Fagussylvatica",
          year_start =year_start,
          year_end = year_end,
          man="off",
          output="daily",
          inputdir = soro,
          outputdir = base_out)
```

Read and evaluate the output

In the next piece of code, the model output is read into the R-environment and the variable of interest is plotted against the measured data (Fig. 3).

```
out_path <- list.files(base_out,pattern = as.character(year_start),full.names = T)
df <- data.table::fread(out_path,fill=T)
df$date <- lubridate::make_date(df$YEAR,df$MONTH,df$DAY)

evaluation <- merge.data.frame(df[,c("date","GPP")],obs_data[,c("date","GPP_obs")])

#basic performance metric
rsqr <- round(cor(evaluation$GPP,evaluation$GPP_obs)^2,2)

#plot flux data
ggplot(evaluation)+
 geom_point(aes(date,GPP_obs),alpha=1)+
 geom_line(aes(date,GPP),col="red",linewidth=1,alpha=.8)+

 ylab(bquote(paste("GPP in gC ",m^-2,day^-1)))+
 annotate("text",as.Date("1997-06-06"),25,label=bquote(paste(
  R ^ 2, "=",.(rsqr))))
```

Case 2: virtual stand generation at Hyytiälä

In this real-case application is shown the use of the *R3DFEM* package for the creation of virtual stands on the Hyytiälä site (Finland).

```
library(R3DFEM)
library(ggplot2)
```

set up the directories

```
indir <- system.file("extdata","hyytiala",package = "R3DFEM")
tmp_outdir <- file.path(tempdir(),"output")
dir.create(tmp_outdir)
```

creates the "virtual stands"

The main function in this application is *virtual_stand_generator*. The function *virtual_stand_generator* creates a new folder in *outputdir* called "virtual stand" where the new virtual stands information are saved. Figure 4 shows the structural variable of stands of different ages created with the virtual_stand_generator function.

```
virtual_stand_generator(site="Hyytiala",
                species="Pinussylvestris",
                stand_age = c(20,30,40,50,60),
                man="off",
                inputdir=indir,
                outputdir = tmp_outdir)
```

checks the output

```
#original stand file
original_stand <- read.table(list.files(indir,full.names = T,pattern =
"stand"),header=T,sep=",")
#the virtual stand files
virtual_stand_path <- list.files(file.path(tmp_outdir,"virtual_stand"),full.names = T)
virtual_stand_path
#merge all the files for plotting
virtual_stand <- lapply(virtual_stand_path, read.table,header=T,sep=",")
virtual_stand <- do.call(rbind,virtual_stand)
stands <- rbind(original_stand,virtual_stand)
stands$Age <- as.factor(stands$Age)
#reshape to long format
vs_melt <-
reshape2::melt(stands,id.vars="Age",measure.vars=c("N","AvDBH","Height"))
#plot
ggplot(vs_melt,aes(x=Age,y=value,fill=Age))+
 geom_bar(stat = "identity")+
 scale_fill_viridis_d(option="H")+
 facet_wrap(~variable,scales = "free")+
 theme(axis.title = element_text(size = 25),
     axis.text = element_text(size = 25),
     strip.text = element_text(size = 25),
     legend.title = element_text(size = 25),
     legend.text = element_text(size = 25))
```

Case 3: climate change scenario at Bilỳ Křiž

This real-case application shown the use of the *R3DFEM* package for running simulations under different climate change scenarios. We will use a baseline scenario (created by detrending and repeating observed climate for 100 years) and the RCP 8.5 scenarios, the most severe in terms of increase in temperature, solar radiation and atmospheric CO2 increase. Climate data under RCP 8.5 is bias-adjusted downscaled climate data derived from the HadGEM2-ES Earth System Model. The package is also used for plotting some input and model output data.

```
library(R3DFEM)
library(ggplot2)
```

set up the directories

```
bilykriz <- system.file("extdata","bilykriz",package = "R3DFEM")
path_scenaros <- list.dirs(bilykriz,recursive = F)
```

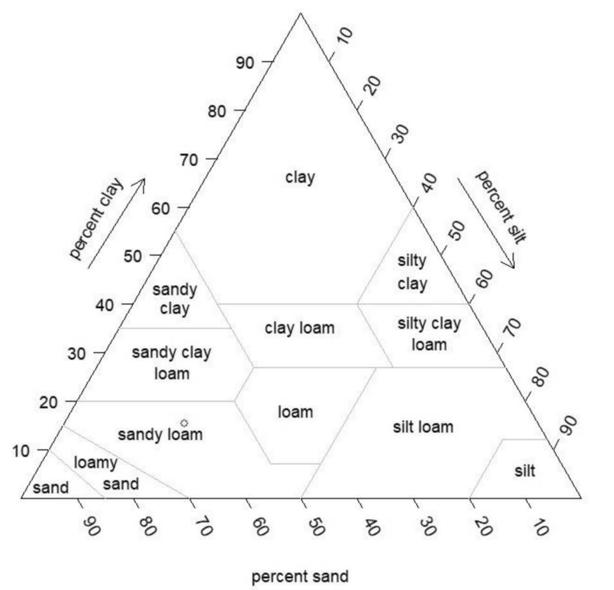

Fig. 2 Soil texture diagram obtained with the function plot_soil_3DFEM at Sorø

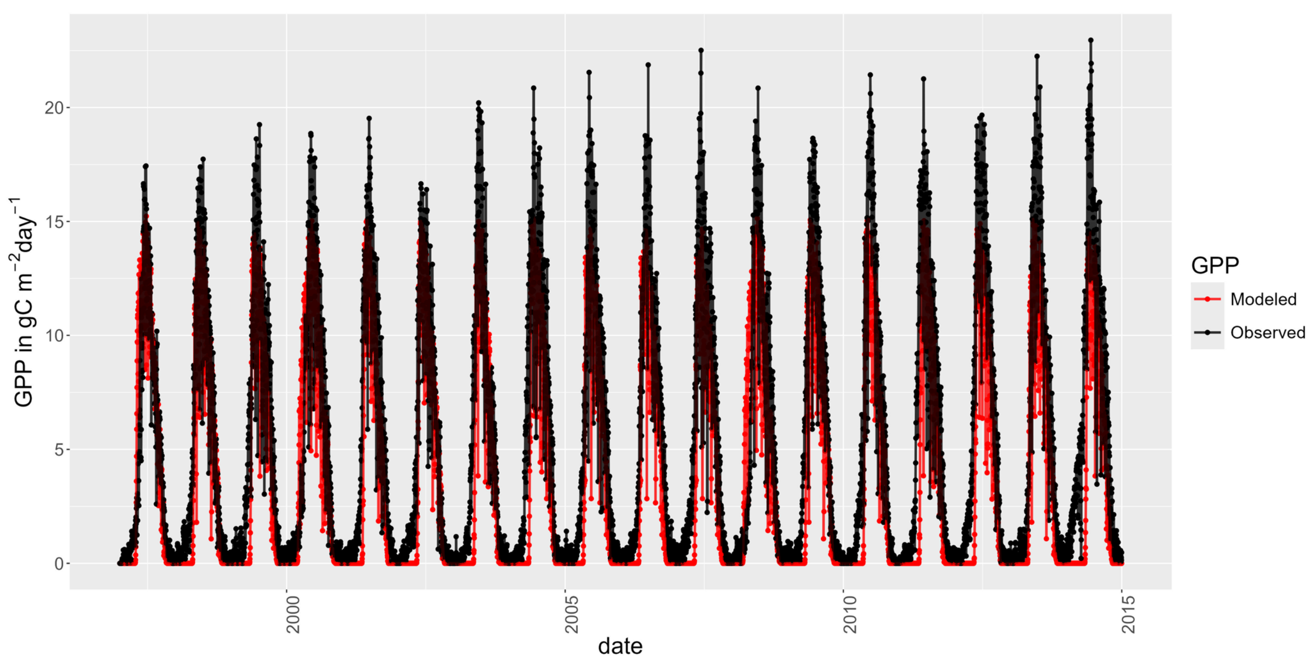

Fig. 3 Comparison of daily GPP (gC m^{-2} day.$^{-1}$) flux between model simulation (in red) and observed eddy covariance flux data (black dot)

Plot mean temperature for both scenario

Here the function *plot_meteo_3DFEM* is used to produce the time-series plot of the mean temperature from the meteo file of both scenarios (Fig. 5).

```
#plot file meteo for baseline scenario
t00 <-
 plot_meteo_3DFEM(
  list.files(path_scenaros[1], pattern = "meteo", full.names = T),
  var = "Ta_f",
  daterange = c("2000-01-01", "2022-12-31"),
  window = 365
 ) +
 labs(title = "Baseline scenario")
#plot file meteo for RCP 8.5
t85 <-
 plot_meteo_3DFEM(
  list.files(path_scenaros[2], pattern = "meteo", full.names = T),
  var = "Ta_f",
  daterange = c("2000-01-01", "2022-12-31"),
  window = 365
 )+
 labs(title = "RCP 8.5")
#plot  temperature for both scenarios
gridExtra::grid.arrange(t00,t85,nrow=2)
```

Run simulations

This piece of code illustrates a possible way to launch multiple simulations in loop (in this case, two simulations). Since each simulation is independent from the others, it is possible to launch the simulations in parallel, using the different parallelization packages offered by R, for example, the for each (Microsoft and Weston 2022), future (Bengtsson 2021) and snow packages, with the possible use of different backhands like doParallel, doMC or doSnow (not illustrated here).

```
base_out <- tempdir()
dir.create(base_out)
year_start <- 1997
yera_end <- 2099
for(i in seq_along(path_scenaros)){
 outdir <- file.path(base_out,basename(path_scenaros[i]),"output")
 dir.create(outdir,recursive = T)

 run_3DCMCCFEM(site="BilyKriz",
          species = "Piceaabies",
          year_start =year_start,
          year_end = yera_end,
          man="off",
          output="annual",
          inputdir = path_scenaros[i],
          outputdir = outdir)
}
```

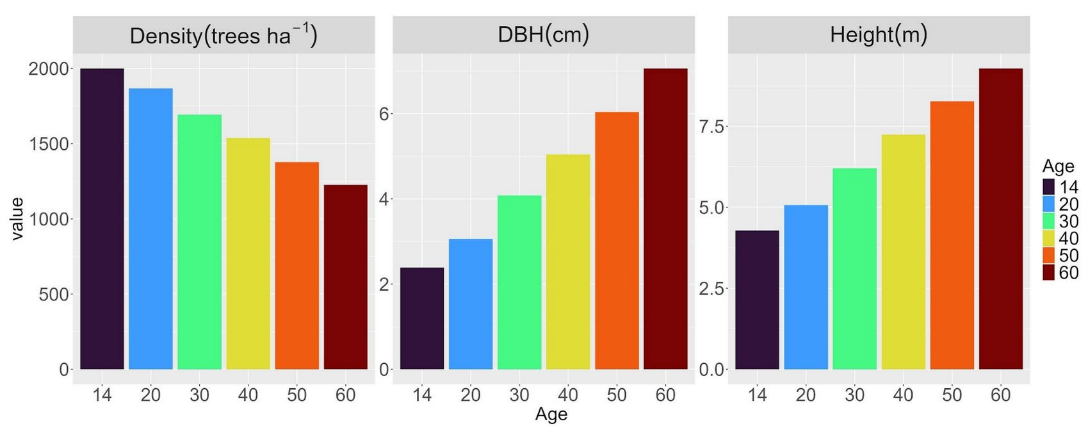

Fig. 4 Structural variables of stands of different ages. The 14-year-old stand is the original one from which the"virtual stands" were created

Read and plot the outputs

Analogously, it is possible to read each output file in a loop and to build a single data.frame containing the results of all simulations. In this way, it is possible to compare the different model results in one plot, as shown in Fig. 6.

```
l <- as.list( seq_along(path_scenaros))
for(i in seq_along(path_scenaros)){

 outdir <- file.path(base_out,basename(path_scenaros[i]),"output")
 out_path <- list.files(outdir,pattern = as.character(year_start),full.names = T)
 df <- data.table::fread(out_path,fill=T)
 df <- df[complete.cases(df),]
 df$scenario <- basename(path_scenaros[i])
 l[[i]] <- df
}

data <- data.table::rbindlist(l)
#plot fluxes data
m <-
reshape2::melt(data,id.vars=c("scenario","YEAR"),measure.vars=c("GPP","NPP","RA"))

ggplot(m,aes(YEAR,value,col=scenario))+
 geom_line(linewidth=1.5)+
 facet_wrap(~variable,scale="free",ncol=1)
```

In this example under the RCP 8.5 climate scenario, the stand dies because of carbon starvation, i.e., emptying of the carbon reserve pool of the trees due to plant's respiration exceeding photosynthesis (see also Collalti et al. 2018, 2020). In this case, the variables related to the vegetation's incoming fluxes (e.g., photosynthesis) go to 0. In contrast, the outgoing fluxes (e.g., heterotrophic respiration due to decomposition) and stocks vary accordingly, and the simulation continues until the expected simulation time frame. This is an extreme case under the most impacting climate scenarios (i.e., RCP8.5) and under well well-known “hot” climate model (i.e., HadGEM2-ES Earth System Model) making part of the ISIMIP climate dataset.

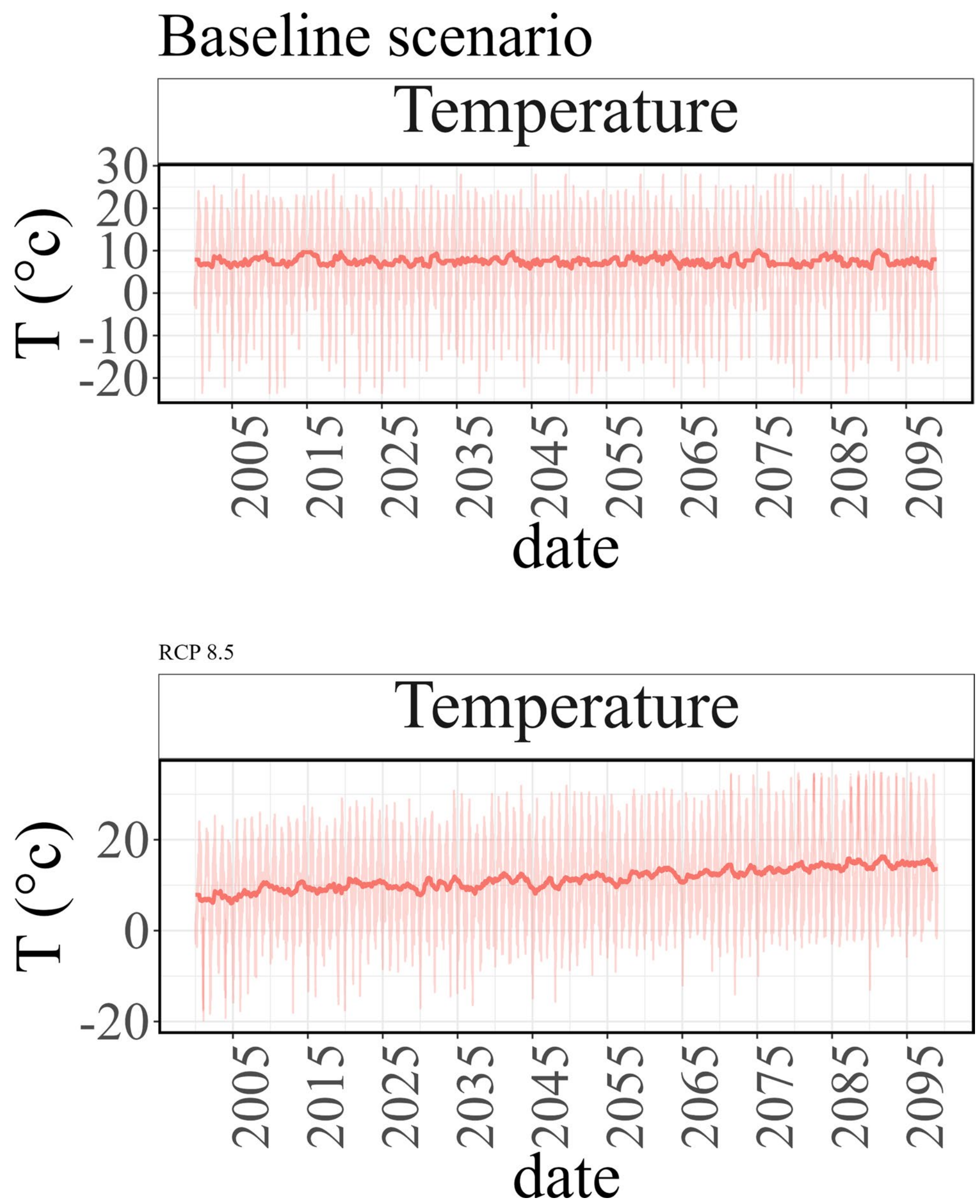

Fig. 5 Mean temperature at Bilŷ Křiž under the current climate scenario (baseline, top panel) and the most severe climate change scenario (RCP 8.5, bottom panel)

Final consideration

PBFMs offer a complementary tool to ground-based forest inventory networks and remote sensing observations for monitoring and predicting future wood and carbon stocks in forest ecosystems and several other variables that are otherwise difficult to measure or monitor continuously. However, the reliability of any model must be verified and tested in different contexts and environments. To do this, as many people as possible should have easier access to these tools. With this aim, we wrap the biogeochemical, biophysical, process-based model 3D-CMCC-FEM in an R-package, hoping to expand its use to a wider range of users. Our package provides a ready-to-use tool that allows quick control of inputs and outputs in an accessible programming language like R, ultimately simplifying the use of the 3D-CMCC-FEM model, allowing more researchers to make the most of the PBFM capabilities. The simplicity of the developed functions allows even people with minimal knowledge of the R programming language to interact successfully with the model. Despite this advantage, we want to stress the necessity to fully understand the model's

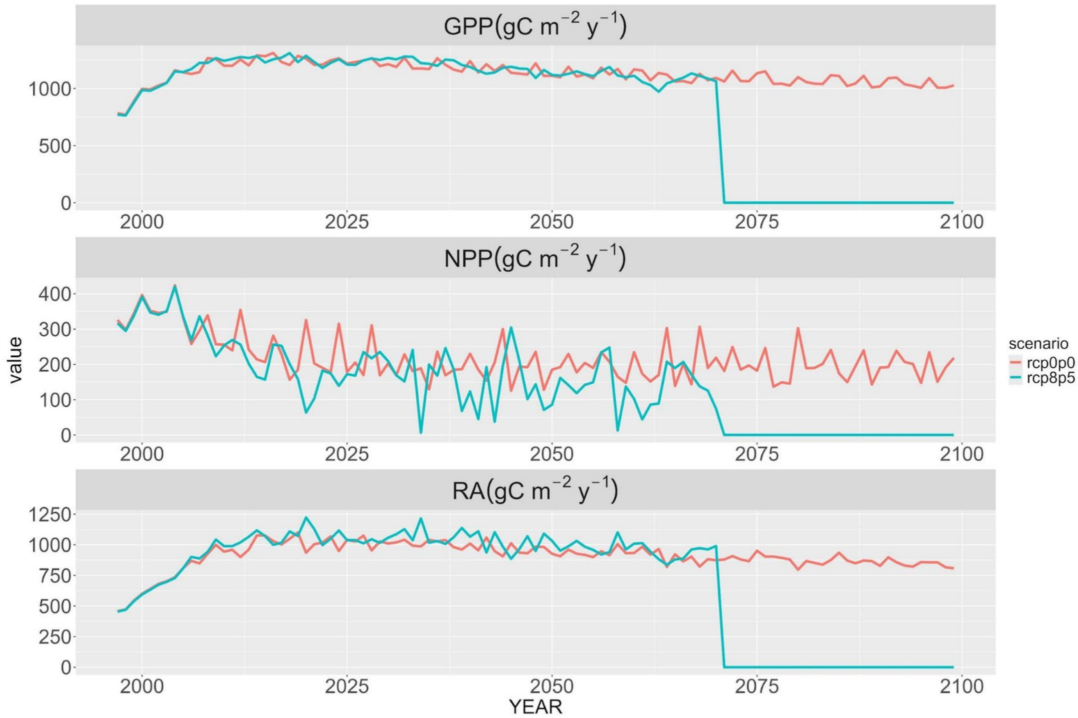

Fig. 6 Main fluxes (GPP, NPP, RA; gC m^{-2} day^{-1}) at Bilỳ Kříž under the baseline climate and RCP 8.5 scenarios

underlying characteristics, processes and their interactions before approaching it and testing it on real case studies. Interested readers can find up-to-date documentation and studies on the model's official web page (https://www.forest-modelling-lab.com/the-3d-cmcc-model) and on the model code repository (https://www.github.com/Forest-Modelling-Lab/3D-CMCC-FEM).

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Data availability No datasets were generated or analysed during the current study.

Code availability The source code of the *R3DFEM* package is accessible via GitHub at https://github.com/Forest-Modelling-Lab/R3DFEM. After the download and installation disk occupancy of the *R3DFEM* package is approximately 33 MB and it works on Microsoft Windows platforms (Table 2).

Declarations

Competing interest The authors declare no competing interests.The authors declare no competing interests.

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