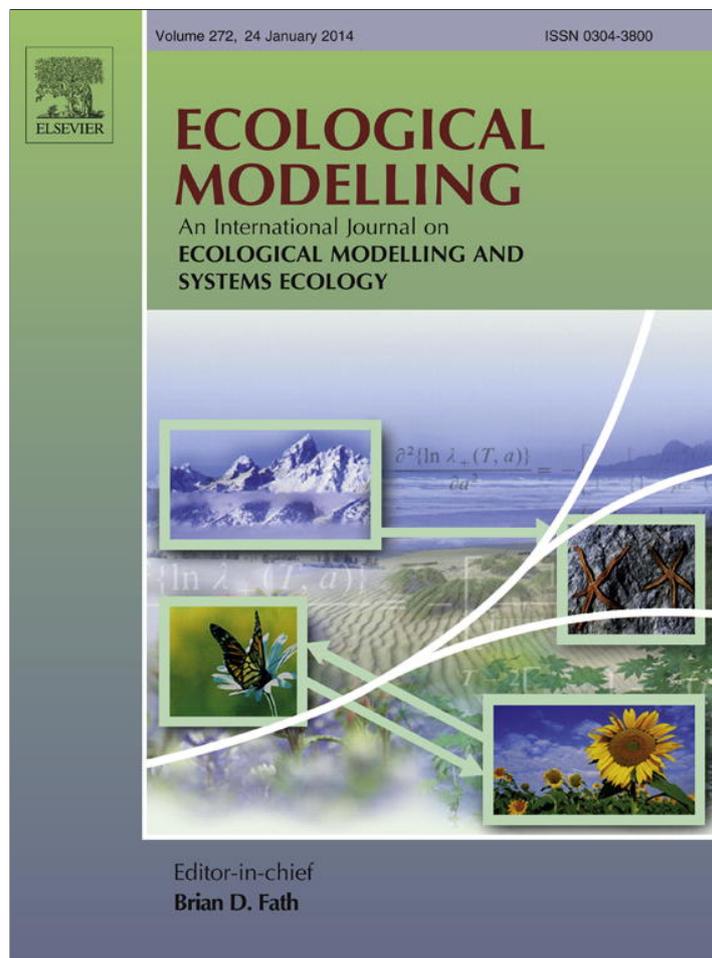


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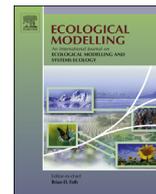
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## Ecological Modelling

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# A process-based model to simulate growth in forests with complex structure: Evaluation and use of 3D-CMCC Forest Ecosystem Model in a deciduous forest in Central Italy



Alessio Collalti<sup>a,b,\*</sup>, Lucia Perugini<sup>b</sup>, Monia Santini<sup>a</sup>, Tommaso Chiti<sup>b</sup>, Angelo Nolè<sup>c</sup>, Giorgio Matteucci<sup>d,e</sup>, Riccardo Valentini<sup>a,b</sup>

<sup>a</sup> EuroMediterranean Center on Climate Changes – Impacts on Agriculture, Forest and Natural Ecosystem Division (IAFENT), 01100 Viterbo, VT, Italy

<sup>b</sup> University of Tuscia – Department for Innovation in Biological, Agro-Food and Forest Systems (DIBAF), 01100 Viterbo, VT, Italy

<sup>c</sup> School of Agricultural, Forestry, Food and Environmental Sciences (SAFAA) – University of Basilicata, 85100 Potenza, PZ, Italy

<sup>d</sup> CNR-ISAFOF – National Research Council, Institute for Agricultural and Forestry Systems in the Mediterranean, 87036 Rende, CS, Italy

<sup>e</sup> CNR-IBAF – National Research Council of Italy, Institute of Agroenvironmental and Forest Biology, 00015 Monterotondo Scalo, RM, Italy

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## ABSTRACT

Forest ecosystems are characterized by high spatial heterogeneity, often related to complex composition and vertical structure which is a challenge in many process-based models. The need to expand process-based models (PBMs) to take in account such structural complexity led to development and testing of a new approach into Forest Ecosystem Models (FEMs), named 3D-CMCC-FEM, able to investigate carbon and water fluxes, including biomass pools and their partitioning, for complex multi-layer forests. 3D-CMCC FEM integrates several characteristics of the functional-structural tree models and the robustness of the light use efficiency (LUE) approach to investigate forest growth patterns and yield processes. The modelling approach was tested by simulating the effects of competition for light and water, growth and yield of a two-layered deciduous forest dominated by Turkey Oak in central Italy for a period of eight years. The model outputs were validated against a series of independently measured data for the major biomass pools, the inter-annual stem increments and above-ground net primary productivity of the overstorey and understorey, respectively. The comparison of Leaf Area Index, Gross Primary Production, and evapotranspiration produced by the model against MODIS data showed agreement in results. In addition, the multi-layered model approach was evaluated against a series of simplified versions to determine whether the enhanced complexity of the model positively contributed to its predictive ability. The proposed model reduced the error in the estimates of forest productivity (e.g. NPP) and dynamics (e.g. growth, mortality) and indicates the importance of considering, as far as possible, the structural complexity in PBMs.

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## 1. Introduction

In recent years, much progress was achieved in the development of mechanistic forest growth models integrating data on energy, carbon, nutrient, and water cycles (Mäkelä et al., 2000). Nevertheless, existing models present some shortcomings in predicting forest growth and carbon dynamics, especially for forests with high structural complexity. Many natural or semi-natural forests are composed of several tree species in various storeys with different

height classes and cohorts (age classes). Thus, the natural forest mosaic is characterized with extensive interactions of multiple tree species, forest growth, and light conditions, which in turn cause vertical and horizontal differentiation in the natural forest mosaic (Bossel and Krieger, 1994). The architecture of trees in particular and a forest in general is the outcome of diverse ecological and physiological processes (Harmon et al., 1990). Furthermore the spatial distribution of trees influences habitat heterogeneity and affects regeneration patterns, tree growth, mortality rate, and resource-use in the forest floor (Lasserre et al., 2006). The key drivers shaping the forest structure are triggered by the competition for resources (light, nutrients, and water), forest management, and human and natural disturbances (e.g. fire). Competition for light and space has impact on tree height and diameter growth, forest canopy cover, and morphology and physiology of leaves (Valladares et al., 2002), whereas forest management and/or

\* Corresponding author at: EuroMediterranean Center on Climate Changes (CMCC), Division of Climate Change Impacts on Agriculture, Forests and Natural Ecosystems (IAFENT), Via Antonio Pacinotti 5, 01100 Viterbo, Italy.  
Tel.: +39 0761357251; fax: +39 0761357389.

E-mail addresses: [alessio.collalti@cmcc.it](mailto:alessio.collalti@cmcc.it), [a.collalti@unitus.it](mailto:a.collalti@unitus.it) (A. Collalti).

natural disturbances modify the complexity of vertical and horizontal structure and interfere with auto-regulation feedbacks and overall forest stability (Swanson and Franklin, 1992; Rubio and Escudero, 2003).

Forest ecosystem complexity is well represented in the Mediterranean basin vegetation and the Italian region, which is characterized by unique physiological features and fragmented landscapes shaped by a long history of human activities (Falcucci et al., 2007; Santini and Valentini, 2011). To address the complexity and provide a more realistic representation of the interactions among the processes in forests with complex structures, a modified approach for analysis is required. Despite the fact that forest complexity is very relevant for Italy, unfortunately few models are able to represent the particular ecosystem structure (Seidl et al., 2012). Light use efficiency models (LUE, Monteith, 1977) widely used for simulating energy, water and carbon exchanges within forests at variable spatial resolution, are limited in terms of their capacity to simulate growth and yield outside plantations (e.g. 3-PG, Landsberg and Waring, 1997; Landsberg et al., 2003; C-Fix, Veroustraete et al., 2002). The DGVMs (Dynamic Global Vegetation Models) family, including LPJ (Sitch et al., 2003), are efficient at coarse spatial resolution ( $0.5^\circ \times 0.5^\circ$ ) but do not integrate stand structure into analysis (Duursma and Mäkelä, 2007).

The combination of Functional–Structural Tree Models (FSTMs, Lacoite, 2000) with the spatially explicit models (e.g. Bugmann, 2001; Sortie, Pacala et al., 1996) allows for simulating a wide range of eco-physiological and structural processes, as well as compositional dynamics with a relatively high resolution (e.g. hectare scale) for structurally complex forests. These assets are however counterbalanced by a larger amount of initialization data or parameters, and require high computational effort. Generally, a weakness of one type of model is a strength of the other, and vice versa. To overcome these limitations in the applicability of the existing models for Mediterranean forests with complex structure, a different approach was developed to combine the simplicity of LUE models with the complexity of the three-dimensional functional forest models, in order to develop an hybrid approach which is able to represent the overall complexity of mixed multi-layered forests without increasing excessively the effort of parameterization and generalization. Based on this approach the 3D-CMCC FEM (three Dimensional Forest Ecosystem Model of the euro-Mediterranean Centre for Climate Change) was designed to investigate processes involved in the growth of forests with high complexity structure. The proposed model is appropriate for short-to-medium scale with minor limitation in terms of analyzing changes in species composition and forest regeneration dynamics. The model was validated over a time period of eight years and the results were compared with independent field data on biomass stocks and increments. Model complexity was furthermore assessed through evaluation exercises based on simulations with different representations of forest structural complexity and demonstrated to improve performance of the full model. The objectives of this paper are to: (1) document the model's architecture, its scientific foundation, and assumptions and mathematical formulations of the 3D-CMCC FEM, (2) demonstrate the model's predictive ability for a test site in Italy through a validation activity and a comparison with MODIS products, (3) assess the model's performance with respect to its simplified versions, (4) and discuss and propose potential model improvements.

## 2. Methods

### 2.1. Model description

The 3D-CMCC FEM is a hybrid PBM coupled with the concepts of the canopy layer models for analysis of forest dynamics (Collalti,

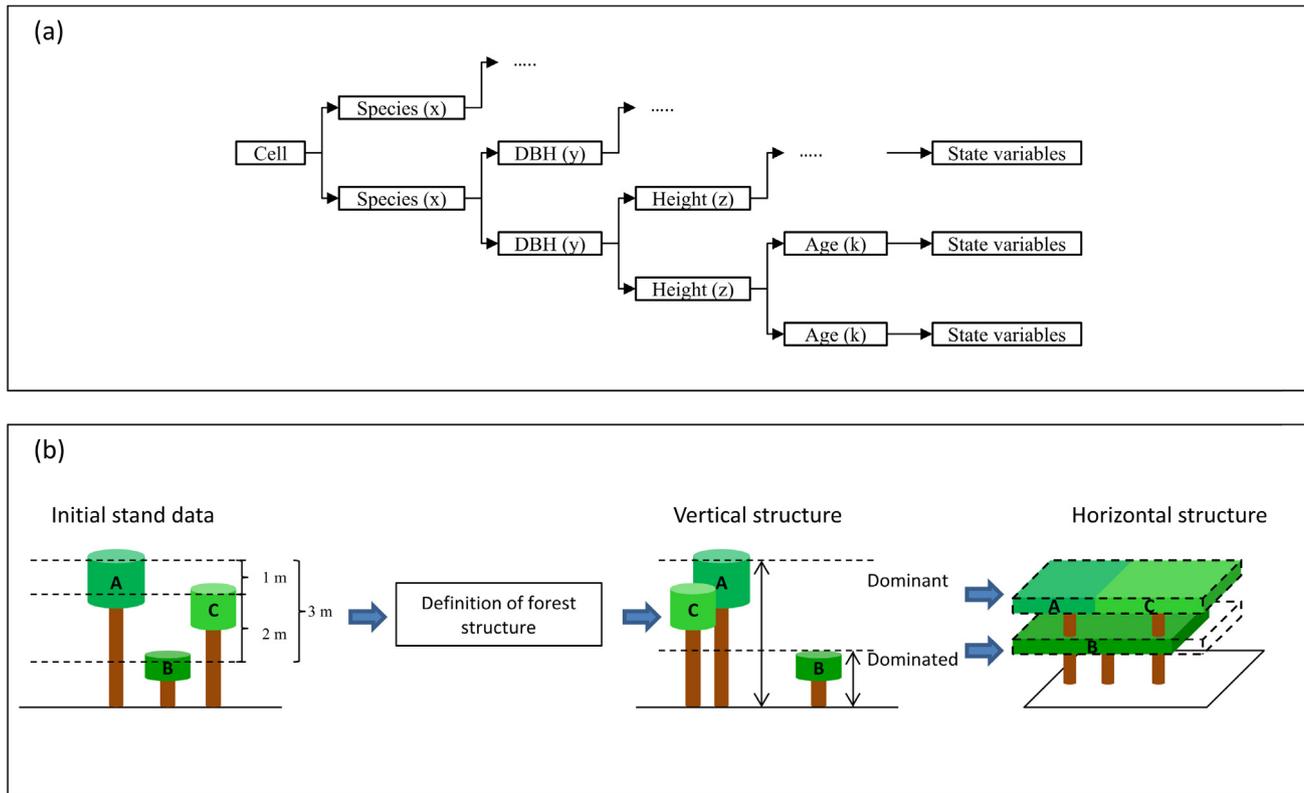
2011), Functional–Structural Tree Models (FSTMs) (Lacoite, 2000), and empirical models predicting intra and inter-annual patterns of carbon yield. The rationale behind this approach is deriving a hybrid model in which the shortcomings of one model family are enhanced by other model families through an integrated approach. Processes simulated in the model are rather detailed to represent small areas with a resolution of one hectare. The solutions adopted in the 3D-CMCC FEM make the model theoretically applicable to a wide variety of complex forest ecosystems, multi-layered both mono- and multi-species stands, both even and uneven-aged structures. The solutions adopted in the 3D-CMCC FEM make the model theoretically applicable to a wide variety of complex forest ecosystems typical for Mediterranean countries. The model takes advantage of eco-physiological information and allometric relationships at species level, derived from field investigation or from literature. The model is partially inspired by existing models such as 3-PG (Almeida et al., 2004; Landsberg and Waring, 1997; Nightingale et al., 2008; Nolè et al., 2009; Sands and Landsberg, 2002; Tickle et al., 2001), 3PG+ (Feikema et al., 2010a,b), Treedyn 3 (Bossel, 1996), Triplex (Peng et al., 2002; Zhou et al., 2004), Forest 5.1 (Robinson and Ek, 2003), Formix2 (Bossel and Krieger, 1994), FinnFor (Kellomaki and Vaisanen, 1997), Sortie (Pacala et al., 1996), BIOME family (Haxeltine and Prentice, 1996; Running and Hunt, 1993; Thornton, 2010) and LPJ (Sitch et al., 2003, 2008). The 3D-CMCC FEM merges the computational architecture of the gap and layer models and the relative simplicity of the well-documented LUE approaches proposed by 3-PG and Triplex. The model, written in C programming language, is divided into several subroutines composed of a series of non-linear differential equations to simulate the major eco-physiological processes occurring at the hectare scale. The architecture allows aggregating trees into representative classes based on their species-specific and structural characteristics that are identified by the model as codes through indexes, i.e. species ( $x$  index), diameter class ( $y$  index), height class ( $z$  index), and age cohort ( $k$  index) (see Fig. 1a). Each nested class is characterized by its species-related parameterization and variables e.g. biomass pools, crown area, light attenuation and mortality. The trees' distribution is represented at three dimensional spatial levels and homogeneously distributed into the grid cell, following the approach proposed by Klausmeier and Tilman (2002) and LPJ (Sitch et al., 2003) (see Fig. 1b). Based on the assumption made by Magnani et al. (2007) that the above-ground net primary production decreases along with the ageing of a forest, the model explicitly takes into account all ages within grid cell, determining a year by year yield reduction due to senescence (Landsberg and Waring, 1997; Waring and McDowell, 2002).

The rapidly changing flow rates including Gross Primary Production and evapotranspiration and the other eco-physiological processes are modelled at a monthly time scale, while the corresponding dynamic changes within the forest structure, such as dendrometry, regeneration, and mortality, are modelled at annual time scale (Fig. 2).

#### 2.1.1. Input data

The meteorological data required by the model at monthly time step are usually available from weather stations. The data include: mean daily incident solar radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ), mean monthly air temperature ( $^\circ\text{C}$ ), monthly average relative humidity (%) that is converted by the model into vapour pressure deficit (Zhou et al., 2004), and monthly cumulated rainfall (mm).

For initialization, the model requires data on the initial stand conditions: species name, age, mean height, diameter at breast height (DBH), number of trees and foliage biomass (the latter only for evergreen species). The initial data are aggregated per classes (height classes, cohorts and species) by a pre-processing activity as following: (1) the relative values of diameters class is associated for



**Fig. 1.** Model data management flowchart (a) and model forest structure definition (b). For each matrix cell the model can be initialized taking into account each species ( $x$  index). For each species the model can consider more than one diameter (DBH) class ( $y$  index) that can have more than one cohorts ( $k$  index). Each nested class has its state variables, at the beginning of each year simulation the model redefines the vertical (i.e. number of layers and class position into the vertical structure,  $z$  value) and horizontal (i.e. class canopy coverage) forest structure depending on initial cell data (first year of simulation) or changes in state variables (next years).

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 (Fig. 1a and Table 1). Species parameters are mostly based on species-specific eco-physiological and allometric characteristics and can be partially derived from forest inventories and literature. Table 2 provides the full list of the required species and site parameters for model run.

### 2.1.2. Output data

The main outputs of the 3D-CMCC FEM (either at 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 (Table 3). Results are obtained either at class-level (species, diameter, height, or age class level), layer-level (as sum of all tree height classes in the same layer), and grid level (as sum of all classes). 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.

### 2.1.3. Sub-models description

The 3D-CMCC FEM is subdivided into a series of sub-models describing the main eco-physiological processes of forest dynamics and the key factors that control carbon and water cycle in the

forest at hectare level. The model runs in succession the same general routines (Fig. 2) for all the classes detected but explicitly takes into account their vertical position within forest structure and then modifying step by step the variables that drive the processes (e.g. light and water availability) using different parameter values for species in the cell.

**2.1.3.1. Definition of forest structure.** At the beginning of simulation, the model defines autonomously physiognomy and structure of the forest in terms of the number of storeys and their grid cell coverage (Fig. 1b). Initially, the model sorts data by ascending height classes and after groups classes into a variable number of storeys (the model allows more than one cohort or species in the same layer), determined by height classes whose reciprocal height differences are larger than a value set by the user (LimLay) (representing the third dimension or the depth of the cell). These considerations on vertical forest structure are necessary to represent competition among different layers with regard to light gradient, evapotranspiration, rainfall interception, and soil water uptake. Thus, the model is flexible and extended in considering forest structure. The horizontal structure (crown layer coverage) is defined using empirical algorithms on the storey density (total number of trees per storey,  $DEN_z$ ), the diameter at breast height (DBH), and the crown diameter to compute crown surface area of a single tree and upscale it

**Table 1**

Test site initialization data,  $W_s$ ,  $W_r$ , and  $W_f$  refer to the initial biomass pools (stem, root and foliage respectively) of the classes  $x$ ,  $y$ ,  $z$  and  $k$ .

Species ( $x$ index)	Diameter (cm) ( $y$ index)	Height (m) ( $z$ index)	Age (year) ( $k$ index)	Number of trees	Phenotype	$W_s$ (Mg ha <sup>-1</sup> )	$W_r$ (Mg ha <sup>-1</sup> )	$W_f$ (Mg ha <sup>-1</sup> )
<i>Q. cerris</i>	23.77	20.84	70	622	Deciduous	297.06	71.29	0
<i>Q. cerris</i>	6.36	8.7	20	2156	Deciduous	29.71	7.13	0

**Table 2**

List, interval values and source of species-related parameters needed and used for parameterization of *Quercus cerris* L., the site related and model settings parameters. The values enclosed in parenthesis are the average value among the literature data used in this study (dim = dimensionless parameter), for parameters FR, FNO, FNN and MO (see Landsberg and Waring, 1997).

Description	Symbol	Unit	Value	Bibliography
<i>Species-related parameters</i>				
Light use efficiency max	$\varepsilon_{\max}$	gC molPAR <sup>-1</sup>	0.3564	For <i>Quercus</i> spp (Waring et al., 1995)
Foliar extinction coefficient	$k$	dim	0.54–0.65 (0.60)	Chiesi et al. (2007), Cutini et al. (1998), Pietsch et al. (2005)
LAI value for max canopy conductance	$L_{\text{cmax}}$	m <sup>2</sup> m <sup>-2</sup>	8	For <i>Quercus</i> spp. (Breuer et al., 2003)
LAI value for max rainfall interception	$L_{\text{imax}}$	m <sup>2</sup> m <sup>-2</sup>	5	(Xenakis et al., 2008)
Max proportion of rainfall intercepted and evaporated from canopy	$i_{\text{rmax}}$	dim	0.15	Xenakis et al. (2008)
Specific leaf area	SLA	cm <sup>2</sup> gC <sup>-1</sup>	140–320 345(240)	Breda (2003), Chiesi et al. (2007), Covone (2006), Cutini et al. (1998), Pietsch et al. (2005)
Branch and bark fraction at juvenile age	$p_{\text{BBO}}$	dim	0.40	Feikema et al. (2010a,b)
Branch and bark fraction at mature age	$p_{\text{BB}}$	dim	0.25	Feikema et al. (2010a,b)
Age at which $p_{\text{BB}} = (p_{\text{BBO}} + p_{\text{BB}})/2$	$t_{\text{BB}}$	year	10	Feikema et al. (2010a,b)
Min basic density for juvenile tree	$\rho_{\text{min}}$	t m <sup>-3</sup>	0.4	For <i>Quercus robur/petrea</i> (Pietsch et al., 2005)
Max basic density for older trees	$\rho_{\text{max}}$	t m <sup>-3</sup>	0.6	For <i>Quercus robur/petrea</i> (Pietsch et al., 2005)
Age at which $\rho = (\rho_{\text{min}} + \rho_{\text{max}})/2$	$t_{\rho}$	year	4	Sands (2004)
Stomatal response to VPD	$k_{\text{D}}$	mbar	0.05	Xenakis et al. (2008)
Canopy boundary layer conductance	$g_{\text{B}}$	m s <sup>-1</sup>	0.01	Chiesi et al. (2007)
Max canopy conductance	$g_{\text{cmax}}$	m s <sup>-1</sup>	0.02	For <i>Quercus</i> spp. Breuer et al. (2003)
Maximum age	$t_{\text{X}}$	year	100	Berneti (1995)
Relative age to give modifier = 0.5	$r_{\text{age}}$	dim	0.75	Xenakis et al. (2008)
Power of relative Age in modifier	$n_{\text{age}}$	dim	4	Xenakis et al. (2008)
Min temperature for tree growth	$T_{\text{min}}$	°C	0	For <i>Quercus ilex</i> (Hoff et al., 2002)
Max temperature for tree growth	$T_{\text{max}}$	°C	40	For <i>Quercus ilex</i> (Hoff et al., 2002)
Opt temperature for tree growth	$T_{\text{opt}}$	°C	15	Berneti (1995)
Average monthly temperature for starting growth	$T_{\text{start}}$	°C	5	Čermák et al. (2008), Schwalm and Ek (2004)
Average monthly temperature for ending growth	$T_{\text{end}}$	°C	5	Čermák et al. (2008)
Allocation parameter	$\omega$	dim	0.8	Arora and Boer (2005)
Parameter controlling allocation to leaves	$\varepsilon_{\text{L}}$	dim	0.35	Arora and Boer (2005)
Parameter controlling allocation to stem	$\varepsilon_{\text{S}}$	dim	0.1	Arora and Boer (2005)
Parameter controlling allocation to roots	$\varepsilon_{\text{R}}$	dim	0.55	Arora and Boer (2005)
Litterfall rate	$\gamma_{\text{FX}}$	year	1	For deciduous tree litterfall rate is always = 1
Average yearly root turnover rate	$\gamma_{\text{R}}$	year	0.02	Sands (2004)
Scaling coefficient in stem mass v diameter. relationship	$a_{\text{S}}$	dim	0.095	Sands (2004)
Scaling exponent in the stem mass v. diameter relationship	$n_{\text{S}}$	dim	2.69	For <i>Quercus alba</i> (Pilli et al., 2006)
Maximum ratio DBH-crown diameter for low density	$DBHDC_{\text{max}}$	dim	0.28	For <i>Quercus</i> spp (Bechtold, 2003)
Minimum ratio DBH-crown diameter for high density	$DBHDC_{\text{min}}$	dim	0.16	For <i>Quercus</i> spp (Bechtold, 2003)
Max height	$H_{\text{max}}$	m	40	Nocetti et al. (2007)
Max DBH	$D_{\text{max}}$	cm	80	Berneti (1995)
H/D ratio in carbon partitioning for high density	$HD_{\text{max}}$	dim	1.4	Prof. Portoghesi (personal communication)
H/D ratio in carbon partitioning for low density	$HD_{\text{min}}$	dim	0.7	Prof. Portoghesi (personal communication)
Slope of asymptotic height	$H_{\text{power}}$	dim	0.042	For <i>Quercus rubra</i> (Sortie-ND)
Chapman-Richards asymptotic maximum height	$CR_{\text{A}}$	dim	34.597	For <i>Quercus</i> spp. (Kershaw et al.)
Chapman-Richards exponential decay parameter	$CR_{\text{B}}$	dim	0.038	For <i>Quercus</i> spp. (Kershaw et al.)
Chapman-Richards shape parameter	$CR_{\text{C}}$	dim	1.104	For <i>Quercus</i> spp. (Kershaw et al.)
Max stem mass per tree at the density of 1000 trees/ha	$W_{\text{Sx1000}}$	kg tree <sup>-1</sup>	350	Sands (2004)
Fraction mean single tree foliage biomass lost due to self-thinning	$m_{\text{F}}$	dim	0	–
Fraction mean single tree root biomass lost due to self-thinning	$m_{\text{R}}$	dim	0.2	Hanson et al. (2001)
Fraction mean single tree stem biomass lost due to self-thinning	$m_{\text{S}}$	dim	0.2	Hanson et al. (2001)
<i>Site related parameters</i>				
Latitude and Longitude	Lat, Long	° and ′	See text	–
GPP/NPP ratio	Y	dim	0.48	For temperate forests (Luyssaert et al., 2007; Oriani, 2010)
Initial available soil water	iASW	mm	150	Oriani (2010)
Maximum available soil water	MaxASW	mm	300	Oriani (2010)
Minimum available soil water	MinASW	mm	50	Oriani (2010)
Fertility rating	FR	dim	0.8	Oriani (2010)
Value of fertility modifier when FR=0	FNO	dim	0.5	Oriani (2010)
Power of (1-FR) in fertility modifier	FNN	dim	0.5	Oriani (2010)
Value of 'm' when FR=0	MO	dim	0.2	Oriani (2010)
Maximum stem density	DEN <sub>max</sub>	Trees/m <sup>2</sup>	0.4	Oriani (2010)
Minimum stem density	DEN <sub>min</sub>	Trees/m <sup>2</sup>	0.01	Oriani (2010)
Tree height difference for storey creation	H <sub>diff</sub>	m	2	This study
<i>Model settings</i>				
Size of cell	sizeCell	m <sup>2</sup>	10,000	This study
Limit layer	LimLay	m	2	This study
Maximum canopy cover	CC <sub>max</sub>	dim	0.95	–
Minimum canopy cover	CC <sub>min</sub>	dim	0.001	–



**Table 3**

List of output data produced by the 3D-CMCC Forest Model. The values are computed for classes, layers and stand level (Y = yearly output, M = monthly output).

Description	Unit	Time step
<i>Forest structure</i>		
Class position into the layers	–	M
Layer canopy cover	%	M
Layer gap	%	M
<i>Light condition for each class</i>		
Vegetative months	month	Y
Light transmitted	%	M
Light absorbed	%	M
Net radiation	MJ m <sup>-2</sup>	M
Par	molPAR m <sup>-2</sup>	M
Apar	molPAR m <sup>-2</sup>	M
<i>Water balance</i>		
Available soil water	mm	M
Rain interception	mm	M
Canopy conductance	m s <sup>-1</sup>	M
Soil evaporation	mm	M/Y
Canopy evapotranspiration	mm	M/Y
<i>Biomass production</i>		
Gross Primary Production	gC m <sup>-2</sup>	M/Y
Net Primary Production	gC m <sup>-2</sup> /MgDM ha <sup>-1</sup>	M/Y
<i>Biomass allocation</i>		
NPP to root	gC m <sup>-2</sup> /MgDM ha <sup>-1</sup>	M/Y
NPP to stem	gC m <sup>-2</sup> /MgDM ha <sup>-1</sup>	M/Y
NPP to foliage	gC m <sup>-2</sup> /MgDM ha <sup>-1</sup>	M/Y
Litter biomass	gC m <sup>-2</sup> /MgDM ha <sup>-1</sup>	Y
Average stem mass	Kg tree <sup>-1</sup>	Y
Lai	m <sup>2</sup> m <sup>-2</sup>	M/Y
Fraction of branch and bark	%	M/Y
<i>Mortality</i>		
Number of dead trees	Tree ha <sup>-1</sup>	Y
<i>Stand attributes</i>		
DBH	cm	Y
Height	m	Y
Crown diameter	m	Y
Crown area	m <sup>2</sup>	Y
Basal area	m <sup>2</sup> tree <sup>-1</sup>	Y
Mean annual volume increment (MAI)	m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup>	Y
Current annual volume increment (CAI)	m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup>	Y

2.1.3.2. *Light competition.* Competition for light, water and nutrients is one of the most important factors influencing biomass allocation patterns ultimately aiming at the maximization of growth (Tilman, 1988). A multi-layered model is suitable for estimating the attenuation and the spatial variation of leaf photosynthesis or water use within the canopy (Wang and Leuning, 1998). The light competition module in 3D-CMCC FEM is essentially a modified version of the Lambert-Beer law (Monteith and Unsworth, 1990) approximated by the Monsi-Saeki formulation of exponential attenuation and coupled with the “Big-leaf” approach developed for a multi-layered model (Medlyn et al., 2003b; Sands, 1995; Sellers et al., 1992). The modified version permits calculating the monthly amount of light available for a variable number of stories. The amount of light is a factor used in assessment of carbon assimilated through the light use efficiency approach and other light-dependent processes, including soil evaporation and evapotranspiration. The model treats each storey as one “Big leaf” (Farquhar, 1989) by scaling each physiological process from leaf to canopy level and considering the exchange between upper storey and lower storeys. Thus each canopy storey absorbs a substantial fraction of the received light, while part of the light reaches the forest floor and creates different light conditions and growth rates for the understoreys.

The average amount of absorbed and unabsorbed light is function of the covered and uncovered area of the tree crowns within

each storey and is considered in the assessment of light available for the understoreys.

The amount of light available for photosynthetic processes (APAR, Absorbed Photosynthetic Active Radiation, molPAR m<sup>-2</sup> month<sup>-1</sup>) for the species *x*, with diameter *y* and age *k* in the overstorey is computed following the general Beer approach (for simplicity we present equations of a simple case of two layers):

$$APAR_{x,y,k,z_{overstorey}} = PAR_0 \times (1 - \exp^{-k_x LAI_{x,y,k,z_{overstorey}}}) \quad (4)$$

where  $PAR_0$  (molPAR m<sup>-2</sup> month<sup>-1</sup>) is the photosynthetically active radiation above the overstorey, while the exponential term represents the percentage of absorbed fraction, *k* is the species-specific light extinction coefficient that is a function of the angle of inclination of leaves and transmissivity of foliage (variable from 0 to 1), and LAI is the Leaf Area Index (m<sup>2</sup> m<sup>-2</sup>) of the species *x* with diameter *y*, and age *k* in the dominant layer. The PAR available for the lower storey ( $PAR_{z_{understoreys}}$ ) is a ‘mixture’ of  $PAR_0$  absorbed and transmitted through the overstorey gap. The model considers absorbed light as a function of the overstorey canopy cover ( $CC_{z_{overstorey}}$ ), LAI and *k*, and the portion of light that is left over to overstorey canopy interception (e.g. not absorbed) through the formula derived by Cannel and Grace (1993), Duursma and Mäkelä (2007), and Feikema et al. (2010a,b):

$$PAR_{z_{understoreys}} = \frac{((PAR_0 - \sum APAR_{z_{overstorey}}) \times \sum CC_{z_{overstorey}}) + (PAR_0 \times (1 - \sum CC_{z_{overstorey}}))}{SIZECELL} \quad (5)$$

The upper part of the equation is the amount of PAR absorbed by the overstorey in function of its coverage. The second part represents unabsorbed PAR in function of the gap. SIZECELL is the cell resolution (m<sup>2</sup>). The absorbed PAR ( $APAR_{z_{understoreys}}$ ) is calculated as follows:

$$APAR_{x,y,k,z_{understoreys}} = PAR_{z_{understoreys}} \times (1 - \exp^{-k_x LAI_{x,y,k,z_{understoreys}}}) \quad (6)$$

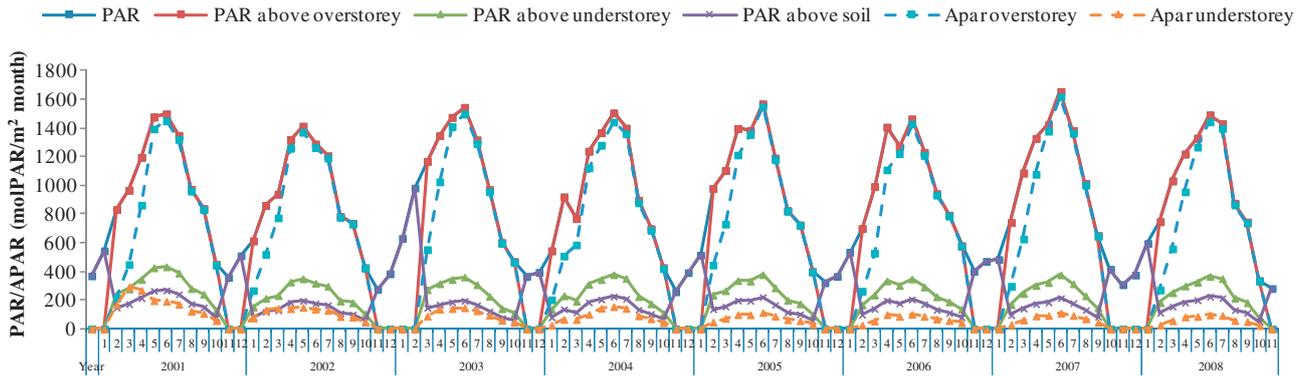
Each lower stratum receives a fraction of light depending on canopy cover, gap, LAI and *k* (so an averaged value between coverage and gaps) of the upper layers and absorbs a portion of light depending on its LAI and *k*. The same iterative process is used to determine the amount of light available for *n* layers down to the soil level (Fig. 3).

2.1.3.3. *Tree growth, yield and forest dynamic.* The 3D-CMCC FEM approach integrates the current knowledge of major ecological/biophysical processes, while adopting the key features of the LUE family models (Medlyn et al., 2003a; Veroustraete et al., 2002). The amount of carbon flux is determined by the radiation intercepted by the canopies and the potential radiation use efficiency or maximum quantum canopy efficiency ( $\epsilon_x$ , gDM MJ<sup>-1</sup> or  $\alpha_x$ ,  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  PAR). Similar to the 3-PG model (Landsberg and Waring, 1997), the latter is constrained with environmental factors or *modifiers*, (variables from 0 to 1), including vapour pressure deficit, air temperature, soil water content and site nutrient status, and stand age factor (Sands, 1996). GPP (gC m<sup>-2</sup> month<sup>-1</sup>) for each class is calculated using the following equation:

$$GPP_{x,y,z,k} = (\epsilon_x \text{ or } \alpha_x) \times APAR_z \times modifiers_{x,k} \quad (7)$$

In case of two layers (for simplicity the case of two layers are described here) the GPP formula is:

$$GPP_{x,y,z_{overstorey},k} = \epsilon_x \times APAR_{z_{overstorey}} \times modifiers_{x,k} \text{ for overstorey} \quad (7.1)$$



**Fig. 3.** Monthly mean PAR (continuous line) and mean APAR (dotted line) ( $\text{molPAR m}^{-2} \text{ month}^{-1}$ ) distribution (2001–2008) through the two storeys (square point is referred to overstorey, triangle point to understorey, cross point to soil) from to the top of the canopies to the soil level.

$$GPP_{x,y,z, \text{understorey},k} = \varepsilon_x \times APAR_{z, \text{understorey}} \times \text{modifiers}_{x,k} \text{ for understorey} \quad (7.2)$$

The stand GPP at monthly scale is the sum of all GPP classes:

$$GPP_{\text{stand}} = \sum_{z=1}^N GPP_{x,y,k} \quad (8)$$

where  $N$  is the number of layers considered.

NPP ( $\text{Mg ha}^{-1} \text{ month}^{-1}$  of dry matter) is considered as a constant fraction of GPP where  $Y$  is the GPP/NPP ratio (Waring and Landsberg, 1998; Mahi et al., 1999; Law et al., 2000) and can be considered an acceptable simplification as confirmed by Monteith (1981) and Van Oijen et al. (2010) for monthly time step simulations. The NPP is strongly related to the class cell coverage ( $CC_{x,y,z,k}$ ) within the layer, in a similar way as proposed for single tree by Robinson and Ek (2003), and is calculated for each class as follows:

$$NPP_{x,y,z,k} = GPP_{x,y,z,k} \times CC_{x,y,z,k} \times Y \quad (9)$$

The stand NPP is the sum of all NPP calculated for each class and layer:

$$NPP = \sum_{z=1}^N NPP_{x,y,k} \quad (10)$$

**2.1.3.4. Carbon partitioning and allocation.** Partitioning and allocation of the assimilated carbon (at monthly time step) is based on constant coefficients constrained by soil water content and light competition, varying each month according to the phenological stage (Arora and Boer, 2005) and the vegetative period determined by the variables  $T_{\text{start}}$  and  $T_{\text{end}}$  for beginning and end of the period, respectively. The model calculates the amount of new biomass at the end of each vegetative month ( $\Delta W = \text{Mg ha}^{-1} \text{ year}^{-1}$  of dry matter) to allocate among the tree compartments (stem, root, and foliage) through dynamic partitioning ratios. Partitioning ratios directly control changes in forest structure in the subsequent years and are directly related to the availability of limiting resources, i.e. light and water (Friedlingstein et al., 1999). The model determines the amount of NPP to allocate into the three compartments using the Frankfurt biosphere model approaches (Ludeke et al., 1994) based on the concept that it is advantageous for plants to allocate C to roots when soil moisture is limiting, to allocate C to leaves when leaves are few in order to increase photosynthetic carbon gain and to allocate C to the stem in order to increase the height/lateral spread of the plant so as to optimize light use when the increase in

leaves results in a decrease in light penetrating the canopy (Arora and Boer, 2005; Bazzaz and Grace, 1997; Ludeke et al., 1994; Salter et al., 2003). The ratios by which the new biomass is allocated to the stem ( $a_S$ ), root ( $a_R$ ) and foliage ( $a_L$ ) pools are given by:

$$a_{S_{x,y,z,k}} = \frac{\varepsilon_{S_x} + \omega_x(1 - L_{x,y,k,z})}{1 + \omega_{x,y,k,z}(2 - L_{x,y,k,z} - f_{SW_{x,y,k,z}})} \quad (11)$$

$$a_{R_{x,y,z,k}} = \frac{\varepsilon_{R_x} + \omega_x(1 - f_{SW_{x,y,k,z}})}{1 + \omega_{x,y,k,z}(2 - L_{x,y,k,z} - f_{SW_{x,y,k,z}})} \quad (12)$$

$$a_{L_{x,y,z,k}} = \frac{\varepsilon_{L_x}}{1 + \omega_x(2 - L_{x,y,k,z} - f_{SW_{x,y,k,z}})} = 1 - a_{R_{x,y,z,k}} - a_{S_{x,y,z,k}} \quad (13)$$

where  $\varepsilon_{S_x}$ ,  $\varepsilon_{R_x}$ ,  $\varepsilon_{L_x}$  are species-specific parameter,  $\omega_x$  controls the 'sensitivity' of allocation to changes in  $f_{SW}$  and  $L$ , as  $\omega_x$  increases allocation is controlled to a greater extent by  $f_{SW}$  and  $L$ , for the limiting case of  $\omega_x = 0$  constants allocation fractions are obtained. The scalars index  $f_{SW}$  represents the soil water modifier (Landsberg and Waring, 1997) and  $L$  is the unabsorbed light (varying between 0 and 1) by the species  $x$  with diameter  $y$ , height  $z$ , and age  $k$  (Arora and Boer, 2005):

$$L_{x,y,k,z, \text{overstorey}} = \exp(-k_x LAI_{x,y,k, \text{overstorey}}) \quad (14)$$

$$L_{x,y,k,z, \text{understorey}} = \exp((-k_x LAI_{x,y,k,z, \text{overstorey}}) + (-k_x LAI_{x,y,k,z, \text{understorey}})) \quad (15)$$

**2.1.3.5. Leaf Area Index.** Leaf Area Index (LAI) is a key structural attribute with substantial control over ecosystem process rates (Running and Gower, 1991). LAI is an index of canopy structure that determines different processes of a forest ecosystem, including light and rain interception, gross productivity, and transpiration. The monthly LAI for each class is calculated as follows:

$$LAI_{x,y,z,k} = \frac{Wf_{x,y,z,k} \times 1000}{CC_{x,y,z,k} \times \text{SIZECELL}} \times \delta_x \quad (16)$$

where  $Wf$  ( $\text{Mg ha}^{-1} \text{ year}^{-1}$  of dry matter) is the biomass allocated to the foliage compartment by class  $x, y, k$  in layer  $z$  at the end of each month,  $CC_{x,y,k,z}$  is the canopy cover of the species  $x$  with diameter  $y$ , height  $z$  and age  $k$ , and  $\delta_x$  is the Specific Leaf Area (SLA in  $\text{m}^2 \text{ kg}^{-1}$ ). The Mg of dry matter is converted into kilograms (1000 in formula). The formula is inspired by the approach Forest 5.1 and Schwalm and Ek (2004) and Härkönen et al. (2010).

**2.1.3.6. Water balance and water competition.** In 3D-CMCC FEM, as for the light competition routine, water competition is essentially considered as asymmetric competition. This choice is confirmed by Rewald and Leuschner (2009), Weigelt and Jolliffe (2003), Weiner and Damgaard (2006), and Wichmann (2001) who describe below-ground competition as a process primarily asymmetric, although to a different degree (Schwinning and Weiner, 1998). Especially when water availability is high, dominating trees grow more efficiently, also due to a high light availability, but may suffer disadvantages through increased respiration and generally reduced relative growth rates when water availability is low (Hara, 1988). The model simulates water competition asymmetry by computing iteratively the soil water balance and the soil water modifier (Landsberg and Waring, 1997), for each forest layer starting from the dominant one up to the dominated understories. The amount of water evapotranspired by the higher storey reduces the amount of available soil water for the metabolic processes in the lower storeys and thus its effective light use efficiency due to lower values of the soil water modifier. The soil water balance is calculated on a monthly base, considering whether or not each species is in the vegetative period, as a balance between the incoming water flux represented by monthly rainfalls and the outputs represented by total evapotranspiration (ET) (i.e. canopy transpiration, canopy interception and soil evaporation) (Ivanov et al., 2008). The evapotranspiration is computed by following a simplified approach of the Penman–Monteith equation (Campbell and Norman, 1998; Monteith and Unsworth, 1990; Waring and Running, 2007) as proposed by Feikema et al.

$$Rad_{z_{understories}} = \frac{(Rad_0 - ((\sum Rad_0 \times \xi_{z_{overstorey}}) \times \sum CC_{z_{overstorey}})) - (Rad_0 \times (1 - \sum CC_{z_{overstorey}}))}{SIZECELL} \quad (24)$$

(2010a,b) and Liu et al. (2003). The contribution of each class/storey is explicitly considered. When all the species are in the dormant season, the model considers only soil evaporation and rainfall in water balance routine. Soil is considered as one bucket layer; soil water availability (ASW) for the growing season is computed for each tree layer using the following formula:

$$ASW = ASW - \Delta ASW \quad (17)$$

$$\Delta ASW = P \times \left( 1 - \sum_{z=layer\ index}^N i_{R_{x,y,z,k}} \right) - \left( \sum_{z=layer\ index}^N i_{T_{x,y,z,k}} + E_s \right) \quad (18)$$

while in a dormant state the water balance is:

$$\Delta ASW = P - E_s \quad (19)$$

where  $\Delta ASW$  is the relative variation in the soil water status,  $i_R$  is the fraction of monthly cumulated rainfall intercepted by the  $N$  layers of each class,  $P$  is the monthly rainfall and  $E_T$  the total monthly evapotranspiration related to the amount of the net radiation intercepted by each strata and computed in the light competition routine (Running and Gower, 1991). Any excess of ASW over MaxASW (maximum holding capacity of the soil) is considered lost as run-off or deep soil drainage.

**2.1.3.7. Soil evaporation and canopy transpiration.** Both in the dormant and growing season, soil evaporation ( $E_s$ ) is computed using the formula suggested by Gerten et al. (2004):

$$E_s = ES_q \times PT_c \times r_\theta \quad (20)$$

$$\frac{ASW}{MaxASW} \quad (21)$$

where  $PT_c$  is the Priestley–Taylor coefficient (Huntingford and Monteith, 1998) and  $r_\theta$  is the relative soil moist ratio (% vol.); ASW

and MaxASW are the available soil water and the maximum available soil water, respectively. The potential soil evaporation ( $ES_q$ ) is given by:

$$ES_q = \left( \frac{e_{20}}{e_{20} + \gamma} \right) \times \frac{Rad_{soil}}{\lambda} \quad (22)$$

where  $\gamma$  is the psychrometric constant ( $\sim 65 \text{ KPa } ^\circ\text{C}^{-1}$ ),  $e_{20}$  is the rate of change of saturated VPD (mbar) with temperature at  $20^\circ\text{C}$  ( $\sim 2.2$ ),  $\lambda$  is the latent heat of vaporization ( $2.45 \times 10^{-6} \text{ J Kg}^{-1}$ ) and  $Rad_{soil}$  is the net radiation (both short- and long-wave components,  $\text{W m}^{-2} \text{ day}^{-1}$ ) at the soil level.

During the growing season, the potential evapotranspiration ( $ET_{p_{x,y,z,k}}$ ) at canopy level ( $\text{mm month}^{-1}$ ) calculation include the actual grid cell canopy coverage and the soil water availability (no evapotranspiration occurs if soil water content is zero):

$$ET_{p_{x,y,z,k}} = \frac{(e_{20} \times Rad_z + (\rho_{Air} \times \lambda \times (VPD) \times g_{Bx}))}{(1 + e_{20} + g_{Bx})/g_c} \quad (23)$$

where  $\rho_{Air}$  is the air density ( $1.2 \text{ kg m}^{-3}$ ),  $\lambda$  is the latent heat of vaporization of water ( $\sim 2.5 \times 10^6 \text{ J Kg}^{-1}$ ),  $VPD_{Conv}$  ( $\sim 6.22 \times 10^{-4}$ ) converts VPD to saturation deficit,  $g_c$  is the canopy conductance ( $\text{mm s}^{-1}$ ) computed from maximum canopy conductance  $g_{c_{xx}}$  reduced by the physiological modifier (Landsberg and Waring, 1997) and  $g_{Bx}$  is the canopy boundary layer conductance for the species  $x$  respectively. The net radiation parameter needed for the algorithm for the lower layer is calculated through the light distribution function:

where  $Rad_{z_{understorey}}$  is the radiation intercepted by the lower layer,  $Rad_0$  is the radiation above the overstorey canopy,  $CC_{z_{overstorey}}$  and  $\xi_{z_{overstorey}}$  are respectively the canopy cover and the percentage of light absorbed by the overstorey canopy. The following formula is used to calculate evapotranspiration:

$$ET_{x,y,z,k} = ET_{p_{x,y,z,k}} + (i_{R_{x,y,z,k}} \times CC_{x,y,z,k}) \times P \quad (25)$$

where  $i_{R_{x,y,z,k}}$  is the fraction of the monthly rainfall intercepted and subsequently evaporated into the atmosphere by each class. The function that controls the rainfall interception balance through the entire canopy architecture takes into account the amount of rain intercepted by each layer and class canopy coverage. Understorey interception is modelled in the same way as overstorey interception, except for the input to the understorey being the throughfall from the upper canopies (Feikema et al., 2010a,b). Each vegetation layer can intercept and store up to a maximum level scaled by the LAI of each stratum as proposed by Landsberg and Waring (1997):

$$i_{R_{x,y,z,k}} = i_{R \max_{x,y,z,k}} \min \left\{ 1, \frac{LAI_{x,y,z,k}}{LAI_{i_{\max}}} \right\} \quad (26)$$

where  $LAI_{i_{\max}}$  is the LAI at which interception reaches its maximum level. The available soil water for plant growth is scaled down by soil physical characteristics represented by soil texture as proposed by Landsberg and Waring (1997) with the evaluation of the scalars index fSW (soil water modifier).

## 2.2. Test site

Preliminary runs for model evaluation focus on a deciduous two-layered, two-cohorts forest located at Torre di Feudozzo (Abruzzo region, Central Italy, Lat  $41^\circ 45' 38''$  N, Log  $14^\circ 11' 22''$  E). The site was selected for its structural complexity and primary data availability. The model was tested against eight years of measured data of annual biomass production, standing above- and below-ground

**Table 4**  
Statistical analysis for stem biomass increment for the dominant and dominated layer; comparison of measured against simulated annual biomass increments at the end of 8 years of simulation. EC = Nash and Sutcliffe coefficient of model efficiency (Nash and Sutcliffe, 1970); EF = model efficiency index (Feikema et al., 2010a,b; Stape et al., 2004); RMSE = root mean square error;  $R^2$  = coefficient of determination; b = slope; n = number of observations; p = p values.

Layer	Variable	Average annual biomass EC increment/(MgDM ha <sup>-1</sup> yr <sup>-1</sup> ) (measured vs simulated)		EF	RMSE (MgDM ha <sup>-1</sup> yr <sup>-1</sup> )	$R^2$	slope	n	p	
<i>Biomass increment</i>										
Dominant	Δ stem biomass	1.9	2.10	0.99	1.06	0.23	0.576	0.945	8	<0.01
Dominated	Δ stem biomass	0.19	0.27	0.993	0.961	0.185	0.852	1.966	8	<0.001
Dominant	Δ stem + Δ root	2.35	2.40	0.94	1.19	0.4	0.61	0.861	8	<0.01
Dominated	Δ stem + Δ root	0.23	0.37	0.99	0.99	0.352	0.888	5.36	8	<0.0001
Stand level	Δ stem + Δ root	2.59	2.77	0.99	0.99	0.374	0.737	1.27	8	<0.001

biomass and forest structural features. Model results were evaluated with the most relevant statistical indexes and a series of model efficiency indexes (Table 4).

The morphology of the site is mainly hilly with an average elevation of 950 m a.s.l. The climate in the area is Mediterranean humid with an average annual temperature of 8.6 °C and an average rainfall of about 1100 mm/yr with infrequent summer droughts. The soil is characterized by Miocene clay overlayers a calcareous matrix. The management history is typical of the central Italian Apennine forests and is characterized by the 1950s conversion of former coppice stands to high forests, corresponding to 151,000 ha across Italy (INFC, 2008).

The stand selected for test simulation is located within a forest patch of nearly 100 ha and it is composed of 70 year old *Quercus cerris* L. (Turkey Oak) in the overstorey and 20-year-old trees in the understorey. The regeneration layer was not considered or modelled in the study. To accurately test the model's capability to simulate complex structures, a plot with a high tree density (2800 trees ha<sup>-1</sup>) was chosen, with two well characterized storeys and two cohorts. The average height is ~20 m and ~7 m and average diameter classes of ~23 cm and ~9 cm for overstorey and understorey, respectively.

The forest stand was initialized with one species ( $x$  index for *Quercus cerris* L.), and, two diameter classes of 23 cm and 9 cm ( $y$  index). Each diameter class was attributed to corresponding height class (23 cm diameter class with a tree height of 20 m and the 9 cm diameter class with 7 m height) and each height class was attributed to one cohort (20 m height class with 70 years and 7 m height class with 20 years) (Table 1). The monthly meteorological data for the period 2001–2008 (<http://www.cra-cma.it/>) were obtained at the weather station of Castel di Sangro (Lat 41°11' N, Long 14°50' E, 810 m a.s.l.). Data for soil parameterization, model initialization validation were available from Oriani (2010), while the information on below ground biomass was derived with the root-shoot ratio of Dufrene et al. (2005) for Turkey Oak, also used by the National Greenhouse Gas inventory for the UNFCCC and the Kyoto Protocol (Federici et al., 2008). Data for species parameterization were collected from literature as reported in Table 2. No parameter values obtained from the test site were used to ensure independence of the model with regard to the site of validation. No addition or calibration/optimization was made to avoid tuning (see Duursma and Mäkelä, 2007) and the reduction of the available data set for the validation phase. If more than one parameter value for a given species was reported in the literature, the average value was used as in White et al. (2000).

### 3. Results

#### 3.1. Light distribution

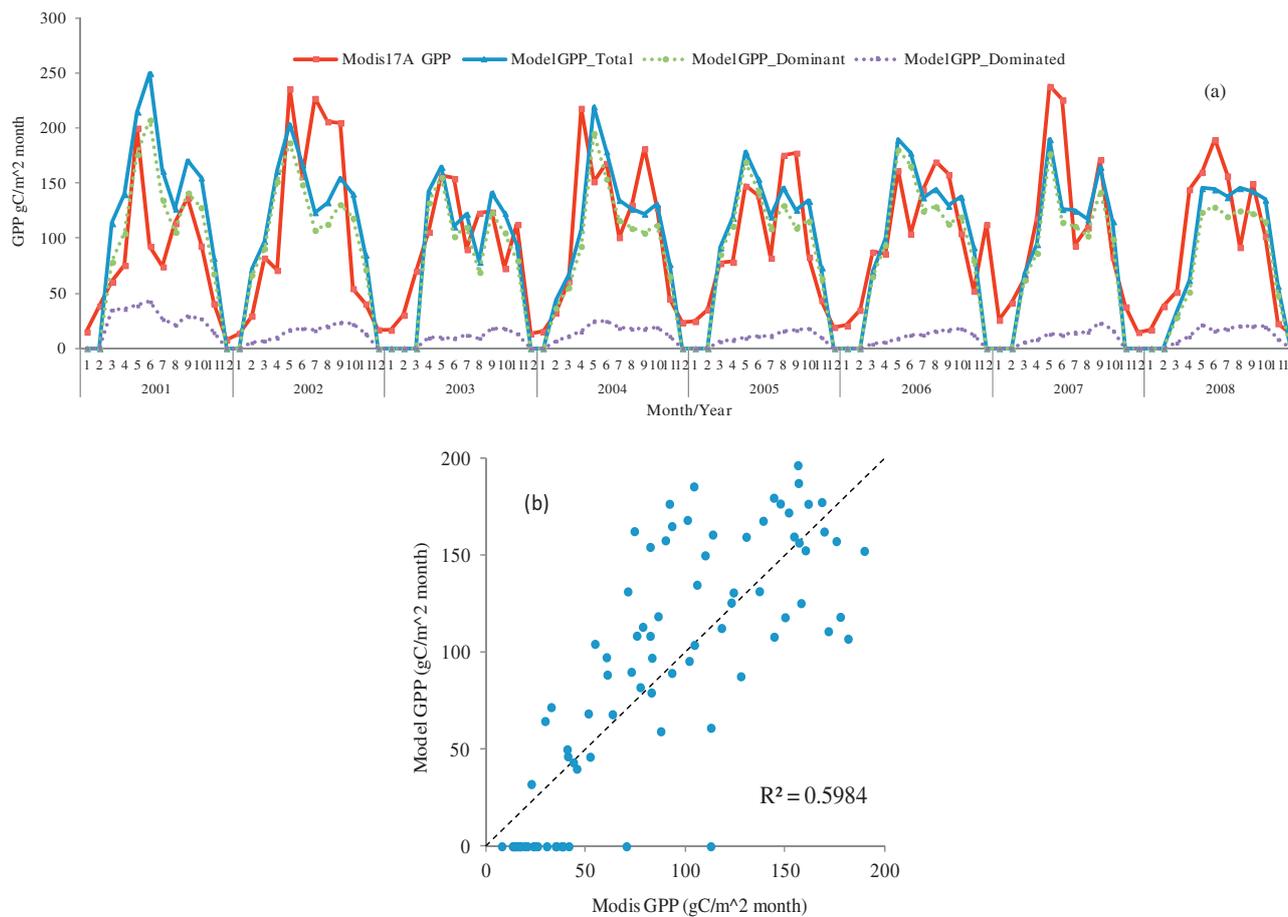
For the eight years of simulation period, the average light absorbed by the overstorey during the growing season was estimated at 75.3% of the average total incoming light

(1045.8 mol PAR m<sup>-2</sup> month<sup>-1</sup>), corresponding to an average monthly reduction for understorey of 787.3 mol PAR m<sup>-2</sup> month<sup>-1</sup>. The light absorbed by overstorey and understorey reached 85.5%, corresponding to 894.06 mol PAR m<sup>-2</sup> month<sup>-1</sup>. Thus, only 14.5% of incoming light reached the forest floor. The correlation between PAR and NPP appears to be the main driver controlling growth and yield with an average annual value of  $R^2 = 0.79$  for the overstorey and  $R^2 = 0.68$  for the understorey. Fig. 3 presents the results for light competition and its absorption by the canopies at monthly time step covering 8 years of the simulation period.

#### 3.2. Gross Primary Production and evapotranspiration

The mean monthly Gross Primary Production (GPP) for the eight years of simulation revealed an average total annual CO<sub>2</sub> flux of 1079.2 gC m<sup>-2</sup> year<sup>-1</sup>, with 85% attributed to the overstorey and 15% to the understorey. Simulation also revealed, the intra annual highest fluxes in the late spring and reduction in the middle summer, sometimes followed by another peak at the end of the summer season (years 2005 and 2007 in particular) (Fig. 4a). The comparison between simulated data and monthly MODIS products ([https://lpdaac.usgs.gov/products/modis\\_products\\_table](https://lpdaac.usgs.gov/products/modis_products_table)) for GPP (MOD17A2,) showed that the model is generally capable of reproducing the monthly simulated patterns ( $R^2 = 0.56$ , slope = 0.81,  $p < 0.0001$ , RMSE = 47.22 gC m<sup>-2</sup> month<sup>-1</sup>, average bias 7.01%) (Fig. 4b), although discrepancies are evident outside the growing season, where MODIS GPP values are different from zero. The simulated inter-annual GPP trends are comparable with MODIS data with three GPP peaks for the years 2002, 2004, and 2006, while the last year of simulation (2008) showed a slight countertrend. Model outputs are also consistent with the values of 1355, 1335, and 1403 gC m<sup>-2</sup> year<sup>-1</sup> reported in literature for Italian Turkey Oak forests by Chiesi et al. (2007), Maselli et al. (2009), and Baldocchi et al. (2010), respectively. The contribution of the understorey to the total stand GPP computed by the model (16%) is comparable with the average values (14%) reported by Misson et al. (2007).

Total modelled evapotranspiration during the growing season is 616.9 mm yr<sup>-1</sup>, of which 82.5% is determined by the overstorey, 13.8% by the understorey, and 4.2% is related to soil evaporation. During the dormant season, the total evapotranspiration is 16.3 mm year<sup>-1</sup> and entirely attributed to the soil evaporation. Differences in the monthly transpiration rate were found between the overstorey and the understorey. Results show a strong increment up to 92% of the total water evapotranspired by the overstorey canopy during late spring and summer seasons, where the leaf onset is completed and the leaves of the overstorey tend to close the canopy almost entirely. In 2002, during the first month of the growing season and in autumn, the understorey reached evapotranspiration rate of 26.5% of the total monthly evapotranspiration. The modelled monthly evapotranspiration data for the overstorey of 523.3 mm year<sup>-1</sup> and the monthly MODIS data (MOD16ET) of 577.1 mm year<sup>-1</sup> (Fig. 5) matched with a relatively high correlation



**Fig. 4.** Comparison (a) and correlation (b) of Modis monthly GPP (Modis 17A) and 3D-CMCC Forest Ecosystem Model monthly GPP. ( $R^2=0.59$ , slope=0.83,  $p<0.0001$ , RMSE=47.226  $\text{gCm}^{-2} \text{month}^{-1}$ ).

( $R^2 = 0.72$ , slope = 1.13 and  $p < 0.0001$ ), a relatively low root mean square error (RMSE = 24.6  $\text{mm year}^{-1}$ ), and bias (3.98%). The modelled ET values are in line with findings reported by Baldocchi et al. (2010) (439  $\text{mm year}^{-1}$ ), Ozhan et al. (2010) (833.2  $\text{mm year}^{-1}$ ), and Vitale et al. (2012) (675.8  $\text{mm year}^{-1}$ ) for Turkey Oak stands in the Mediterranean area. The contribution of the understorey to the total ET is 14% and this number is in the range of the values reported for understoreys by Liu et al. (2003) (8–15%).

### 3.3. Model validation

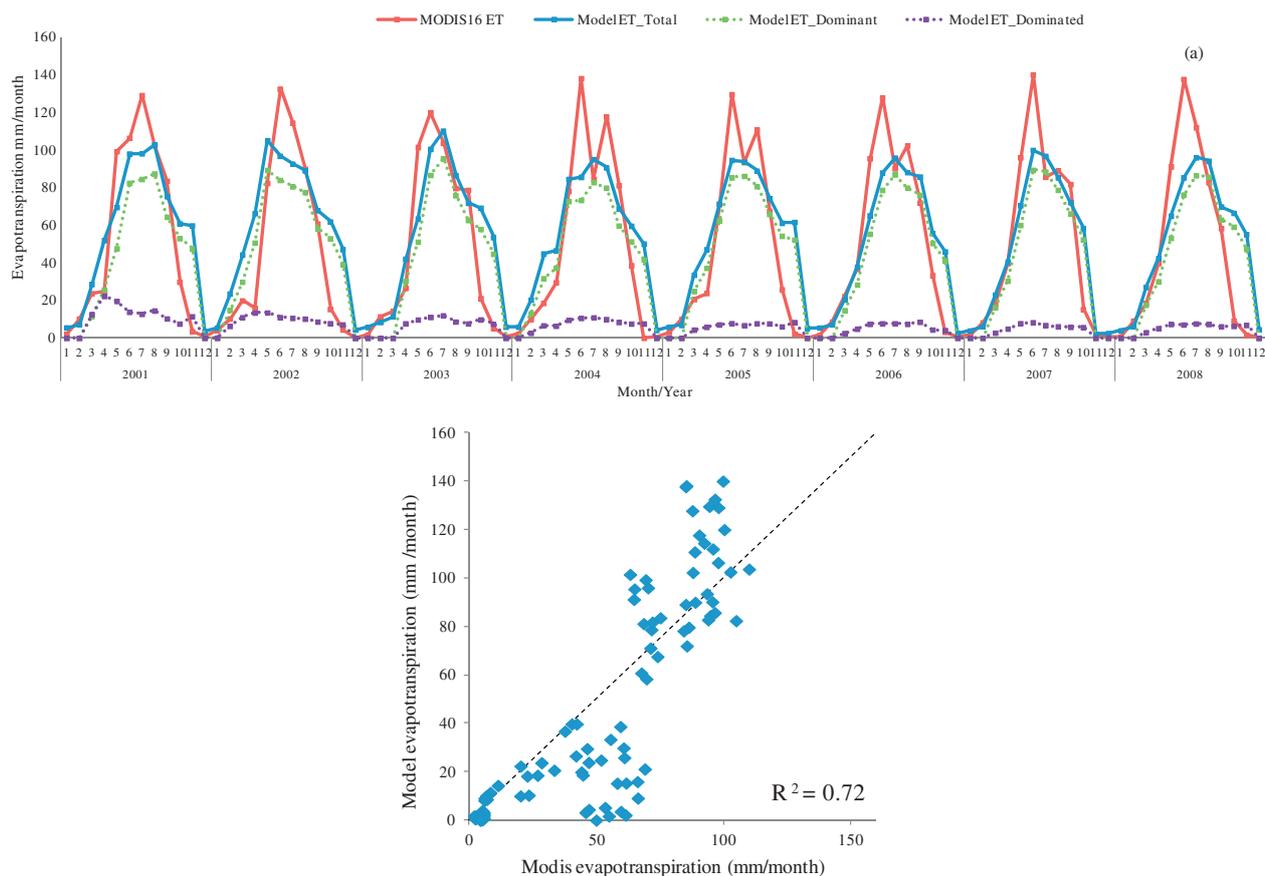
#### 3.3.1. Leaf Area Index and canopy coverage

To evaluate the model's effectiveness and accuracy in simulating the inter-annual variability and allocation to the foliage compartment, the modelled overstorey LAI trend, was compared with annual peak values of MODIS Normalized Difference Vegetation Index (NDVI) and LAI trends (MOD13A2 and MOD15A2) as in Wang et al. (2005). Figs. 6a and b presents the results of the comparison along with the correlation between the LAI simulated by 3D-CMCC FEM and MODIS LAI ( $R^2 = 0.64$ ,  $p < 0.01$ ) and the correlation with MODIS NDVI ( $R^2 = 0.61$ ,  $p < 0.01$ ). The modelled LAI value for 2008 (5  $\text{m}^2 \text{m}^{-2}$ ) is close to the value measured in the same year (5.2  $\text{m}^2 \text{m}^{-2}$ ; Oriani, 2010). For dominated layer, the average of 8 years of LAI values ( $\sim 1.5 \text{m}^2 \text{m}^{-2}$ ) is consistent with the value of  $\sim 2 \text{m}^2 \text{m}^{-2}$  measured by Oriani (2010). The average total amount of simulated biomass allocated to the foliage compartment (2.4  $\text{Mg ha}^{-1} \text{year}^{-1}$  of dry matter) is close to 2.1  $\text{Mg ha}^{-1} \text{year}^{-1}$  reported in literature (Oriani, 2010). The results of the simulations of the evolution of canopy coverage, showed that the overstorey

increases annually by approximately 0.3%, resulting in a total value of 85.9% in 2008, with an average crown area of 13.7  $\text{m}^2$ , which is comparable with the measured coverage of 84.5% and a crown area of 13.5  $\text{m}^2$ .

#### 3.3.2. Stand growth and biomass

The stand NPP simulated by the model is 8.2  $\text{Mg ha}^{-1} \text{year}^{-1}$  close to the value measured by Oriani (2010) (7.4  $\text{Mg ha}^{-1} \text{year}^{-1}$ ) and to the values reported for others Italian Oak forests (8.55  $\text{Mg ha}^{-1} \text{year}^{-1}$ , Chirici et al., 2007). For the total stand growth, 81.7% is allocated in the overstorey and 18.2% in the understorey. The annual net production in 2008 was equal to 6.6  $\text{Mg ha}^{-1} \text{year}^{-1}$ , compared to the measured 7.4  $\text{Mg ha}^{-1} \text{year}^{-1}$  of dry matter (Oriani, 2010). Similarly, the simulated total above-ground net production (4.4  $\text{Mg ha}^{-1} \text{year}^{-1}$  of dry matter) is consistent with measured data (4.7  $\text{Mg ha}^{-1} \text{year}^{-1}$  of dry matter). The root/shoot ratio derived by the model simulation is in agreement both for the overstorey (0.23) and the understorey (0.26) with the value of 0.24 for Turkey Oak in Italy, as reported by Federici et al. (2008) and Vitullo et al. (2007). Interannual patterns of stem and root biomass and total biomass increments ( $\Delta W$ s and  $\Delta W$ r, considering fine and coarse roots) resulting from the simulations (2001–2008) matched with the measured and estimated data by Oriani (2010) (Table 4). The results of statistical analysis fitted well with the field data for stem biomass increments:  $R^2 = 0.58$ , slope = 0.94,  $p < 0.01$  and RMSE = 0.23  $\text{Mg ha}^{-1} \text{year}^{-1}$  for overstorey and  $R^2 = 0.85$ , slope = 1.9,  $p < 0.001$  and RMSE = 0.18  $\text{Mg ha}^{-1} \text{year}^{-1}$  for the understorey with indexes of model efficiency close to unity. Total stem biomass comparison showed  $R^2 = 0.99$ ,  $p < 0.0001$  and



**Fig. 5.** Comparison (a) and correlation (b) of Modis monthly evapotranspiration (MODIS16 ET) and 3D-CMCC Forest Ecosystem Model evapotranspiration ( $R^2 = 0.72$ , slope = 1.13,  $p < 0.0001$ , RMSE = 24.6 mm H<sub>2</sub>O month<sup>-1</sup>,  $n = 96$ ).

RMSE = 0.566 Mg ha<sup>-1</sup> with an average bias of 0.17% for overstorey and  $R^2 = 0.99$ ,  $p < 0.0001$  and RMSE = 0.96 Mg ha<sup>-1</sup>,  $e\% = 2.95$  for the understorey. The RMSE for total root biomass in the overstorey is approximately 0.36 Mg ha<sup>-1</sup> with a total underestimation on the annual increments of about 0.19 Mg ha<sup>-1</sup> year<sup>-1</sup> with  $e\% = 0.25$ . For the understorey, the RMSE is 0.18 Mg ha<sup>-1</sup> year<sup>-1</sup> of dry matter with an overestimation of about 0.9 Mg ha<sup>-1</sup> of dry matter and an average bias of 12.1%. Aggregated results for overstorey and understorey biomass (stem and root biomass) fit the aggregated measured and estimated data (Fig. 7) with  $R^2 = 0.74$ , slope 1.31,  $p < 0.006$ , RMSE = 0.41 Mg ha<sup>-1</sup> year<sup>-1</sup> and  $e\% = 2.7$ .

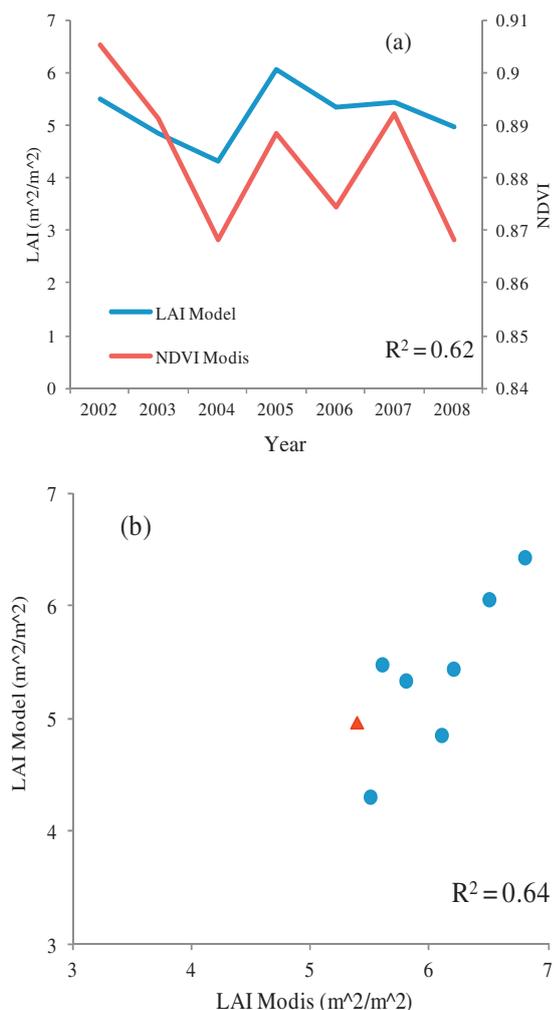
#### 3.4. Analysis of model performances with regard to its complexity

Similarly to other models, the 3D-CMCC requires a large amount of information for its initialization and parameterization. The key question is whether creating more mechanistically accurate models is necessary for predicting carbon sequestration rates: it could be that the simple model captures the primary processes with an acceptable approximation as reported by Coomes et al. (2012). The advantages of using less numerous and more generalized input data such as simplified processes, are evaluated to understand: (i) the bias as a consequence of a more marked Jensen's Inequality (Duursma and Robinson, 2003; Jensen, 1906), related to the consideration of a non-homogeneous stand as homogeneous and (ii) whether the impact of simplifications on data (e.g. using a weighted average of tree heights and ages values) for particular variables (tree mortality and NPP) and on simulated processes does not interfere with production of equally accurate predictions. The evaluation was possible by running the model in a mono-layer version or with

a single age class, according to the data availability and the required resolution. Species parameters were kept the same as described in Table 4 to ensure equal chance among original model application and the four additional or testing cases. This choice is also motivated by the fact that literature lacks reliable parameter range values, thus, generating the risk of tuning or assuming unrealistic values. Four cases were simulated and evaluated (Fig. 8), forcing the model with four different initialization dataset with simplified processes in a sort of model sensitivity analysis. The four cases were:

1. (1L.1A) one single storey and one age class: tree heights and cohorts were grouped into the weighted average of tree height (14.62 m) and cohort (37 years old). The simulation did not integrate the light and water competition routine and only one value for the age modifier was computed.
2. (1L.2A) two age classes (70 and 20 years) in one single storey excluding the light and water competition.
3. (2L.1A) one average age class (37 years) divided into two height classes (20 and 7 m, excluding differences in the age between the two classes).
4. (Dominant) simulation based only on the presence of the overstorey composed by the oldest age class.

In cases 1 and 4, the model has worked 'de facto' as a standard model for plantations without considering height, age classes or canopy coverage differences. The results related to the NPP and biomass pools showed forest production that differed from the measured values on the site. In case 1, the model estimated overall grid cell canopy coverage of about 220% in the first year of simulation. The mortality routine (both crowding and self thinning)



**Fig. 6.** Model validation. Trend of simulated annual peak Leaf Area Index ( $\text{m}^2 \text{m}^{-2}$ ) and Modis the annual peak NDVI (a) ( $R^2 = 0.61$ , slope = 0.87,  $p < 0.01$ ) and correlation between simulated annual peak LAI and Modis annual peak LAI (b) values for the period 2002–2008. The triangle point is the value measured by Oriani in 2008 (dotted line is the 1:1 line) ( $R^2 = 0.64$ , slope = 0.75,  $p < 0.01$ ). The year 2001 is not considered since the model was initialized in that year with the Modis LAI value.

invoked reduction in the number of trees by 1510 units per hectare (corresponding to 54% of stand trees), reaching about 95% of canopy cover. Comparing the model version that integrates all structural forest features against case 1 outputs, the latter overestimated the NPP at the end of the simulation by 20.52%. As in case 1, case 2 determines a crowding mortality of 1316 trees per hectare (corresponding to 47% of stand trees) with a NPP overestimation of 4% due to increased light availability (referred to 1472 trees). In case 3, the canopy coverage did not exceed 95% and the two height classes were well distributed vertically and horizontally without crowding competition. However, the NPP overestimation was 53.5% compared to the original, more complicated version of the model, while case 4 underestimated NPP by 17.95% (Fig. 9)

#### 4. Discussion

The objective of the presented study was to predict light and water competition on forest ecosystems by utilizing a new, enhanced modelling approach. To achieve this aim, the 3D-CMCC FEM model was designed, which coupled concepts of the light use efficiency models with the Functional–Structural Tree models. The model's capabilities were evaluated by: (i) comparing model results

with the data available from MODIS product and (ii) validating model outputs against a series of measured independent data. The outcomes of simulations suggested that novel model programming architecture enables computing the available light and soil water gradient throughout the forest and calculating the PAR fluxes and the evapotranspiration rates from the overstorey down to the forest floor. This feature of the model empowers researchers to identify forest traits, particularly differences in growth among species and cohorts within the vertical structure of the forest and to extend the understanding of the processes at the ecosystem level. Light and water competition, the main driver for tree growth and carbon allocation, was quantitatively also computed by the model. The relationship between PAR and NPP for both storeys showed the varying dependency among photosynthesis, productivity, and stand structure, with a more pronounced light dependency in the overstorey rather than in the understorey, as was confirmed by Misson et al. (2007) for other forest sites as well.

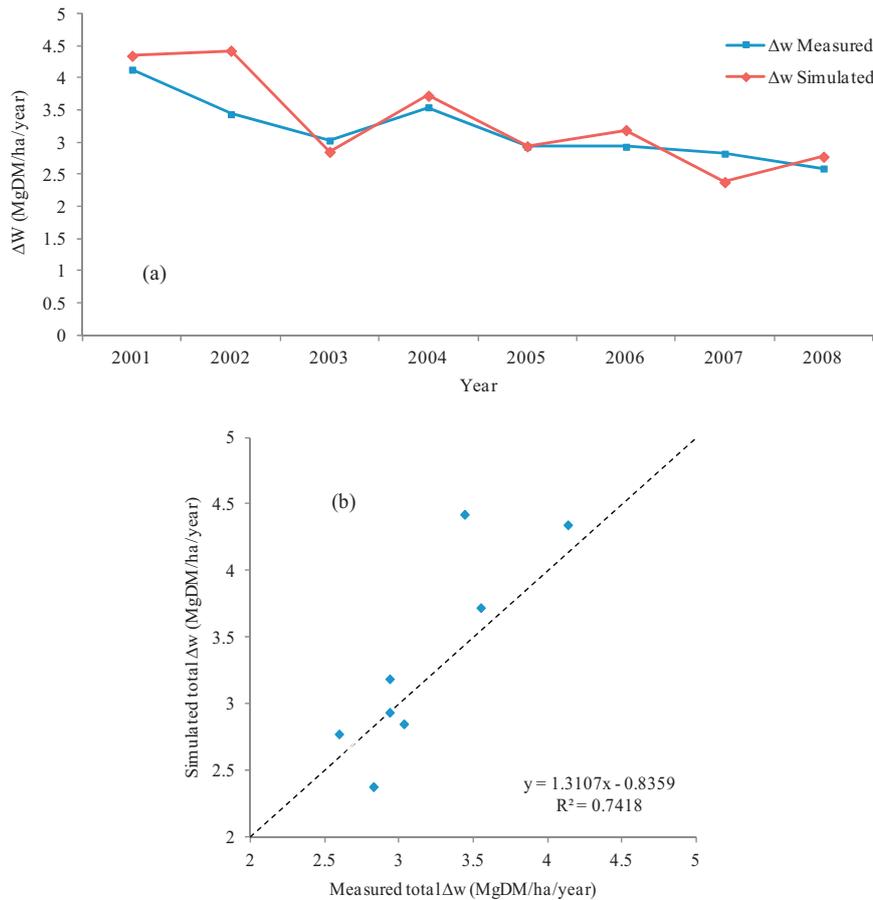
The comparison of GPP, LAI and ET simulated results with the MODIS-derived data was restricted to the overstorey due to the fact that MODIS sensor cannot discriminate the canopy structure, capturing only the features of the upper layer of the ground cover (Peltoniemi et al., 2005; Reichstein et al., 2003; Wang et al., 2004). In addition, at the test site the overstorey canopy was near to closure. Similar limits were highlighted by Liu et al. (2003) in the validation of understorey transpiration for sites in Canada, where data from satellite were available only for overstorey. Although the comparison was affected by inherent uncertainties of remote sensing base algorithms (Hwang et al., 2008) and modelling procedures, it allowed for checking the efficiency of the model in reproducing the intra- and inter-annual trends, similar to the MODIS.

The results produced by the model for annual GPP matched with the correspondent MODIS GPP and captured the strong reduction in GPP and NPP (Figs. 4 and 8) due to the prolonged drought and the heatwaves that occurred in 2003, in Italy (Diodato and Bellocchi, 2008; Fink et al., 2004) and other forest sites across Europe (Rebetez et al., 2006; Van der Werf et al., 2007). Small differences between simulated annual GPP values and those reported in literature were traced; however pertaining different sites' conditions particularly with regard to lower average annual temperatures, higher competition rate, and a more advanced age stand determining an asymptotic/inflection of yield trend.

The modelled values of yearly ET were similar to those estimated by the corresponding MODIS product, with low average bias and root mean square error. The clustering in two blocks of ET values in Fig. 5 may relate to the marked differences in the phenological cycle activity of the overstorey. Low values are traced to the period of leaf onset during the spring months and to the autumn leaf senescence; higher values are dependent on LAI stabilization during the late spring and summer months. The increased ET in the lower layer in spring and autumn suggest the limitation of ET to the soil water bucket size, mainly due to strong competition asymmetry. The asymmetry implies that the dominated canopy layers have a chance to transpire more during spring and autumn seasons, where the amount of available light is higher and competition is lower (Fig. 5). The ET trend for both layers is strictly related to the fact that in Penman–Monteith in which no consideration is made for soil water content but is directly related to the light availability.

The simulated inter-annual trend of dominant LAI follows the patterns offered by MODIS product for NDVI, while the modelled LAI proved to be on average slightly lower than MODIS LAI. The matching results for MODIS and model-simulated LAI indirectly confirms the model's capability to simulate the ratio of biomass allocated to the foliage compartment and directly confirmed by the values measured by Oriani (2010).

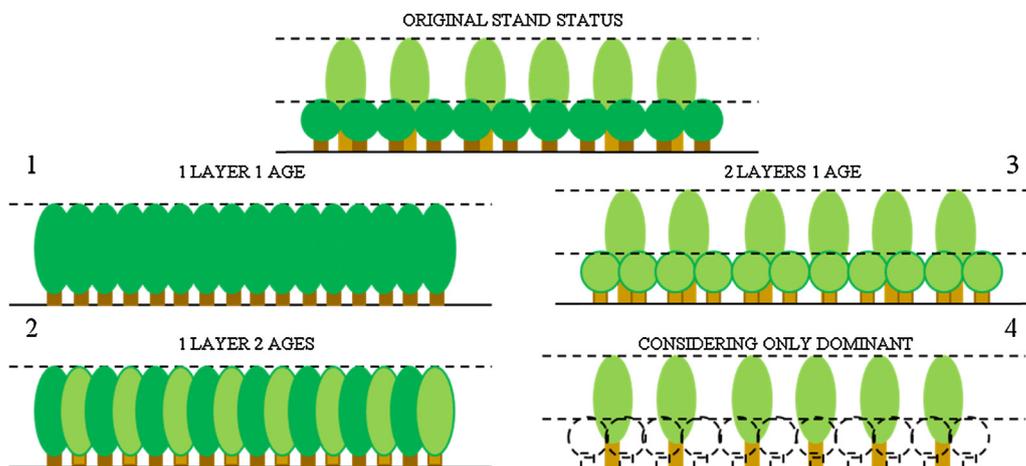
The comparison between simulated annual forest productivity is comparable with the measured at the site values by Oriani (2010)



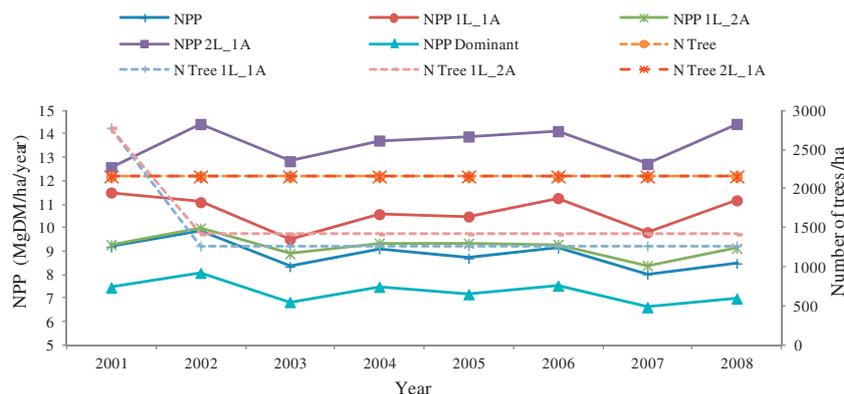
**Fig. 7.** Model validation. Simulated and measured trends (a) of total woody increments for stand ( $\Delta W_s + \Delta W_r$ ) (MgDM ha<sup>-1</sup> year<sup>-1</sup>) and its comparison (b) fitted through the origin (solid line while dashed diagonal is the 1:1 line and  $n=8$ ).

and the patterns reported for others Italian oak forests. Simulated NPP values revealed that the understorey contributed to the total NPP for an average of 18%. This value implied that the understorey vegetation may represent a considerable fraction of forest production, considering that it stands for 10% of dominant biomass, as was reported in other studies as well (Welden and Slauson, 1986; Moren and Lindroth, 2000; Subke and Tenhunen, 2004). The simulated annual trend of stem and root biomass increments and NPP were

comparable with the observed values, explaining between 58% and 91% of variability between measured and observed data. The differences between measured and simulated data for biomass allocation among the considered pools could be attributable to forest's response to climatic events that took place in the previous years before simulations (Hoff et al., 2002). The model slightly overestimated both dominated stem and root increments. Discrepancies were the greatest in years 2001 and 2007, mostly concentrating



**Fig. 8.** Example of forest characteristics used in the four cases used to evaluate the original model version. Case 1 (1L.1A), one single layer and one single cohort; case 2 (1L.2A), one single layer and 2 cohorts, case 3 (2L.1A) two layers and one cohort; case 4 (dominant) only dominant layer and the oldest cohort was considered.



**Fig. 9.** Model results for NPP ( $\text{Mg ha}^{-1} \text{yr}^{-1}$ ) (solid line) and number of trees (number of trees per hectare, N.TREE) (dotted line) for the four simulations with simplified model versions (case  $n$ ) and simplified stand initialization data against original model version and stand data (2L.1A = two layers and one age class, 1L.1A = one layer and one age class, 1L.2A = one layer two age classes, dominant = only dominant layer considered).

on the growing season for years when the remarkable reduction in precipitation caused a decrease in carbon assimilation and different carbon allocation ratios among the three biomass pools. There are several hypothesis for the overprediction of dominated layer production under modelled simulations. First, an underestimation of the dominant LAI and consequently overestimation of available light for dominated layer, could trigger overprediction. Second, overprediction could be attributed to the asymmetry rate in water competition within the soil water routine. As confirmed by [Rewald and Leuschner \(2009\)](#) and [Wichmann \(2001\)](#), the asymmetric degree in water competition is highly variable and strongly affected by the amount of water available within soil. Third, the choice of using a single value for the GPP/NPP ratio leads to an overestimation of the NPP for the youngest layer and an underestimation for the older. In addition, model outputs on root biomass increments were validated against estimated data. Thus, uncertainties for this pool were caused by the scarcity of information on the belowground pool. The modelled root-to-shoot ratios of the overstorey (0.23) and understorey (0.26) were within the range of data reported in literature for Italian Turkey Oak forests. The difference between the values of the two storeys could be subjected to the asymmetric water competition simulated by the model.

Furthermore, the model was tested with different algorithms and approaches (e.g. soil water modifier related to soil water potential or evapotranspiration related to soil water content) to enhance modelling predictions. Evaluation revealed that the model's weakness was mainly related to the monthly time scale, necessitating improvements for a daily time step version of the model. The choice was motivated by the fact that many model examinations on soil water fluxes, introducing the soil water potential for computing the soil water modifier, the monthly scale showed to be the major obstacle to accurately reproduce the soil water dynamics with a strong sensitivity to distribution of precipitation. In addition, further studies should be directed at developing the soil level processes for more than one soil layer, following the same approach developed for multi-layered tree canopies. Future research efforts should necessarily aim at estimating the effects of position within forest structure and the effects of differences among species and ages on respiration (i.e. GPP/NPP ratio), as suggested by [DeLucia et al. \(2007\)](#), [Ryan et al. \(2004\)](#), and [Zaehle et al. \(2006\)](#). This area is unfortunately still highly uncovered by research and models.

The outcomes of simplified runs of the model (i.e. neglecting forest structure characteristics and/or structural processes, in particular) uncovered remarkable errors, especially in case 3, when compared with the measured values of yield with a general overestimation (cases 1, 2, and 3) and underestimation (case 4). In case 1 a high rate of mortality was estimated, while no factual mortality

was observed in the test site. Grouping all trees into one height class determined a crown overlap, invoking the crowding competition routine for the understorey. The canopy coverage at the level of 0.95 caused the canopy closure and, consequently, the absorption of almost all available light. In case 2, a strong reduction in the number of trees was observed similarly to case 1, although with lower overestimation in the NPP values due to the fact that the two cohorts were maintained and the age decline for the oldest class resulted in a yield reduction. In case 3, no mortality occurred for the period of 8 years, the vertical space was balanced between the two height classes with no overlapping of the crowns, although wide discrepancies were found in comparison the modelled and measured NPP values. The overestimation of the modelled NPP compared to the measured value, was attributed to the reduction of age in the overstorey (from 70 to 37 years) and a minor age effect, implying a higher light use efficiency. Such a strong age effect on biomass production demonstrated, as confirmed by the values reported in [Di Filippo et al. \(2010\)](#) for Turkey Oak, that age variable and GPP/NPP ratio values are not negligible and should be properly taken into consideration in forest modelling. In case 4, the model was run as 3-PG model, considering only the overstorey. The simulation reported a reduction of the total stand NPP. The results for the four cases confirmed that simplifications of modelled processes and the accuracy in initialization data used have led to a significant decrease in the model's predictive ability. In overall, the results of the simplified model version that did not consider forest structure but covered the age-related decline produced minor discrepancies between simulated and measured NPP values and yet induced a strong mortality. On the contrary, if physiological differences pertaining to tree ages are not taken into account while forest structure is considered, the NPP overestimated the measured values and no mortality occurred within the stand. Thus, the possibility to consider each species, each cohort or hierarchical position in the forest architecture allowed producing more accurate results extremely useful also for forest management decision makers.

## 5. Conclusions

The paper presented the first attempts to evaluate the capability and the efficiency of using the 3D-CMCC FEM to reproduce forest growth in a multi-layered and multi-aged forest of central Italy. This has been possible taking explicitly into account the effects of stand structure on light, water interception and photosynthesis, the factors that are frequently ignored in process-based models ([Landsberg and Waring, 1997](#)). Generally detailed models require many parameters and large computing time to estimate these effects ([Duursma and Mäkelä, 2007](#)). For this reason, understorey

eco-physiological processes are usually neglected in many models, although their contributions are significant in forest ecosystems. The need to understand forest dynamics and to quantify the production for a wider variety of multi layered and multi-aged forests led to the development of a computationally different approach for a process-based ecosystem model. While the presented and tested approach still requires relatively high number of parameterization data and is based on rather simplified assumptions, on the other hand it proved to be a useful tool to fill the gap inherent in other models and measurement techniques. The 3D-CMCC FEM was run for a Turkey Oak forest in Italy without calibrating (or tuning) any of the parameters resulting in a satisfactorily simulation of the forest production of the test site. A more rigorous validation of the model's potential to simulate GPP, evapotranspiration, and LAI is a high priority in the ongoing development and further enhancement of the model. Particularly, validation is required for the broadest range of different forest structure conditions and for longer time period. Although the model is still in an embryonic stage these results encourage further testing of the model's capabilities and its applicability to other forest typologies composed by higher number of species, cohorts, and stores.

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolmodel.2013.09.016>. These data include Google maps of the most important areas described in this article.

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