Assessing the combined effects of forest management and climate change on carbon and water fluxes in European beech forests

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Highlights

- We analyzed modelled carbon and water fluxes in managed and unmanaged European beech stands under current and future climate change scenarios in two Italian sites.
- Climate change scenarios showed increased carbon and water fluxes in the northern region, while fluxes decreased in the southern region compared to the current climate.
- 3D-CMCC-FEM and MEDFATE show satisfactorily results in simulating Gross Primary Production and Latent Heat at the selected sites
- The 3D-CMCC-FEM model predicts potential early warning signals of stress due to carbon starvation in unmanaged beech forests in the southern region.
- The MEDFATE model predicts an elevated stem embolism rate in both managed and unmanaged stands in the southern region.
- The thinning intensity of about 40% of the stand density in the south region negatively affected carbon fluxes.

Abstract

The consequences of climate change continue to threaten European forests, particularly for species located at the edges of their latitudinal and altitudinal ranges. While extensively studied in Central Europe, European beech forests require further investigation to understand how climate change affects these ecosystems in Mediterranean areas. Proposed silvicultural options increasingly aim at sustainable management to reduce biotic and abiotic stresses and enhance these forest ecosystems' resistance and resilience mechanisms. Process-based models can help us to simulate such phenomena and potentially capture early stress signals and make projections while considering the effect of different management approaches. Utilizing two state-of-the-science process-based models, 3D-CMCC-FEM and MEDFATE we simulated and analyzed carbon (C) and water (H_20) fluxes in diverse forest plots under managed vs. unmanaged scenarios and under current and future climate scenarios (RCP4.5 and RCP8.5), in two sites, nearly opposite in latitude, on the Italian peninsula, Cansiglio in the north and Mongiana in the south. To ensure confidence in the models' results, we first evaluated their performance on simulating C and H_2O flux, excluding management, in two independent beech forests along a latitudinal gradient from Denmark to central Italy. The results from both models for C and H_2O flux assessment showed generally good model accuracy. At the Cansiglio site in northern Italy, both models simulated a general increase in C and H_2O fluxes under the RCP8.5 climate scenario compared to the current climate, but no benefit in managed plots compared to unmanaged ones, as the site does not have water availability limitations and thus competition for water is low. However, initial signs of xylem embolism were simulated in the RCP8.5 scenario. At the Mongiana site in southern Italy, both models simulate a decrease in C and H_2O fluxes under the climate change scenarios compared to the current climate, with an increase in C and

H_2O fluxes considering certain management regimes compared to unmanaged scenarios. Conversely, in both models, under unmanaged scenarios plots are simulated to experience first signals of mortality prematurely due to water stress (MEDFATE) and carbon starvation (3D-CMCC-FEM) scenarios. In conclusion, while management interventions may be considered a viable solution for the conservation of beech forests under future climate conditions at moister sites like Cansiglio, in drier sites like Mongiana may not lie in management interventions alone, but rather in the establishment of synergistic mechanisms with other species.

Keywords: Climate change, *Fagus sylvatica,* Forest management, Carbon fluxes, Water fluxes, Stress mitigation, Process-based models.

1. Introduction

Predicting the future evolution of European forests is essential to continue to benefit from the ecosystem services they provide for human well-being. Forests provide, for instance, climate change mitigation through their ability to store atmospheric carbon dioxide in biomass and soil (Augusto and Boča 2022; Pan et al. 2024). In 2020, the European Green Deal prioritized the vital role of forests and the forestry sector in attaining sustainability objectives, such as promoting sustainable forest management, enhancing forest resilience, and climate change mitigation (European Commission, 2021). Technological advances and studies of forest ecosystem responses to management practices continue to promote the evolution of strategies that maintain or enhance forest ecosystem services, such as promoting biological diversity, water resources, soil protection, or carbon sequestration (Pukkala 2016). Different types of forest management systems have been adopted in Europe over the years (e.g., clear-cutting or shelterwood) depending, among others, on the wood product desired, the stand age, and structure (Brunet et al. 2010).

Forest management can be a key element in mitigating the effects of climate warming, maintaining the current primary productivity, and the current distribution of tree species or altering forest composition with more suited and productive species (Bosela et al. 2016). Indeed, the carbon sequestration capacity and productivity of forests are dependent, mostly, on species composition, site conditions as well as on stand age (Rötzer et al. 2010; Vangi et al. 2024a,b) which are results of past and present forest management activities. According to Collalti et al. (2018) and Dalmonech et al. (2022), monospecific forests would appear unable to further increase the current rates of carbon storage and biomass production in future climate scenarios, considering current management practices, but at the same time demonstrating that managing under Business as Usual (BAU) practices still allows forests to accumulate biomass at higher rates compared to stands left to develop undisturbed.

European beech (*Fagus sylvatica* L.), is an important deciduous tree species widely distributed in Europe, from southern Scandinavia to Sicily and from Spain to northwest Turkey (Durrant et al. 2016). In Italy, according to the National Forest Inventory (INFC 2015), beech forests cover a total area of 1,053,183 hectares, accounting for about 11.7% of the country's overall forested land. European beech forests demonstrate susceptibility to temperature and precipitation fluctuations, for instance, a warmer environment and less precipitation are forcing shifts in distribution area or the onset of loss of canopy greenness (Axer et al. 2021; Noce et al. 2017, 2023; Zuccarini et al. 2023; Rezaie et al. 2018). According to Skrk et al. (2023), the decline in growth of the beech forests primarily occurs in the warm marginal conditions prevalent near the geographical edge of its distribution with a sub-Mediterranean climatic regime, posing a threat to the survival of beech populations in those areas. However, tree ring analyses have also revealed an unexpected increase in growth in the south Mediterranean region of Albania and Macedonia beech forests, at the end of the 20th century, challenging the presumed

suppression of forest ecosystems due to drought (Tegel et al. 2014). Puchi et al. (2024) additionally shed light on the susceptibility to extreme drought events of beech forests found at higher latitudes compared to those found at lower latitudes in the Italian peninsula by highlighting an increase, for the latter, in growth related to the abundance of precipitation. In this context, it is important to minimize the uncertainty surrounding the response of the carbon, water, and energy cycles within beech forest ecosystems, especially as they have been shown to adapt to varying environmental drivers (Deb Burman et al. 2024).

Forest models are useful tools for studying forest dynamics, such as growth and mortality, as well as water (H_2O) and carbon (C) use efficiency, and carbon stocks as key variables of forest mitigation potential (Vacchiano et al. 2012; Pilli et al. 2022; Testolin et al. 2023; Morichetti et al. 2024). For many years, forest modelling has been widely used by forest ecologists for tackling numerous applied research questions and is continuously evolving to include increasingly complex processes to improve model predictions of forest ecosystem responses to changing climates (Riviere et al. 2020; Kimmins et al. 2008; Maréchaux et al. 2021). By comparing the predictive performance of different models under current environmental conditions, it is possible to gain confidence in the reliability of their predictions of future trends and make informed decisions in forest ecosystem management and planning processes (Huber et al. 2013; Mahnken et al. 2022).

The main goal of the present study is to investigate the effects of different forest management regimes for European beech forests in the Mediterranean area, seeking further insights into the C and H_2O fluxes of this species under different management practices and environmental conditions. The study sites vary in terms of environmental factors that can affect gross primary productivity (GPP), and latent heat (LE) the two variables considered in this analysis. Specifically, we tested: (i) to what extent different

forest management options can influence C and H_2O fluxes under the present-day climate; (ii) how harsher climate conditions may affect the C and H_2O fluxes under different management options. To address these questions, we performed forest ecosystem simulations using two state-of-the-science process-based models, 3D-CMCC-FEM Collalti et al. (2024) and MEDFATE (De Cáceres et al. 2023). First, we parameterized and evaluated model performance for C and H_2O fluxes at three forest stands dominated by beech forests: the Sorø (DK-Sor), Hesse (FR-Hes), and Collelongo (IT-Col) sites, which are included in the PROFOUND Database (PROFOUND DB) (Reyer et al. 2020a, b). Subsequently, we assessed the carbon and water fluxes at two independent beech forest sites in Italy (Cansiglio and Mongiana) by simulating their development under various management options and evaluating their sensitivity to current and more severe climate conditions.

2. Material and Methods

2.1 3D-CMCC-FEM model

The 3D-CMCC-FEM v.5.6 ('Three-Dimensional – Coupled Model Carbon Cycle – Forest Ecosystem Module') (Collalti et al. 2014, 2016, 2017, 2018, 2020a, 2023, 2024; Marconi et al. 2017; Dalmonech et al. 2022, 2024; Vangi et al. 2024a, 2024b; Morichetti et al. 2024) is an eco-physiological, biogeochemical and biophysical model. The model simulates C and H_2O fluxes occurring within forest ecosystems on a daily, monthly, or annual basis, depending on the processes to simulate, with a common spatial scale of 1 hectare (Collalti et al. 2016). Photosynthesis is simulated using the biochemical model of Farquhar–von Caemmerer–Berry (Farquhar et al. 1980), integrating the sunlit and shaded leaves of the canopy (De Pury and Farquhar, 1997). For the temperature dependence of the Michaelis-Menten coefficient for Rubisco and the CO_2 compensation point without mitochondrial respiration, the model adopts the parameterization described in Bernacchi

et al. (2001, 2003). The net balance at the autotrophic level is represented by net primary production in eq 1:

$$NPP = GPP - R_a \quad (1)$$

where R_a includes both maintenance respiration (R_m) and growth respiration (R_g). When R_m exceeds GPP, resulting in a negative NPP, the trees utilize their non-structural carbon reserves (NSC) (i.e., soluble sugars and starch) to meet the carbon demand (Collalti et al. 2016; Merganikova et al. 2019). In deciduous trees, NSC is used to create new leaves during the bud-burst phase, is then replenished during the growing season under favourable photosynthetic conditions, and finally remobilized in tissues to prepare for dormancy at the end of the growth phase. The replenishment of non-structural carbon reserves is prioritized to reach the minimum safety threshold (i.e., 11% of sapwood dry mass for deciduous trees). Failure to consume almost all reserves may trigger defoliation mechanisms, or in the case of complete depletion (e.g., during prolonged stress periods), it may lead to the death of the entire cohort of trees (i.e., carbon starvation). The stomatal conductance g_s is calculated using the Jarvis equation (Jarvis 1976). The equation includes a species-specific parameter $g_{s\,max}$ (i.e. maximum stomatal conductance) controlled by some factors such as light, atmospheric CO_2 concentration, air temperature, soil water content, vapour pressure deficit (VPD), and stand age. According to Waring and Running (2007) and Monteith and Unsworth (2008), the Penman-Monteith Equation (PME) is used to calculate the latent heat (LE) fluxes of evaporation as a function of incoming radiation, *VPD*, and conductances at a daily scale summing up the canopy, soil, and snow (if any) latent heat expressed as Wm^{-2}.

The 3D-CMCC-FEM accounts for forest stand dynamics, including growth, competition for light, and tree mortality under different climatic conditions, considering both CO_2

fertilization effects and temperature acclimation (Collalti et al. 2018, 2019; Kattge and Knorr, 2007). Several mortality routines are considered in the model, such as age-dependent mortality, background mortality (stochastic mortality), self-thinning mortality, and the aforementioned mortality due to carbon starvation. In addition to mortality, biomass removal in 3D-CMCC-FEM is the result of forest management practices, such as thinning and final harvest (Collalti et al. 2018; Dalmonech et al. 2022; Testolin et al. 2023). The required model input data include stand age, average DBH (Diameter at Breast Height), stand density, and tree height (Collalti et al. 2014). The soil compartment is represented using one single bucket layer, in which the available soil water (ASW, in mm) is updated every day considering the water inflows (precipitation, and, if provided, irrigation) and outflows (evapotranspiration; i.e., the sum of evaporation from the soil and transpiration of the canopy). The remaining water between these two opposite (in sign) fluxes that exceeds the site-specific soil water holding capacity is considered lost as runoff. For a full 3D-CMCC-FEM description see (https://doi.org/10.32018/ForModLab-book-2024).

2.2 MEDFATE model

MEDFATE v.4.2.0 is an R-based modelling framework that allows the simulation of the function and dynamics of forest ecosystems, with a specific emphasis on drought impacts under Mediterranean conditions (De Cáceres et al. 2021, 2023). MEDFATE calculates energy balance, photosynthesis, stomatal regulation, and plant transpiration of gas exchange separately at sub-daily steps. Like 3D-CMCC-FEM, MEDFATE also simulates photosynthesis at the leaf-level using the biochemical model of Farquhar–von Caemmerer–Berry (Farquhar et al. 1980) for sunlit and shaded leaves (De Pury and Farquhar, 1997). MEDFATE can simulate plant hydraulics and stomatal regulation according to two different approaches: (a) steady-state plant hydraulics and optimality-

based stomatal regulation (Sperry et al. 1998; Sperry et al. 2017); and (b) transient plant hydraulics including water compartments and empirical stomatal regulation (Sureau-ECOS; Ruffault et al. 2022). In this work we took the second approach, i.e. Sureau-ECOS (Ruffault et al. 2022).

The hydraulic architecture of the Sureau-ECOS module comprises arbitrary soil layers. The rhizosphere consists of coarse and fine root biomass, calculated for each soil layer. The total root xylem conductance is determined by factors such as root length (limited by soil depth), weight, and distribution across the different layers. In addition, the resistance to water flow is also dependent by two plant compartments (leaf and stem each composed of symplasm and apoplasm). Overall, plant conductance is defined by the sum of resistances across the hydraulic network (i.e., soil, stem, and leaves), taking into account processes such as plant capacitance effects (i.e., the variation of symplasmic water reservoirs in the stem and leaves) and cavitation flows (i.e., water released to the streamflow from cavitated cells to non-cavitated cells during cavitation) (Hölttä et al. 2009). It also considers cuticular transpiration of the stem and leaf flows. Each element (roots, stem, leaves) of the hydraulic network has a vulnerability curve, $k(\boldsymbol{\Psi})$, that declines as water pressure becomes more negative. The xylem vulnerability curve is modelled using a sigmoid function, defined by the equation:

$$k(\Psi) = 1 - \left(1/1 + exp^{(slope/25)\cdot(\Psi-\Psi 50)}\right) \qquad (2)$$

where $\boldsymbol{\Psi}50$ is the water potential corresponding to 50% of conductance, and "slope" is the slope of the curve at that point.

The stem vulnerability curve can be used to determine the proportion of stem conductance loss (PLC_{stem}), which is associated with vessel embolism. This embolism

reduces overall tree transpiration and photosynthesis. Plant hydraulic failure, and consequently tree death, can occur if the PLC_{stem} exceeds the 50% threshold.

Gas exchange in the Sureau-ECOS module depends both on stomatal conductance (which depends on light, water availability, and air temperature) and leaf cuticular conductance, which changes with leaf temperature due to changes in the permeability of the epidermis. Stomatal regulation, differently from the 3D-CMCC-FEM, follows the Baldocchi (1994) approach, which allows coupling leaf photosynthesis with water losses. In addition, a multiplicative factor depending on leaf water potential is used to decrease stomatal conductance under drought conditions, following a sigmoidal function similar to that of stem vulnerability.

Soil water balance is computed daily and MEDFATE can consider an arbitrary number of soil layers with varying depths in which the water movement within the soil follows a dual-permeability model (Jarvis et al. 1991; Larsbo et al. 2005). Soil water content (ΔV_{soil}, in mm) is calculated taking into account variables such as infiltration, capillarity rise, deep drainage, saturation effect, evaporation from the soil surface, transpiration of the herbaceous plant, and woody plant water uptake. A full MEDFATE description is available at: https://emf-creaf.github.io/medfatebook/index.html.

2.3 Evaluation sites

Model evaluation was performed in three PROFOUND European beech sites, i.e., Sorø (DK-Sor, Denmark), Hesse (FR-Hes, France), and Collelongo (IT-Col, Italy), in which we retrieved information on soil texture, soil depth, and stand inventory data of forest structure for model initialization (Reyer et al. 2020a,b). Moreover, these sites are equipped with the Eddy Covariance towers (EC; Pastorello et al. 2020) for long-term continuous monitoring of atmospheric carbon, water, and energy fluxes of the forests (Fig. 1). The DK-Sor site is located in the forest Lille Bogeskov on the island of Zealand in Denmark. FR-Hes is situated in the northeastern region of France and lies in the plain at

266 the base of the Vosges Mountains. IT-Col (Selva Piana stand), is a permanent
267 experimental plot installed in 1991 and situated in a mountainous area of the Abruzzo
268 region, the centre of Italy.
269 The pedological characterization of soils exhibits distinct variations across the studied
270 sites. The soil at the DK-Sor site is predominantly classified as either Alfisols or Mollisols,
271 the FR-Hes site showcases an intermediary nature, displaying characteristics akin to
272 both luvisols and stagnic luvisols and at the IT-Col site, the prevailing soil type is
273 identified as Humic alisols, according to the USDA soil classification system. Full details
274 of these sites are reported in Table 1.
275 The variables accounted for in the evaluation were obtained from the Fluxdata website
276 (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/) from the FLUXNET2015
277 database (Pastorello et al. 2020). The variables considered are the daily GPP, estimated
278 from Net Ecosystem Exchange (NEE) measurements and quality checked using the
279 constant USTAR turbulence correction according to Papale et al. (2006) and the Latent
280 Heat flux (LE) with energy balance closure correction (i.e. LE_CORR) (Pastorello et al.
281 2020).
282
283 **2.4 Study sites**
284 The two independent sites considered here are part of the LIFE project ManFor C.BD (De
285 Cinti et al. 2016), i.e., Cansiglio and Mongiana (Fig. 1). Each site consists of nine long-term
286 monitored plots of differently managed beech stands, with a spatial extension for each
287 area of above 3 hectares, for a total of about 27 hectares of the experimental area. Three
288 different treatments were applied according to the LIFE-ManFor project (see Fig S1-S2).
289 For each site, three of the nine plots considered were left unmanaged (i.e., no cutting and
290 leaving the stands to natural development) defined as 'Control' plots, three plots were
291 managed following the historical shelterwood system ('Traditional'), and three with

innovative cutting ('Innovative'). In Cansiglio, considering the developmental stage of the stand was an establishment cut, to open growing space in the canopy for establishment of regeneration. The 'Innovative' cutting consisted in the selection of a non-fixed number of scattered, well-shaped trees (the 'candidate trees') and a thinning of neighbouring competitors to reduce competition and promote better growth. In Mongiana, 'Traditional' silvicultural treatment was the first preparatory cut aiming to increase vitality and health of the intended residual trees in the stand. The 'Innovative' option was the identification of 45-50 as 'candidate trees' per hectare and the removal of only direct competitors.

Cansiglio site is situated in a mountainous area in the Veneto region, northern Italy. Mongiana site is situated in a mountainous area in Calabria region, southern Italy. The latter shows higher mean annual temperature (MAT) and lower mean annual precipitation (MAP) (i.e., drier conditions) than the Cansiglio site located at higher latitudes (Table 1). During the field campaigns conducted in 2011 and 2019 (Cansiglio) and in 2012 and 2019 (Mongiana), data on forest structure and soil texture were collected. At the Cansiglio site, soils are identified as Haplic luvisols whereas at Mongiana, the predominant soil classifications consist of Inceptisols and Entisols, according to the USDA soil classification system. The variables analyzed in these sites, like in the evaluation sites, were GPP and LE. A summary of these sites is reported in Table 1.

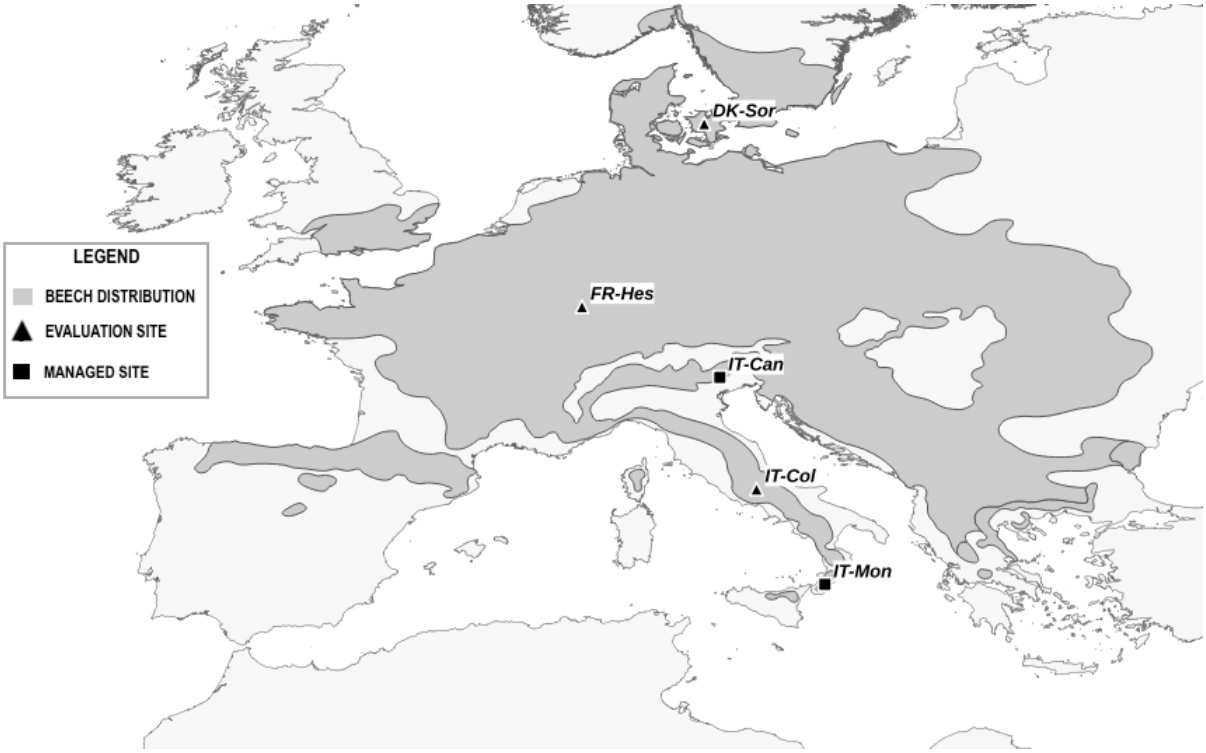

Fig 1. Map of the study sites. Red dots represent sites utilized for validating fluxes, while the blue dot signifies sites designated for management investigation.

Table 1. Characteristics of the study sites. The age of the stands refers to 2010. The mean annual temperature (MAT) and mean annual precipitation (MAP) for DK-Sor, FR-Hes and IT-Col refer to the period evaluated (i.e., 2006-2010 for the Sorø and Collelongo site and 2014-2018 for the Hesse site).

SITE DESCRIPTION					
	Evaluation sites			Managed sites	
Variable	**DK-Sor**	**FR-Hes**	**IT-Col**	**Cansiglio**	**Mongiana**
Coordinates (WGS84)	55°49'N, 11°64' E	48°66'N, 7°08'E	41°85'N, 13°59'E	46°02'N, 12°22'E	38°29'N, 16°14'E
Country	Denmark	France	Italy	Italy	Italy
Altitude (m a.s.l.)	40	305	1500	1300	1300
Area (ha)	1	1	1	27	27
MAT (°C)	8.52	10.27	6.95	6.44	11.01
MAP (mm)	818	853	1075	2219	1701
Slope (%)	-	5	35	12	10
Aspect (°)	0	0	252	135	135
Stand age (yr)	90	45	118	120	90

2.5 Meteorological data

For the evaluation sites (i.e., DK-Sor, FR-Hes, IT-Col) observed meteorological data were retrieved from the harmonized PROFOUND database (Reyer et al. 2020a,b) and Fluxnet database (https://data.icos-cp.eu/).

For the Mongiana and Cansiglio sites, meteorological data for 2010-2022 were obtained at daily temporal resolution from the Regional Environmental Protection Agencies (ARPAs) of the relevant region and responsible for monitoring climate variables with weather stations. The choice of thermo-pluviometric weather station was based on the minimum distance from the study area (between 2 km and 20 km away from the study sites, respectively) and on the data availability and integration with other weather stations in the proximity. The Bagnouls–Gaussen graph (Fig. S3) shows the mean monthly precipitation (mm) and air temperature (°C) recorded for every station inside the catchment.

Climate scenarios, used as inputs for two models at the Cansiglio and Mongiana sites, were from the COSMO-CLM simulation at ca. 2.2 km resolution over Italy (Raffa et al. 2023).

The daily variables considered for 3D-CMCC-FEM were mean solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), precipitation (mm day^{-1}), and the mean relative air humidity (%). In contrast, the MEDFATE model uses mean solar radiation, maximum and minimum air temperature, precipitation, the daily maximum and minimum relative air humidity and wind speed (m s^{-1}).

2.6 Modelling set-up

A set of parameters specific for *Fagus sylvatica* L. was provided as input to the model 3D-CMCC-FEM as described in Collalti et al. (2023) while for MEDFATE as in De Cáceres et al. (2023). To remove any confounding factors related to parameterization, the values of parameters related to the photosynthesis and stomatal conductance were kept

constant between the two models (see Table 2). The maximum stomatal conductance ($g_{s\ max}$) was set for 3D-CMCC-FEM according to Pietsch et al. (2005) as in BIOME BGC model. The maximum RuBisCO carboxylation rate (V_{cmax}) and the maximum electron transport rate for the RuBP regeneration (J_{max}) at 25°C are corrected for leaf temperature according to Medlyn et al. (1999) and soil water content as in Bonan et al. (2011). In MEDFATE the V_{cmax} and J_{max} at 25°C are modified according to Leuning (2002) leaf temperature dependence and modelled according to Medlyn et al. (1999) and Collatz et al. (1991).

We then used the LAI and Available Soil Water (AWS) values obtained from the 3D-CMCC-FEM outputs as input for running simulations with the MEDFATE model. This allowed us to isolate and evaluate the specific effects of the processes of interest, such as the influence of NSC on stomatal conductance and photosynthesis, compared to the impact of hydraulic constraints on these same physiological processes.

The LAI values were forced annually from 3D-CMCC-FEM to MEDFATE model since it is currently not possible to prescribe LAI values in the 3D-CMCC-FEM model (i.e., it is calculated prognostically). Precisely, here we used MEDFATE to simulate C and H_2O fluxes only, while taking into account plant hydraulics (De Cáceres et al. 2021), from the forest structure predicted by 3D-CMCC-FEM. For MEDFATE water balance, LAI values determine the competition for light and also drive the competition for soil water, along with the root distribution across soil layers.

PARAMETERS AND VARIABLES		
Variables	**Value**	**Unit**
$g_{s\,max}$	0.006	m s^{-1}
J_{max}	-160	μmol photons m^{-2} s^{-1}
V_{cmax}	-95	μmol CO_2 m^{-2} s^{-1}
LAI	from 3D-CMCC-FEM to MEDFATE	m^2 m^{-2}
ASW	from 3D-CMCC-FEM to MEDFATE	mm

Table 2. Parameters set for both models during the simulations.

2.7 Model evaluation

Both models were run for five years on the evaluation sites, with the simulation period determined by the availability of observed data provided, as already mentioned, from the PROFOUND database, specifically, from 2006 to 2010 at DK-Sor and IT-Col sites while for FR-Hes starting from 2014 to 2018. The performance metrics of the results of the evaluation for each site for the GPP and LE variables were the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE).

2.8 Model application in managed sites

In the managed sites (i.e., Cansiglio and Mongiana), simulations were performed using Historical climate ('Hist') and, to analyse models' sensitivities to climate change, under two Representative Concentration Pathways 4.5 and 8.5 ('Moderate' and 'Hot Climate'), respectively. The 'Hist' climate was used to run simulations at the Cansiglio site starting from 2011 to 2022 and for the Mongiana site starting from 2012 to 2022. In contrast, simulations using RCP4.5 and RCP8.5 climate ran accounting for the same time span, that is, 11 years for the Cansiglio site and 10 years for the Mongiana site, but considering the last years of the climate change scenarios (i.e., 2059-2070 and 2060-2070, respectively) to create harsher temperature and precipitation conditions, but with an increased atmospheric CO_2 concentration (in ppm).

For each of the nine sampled areas, in Cansiglio and Mongiana sites, we considered a representative area of 1 hectare for each type of plot: 'Control', 'Traditional', and 'Innovative'. At the beginning of the simulations, each site thus included a total of 9 plots, each 1 hectare in size—comprising 3 'Control' plots, 3 'Traditional' plots, and 3 'Innovative' plots. This setup resulted in a total of nine hectares being simulated per site where a certain percentage of the Basal Area (BA) was removed by the model 3D-CMCC-FEM according to the LIFE-ManFor project (see Table S2). 'Traditional' and 'Innovative' cutting took place for the first time in 2012 (Cansiglio) and 2013 (Mongiana), respectively. Following preliminary results, since the Mongiana site experienced a lighter thinning intensity compared to the Cansiglio site (refer to Table S2), consequently, for the Mongiana site, we considered an alternative management option involving the removal of 40% of the BA. This was done to evaluate whether a more intensive management approach ('SM') could have influenced models' results on Gross Primary Productivity (GPP) and Latent Heat (LE) fluxes.

3. Results

3.1 Model evaluation

The daily gross primary productivity (GPP) at DK-Sor, FR-Hes, and IT-Col sites was estimated from EC and simulated by 3D-CMCC-FEM and MEDFATE, are shown in Fig. 2. At DK-Sor site, the 3D-CMCC-FEM simulates a mean daily GPP of 5.14 gC m^{-2} day^{-1}, while MEDFATE 5.13 gC m^{-2} day^{-1}; and EC 5.54 gC m^{-2} day^{-1}; at the FR-Hes site, 3D-CMCC-FEM mean daily GPP of 6.18 gC m^{-2} day^{-1} compared to MEDFATE 4.82 gC m^{-2} day^{-1}, and EC 4.99 gC m^{-2} day^{-1}; lastly at the IT-Col site, 3D-CMCC-FEM mean daily GPP of 4.88 gC m^{-2} day^{-1} compared to MEDFATE 4.19 gC m^{-2} day^{-1}; and EC 4.11 gC m^{-2} day^{-1}; Additionally, at the DK-Sor site, the 3D-CMCC-FEM mean daily LE to the atmosphere of 2.83 MJ m^{-2} day^{-1}, while the MEDFATE mean value of 2.22 MJ m^{-2} day^{-1}; and EC 3.19 MJ m^{-2} day^{-1}; at the FR-Hes site, 3D-CMCC-FEM mean daily LE of 4.16 MJ m^{-2} day^{-1} compared to MEDFATE 3.01 MJ m^{-2} day^{-1}; and EC 4.47 MJ m^{-2} day^{-1}; in the end at the IT-Col site, 3D-CMCC-FEM mean daily LE of 2.02 MJ m^{-2} day^{-1} compared to MEDFATE 2.57 MJ m^{-2} day^{-1}; while EC 3.93 MJ m^{-2} day^{-1}. The GPP predicted by 3D-CMCC-FEM has shown higher values of R^2 (0.92) at DK-Sor and the lowest value at FR-Hes site (R^2 = 0.76) whilst a value of R^2 = 0.83 at IT-Col site, respectively. For the MEDFATE model, the GPP predicted highest value of R^2 (0.85) was at DK-Sor the lowest (R^2 = 0.68) at IT-Col and at FR-Hes R^2 = 0.76 the same showed for the 3D-CMCC-FEM model, respectively. Differently, the highest R^2 (0.89) value for 3D-CMCC-FEM considering LE predicted vs. observed was at FR-Hes site and almost the same values for DK-Sor and IT-Col sites (R^2 = 0.85 and 0.84, respectively). MEDFATE, for predicted vs. observed LE variable, has shown the highest R^2 (0.77) at IT-Col site, lower R^2 (0.69) value at FR-Hes site and the lowest R^2 (0.62) value at DK-Sor site, respectively. In general, both the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) values in all sites were reasonably low,

falling within the ranges of 3.31 to 2.02 gC m^{-2} day^{-1} and 2.46 to 1.47 MJ m^{-2} day^{-1}, for both models and for both the variables. In Fig. 3 and Table 3 are reported the summary of the evaluation metrics performance results.

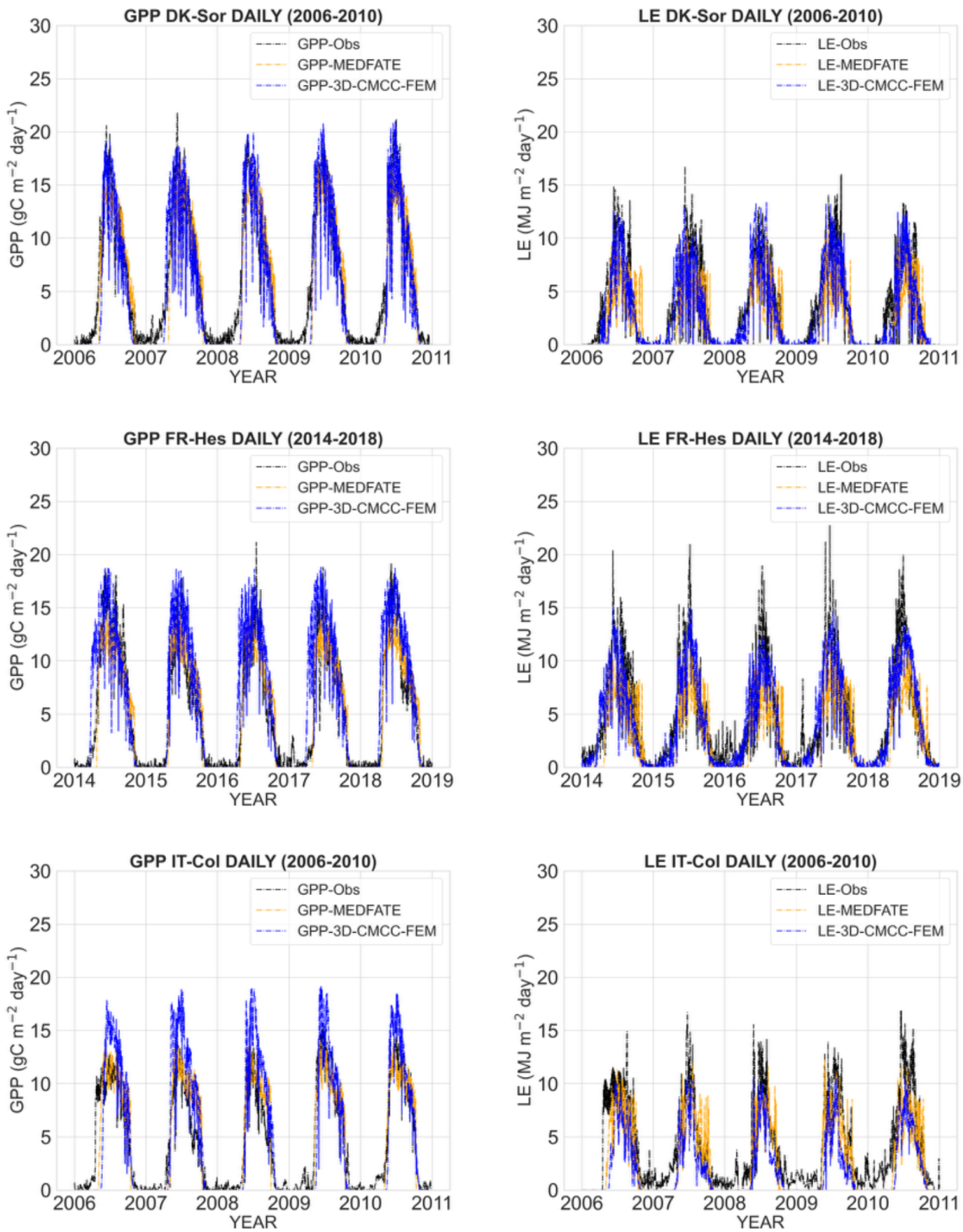

Fig 2. Daily mean variations of GPP (gC m^{-2} day^{-1}) and LE (MJ m^{-2} day^{-1}) estimated from the direct micrometeorological eddy covariance measurements (GPP-Obs and LE-Obs) and models' simulation (GPP-3D-CMCC-FEM, LE-3D-CMCC-FEM and, GPP-MEDFATE, LE-MEDFATE) during the evaluation period at the DK-Sor, IT-Col and FR-Hes at the Beech forest in 2006-2010 and 2014-2018, respectively.

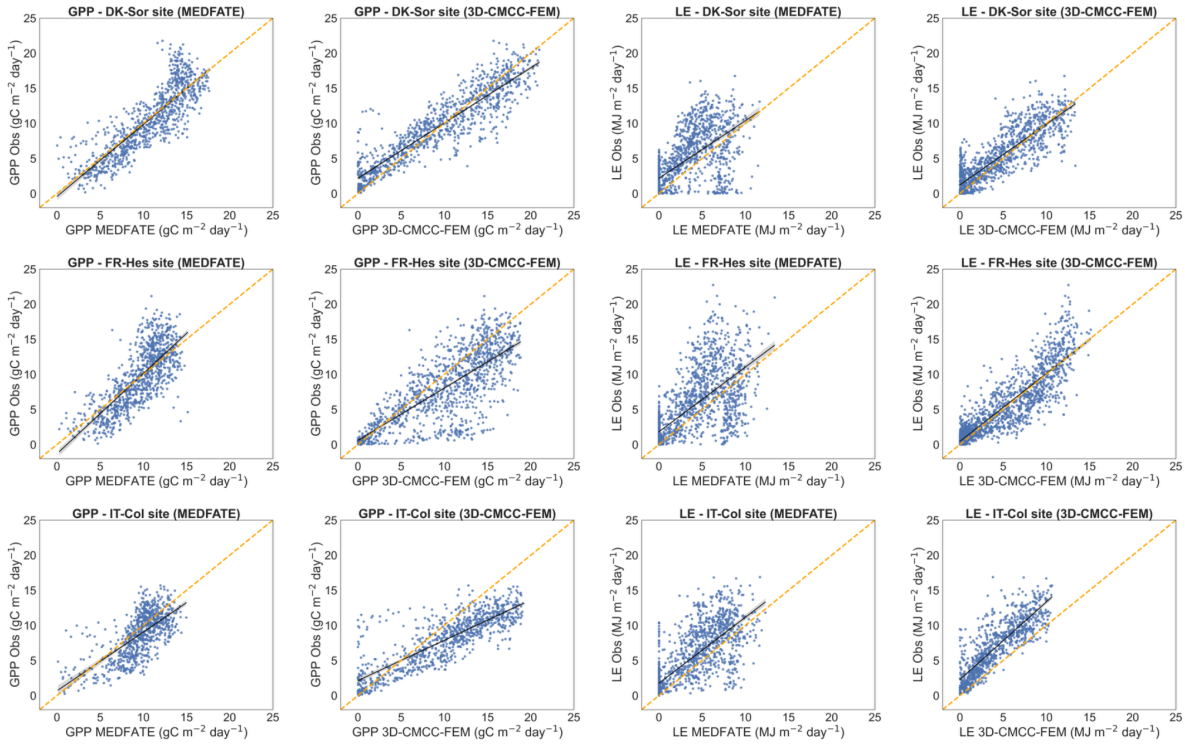

Fig 3. Scatter plots and linear regressions of GPP (gC m^{-2} day^{-1}) and LE (MJ m^{-2} day^{-1}) of the models versus the direct micrometeorological eddy covariance measurements (Obs) at the Sorø (DK-Sor; 2006-2010 period), Collelongo (IT-Col; 2006-2010 period) and Hesse (FR-Hes; 2014-2018 period).

Table 3. The correlation coefficient (R^2), the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) for, the GPP (gC m^{-2} day^{-1}) and LE (MJ m^{-2} day^{-1}) of the daily simulations at DK-Sor, IT-Col, and FR-Hes sites performed from both models 3D-CMCC-FEM and MEDFATE in the beech forest stands.

	3D-CMCC-FEM						MEDFATE					
	GPP			LE			GPP			LE		
	R^2	RMSE	MAE	R^2	RMSE	MAE	R^2	RMSE	MAE	R^2	RMSE	MAE
DK-Sor	0.91	2.17	1.65	0.85	2.02	1.58	0.85	2.52	1.97	0.62	3.09	2.39
FR-Hes	0.76	3.30	2.46	0.89	2.09	1.47	0.76	2.80	2.21	0.69	3.31	2.37
IT-Col	0.83	2.09	1.56	0.84	2.05	1.57	0.68	2.32	1.87	0.77	2.64	1.90

3.2 Simulation results at Cansiglio

The Fig. 4, shows the simulation results using the 3D-CMCC-FEM and MEDFATE models in the Cansiglio site. For the 3D-CMCC-FEM the 'Control' plot exhibited the lowest GPP values under 'Hist' climate conditions, averaging 1681 gC m^{-2} $year^{-1}$. These values increased slightly to 1982 gC m^{-2} $year^{-1}$ under the RCP4.5 climate and further rose to 2204 gC m^{-2} $year^{-1}$ in the RCP8.5 climate. Similarly, for plots managed with 'Traditional' methods, the trends were consistent with the 'Control' plot, showing average GPP values of 1603, 1942, and 2141 gC m^{-2} $year^{-1}$ under 'Hist', RCP4.5 and RCP8.5 climate, respectively. However, 'Innovative' management showed lower GPP fluxes across all three climate scenarios, with average values of 1534, 1882, and 2075 gC m^{-2} $year^{-1}$ under 'Hist', RCP4.5 and RCP8.5 climate, respectively. The MEDFATE model showed higher

mean absolute GPP increases than the 3D-CMCC-FEM model under RCP4.5 and RCP8.5 climates, respectively. Under the 'Hist' climate and all treatments, the mean GPP values were about 1638 gC m^{-2} $year^{-1}$, whereas under the RCP4.5 climate, they rose to 2516 gC m^{-2} $year^{-1}$ and to 2995 gC m^{-2} $year^{-1}$ under RCP8.5 climate. Analyzing in Fig. 4 the trends of LE for the 3D-CMCC-FEM model, these trends closely follow those of GPP concerning management treatments. The 3D-CMCC-FEM LE values for the 'Control' plots, similar to GPP, were lowest for the 'Hist' climate with an average value over the simulation years of 1200 and 1501 MJ m^{-2} $year^{-1}$ for the RCP4.5 climate, and 1391 MJ m^{-2} $year^{-1}$ for the RCP8.5 climate, respectively. The LE of the 'Traditional' management, predicts values of 1129 in the 'Hist' climate, 1440 in the RCP4.5 climate, and 1338 MJ m^{-2} yr^{-1} in the RCP8.5 climate, respectively. For the 'Innovative' management, the mean LE values of 1121 in the 'Hist' climate, 1403 for the RCP4.5 climate, and 1306 MJ m^{-2} yr^{-1} for the RCP8.5 climate, respectively. Similar to the GPP fluxes, the MEDFATE model simulated reductions in LE fluxes among the treatments and higher values across the climates. The mean LE value modelled in the 'Hist' climate, grouped by treatments (because of slight differences among managements), was about 920, 1419 in the RCP4.5 climate, and 1456 MJ m^{-2} yr^{-1} in the RCP8.5 climate, respectively. MEDFATE simulated a stem xylem conductance loss of approximately 40% in the seventh, eighth, and twelfth years of simulation for the RCP8.5 climate scenario in the 'Control' plot, while for the managed plots, this loss was predicted only in the seventh year. Conversely, near-zero or negligible stem embolism were simulated under the 'Hist' and RCP4.5 climate scenarios. The 3D-CMCC-FEM simulated higher values, albeit in a small percentage (i.e., between 8-10%), of NSC, increasing proportionally to the intensity of basal area removed, better observable in the graph at the tree level.

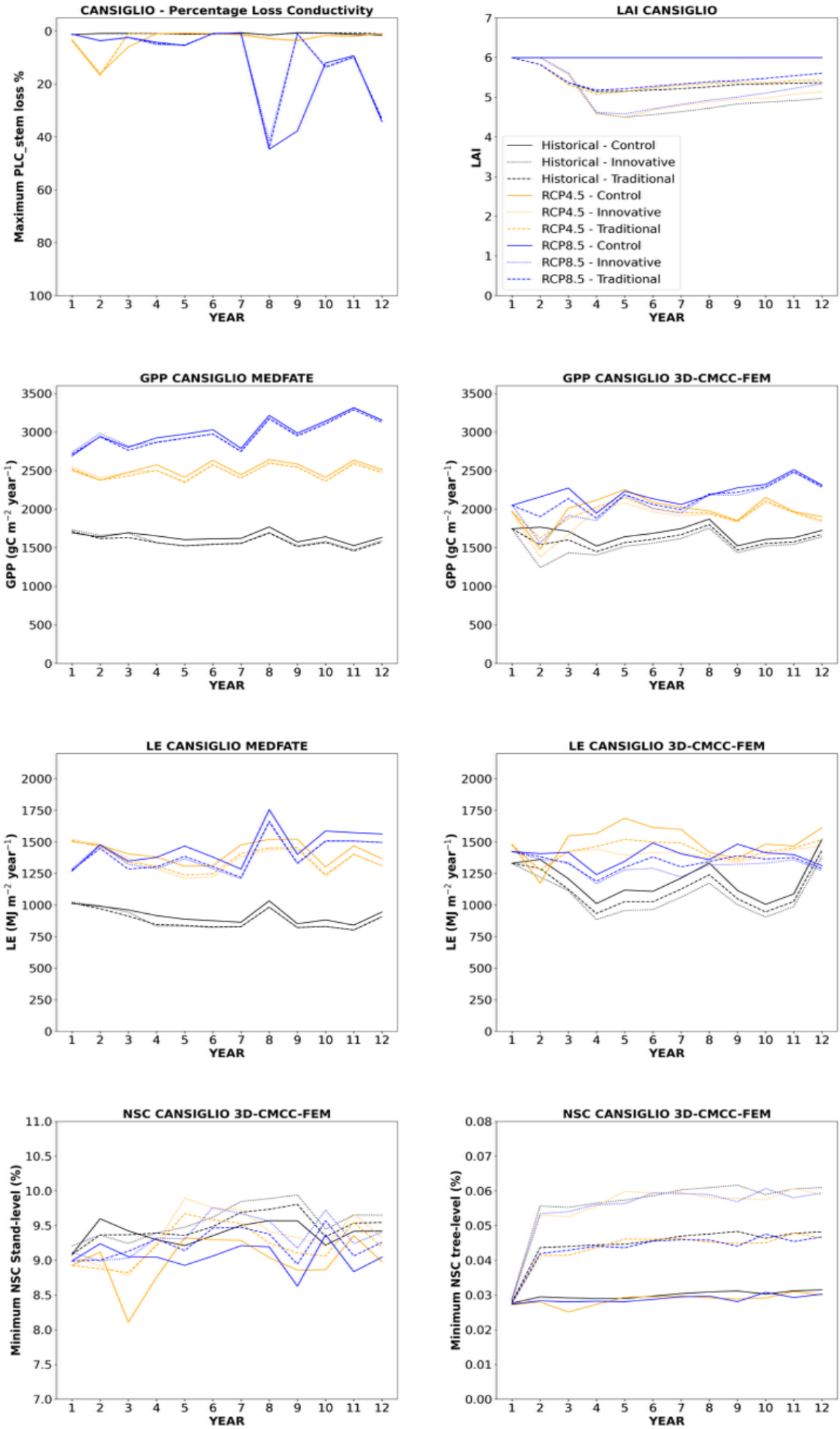
CANSIGLIO - Percentage Loss Conductivity
Maximum PLC_stem loss %
YEAR
LAI CANSIGLIO
LAI
Historical - Control
Historical - Innovative
Historical - Traditional
RCP4.5 - Control
RCP4.5 - Innovative
RCP4.5 - Traditional
RCP8.5 - Control
RCP8.5 - Innovative
RCP8.5 - Traditional
GPP CANSIGLIO MEDFATE
GPP (gC m⁻² year⁻¹)
GPP CANSIGLIO 3D-CMCC-FEM
LE CANSIGLIO MEDFATE
LE (MJ m⁻² year⁻¹)
LE CANSIGLIO 3D-CMCC-FEM
NSC CANSIGLIO 3D-CMCC-FEM
Minimum NSC Stand-level (%)
NSC CANSIGLIO 3D-CMCC-FEM
Minimum NSC tree-level (%)

Fig 4. Comparative analysis between models output at the Cansiglio site. The top-left panel displays the PLC_{stem} as modelled by MEDFATE, while the top-right panel shows the modelled LAI for 3D-CMCC-FEM (and used by MEDFATE). The middle-up panels (left and right) present annual GPP (gC m^{-2} $year^{-1}$) as modelled by the MEDFATE and 3D-CMCC-FEM, respectively. The middle-down panels (left and right) depict annual LE (MJ m^{-2} yr^{-1}) as modelled by the MEDFATE and 3D-CMCC-FEM, respectively. The bottom panels (left and right) depict the annual minimum of NSC concentration (%) at the stand and tree level, respectively, as modelled by the 3D-CMCC-FEM. Different plot management strategies are represented by distinct line styles: solid lines for 'Control' plots ('no management'), dotted lines for 'Innovative' plots, and dashed lines for 'Traditional' plots (Shelterwood). Climate scenarios are indicated by line colours: black for 'Hist' climate data (2010-2022), orange and blue for RCP4.5 and RCP8.5 climate (2059-2070), respectively.

3.3 Simulation results at Mongiana

Simulation results at the (drier) Mongiana site well depicted the differences with the rainy Cansiglio site (Fig. 5). The 3D-CMCC-FEM model showed no significant differences in the mean values of GPP among various management interventions under 'Hist' climate conditions, with a mean value of 2151 gC m^{-2} yr^{-1}. Compared to the Cansiglio site, Mongiana exhibited lower average *GPP* values. Under RCP4.5 climate conditions, the GPP for the 'Control' plot was 1864 gC m^{-2} yr^{-1}. In contrast, the 'Traditional' and 'Innovative' management interventions yielded higher average GPP values of 2115 gC m^{-2} yr^{-1} and 2086 gC m^{-2} yr^{-1}, under the current climate, respectively. The GPP values under the more intensive management ('SM') and RCP4.5 climate decreased even further than those of the 'Control' plot, with an average value of 1650 gC m^{-2} yr^{-1}. Under the RCP8.5, no differences in GPP were observed among management strategies, with values of about 1525 gC m^{-2} yr^{-1}. Moreover, under the RCP8.5, the 'Control' plot experienced complete mortality after five years of simulations. The MEDFATE model predicted slightly higher average values of GPP in the 'Control' plots (2099 gC m^{-2} yr^{-1}) compared to the managed plots (2087 gC m^{-2} yr^{-1}, encompassing both 'Traditional' and 'Innovative' of two management strategies), with no significant differences observed among the management strategies and under 'Hist' climate. Under the RCP4.5 and RCP8.5, the GPP

values were 1608 gC m^{-2} yr^{-1} and 1935 gC m^{-2} yr^{-1}, respectively. The PLC_{stem} graph in Fig. 5 indicated very high xylem embolism levels (i.e., reaching 100% every year) under RCP4.5 and RCP8.5 already in the first year of simulations. A pronounced embolism event was observed under the 'Hist' climate in 2017, 2018, 2019 and 2022 in a range of 30-45% for the 'Control' plots, while the managed plots experienced a maximum embolism of approximately 40% in 2017. Conversely, for the LE, the 3D-CMCC-FEM model did not report any significant differences between managed and unmanaged plots. The average LE value for the 'Hist' climate was 1796 MJ m^{-2} yr^{-1}, which decreased to 1220 MJ m^{-2} yr^{-1} under the RCP4.5 and 1190 MJ m^{-2} yr^{-1} under the RCP8.5 in managed plots. The 'Control' plot under the RCP8.5, as previously described, experienced mortality in the sixth year of simulation. Similarly to the previously described GPP fluxes, the MEDFATE model reported a slight difference in LE fluxes between the 'Control' plot under historical climate conditions (1623 MJ m^{-2} yr^{-1}) and the managed plots (1603 MJ m^{-2} yr^{-1}). For the RCP4.5 and RCP8.5, the LE values were 1100 MJ m^{-2} yr^{-1} and 1089 MJ m^{-2} yr^{-1}, respectively. The LE values of the 'Control' plots are not reported neither for RCP4.5 nor for RCP8.5 because of the mortality experienced for the simulation years.

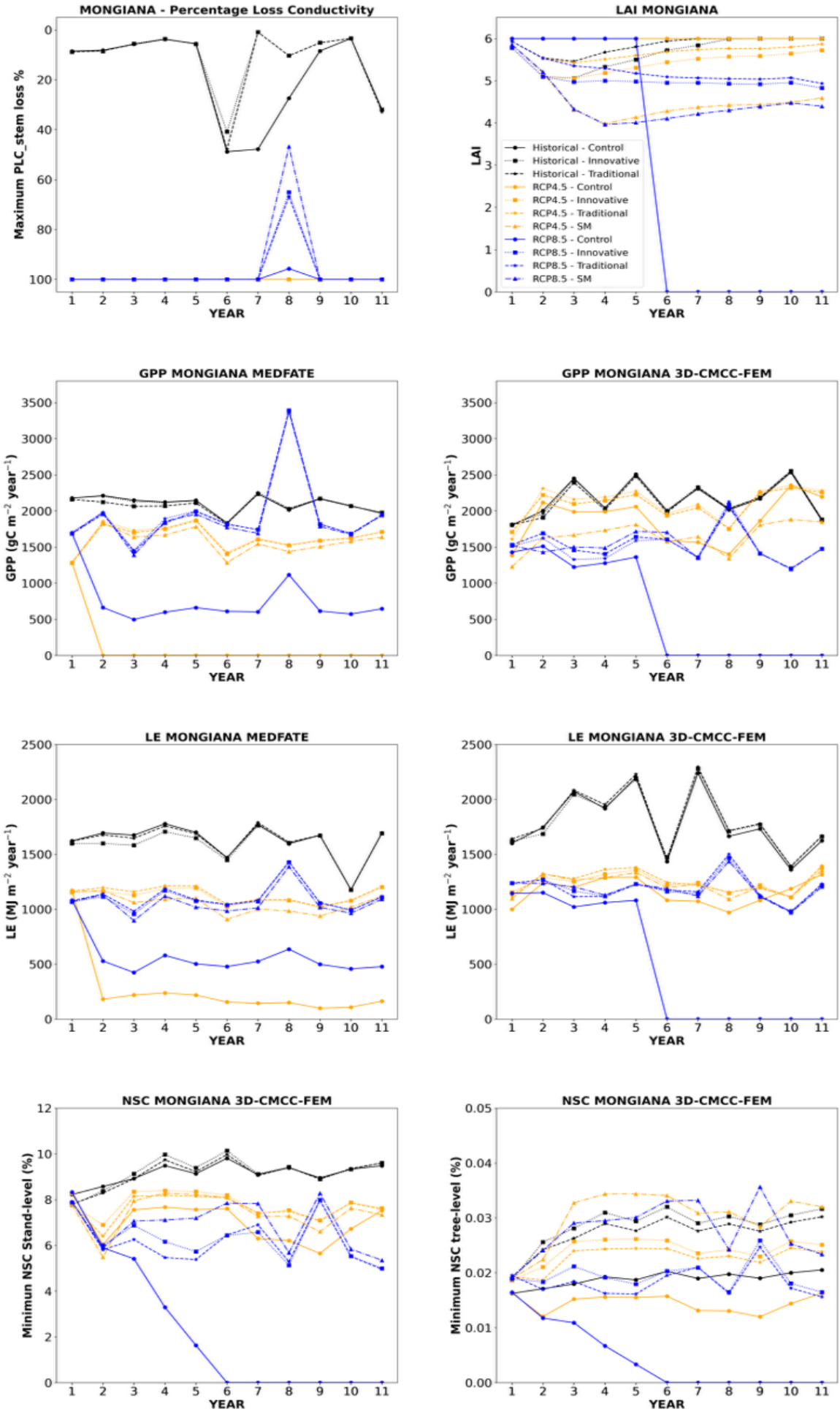
MONGIANA - Percentage Loss Conductivity
Maximum PLC_stem loss %
YEAR
LAI MONGIANA
LAI
YEAR
Historical - Control
Historical - Innovative
Historical - Traditional
RCP4.5 - Control
RCP4.5 - Innovative
RCP4.5 - Traditional
RCP4.5 - SM
RCP8.5 - Control
RCP8.5 - Innovative
RCP8.5 - Traditional
RCP8.5 - SM
GPP MONGIANA MEDFATE
GPP (gC m^{-2} year^{-1})
YEAR
GPP MONGIANA 3D-CMCC-FEM
GPP (gC m^{-2} year^{-1})
YEAR
LE MONGIANA MEDFATE
LE (MJ m^{-2} year^{-1})
YEAR
LE MONGIANA 3D-CMCC-FEM
LE (MJ m^{-2} year^{-1})
YEAR
NSC MONGIANA 3D-CMCC-FEM
Minimun NSC Stand-level (%)
YEAR
NSC MONGIANA 3D-CMCC-FEM
Minimum NSC tree-level (%)
YEAR

Fig 5. Comparative analysis between models output at the Mongiana site. The top-left panel displays the percent loss of PLC_{stem} as modelled by MEDFATE while the top-right panel shows the modelled LAI for 3D-CMCC-FEM (and used by MEDFATE). The middle-up panels (left and right) present annual GPP (gC m^{-2} $year^{-1}$) as modelled by the MEDFATE and 3D-CMCC-FEM, respectively. The middle-down panels (left and right) depict annual LE (MJ m^{-2} yr^{-1}) as modelled by the MEDFATE and 3D-CMCC-FEM, respectively. The bottom panels (left and right) depict the annual minimum of *NSC* concentration (%) at the stand and tree level, respectively, as modelled by the 3D-CMCC-FEM. Different plot management strategies are represented by distinct line styles: solid lines with circles for 'Control' plots ('no management'), dotted lines with squares for 'Innovative' plots, dashed lines with stars for 'Traditional' plots (Shelterwood) and dash-dotted lines with triangles for 'SM' management. Climate scenarios are indicated by line colours: black for 'Hist' climate data (2010-2022), orange and blue for RCP4.5 and RCP8.5 climate (2060-2070), respectively.

4. Discussions

First, this study investigated the performance of the two different process-based models in simulating different beech stands across Europe starting to the north of Europe towards the south under different environmental conditions. Secondly, the study focused both on the impact of management options and by considering different climatic conditions in two specific beech forest stands in the north and south of the Italian peninsula. With advances in ecological modelling, predicting the human impact of management has become an increasingly paramount component of forest ecosystem studies. The increasing information demand about stand-level dynamics can be supported by the forest models for decision-making in forestry (Pretzsch et al. 2008).

4.1 Model evaluation

To assess the models' accuracy in predicting carbon and water fluxes, we compared the GPP and the LE data obtained from the EC towers. Both models predicted estimates of GPP and LE accurately and ensured a good range of general applicability of both models (Kramer et al. 2002; Verbeeck et al. 2008). The 3D-CMCC-FEM model seems to overestimate GPP daily values along latitudinal gradients starting from the north (DK-Sor) to the south (IT-Col), as already found in Collalti et al. (2016). MEDFATE in contrast,

showed a little overestimation of GPP only at the IT-Col site. The LE predicted by 3D-CMCC-FEM is more accurate than MEDFATE prediction for DK-Sor and FR-Hes sites but not in IT-Col site in which 3D-CMCC-FEM has shown to underestimate compared to the observed EC values. For MEDFATE the underestimation of LE was observed in all the evaluation sites.

The spread observed for the GPP and LE fluxes between the two models can be attributed to the different assumptions that govern stomatal regulation since both models use the Farquhar-von Caemmerer-Berry biochemical model to calculate photosynthesis. The over or underestimation of the flows estimated by the models both for GPP and the LE compared to the data observed from the EC towers can be attributed either to the presence of the understory (although commonly sporadic in mature beech stands), which was not considered in the simulations by both models, and to the errors on daily measurement by EC technique (Loescher et al. 2006) or from phenological shifts (Richardson et al. 2010). However, the leaf phenological pattern of the European beech in these sites is well represented by the two models in almost all of the years according to EC data as shown in supplementary materials (see Fig. S4, S5, S6, S7, S8, S9 and Fig S10). It is important to note that we did not specifically calibrate the model parameters from the eddy covariance data for each site. Instead, as already done by Dufrêne et al. (2005), both models were parameterized using values from existing literature and with one single set of parameter values for all sites.

4.2 Climate change and forest management at the Cansigio and Mongiana site

The pre-Alpine site of Cansiglio showed slight differences in the fluxes (i.e., GPP and LE) between three different management practices applied and the three climates used. Future climate has shown to be higher temperature if compared to the historical one with MAT higher of about 3.93°C under RCP4.5 and 4.95°C under RCP8.5 for the Cansiglio

site and of 4.52°C under RCP4.5 and 5.42°C under RCP8.5 at the Mongiana site. Similarly MAP has shown to be lower for 510 in mm under RCP4.5 and 602 in mm under RCP8.5 for the Cansiglio site and lower of 902 in mm under RCP4.5 and 914 in mm under RCP8.5 at the Mongiana site.

Regarding management, the response of the 3D-CMCC-FEM to the removal of a percentage of the basal area from the stand led to a decrease in GPP in the 'Traditional' cutting and to an even greater extent in the 'Innovative' cutting compared to the 'Control' (i.e., no management). Similarly to 3D-CMCC-FEM, the MEDFATE model simulates slight differences in fluxes amount (e.g. lower values for 'Traditional' and 'Innovative' cutting than 'Control' plots) between the management regimes in the plots. However, differences were observed in both models under the three different climates used in the simulations, where GPP fluxes increased from the 'Hist' climate to RCP4.5 and reached the maximum for RCP8.5, respectively. This suggests a plastic response (e.g. photosynthesis and stomatal response) of the stands to harsher conditions in both models, indicating, potentially, a high acclimation capacity (Petrik et al. 2022) and the CO_2 fertilisation effect also found in De Wergifosse et al. (2022) and Reyer et al. (2013), especially in this site with no apparent water limitation both under current and projected future climates. However, for high-altitude stands, there could be a negative effect on growth under warmer conditions, as suggested by Chmura et al. (2024). The LE results for the 3D-CMCC-FEM showed a decrease in values over the simulation period for managed stands compared to unmanaged ones with higher values. However, under the RCP4.5, the LE values are higher compared to both the 'Hist' climate and the RCP8.5 one due to greater annual cumulative precipitation compared to the RCP8.5 and higher, on average, temperatures compared to the 'Hist' one. Conversely, MEDFATE model was shown to be more sensitive to climate, with a clearer distinction between the 'Hist' climate, the RCP4.5 and RCP8.5 climates, with higher and nearly equal values in the

661 harsher conditions (i.e., RCP4.5 and RCP8.5 climates), with slight differences in the
662 management treatments as obtained by 3D-CMCC-FEM. The Non-Structural carbon
663 (NSC) amount showed the highest values in 'Innovative' plots, followed by 'Traditional'
664 plots, and the lowest values in 'Control' plots, suggesting a benefit in carbon stock
665 accumulation with more carbon going for carbon biomass and less for reserve-
666 replenishment for these stands under management interventions. However, for the three
667 climate scenarios, NSC levels remain nearly the same throughout all the simulation years.
668 It is also important to note that under the climate scenarios, MEDFATE simulated an initial
669 loss of stem conductance indicating the onset of water stress for the stand. Although in
670 RCP4.5 this is negligible, in RCP8.5 PLC_{stem} values reach a maximum xylem cavitation
671 value of about 40% in the eighth year of simulation for managed plots while for 'Control'
672 plots in the eighth, ninth and twelfth years, highlighting potential benefits of management
673 to reduce drought stress (Giuggiola et al. 2018; Schmied et al. 2023).
674 The GPP at the southern Apennine site of Mongiana showed a decrease in the simulations
675 when simulated by 3D-CMCC-FEM model as a result of harsher environmental
676 conditions, as resulted also in the study by Yu et al. (2022), in which the productivity of
677 European beech in southern regions are expected to decrease as affected by more
678 severe climate conditions such as decreased precipitation and increased in air
679 temperature. Indeed, the increase in air temperature, a reduction in soil water
680 availability, and the rise in vapor pressure deficit (*VPD*) lead to stomatal closure,
681 increased mesophyll resistance, and elevated abscisic acid production, all of which
682 contribute to a decrease in the carbon assimilation rate (Priwitzer et al. 2014). Specifically,
683 GPP are higher under 'Hist' climate conditions, decrease under the RCP4.5, and ultimately
684 reach even lower values under the RCP8.5. Under the RCP8.5 at the fifth year of
685 simulation, the stand in the 'Control' plot is simulated to die due to carbon starvation.
686 The annual decline in NSC (Fig. 5) due to an imbalance between carbon uptake

(photosynthesis) and the demands for growth and respiration suggests that the trees are unable to replenish their carbon reserves. The depletion of NSC reserves may ultimately disrupt processes such as osmoregulation and phenology (Martínez-Vilalta et al. 2016), potentially leading to stand defoliation and/or mortality. The management options did not show changes in GPP under the 'Hist' climate. However, the increase of GPP was observed under the RCP4.5 in the plots where 'Innovative' and 'Traditional' cutting occurred, although no differences were observed between them. The same increase in GPPs, for instance, was reported in Fibbi et al. (2019), for beech forest under climate scenarios in Italy. In contrast, the more intense cutting exhibited even lower GPP values than the 'Control' plots. This is likely due to the overly intense thinning, which contrasts the microclimate effects within this forest stand reducing the potential to offset climate warming at the local scale (Rita et al., 2021). With the decrease in precipitation under the RCP4.5 and RCP8.5 climate scenarios compared to the 'Hist' climate, LE decreased. There were no significant differences in LE among the various management regimes. For the MEDFATE model, negligible or no differences in GPP were observed under all the climates among various management options. Although the GPP values estimated by the MEDFATE model under the RCP4.5 and RCP8.5 are similar to those obtained from the 3D-CMCC-FEM model, a closer analysis of the daily outputs (data not shown) reveals that trees photosynthesize until the end of July, after which they experience significant embolism (i.e., maximum value of 100%), as indicated by the PLC_{stem} graph, indicating that the decrease in precipitation led to summer soil moisture depletion and lethal drought stress levels. Furthermore, the 'Control' plots experienced mortality even before reaching the summer period. It is also important to note that under 'Hist' climate conditions, the MEDFATE model indicated a stem embolization loss ranging from approximately 10% to 45% during the drought period (e.g. 2018-2020) in Europe (Italiano et al. 2024; Thom et al. 2023; Lombardi et al. 2023). The embolization was more

pronounced and long-lasting in the 'Control' plots compared to the managed ones. The same trends were obtained for LE.

5. Conclusion

The use of these two process-based models provides robust evidence for their application in estimating fluxes, consistent with long-term EC tower measurements in beech forests. Despite the minimal parametrization effort to align the two models and the avoidance of site-specific parameters, reliable results can still be obtained, as confirmed by the outputs from the Sorø, Hesse, and Collelongo sites. Regarding the sub-Alpine Cansiglio site, although water limitation does not significantly impact fluxes or the health of the forest under Moderate climate conditions (RCP4.5), a potential concern is the embolization predicted by the MEDFATE model under the Hot climate (RCP8.5) at this site, despite similar levels of precipitation. The high susceptibility of beech forests at the southern Apennine site of Mongiana to more severe (i.e. hotter and drier) climatic conditions could lead to the collapse of this forest ecosystem, even with the application of management options aimed at reducing competition. This necessitates strategic management planning, including the ability to project (e.g forest models) and evaluate future forest conditions for better management schemes (Taylor et al. 2009). However, the ability of these forests to survive or resist the impacts of climate change may not depend solely on density reduction interventions. A broader approach that incorporates various process-based models to further evaluate silvicultural options on fluxes can significantly enhance our understanding of the critical role decision-making in forestry plays in vulnerable ecosystems. Additionally, identifying complementary species for mixed forests could be pivotal in bolstering beech ecosystem resilience.

CRediT authorship contribution statement

Vincenzo Saponaro: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Miquel De Càceres:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing. **Daniela Dalmonech:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing. **Ettore D'Andrea:** Resources, Methodology, Data curation, Writing – review & editing. **Elia Vangi:** Resources, Writing – review & editing. **Alessio Collalti:** Conceptualization, Methodology, Resources, Software, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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data and the climate used in this work. This work used eddy covariance data acquired and shared by the FLUXNET community, including these networks: AmeriFlux, AfriFlux, AsiaFlux, CarboAfrica, CarboEuropeIP, CarboItaly, CarboMont, ChinaFlux, Fluxnet-Canada, GreenGrass, ICOS, KoFlux, LBA, NECC, OzFlux-TERN, TCOS-Siberia, and USCCC. The 3D-CMCC-FEM model code is publicly available and can be found on the GitHub platform at: https://github.com/Forest-Modelling-Lab/3D-CMCC-FEM. The MEDFATE model code is publicly available and can be found on the GitHub platform at: https://github.com/emf-creaf/medfate.

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