Assessing models' sensitivity to the effects of forest management and climate change on carbon and water fluxes in European beech forests

Vincenzo Saponaro[1,2*], Miquel De Cáceres[3], Daniela Dalmonech[1,4], Ettore D'Andrea[4,5], Elia Vangi[1], Alessio Collalti[1,4]

Affiliations:

1. Forest Modelling Lab., Institute for Agriculture and Forestry Systems in the Mediterranean, National Research Council of Italy (CNR-ISAFOM), Perugia, Italy;
2. Department for Innovation in Biological, Agri-Food and Forest Systems (DIBAF), University of Tuscia, Viterbo, Italy;
3. CREAF, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain
4. National Biodiversity Future Center (NBFC), Palermo, Italy
5. Research Institute on Terrestrial Ecosystems, National Research Council of Italy (CNR-IRET), Porano, Italy

[*]***Corresponding author***: vincenzo.saponaro@isafom.cnr.it

Highlights

- Modelled carbon and water fluxes under different climates and management regimes
- Different climates increases fluxes in the north and decreases them in the south
- 3D-CMCC-FEM and MEDFATE satisfactorily predicted productivity and latent heat
- 3D-CMCC-FEM predicts carbon starvation, MEDFATE predicts stem embolism in the south
- High thinning intensity of the stand in the south 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 will affect 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 (PBMs) can help us to simulate such phenomena and capture early stress signals while considering the effect of different management approaches. In this study, we focus on estimating sensitivity of two state-of-the-art PBMs forest models by simulating carbon and water fluxes at the stand level to assess productivity changes and feedback resulting from different climatic forcings. Utilizing 3D-CMCC-FEM and MEDFATE models, we simulated and analyzed carbon (C) and water (H_2O) fluxes in diverse forest plots under managed vs. unmanaged scenarios and under current climate and different climatic forcings (RCP4.5 and RCP8.5), in two sites, 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 in simulating C and H_2O flux in three additional beech forests along a latitudinal gradient spanning 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. Still, 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. At the Mongiana site in southern Italy, both models simulate a decrease in C and H_2O fluxes and sensitivity to the different climatic forcings compared to the current climate,

with an increase in C and H_2O fluxes considering specific 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 sensitivity, *Fagus sylvatica* L., Forest management sensitivity, 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 offer, for instance, climate change mitigation through their ability to store atmospheric carbon dioxide in biomass and soil (Augusto and Bo, 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 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, primarily, on species composition, site conditions as well as on stand age (Rötzer et al., 2010; Vangi et al., 2024a, b), which are affected by past and present forest management activities. According to Collalti et al. (2018) and Dalmonech et al. (2022), monospecific forests in Europe 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 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 dry and 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).

Process-based models (PBMs) 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 the field 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 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 sensitivity of two state-of-the-science PBMs: 3D-CMCC-FEM (Collalti et al., 2014) and MEDFATE (De Cáceres et al., 2023). First under different forest management regimes and climate change scenarios 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 changing environmental conditions. The study sites vary in terms of environmental factors that

can affect gross primary productivity (GPP), as well as latent heat (LE), which are 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; and, (ii) how harsher climate conditions may affect the C and H_2O fluxes under different management options. To address these questions 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 C and H_2O fluxes at two target and independent beech forest sites in Italy (Cansiglio and Mongiana) by simulating their development under various management options and evaluating their (model) 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., 2024 (and references therein); 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 daily, monthly, or annually, depending on the processes to simulate, with a common spatial scale of one 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., 2020a; Merganikova et al., 2019). In deciduous trees, NSC is used to create new leaves during the bud-burst phase, replenishes 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 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 results from 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 contains 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 dependent on 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 $k(\Psi)$, that declines as water pressure becomes more negative. The xylem vulnerability curve is modelled using a sigmoid function, defined by the equation:

$$k(\Psi) = k_{max}/1 + exp^{(slope/25)\cdot(\Psi-\Psi 50)} \quad (2)$$

where k_{max} is the maximum hydraulic conductance, $\Psi 50$ 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}) associated with vessel embolism. This embolism reduces

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

Gas exchange in the Sureau-ECOS module depends 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, unlike 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 stem vulnerability.

Soil water balance is computed daily. 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 on the plain

at the base of the Vosges Mountains. IT-Col (Selva Piana stand) is a permanent experimental plot installed in 1991 and situated in a mountainous area of the Abruzzo region, the centre of Italy.

The pedological characterization of soils exhibits distinct variations across the studied sites. The soil at the DK-Sor site is predominantly classified as either Alfisols or Mollisols. The FR-Hes site showcases an intermediary nature, displaying characteristics akin to both luvisols and stannic luvisols. At the IT-Col site, the prevailing soil type is identified as Humic alisols, according to the USDA soil classification system. Full details of these sites are reported in Table 1.

The variables accounted for in the evaluation were obtained from the Fluxdata website (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/) from the FLUXNET2015 database (Pastorello et al., 2020). The variables considered are the daily GPP, estimated from Net Ecosystem Exchange (NEE) measurements and quality checked using the constant USTAR turbulence correction according to Papale et al. (2006) and the Latent Heat flux (LE) with energy balance closure correction (i.e., 'LE_CORR') (Pastorello et al., 2020).

2.4 Study sites

The two target sites considered in this study are Cansiglio and Mongiana Forests (Fig. 1) (De Cinti et al., 2016). Each site consists of nine long-term monitored plots of differently managed beech stands, with a spatial extension for each area above 3 hectares, for about 27 hectares of the experimental area. Three different treatments were applied (see Fig. S1-S2). For each site, three of the nine plots considered were left unmanaged (i.e., no cutting and leaving the stands to natural development), defined as 'Control' plots, three plots were 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 the establishment of regeneration. The 'Innovative' cutting consisted of selecting 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 to increase the 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 removing only direct competitors.

The Cansiglio site is situated in a mountainous area in the Veneto region, northern Italy. Mongiana site is located in a mountainous area in the Calabria region of southern Italy. The latter shows higher mean annual temperature (MAT, C°) and lower mean annual precipitation (MAP, mm $year^{-1}$) (i.e., drier conditions) than the Cansiglio site located at higher latitudes (Table 1). Data on forest structure and soil texture were collected during the field campaigns conducted in 2011 and 2019 (Cansiglio) and in 2012 and 2019 (Mongiana). 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 for these sites is reported in Table 1.

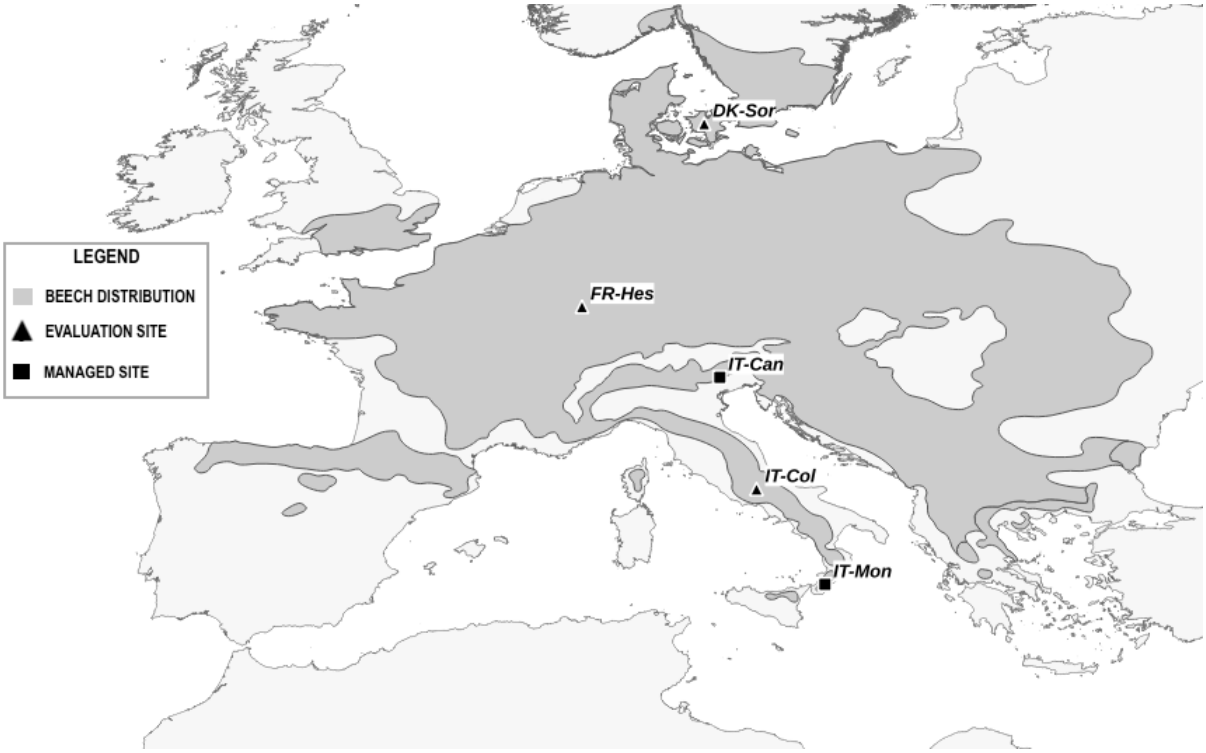

Fig 1. Map of the study sites. Red dots represent sites for validating fluxes, while the blue dot signifies sites designated for management investigation.

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) while for Cansiglio and Mongiana from 2010 to 2022. The sum of precipitation in summer refers to June (J), July (J) and August (A) for the same period.

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
Summer prec (J-J-A)(mm)	292	205	120	493	141

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 relevant region's Regional Environmental Protection Agencies (ARPAs), which are 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 a resolution of approximately 2.2 km 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 parameters related to 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. In 3D-CMCC-FEM, 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 the 3D-CMCC-FEM to the 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 considering 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.

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

PARAMETERS AND VARIABLES		
Name	**Value**	**Unit**
$g_{s\ max}$	0.006 Pietsch et al. (2005)	m s^{-1}
J_{max}	~160 De Cáceres et al. (2023)	µmol photons m^{-2} s^{-1}
V_{cmax}	~95 De Cáceres et al. (2023)	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

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).

402

403 **2.8 Model application in managed sites**

404 In the managed sites (i.e., Cansiglio and Mongiana), simulations were performed using
405 Historical climate ('Hist') and, to analyse models' sensitivities to climate change, under
406 two Representative Concentration Pathways 4.5 and 8.5 ('Moderate' and 'Hot Climate'),
407 respectively. The 'Hist' climate was used to run simulations at the Cansiglio site from
408 2011 to 2022 and the Mongiana site from 2012 to 2022. In contrast, simulations using
409 RCP4.5 and RCP8.5 climate ran accounting for the same period, that is, 11 years for the
410 Cansiglio site and ten years for the Mongiana site, but considering the last years of the
411 climate change scenarios (i.e., 2059-2070 and 2060-2070, respectively) to create
412 harsher temperature and precipitation conditions, but with an increased atmospheric
413 CO_2 concentration (in μmol mol^{-1}).

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

Gross Primary Productivity (GPP) and Latent Heat (LE) fluxes related to the reduction in competition and enhancing water availability.

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 the summary of the evaluation metrics performance results.

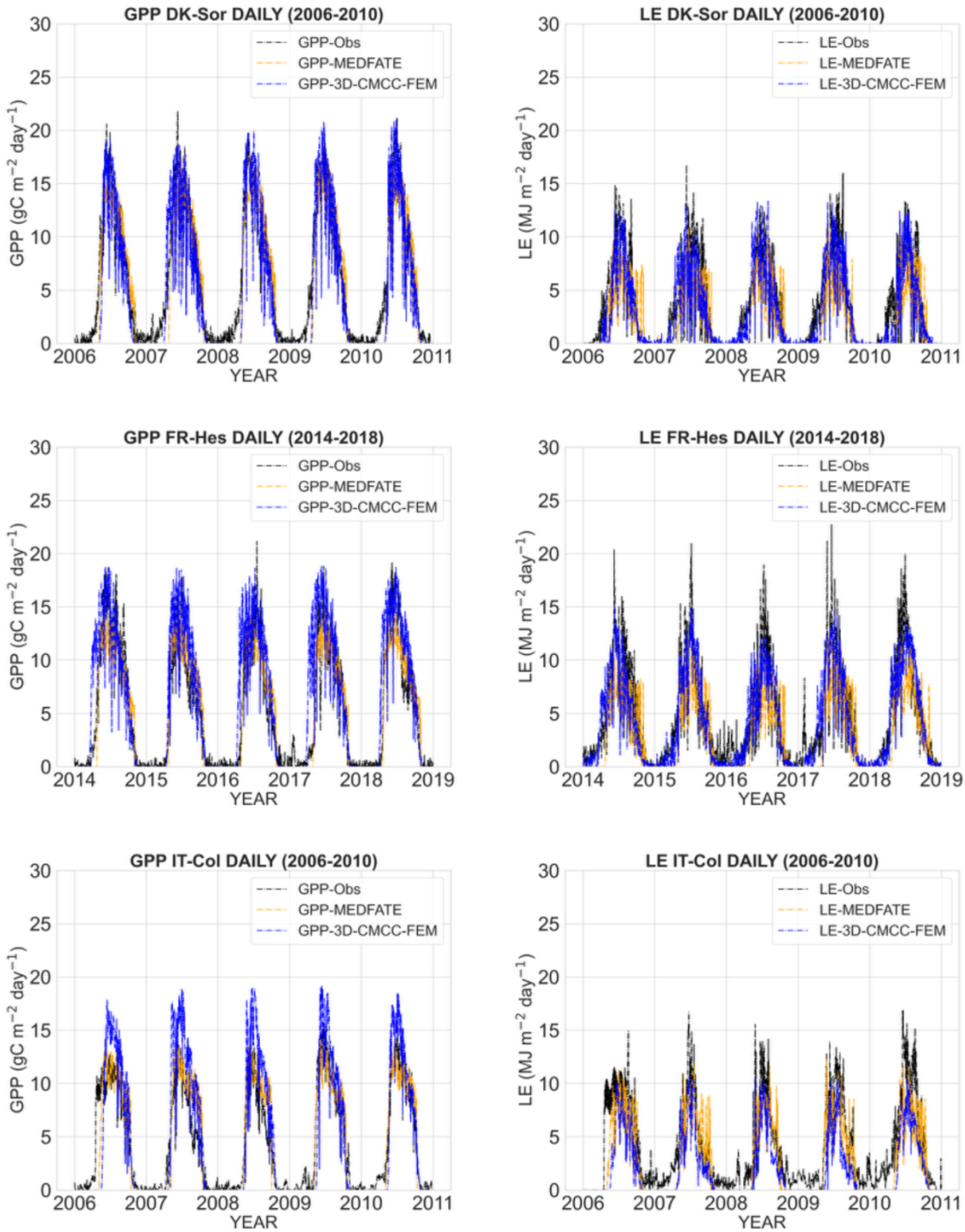

Fig 2. Daily mean variations of GPP (gC m^{-2} day^{-1}) and LE (MJ m^{-2} day^{-1}) estimated from the direct micrometeorological eddy covariance measurements (GPP-Obs and LE-Obs) and models' simulation (GPP-3D-CMCC-FEM, LE-3D-CMCC-FEM and, GPP-MEDFATE, LE-MEDFATE) during the evaluation period at the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

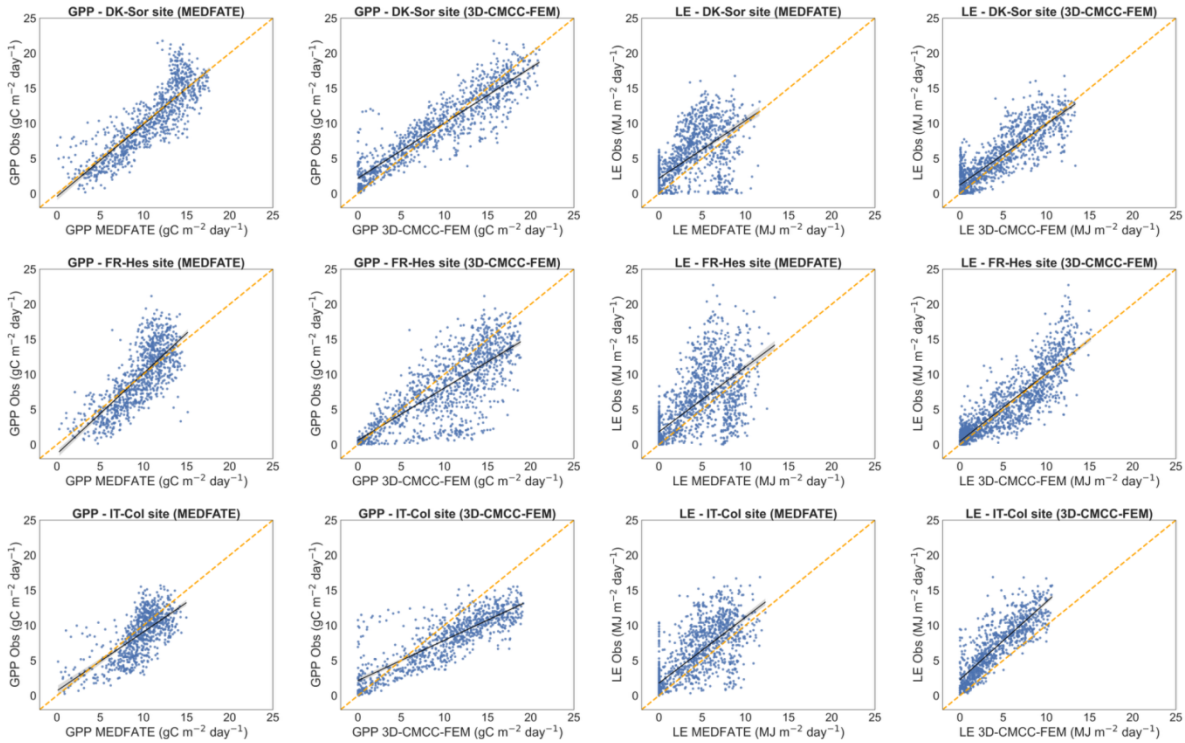

Fig 3. Scatter plots and linear regressions of GPP (gC m^{-2} day^{-1}) and LE (MJ m^{-2} day^{-1}) of the models versus the direct micrometeorological eddy covariance measurements (Obs) at the Sorø (DK-Sor; 2006-2010 period), Collelongo (IT-Col; 2006-2010 period) and Hesse (FR-Hes; 2014-2018 period).

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

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} $year^{-1}$ under 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 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 were 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. In contrast, this loss was predicted only in the seventh year for the managed plots. 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.

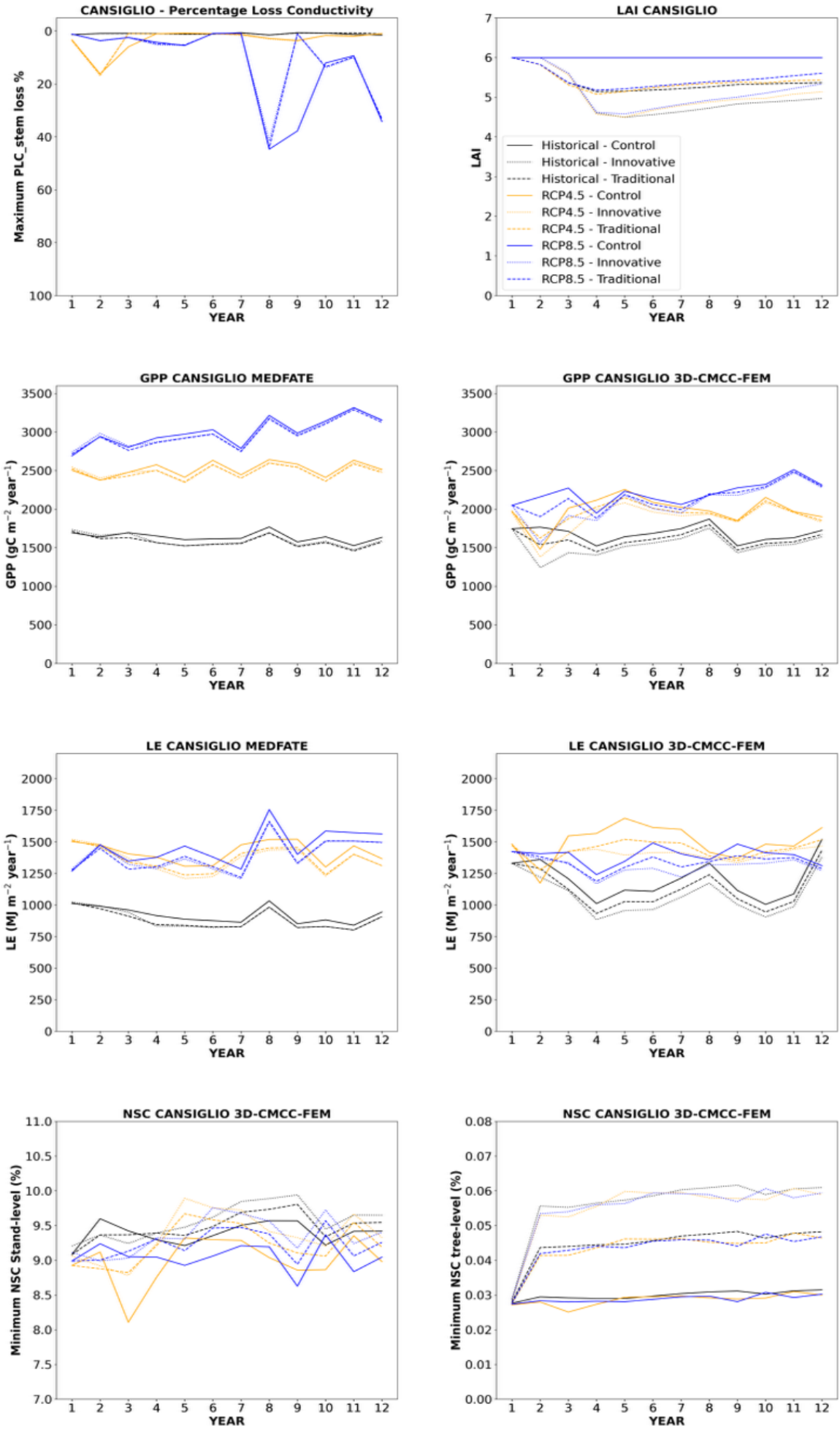
CANSIGLIO - Percentage Loss Conductivity
Maximum PLC_stem loss %
YEAR
LAI CANSIGLIO
LAI
Historical - Control
Historical - Innovative
Historical - Traditional
RCP4.5 - Control
RCP4.5 - Innovative
RCP4.5 - Traditional
RCP8.5 - Control
RCP8.5 - Innovative
RCP8.5 - Traditional
GPP CANSIGLIO MEDFATE
GPP (gC 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}) 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, under the current climate, 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}. 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 30-45% range for the 'Control' plots, while the managed plots experienced a maximum embolism of approximately 40% in 2017. Conversely, the 3D-CMCC-FEM model did not report any significant differences between managed and unmanaged plots for the LE. 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. As previously described, the 'Control' plot under the RCP8.5 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.

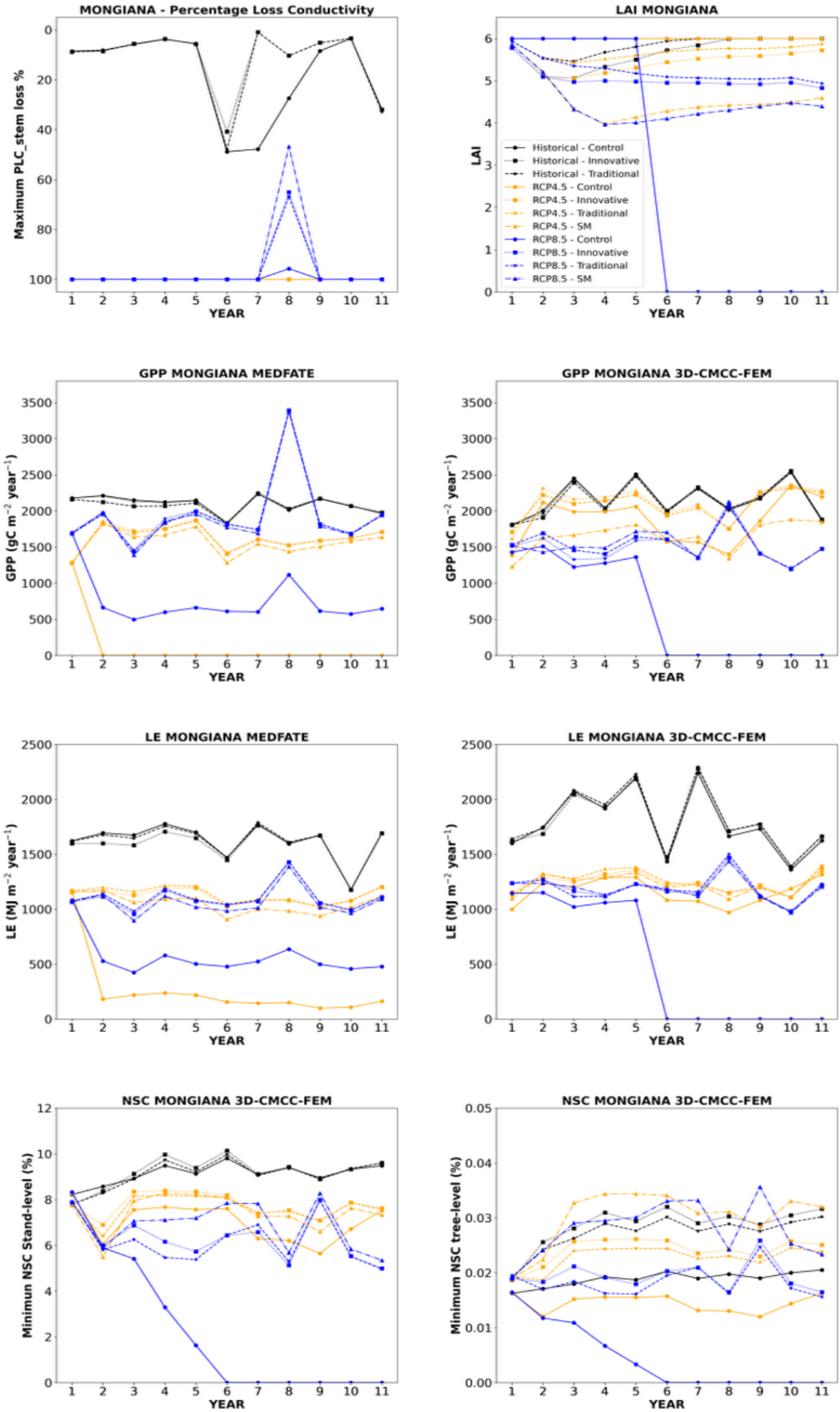
MONGIANA - Percentage Loss Conductivity
Maximum PLC_stem loss %
YEAR
LAI MONGIANA
LAI
YEAR
Historical - Control
Historical - Innovative
Historical - Traditional
RCP4.5 - Control
RCP4.5 - Innovative
RCP4.5 - Traditional
RCP4.5 - SM
RCP8.5 - Control
RCP8.5 - Innovative
RCP8.5 - Traditional
RCP8.5 - SM
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}) 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. Discussion

First, this study evaluated the performance of two different process-based models in simulating different beech stands across Europe, starting to the north of Europe and moving towards the south under different environmental conditions. Secondly, the study focused on models' sensitivity to management and different management options and considering different climatic conditions in two specific beech forest stands in the north and south of the Italian peninsula.

4.1 Model evaluation

To assess the models' accuracy in predicting C and H_2O fluxes, we compared the GPP and the LE data obtained from the EC towers. Both models predicted 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 slightly 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 slight overestimation of GPP only at 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 may 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 errors on daily measurement by EC technique (Loescher et al., 2006) or because a not perfect fit in the modeled seasonality (i.e., the begin and the end of the growing season) (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 Dufrêne et al. (2005) already did, both models were parameterized using existing literature values and with one 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 and the three climates used. Future climate is expected 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 4.52°C under RCP4.5 and 5.42°C under RCP8.5 at the Mongiana site. Similarly, MAP is expected to be 510 mm lower under RCP4.5 and 602 mm lower under RCP8.5

at the Cansiglio site, while 902 mm lower under RCP4.5 and 914 mm lower 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 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. These results align with those of Guillemot et al. (2014), who observed a slight decrease in GPP in managed compared to unmanaged temperate beech forests in France under different thinning regimes. However, differences were observed in both models under the three different climates used in the simulations. GPP 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, as simulated by models, to harsher conditions, indicating, potentially, a high drought acclimation capacity (Petrik et al., 2022) and increased GPP because of the so-called 'atmospheric CO_2 fertilization' effect as also found by de Wergifosse et al. (2022) and Reyer et al. (2013), especially in sites with no apparent water limitation both under current and projected future climate conditions. The anisohydric behavior of *Fagus sylvatica* L. results in prolonged stomatal opening relative to isohydric species, although Puchi et al. (2024) recently found large variability in European beech responses, maintaining prolonged photosynthetic activity, though this response is modulated by summer precipitation and the availability of soil water storage (Leuschner et al., 2021; Baudis et al., 2015). However, for high-altitude stands, growth could be negatively affected under warmer conditions, as suggested by Chmura et al. (2024). The LE results for the 3D-CMCC-FEM showed lower values over the simulation

period for managed stands than unmanaged ones showing lesser sensitivity to forest management if compared to MEDFATE. However, under the RCP4.5, the LE values were higher compared to both the 'Hist' climate and the RCP8.5 one due to greater annual cumulative precipitation than the RCP8.5 and higher, on average, temperatures than the 'Hist' scenario.

Conversely, the 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 harsher conditions (i.e., RCP4.5 and RCP8.5 climates), with slight differences in the management treatments as obtained by 3D-CMCC-FEM. The Non-Structural carbon (NSC) amount showed the highest values in 'Innovative' plots, followed by 'Traditional' plots, and the lowest values in 'Control' plots, suggesting a benefit in carbon stock accumulation with more carbon going for carbon biomass and less for reserve-replenishment for these stands under management interventions. However, NSC levels remain nearly the same for the three climate scenarios throughout all the simulation years. It is important to note that MEDFATE simulated an initial loss of stem conductance under the climate scenarios, indicating the onset of water stress for the stand. Although in RCP4.5 this is negligible, in RCP8.5 PLC_{stem} values reach a maximum xylem cavitation value of about 40% in the eighth year of simulation for managed plots while for 'Control' plots in the eighth, ninth, and twelfth years, highlighting potential benefits of management to reduce drought stress (Giuggiola et al., 2018; Schmied et al., 2023).

The GPP at the southern Apennine site of Mongiana showed a decrease under RCP4.5 and RCP8.5 scenarios when simulated by the 3D-CMCC-FEM model as a result of harsher environmental conditions, as also resulted in the study by Yu et al. (2022), in which the productivity and then the growth of European beech in southern regions are expected to decrease as affected by more severe climate conditions such as decreased

precipitation and increased in air temperature (Tognetti et al., 2019). Indeed, the increase in air temperature, a reduction in soil water availability, and the rise in vapor pressure deficit (VPD) lead to earlier stomatal closure, increased mesophyll resistance, and elevated abscisic acid production (Kane and McAdam, 2023), all of which contribute to a decrease in the carbon assimilation rate (Priwitzer et al., 2014; Grossiord et al., 2020). Specifically, GPP is higher under 'Hist' climate conditions, decreases under the RCP4.5, and ultimately reaches even lower values under the RCP8.5. Under the RCP8.5 at the fifth year of simulation, the stand in the 'Control' plot is simulated to die due to carbon starvation. 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. For instance, the same increase in GPP was reported by Fibbi et al. (2019) for beech forest under climate change scenarios in Italy. The thinning reduces the LAI and increase the soil water availability, which positively influence stomatal conductance and carbon assimilation, providing an acclimation mechanism to drought during periods of water scarcity (Lüttschwager and Jochheim, 2020; Diaconu et al., 2017).

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). Heavy thinning, on the other hand, can increase light

722 penetration, soil evaporation, and wind speed, thereby heightening tree sensitivity to
723 vapor pressure deficit under dry conditions (Schmied et al., 2023; Simonin et al., 2007).
724 LE decreased with the decrease in precipitation under the RCP4.5 and RCP8.5 climate
725 scenarios compared to the 'Hist' climate. There were no significant differences in LE
726 among the various management regimes. For the MEDFATE model, negligible or no
727 differences in GPP were observed under all the climates among various management
728 options. Although the GPP values estimated by the MEDFATE model under the RCP4.5
729 and RCP8.5 are similar to those obtained from the 3D-CMCC-FEM model, a closer
730 analysis of the daily outputs (data not shown) reveals that trees photosynthesize until
731 the end of July, after which they experience significant embolism (i.e., maximum value
732 of 100%), as indicated by the PLC_{stem} graph, indicating that the decrease in
733 precipitation led to summer soil moisture depletion and lethal drought stress levels.
734 Furthermore, the 'Control' plots experienced mortality even before reaching the
735 summer period. In recent decades, prolonged drought stress in Mediterranean
736 mountain regions has significantly reduced the productivity of beech forests, resulting
737 in a decline in Basal Area Increment (BAI) and overall growth (Piovesan et al., 2008). It
738 is also important to note that under 'Hist' climate conditions, the MEDFATE model
739 indicated a stem embolization loss ranging from approximately 10% to 45% during the
740 drought period (i.e., 2018-2020) in Europe (Italiano et al., 2024; Thom et al., 2023,
741 Lombardi et al., 2023). The embolization was more pronounced and long-lasting in the
742 'Control' plots than the managed ones. The same trends were obtained for LE.
743
744 **5. Conclusion**
745 These two process-based models provide robust evidence for their application in
746 estimating fluxes, consistent with long-term EC tower measurements in European
747 beech forests. Despite the minimal parametrization effort to align the two models and
748 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 to reduce competition. This necessitates strategic management planning, including the ability to project (e.g., with 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. Prioritizing the exploration of alternative sustainable management strategies to promote carbon sequestration in both above-ground biomass and soil is crucial for enhancing climate change mitigation efforts. Additionally, evaluating silvicultural plans such as the introduction of complementary species can improve the resilience of vulnerable beech ecosystems. A modeling approach, similar to the one used in this study, offers a valuable tool for assessing these alternative strategies and refining forestry management practices. By integrating these approaches, we can strengthen the long-term sustainability of forests while preserving the ecological balance of vulnerable regions.

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.

Acknowledgements

We would like to thank the University of Tuscia, the CNR ISAFOM of Perugia and the company ENI s.p.a. for the realization of this work. Special thanks to the Institute Research Center for Ecological and Forestry Applications (CREAF) of Barcelona that supported the research by the Spanish "Ministerio de Ciencia e Innovación" (MCIN/AEI/10.13039/501100011033) (grant agreement No. PID2021-126679OB-I00). The authors sincerely thank the ARPA Veneto and Calabria for providing the meteorological data. The Fondazione Centro Euro-Mediterraneo sui Cambiamenti

Climatici (CMCC) for providing climate change scenarios. The Cost-Action PROFOUND for providing both the stand ancillary data and the climate used in this work. D.D., E.V. and A.C. has been partially supported by MIUR Project (PRIN 2020) "Unraveling interactions between WATER and carbon cycles during drought and their impact on water resources and forest and grassland ecosySTEMs in the Mediterranean climate (WATERSTEM)" (Project number: 20202WF53Z), "WAFER" at CNR (Consiglio Nazionale delle Ricerche) and by PRIN 2020 (cod. 2020E52THS) - Research Projects of National Relevance funded by the Italian Ministry of University and Research entitled: "Multi-scale observations to predict Forest response to pollution and climate change" (MULTIFOR, project number: 2020E52THS). D.D., E.V., A.C. acknowledge also funding by the project OptForEU Horizon Europe research and innovation programme under grant agreement No. 101060554. D.D. and A.C. also acknowledge the project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU under award Number: Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP B83C22002930006, Project title "National Biodiversity Future Centre - NBFC". 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.

References

Augusto, L., Boča, A. (2022). *Tree functional traits, forest biomass, and tree species diversity interact with site properties to drive forest soil carbon.* Nat. Commun. 13, 1–12. https://doi.org/10.1038/s41467-022-28748-0

Axer, M., Schlicht, R., Kronenberg, R., Wagner, S. (2021). *The Potential for Future Shifts in Tree Species Distribution Provided by Dispersal and Ecological Niches: A Comparison between Beech and Oak in Europe.* Sustainability, 13, 13067. https://doi.org/10.3390/ su132313067

Baldocchi, D. (1994). *An analytical solution for coupled leaf photosynthesis and stomatal conductance models.* Tree Physiology, 14(7–8–9), 1069–1079. https://doi.org/10.1093/treephys/14.7-8-9.1069

Baudis, M., Premper, T., Welk, E., & Bruelheide, H. (2015). *The response of three Fagus sylvatica L. provenances to water availability at different soil depths.* Ecological Research, 30(5), 853–865. https://doi.org/10.1007/s11284-015-1287-x

Bernacchi, C. J., Singsaas, E. L., Pimentel, C., Portis, A. R., & Long, S. P. (2001). *Improved temperature response functions for models of Rubisco-limited photosynthesis.* Plant Cell & Environment, 24(2), 253–259. https://doi.org/10.1111/j.1365-3040.2001.00668.x

Bernacchi, C. J., Calfapietra, C., Davey, P. A., Wittig, V. E., Scarascia-Mugnozza, G. E., Raines, C. A., & Long, S. P. (2003). *Photosynthesis and stomatal conductance responses of poplars to free-air CO2 enrichment (PopFACE) during the first growth cycle and immediately following coppice.* New Phytologist, 159(3), 609–621. https://doi.org/10.1046/j.1469-8137.2003.00850.x

Bosela, M., Štefančík, I., Petráš, R., Vacek, S. (2016). *The effects of climate warming on the growth of European beech forests depend critically on thinning strategy and site productivity.* Agric. For. Meteorol. 222, 21–31. https://doi.org/10.1016/j.agrformet.2016.03.005

Brunet, J.; Fritz, Ö.; Richnau, G. (2010). *Biodiversity in European beech forests—A review with recommendations for sustainable forest management*. Ecol. Bull. 53, 77–94, Available online: http://www.jstor.org/stable/41442021

Bonan, G. B., Lawrence, P. J., Oleson, K. W., Levis, S., Jung, M., Reichstein, M., Lawrence, D. M., & Swenson, S. C. (2011). *Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data.* Journal of Geophysical Research Atmospheres, 116(G2). https://doi.org/10.1029/2010jg001593

Chmura, D. J., Banach, J., Kempf, M., Kowalczyk, J., Mohytych, V., Szeligowski, H., Buraczyk, W., & Kowalkowski, W. (2024). *Growth and productivity of European beech populations show plastic response to climatic transfer at the north-eastern border of the species range.* Forest Ecology and Management, 565, 122043. https://doi.org/10.1016/j.foreco.2024.122043

Collalti, A., Perugini, L., Santini, M., Chiti, T., Nolè, A., Matteucci, G., Valentini, R. (2014). *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.* Ecol. Modell. 272, 362–378. https://doi.org/10.1016/j.ecolmodel.2013.09.016

Collalti, A., Marconi, S., Ibrom, A., Trotta, C., Anav, A., D'andrea, E., Matteucci, G., Montagnani, L., Gielen, B., Mammarella, I., Grünwald, T., Knohl, A., Berninger, F., Zhao, Y., Valentini, R., Santini, M. (2016). *Validation of 3D-CMCC Forest Ecosystem*

Model (v.5.1) against eddy covariance data for 10 European forest sites. Geosci. Model Dev. 9, 479–504. https://doi.org/10.5194/gmd-9-479-2016

Collalti, A., Biondo, C., Buttafuoco, G., Maesano, M., Caloiero, T., Lucà, F., Pellicone, G., Ricca, N., Salvati, R., Veltri, A., Mugnozza, G. S., & Matteucci, G. (2017). *Simulation, calibration and validation protocols for the model 3D-CMCC-CNR-FEM: a case study in the Bonis' watershed (Calabria, Italy).* Forest@, 14(4), 247–256. https://doi.org/10.3832/efor2368-014

Collalti, A., Trotta, C., Keenan, T.F., Ibrom, A., Bond-Lamberty, B., Grote, R., Vicca, S., Reyer, C.P.O., Migliavacca, M., Veroustraete, F., Anav, A., Campioli, M., Scoccimarro, E., Šigut, L., Grieco, E., Cescatti, A., Matteucci, G. (2018). *Thinning Can Reduce Losses in Carbon Use Efficiency and Carbon Stocks in Managed Forests Under Warmer Climate.* J. Adv. Model. Earth Syst. 10, 2427–2452. https://doi.org/10.1029/2018MS001275

Collalti, A., Thornton, P.E., Cescatti, A., Rita, A., Borghetti, M., Nolè, A., Trotta, C., Ciais, P., Matteucci, G. (2019). *The sensitivity of the forest carbon budget shifts across processes along with stand development and climate change.* Ecol. Appl. 29, 1–18. https://doi.org/10.1002/eap.1837

Collalti, A., Tjoelker, M.G., Hoch, G., Mäkelä, A., Guidolotti, G., Heskel, M., Petit, G., Ryan, M.G., Battipaglia, G., Matteucci, G., Prentice, I.C. (2020). *Plant respiration: Controlled by photosynthesis or biomass?* Glob. Chang. Biol. 26, 1739–1753. https://doi.org/10.1111/gcb.14857

Collalti, A., Dalmonech, D., Marano, G., Vangi, E., Puchi, P., Grieco, E., Orrico, M. (2023). *3D-CMCC-FEM (Coupled Model Carbon Cycle). BioGeoChemical and Biophysical Forest Ecosystem - User's Guide.* CNR Edizioni; ISBN 978-88-8080-573-1 (electronic edition) https://doi.org/10.32018/3D-CMCC-FEM-2022;

Collalti, A. and Dalmonech, D. and Vangi, E. and Marano, G. and Puchi, P.F. and Morichetti, M. and Saponaro, V. and Orrico, M.R. and Grieco, E. (2024) *Monitoring and Predicting Forest Growth and Dynamics.* CNR Edizioni, Roma.

Collatz, G.J., Ball, J.T., Grivet, C. & Berry, J.A. (1991). *Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: A model that includes a laminar boundary layer.* Agricultural and Forest Meteorology, 54, 107–136.

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: *Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change* - COM(2021) 82 final.

Dalmonech, D., Marano, G., Amthor, J.S., Cescatti, A., Lindner, M., Trotta, C., Collalti, A. (2022). *Feasibility of enhancing carbon sequestration and stock capacity in temperate and boreal European forests via changes to management regimes.* Agric. For. Meteorol. 327, 109203. https://doi.org/10.1016/j.agrformet.2022.109203

Dalmonech, D., Vangi, E., Chiesi, M., Chirici, G., Fibbi, L., Giannetti, F., Marano, G., Massari, C., Nolè, A., Xiao, J., & Collalti, A. (2024). *Regional estimates of gross primary production applying the Process-Based Model 3D-CMCC-FEM vs. Remote-Sensing multiple datasets.* European Journal of Remote Sensing, 57(1). https://doi.org/10.1080/22797254.2023.2301657

De Cáceres, M., Mencuccini, M., Martin-StPaul, N., Limousin, J. M., Coll, L., Poyatos, R., Cabon, A., Granda, V., Forner, A., Valladares, F., & Martínez-Vilalta, J. (2021). *Unravelling the effect of species mixing on water use and drought stress in Mediterranean forests: A modelling approach.* Agricultural and Forest Meteorology, 296, 108233. https://doi.org/10.1016/j.agrformet.2020.108233

De Cáceres, M., Molowny-Horas, R., Cabon, A., Martínez-Vilalta, J., Mencuccini, M., García-Valdés, R., Nadal-Sala, D., Sabaté, S., Martin-StPaul, N., Morin, X.,

D'Adamo, F., Batllori, E., & Améztegui, A. (2023). *MEDFATE 2.9.3: a trait-enabled model to simulate Mediterranean forest function and dynamics at regional scales.* Geoscientific Model Development, 16(11), 3165–3201. https://doi.org/10.5194/gmd-16-3165-2023

De Cinti, B., Bombi, P., Ferretti, F., Cantiani, P., Di Salvatore, U., SimonÄ·iÄ, P., Kutnar, L., Äœeater, M., GarfÃ, V., Mason, F., & Matteucci, G. (2016). *From the experience of LIFE+ ManFor C.BD to the Manual of Best Practices in Sustainable Forest Management.* Italian Journal of Agronomy, 11(s1), 1–175. https://doi.org/10.4081/ija.2016.789

De Pury, D.G.G., Farquhar, G.D., 1997. *Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models.* Plant, Cell Environ. 20, 537–557. https://doi.org/10.1111/j.1365-3040.1997.00094.x

De Wergifosse, L., André, F., Goosse, H., Boczon, A., Cecchini, S., Ciceu, A., Collalti, A., Cools, N., D'Andrea, E., De Vos, B., Hamdi, R., Ingerslev, M., Knudsen, M. A., Kowalska, A., Leca, S., Matteucci, G., Nord-Larsen, T., Sanders, T. G., Schmitz, A., Termonia, A., Vanguelova, E., Van Schaeybroeck, B., Verstraeten, A. Vesterdal, L., Jonard, M. (2022). *Simulating tree growth response to climate change in structurally diverse oak and beech forests.* The Science of the Total Environment, 806, 150422. https://doi.org/10.1016/j.scitotenv.2021.150422

Deb Burman, P. K., A. G. , P., Chakraborty, S., Tiwari, Y. K., Sarma, D., & Gogoi, N. (2024). *Simulating the ecosystem-atmosphere carbon, water and energy fluxes at a subtropical Indian forest using an ecosystem model.* Ecological Modelling, 490, 110637. https://doi.org/10.1016/j.ecolmodel.2024.110637

Diaconu, D., Kahle, H. P., & Spiecker, H. (2017). *Thinning increases drought tolerance of European beech: a case study on two forested slopes on opposite sides of a valley.* European Journal of Forest Research, 136(2), 319–328. https://doi.org/10.1007/s10342-017-1033-8

Dufrene, E., Davi, H., François, C., Maire, G. L., Dantec, V. L., & Granier, A. (2005). *Modelling carbon and water cycles in a beech forest.* Ecological Modelling, 185(2–4), 407–436. https://doi.org/10.1016/j.ecolmodel.2005.01.004

Durrant, H. T., de Rigo, D., Caudullo, G. (2016). *Fagus sylvatica and other beeches in Europe: distribution, habitat, usage and threats.* In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), *European Atlas of Forest Tree Species.* Publ. Off. EU, Luxembourg, pp. e012b90+

Farquhar, G.D., Caemmerer, S., Berry, J.A. (1980). *A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species.* Planta 149, 78-90–90.

Fibbi, L., Moriondo, M., Chiesi, M., Bindi, M., & Maselli, F. (2019). *Impacts of climate change on the gross primary production of Italian forests.* Annals of Forest Science, 76(2). https://doi.org/10.1007/s13595-019-0843-x

Giuggiola, A., Zweifel, R., Feichtinger, L. M., Vollenweider, P., Bugmann, H., Haeni, M., & Rigling, A. (2018). *Competition for water in a xeric forest ecosystem – Effects of understory removal on soil micro-climate, growth and physiology of dominant Scots pine trees.* Forest Ecology and Management, 409, 241–249. https://doi.org/10.1016/j.foreco.2017.11.002

Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T. W., Sperry, J. S., & McDowell, N. G. (2020). *Plant responses to rising vapor pressure deficit.* New Phytologist, 226(6), 1550–1566. https://doi.org/10.1111/nph.16485

Guillemot, J., Delpierre, N., Vallet, P., François, C., Martin-StPaul, N. K., Soudani, K., Nicolas, M., Badeau, V., & Dufrêne, E. (2014). *Assessing the effects of management on forest growth across France: insights from a new functional–structural model.* Annals of Botany, 114(4), 779–793. https://doi.org/10.1093/aob/mcu059

Hölttä, T., Cochard, H., Nikinmaa, E., & Mencuccini, M. (2009). *Capacitive effect of cavitation in xylem conduits: results from a dynamic model.* Plant, Cell & Environment/Plant, Cell and Environment, 32(1), 10–21. https://doi.org/10.1111/j.1365-3040.2008.01894.x

Jarvis, P. G. (1976). *The Interpretation of the Variations in Leaf Water Potential and Stomatal Conductance Found in Canopies in the Field.* Philosophical Transactions of the Royal Society B: Biological Sciences, 273(927), 593–610. doi:10.1098/rstb.1976.0035

Jarvis, N.J., Jansson, P-E., Dik, P.E., Messing, I. (1991). *Modelling water and solute transport in macroporous soil.* I. Model description and sensitivity analysis. Journal of Soil Science, 42, 59–70.

Kane, C., & McAdam, S. (2023). *Abscisic acid driven stomatal closure during drought in anisohydric Fagus sylvatica.* Journal of Plant Hydraulics, 9, 002. https://doi.org/10.20870/jph.2023.002

Kattge, J., Knorr, W., (2007). Temperature acclimation in a biochemical model of photosynthesis: A reanalysis of data from 36 species. Plant, Cell Environ. 30, 1176–1190. https://doi.org/10.1111/j.1365-3040.2007.01690.x

Kimmins, (Hamish) J. P., Blanco, J. A., Seely, B., Welham, C., & Scoullar, K. (2008). *Complexity in modelling forest ecosystems: How much is enough?* Forest Ecology and Management, 256(10), 1646–1658. https://doi.org/10.1016/j.foreco.2008.03.011

Kramer, K., Leinonen, I., Bartelink, H., Berbigier, P., Borghetti, M., Bernhofer, C., Cienciala, E., Dolman, A., Froer, O., Gracia, A., Granier, A., Grünwald, T., Hari, P., Jans, W., Kellomäki, S., Loustau, D., Magnani, F., Markkanen, T., Matteucci, G., Mohren, G.M.J., Moors, E., Nissinen, A., Peltola, H. Sabaté, S., Sanchez, A. (2002). *Evaluation of six process-based forest growth models using eddy-covariance measurements of CO2 and H2O fluxes at six forest sites in Europe.* Global Change Biology, 8(3), 213–230. https://doi.org/10.1046/j.1365-2486.2002.00471.x

Larsbo, M., Roulier, S., Stenemo, F., Kasteel, R., Jarvis, N. (2005). *An Improved Dual-Permeability Model of Water Flow and Solute Transport in the Vadose Zone.* Vadose Zone Journal, 4, 398–406.

Leuning, R. (2002). *Temperature dependence of two parameters in a photosynthesis model.* Plant, Cell and Environment, 25, 1205–1210.

Leuschner, C., Schipka, F., & Backes, K. (2021). *Stomatal regulation and water potential variation in European beech: challenging the iso/anisohydry concept.* Tree Physiology, 42(2), 365–378. https://doi.org/10.1093/treephys/tpab104

Loescher, H. W., Law, B. E., Mahrt, L., Hollinger, D. Y., Campbell, J., & Wofsy, S. C. (2006). *Uncertainties in, and interpretation of, carbon flux estimates using the eddy covariance technique.* Journal of Geophysical Research Atmospheres, 111(D21). https://doi.org/10.1029/2005jd006932

Lombardi, D., Micalizzi, K., & Vitale, M. (2023). *Assessing carbon and water fluxes in a mixed Mediterranean protected forest under climate change: An integrated bottom – up and top – down approach.* Ecological Informatics, 78, 102318. https://doi.org/10.1016/j.ecoinf.2023.102318

Lüttschwager, D., & Jochheim, H. (2020). *Drought Primarily Reduces Canopy Transpiration of Exposed Beech Trees and Decreases the Share of Water Uptake from Deeper Soil Layers.* Forests, 11(5), 537. https://doi.org/10.3390/f11050537

Huber, M. O., Eastaugh, C. S., Gschwantner, T., Hasenauer, H., Kindermann, G., Ledermann, T., Lexer, M. J., Rammer, W., Schörghuber, S., & Sterba, H. (2013). *Comparing simulations of three conceptually different forest models with National Forest Inventory data.* Environmental Modelling & Software, *40*, 88–97. https://doi.org/10.1016/j.envsoft.2012.08.003

INFC (2015). Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. Ministero delle Politiche Agricole Alimentari e Forestali, Ispettorato Generale – Corpo Forestale dello Stato, CRA – Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura. [online] URL: https://www.inventarioforestale.org/it/statistiche_infc/

Italiano, S. S., Camarero, J. J., Borghetti, M., Colangelo, M., Rita, A., & Ripullone, F. (2024). *Drought legacies in mixed Mediterranean forests: Analysing the effects of structural overshoot, functional traits and site factors.* The Science of the Total Environment, 927, 172166. https://doi.org/10.1016/j.scitotenv.2024.172166

Mahnken, M., Cailleret, M., Collalti, A., Trotta, C., Biondo, C., D'Andrea, E., Dalmonech, D., Marano, G., Mäkelä, A., Minunno, F., Peltoniemi, M., Trotsiuk, V., Nadal-Sala, D., Sabaté, S., Vallet, P., Aussenac, R., Cameron, D. R., Bohn, F. J., Grote, R., Augustynczik, A. L. D., Yousefpour, R., Huber, N., Bugmann, H., Merganičová, K., Merganic, J., Valent, P., Lasch-Born, P., Hartig, F., Vega del Valle, I. D., Volkholz, J., Gutsch, M., Matteucci, G., Krejza, J., Ibrom, A., Meesenburg, H., Rötzer, T., van der Maaten-Theunissen, M., van der Maaten, E., & Reyer, C. P. O. (2022). *Accuracy, realism and general applicability of European forest models.* Global Change Biology, 28(23), 6921–6943. https://doi.org/10.1111/gcb.16384

Maréchaux, I., Langerwisch, F., Huth, A., Bugmann, H., Morin, X., Reyer, C. P., Seidl, R., Collalti, A., De Paula, M. D., Fischer, R., Gutsch, M., Lexer, M. J., Lischke, H., Rammig, A., Rödig, E., Sakschewski, B., Taubert, F., Thonicke, K., Vacchiano, G., & Bohn, F. J. (2021). *Tackling unresolved questions in forest ecology: The past and future role of simulation models.* Ecology and Evolution, 11(9), 3746–3770. https://doi.org/10.1002/ece3.7391

Martínez-Vilalta, J., Sala, A., Asensio, D., Galiano, L., Hoch, G., Palacio, S., Piper, F. I., & Lloret, F. (2016). *Dynamics of non-structural carbohydrates in terrestrial plants: a global synthesis.* Ecological Monographs, 86(4), 495–516. https://doi.org/10.1002/ecm.1231

Medlyn, B. E., Badeck, F. W., De Pury, D. G. G., Barton, C. V. M., Broadmeadow, M., Ceulemans, R., De Angelis, P., Forstreuter, M., Jach, M. E., Kellomäki, S., Laitat, E., Marek, M., Philippot, S., Rey, A., Strassemeyer, J., Laitinen, K., Liozon, R., Portier, B., Roberntz, P., Wang, K., Jarvis, P. G. (1999). *Effects of elevated [CO2] on photosynthesis in European forest species: a meta-analysis of model parameters.* Plant Cell & Environment, 22(12), 1475–1495. https://doi.org/10.1046/j.1365-3040.1999.00523.x

Merganičová, K., Merganič, J., Lehtonen, A., Vacchiano, G., Sever, M. Z. O., Augustynczik, A. L. D., Grote, R., Kyselová, I., Mäkelä, A., Yousefpour, R., Krejza, J., Collalti, A., & Reyer, C. P. O. (2019). *Forest carbon allocation modelling under climate change.* Tree Physiology, 39(12), 1937–1960. https://doi.org/10.1093/treephys/tpz105

Monteith, J. L. and M. H. Unsworth (2008). *Principles of Environmental Physics, 3rd Edition*. Burlington, MA, Academic Press https://doi.org/10.3832/ifor1802-009

Morichetti, M., Vangi, E., & Collalti, A. (2024). *Predicted Future Changes in the Mean Seasonal Carbon Cycle Due to Climate Change. Forests*, *15*(7), 1124. https://doi.org/10.3390/f15071124

Noce, S., Collalti, A., & Santini, M. (2017). *Likelihood of changes in forest species suitability, distribution, and diversity under future climate: The case of Southern Europe.* Ecology and Evolution, 7(22), 9358–9375. https://doi.org/10.1002/ece3.3427

Noce, S., Cipriano, C., & Santini, M. (2023). *Altitudinal shifting of major forest tree species in Italian mountains under climate change.* Frontiers in Forests and Global Change, 6. https://doi.org/10.3389/ffgc.2023.1250651

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W. L., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., & Yakir, D. (2006). *Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation.* Biogeosciences, 3(4), 571–583. https://doi.org/10.5194/bg-3-571-2006

Pastorello, G., Trotta, C., Canfora, E., Chu, H., Christianson, D., Cheah, Y.W., Poindexter, C., Chen, J., Elbashandy, A., Humphrey, M., Isaac, P., Polidori, D., Reichstein, M., Ribeca, A., van Ingen, C., Vuichard, N., Zhang, L., Amiro, B., Ammann, C., Arain, M.A., Ardö, J., Arkebauer, T., Arndt, S.K., Arriga, N., Aubinet, M., Aurela, M., Baldocchi, D., Barr, A., Beamesderfer, E., Belelli Marchesini, L., Bergeron, O., Beringer, J., Bernhofer, C., Berveiller, D., Billesbach, D., Black, T.A., Blanken, P.D., Bohrer, G., Boike, J., Bolstad, P.V., Bonal, D., Bonnefond, J.-M., Bowling, D.R., Bracho, R., Brodeur, J., Brümmer, C., Buchmann, N., Burban, B., Burns, S.P., Buysse, P., Cale, P., Cavagna, M., Cellier, P., Chen, S., Chini, I., Christensen, T.R., Cleverly, J., Collalti, A., Consalvo, C., Cook, B.D., Cook, D., Coursolle, C., Cremonese, E., Curtis, P.S., D'Andrea, E., da Rocha, H., Dai, X., Davis, K.J., De Cinti, B., de Grandcourt, A., De Ligne, A., De Oliveira, R.C., Delpierre, N., Desai, A.R., Di Bella, C.M., di Tommasi, P., Dolman, H., Domingo, F., Dong, G., Dore, S., Duce, P., Dufrêne, E., Dunn, A., Dušek, J., Eamus, D., Eichelmann, U., ElKhidir, H.A.M., Eugster, W., Ewenz, C.M., Ewers, B., Famulari, D., Fares, S., Feigenwinter, I., Feitz, A., Fensholt, R., Filippa, G., Fischer, M., Frank, J., Galvagno, M., Gharun, M., Gianelle, D., Gielen, B., Gioli, B., Gitelson, A., Goded, I., Goeckede, M., Goldstein, A.H., Gough, C.M., Goulden, M.L., Graf, A., Griebel, A., Gruening, C., Grünwald, T., Hammerle, A., Han, S., Han, X., Hansen, B.U., Hanson, C., Hatakka, J., He, Y., Hehn, M., Heinesch, B., Hinko-Najera, N., Hörtnagl, L., Hutley, L., Ibrom, A., Ikawa, H., Jackowicz-Korczynski, M., Janouš, D., Jans, W., Jassal, R., Jiang, S., Kato, T., Khomik, M., Klatt, J., Knohl, A., Knox, S., Kobayashi, H., Koerber, G., Kolle, O., Kosugi, Y., Kotani, A., Kowalski, A., Kruijt, B., Kurbatova, J., Kutsch, W.L., Kwon, H., Launiainen, S., Laurila, T., Law, B., Leuning, R., Li, Y., Liddell, M., Limousin, J.-M., Lion, M., Liska, A.J., Lohila, A., López-Ballesteros, A., López-Blanco, E., Loubet, B., Loustau, D., Lucas-Moffat, A., Lüers, J., Ma, S., Macfarlane, C., Magliulo, V., Maier, R., Mammarella, I., Manca, G., Marcolla, B., Margolis, H.A., Marras, S., Massman, W., Mastepanov, M., Matamala, R., Matthes, J.H., Mazzenga, F., McCaughey, H., McHugh, I., McMillan, A.M.S., Merbold, L., Meyer, W., Meyers, T., Miller, S.D., Minerbi, S., Moderow, U., Monson, R.K., Montagnani, L., Moore, C.E., Moors, E., Moreaux, V., Moureaux, C., Munger, J.W., Nakai, T., Neirynck, J., Nesic, Z., Nicolini, G., Noormets, A., Northwood, M., Nosetto, M., Nouvellon, Y., Novick, K., Oechel, W., Olesen, J.E., Ourcival, J.-M., Papuga, S.A., Parmentier, F.-J., Paul-Limoges, E., Pavelka, M., Peichl, M., Pendall, E., Phillips, R.P., Pilegaard, K., Pirk, N., Posse, G., Powell, T., Prasse, H., Prober, S.M., Rambal, S., Rannik, Ü., Raz-Yaseef, N., Rebmann, C., Reed, D., Resco de Dios, V., Restrepo-Coupe, N., Reverter, B.R., Roland, M., Sabbatini, S., Sachs, T., Saleska, S.R., Sánchez-Cañete, E.P., Sanchez-Mejia, Z.M., Schmid, H.P., Schmidt, M., Schneider, K., Schrader, F., Schroder, I., Scott, R.L., Sedlák, P., Serrano-Ortíz, P., Shao, C., Shi, P., Shironya, I., Siebicke, L., Šigut, L., Silberstein, R., Sirca, C., Spano, D., Steinbrecher, R., Stevens, R.M., Sturtevant, C., Suyker, A., Tagesson, T., Takanashi, S., Tang, Y., Tapper, N., Thom, J., Tomassucci, M., Tuovinen, J.-P., Urbanski, S., Valentini, R., van der Molen, M., van Gorsel, E., van Huissteden, K., Varlagin, A., Verfaillie, J., Vesala, T., Vincke, C., Vitale, D., Vygodskaya, N., Walker, J.P., Walter-Shea, E., Wang, H., Weber, R., Westermann, S., Wille, C., Wofsy, S., Wohlfahrt, G.,

Wolf, S., Woodgate, W., Li, Y., Zampedri, R., Zhang, J., Zhou, G., Zona, D., Agarwal, D., Biraud, S., Torn, M., & Papale, D. (2020). *The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data.* Scientific Data, 7(1). https://doi.org/10.1038/s41597-020-0534-3

Pan, Y., Birdsey, R. A., Phillips, O. L., Houghton, R. A., Fang, J., Kauppi, P. E., Keith, H., Kurz, W. A., Ito, A., Lewis, S. L., Nabuurs, G. J., Shvidenko, A., Hashimoto, S., Lerink, B., Schepaschenko, D., Castanho, A., & Murdiyarso, D. (2024). *The enduring world forest carbon sink. Nature*, 631(8021), 563–569. https://doi.org/10.1038/s41586-024-07602-x

Petrik, P., Petek-Petrik, A., Kurjak, D., Mukarram, M., Klein, T., Gömöry, D., Střelcová, K., Frýdl, J., & Konôpková, A. (2022). *Interannual adjustments in stomatal and leaf morphological traits of European beech (Fagus sylvatica L.) demonstrate its climate change acclimation potential.* Plant Biology, 24(7), 1287–1296. https://doi.org/10.1111/plb.13401

Pietsch, S. A., Hasenauer, H., & Thornton, P. E. (2005). *BGC-model parameters for tree species growing in central European forests.* Forest Ecology and Management, 211(3), 264–295. https://doi.org/10.1016/j.foreco.2005.02.046

Pilli, R., Alkama, R., Cescatti, A., Kurz, W. A., & Grassi, G. (2022). *The European forest carbon budget under future climate conditions and current management practices.* Biogeosciences, 19(13), 3263–3284. https://doi.org/10.5194/bg-19-3263-2022

Piovesan, G., Biondi, F., Di Filippo, A., Alessandrini, A., & Maugeri, M. (2008). *Drought-driven growth reduction in old beech (Fagus sylvatica L.) forests of the central Apennines, Italy.* Global Change Biology, 14(6), 1265–1281. https://doi.org/10.1111/j.1365-2486.2008.01570.x

Priwitzer, T., Kurjak, D., Kmeť, J., Sitková, Z., & Leštianska, A. (2014). *Photosynthetic response of European beech to atmospheric and soil drought.* Central European Forestry Journal, 60(1), 32–38. https://doi.org/10.2478/forj-2014-0003

Puchi, P. F., Dalmonech, D., Vangi, E., Battipaglia, G., Tognetti, R., & Collalti, A. (2024). *Contrasting patterns of water use efficiency and annual radial growth among European beech forests along the Italian peninsula.* Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-57293-7

Pukkala, T. (2016). *Which type of forest management provides most ecosystem services?* Forest Ecosystems/Forest Ecosystems, 3(1). https://doi.org/10.1186/s40663-016-0068-5

Raffa, M., Adinolfi, M., Reder, A. et al. (2023). *Very High Resolution Projections over Italy under different CMIP5 IPCC scenarios*. Sci Data 10, 238 . https://doi.org/10.1038/s41597-023-02144-9

Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., & Pilz, T. (2013). *Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide.* Annals of Forest Science, 71(2), 211–225. https://doi.org/10.1007/s13595-013-0306-8

Reyer, C., Silveyra Gonzalez, R., Dolos, K., Hartig, F., Hauf, Y., Noack, M., Lasch-Born, P., Rötzer, T., Pretzsch, H., Meesenburg, H., Fleck, S., Wagner, M., Bolte, A., Sanders, T., Kolari, P., Mäkelä, A., Vesala, T., Mammarella, I., Pumpanen, J., Matteucci, G., Collalti, A., D'Andrea, E., Foltýnová, L., Krejza, J., Ibrom, A., Pilegaard, K., Loustau, D., Bonnefond, J.-M., Berbigier, P., Picart, D., Lafont, S., Dietze, M., Cameron, D., Vieno, M., Tian, H., Palacios-Orueta, A., Cicuendez, V., Recuero, L., Wiese, K., Büchner, M., Lange, S., Volkholz, J., Kim, H., Weedon, G., Sheffield, J., Vega del Valle, I., Suckow, F., Horemans, J., Martel, S., Bohn, F., Steinkamp, J., Chikalanov, A., Mahnken, M., Gutsch, M., Trotta, C., Babst, F., & Frieler, K. (2020a). *The PROFOUND database for evaluating vegetation models and simulating climate*

impacts on European forests version V. 0.3. GFZ Data Services. https://doi.org/10.5880/PIK.2020.006

Reyer, C. P. O., Silveyra Gonzalez, R., Dolos, K., Hartig, F., Hauf, Y., Noack, M., Lasch-Born, P., Rötzer, T., Pretzsch, H., Meesenburg, H., Fleck, S., Wagner, M., Bolte, A., Sanders, T. G. M., Kolari, P., Mäkelä, A., Vesala, T., Mammarella, I., Pumpanen, J., Collalti, A., Trotta, C., Matteucci, G., D'Andrea, E., Foltýnová, L., Krejza, J., Ibrom, A., Pilegaard, K., Loustau, D., Bonnefond, J.-M., Berbigier, P., Picart, D., Lafont, S., Dietze, M., Cameron, D., Vieno, M., Tian, H., Palacios-Orueta, A., Cicuendez, V., Recuero, L., Wiese, K., Büchner, M., Lange, S., Volkholz, J., Kim, H., Horemans, J. A., Bohn, F., Steinkamp, J., Chikalanov, A., Weedon, G. P., Sheffield, J., Babst, F., Vega del Valle, I., Suckow, F., Martel, S., Mahnken, M., Gutsch, M., & Frieler, K. (2020b). *The PROFOUND database for evaluating vegetation models and simulating climate impacts on European forests.* Earth System Science Data, 12(2), 1295–1320. https://doi.org/10.5194/essd-12-1295-2020

Rezaie, N., D'Andrea, E., Bräuning, A., Matteucci, G., Bombi, P., & Lauteri, M. (2018). *Do atmospheric CO2 concentration increase, climate and forest management affect iWUE of common beech? Evidences from carbon isotope analyses in tree rings.* Tree Physiology, 38(8), 1110–1126. https://doi.org/10.1093/treephys/tpy025

Richardson, A.D., Black, T.A., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., Hollinger, D.Y., Kutsch, W.L., Longdoz, B., Luyssaert, S., Migliavacca, M., Montagnani, L., Munger, J.W., Moors, E., Piao, S., Rebmann, C., Reichstein, M., Saigusa, N., Tomelleri, E., Vargas, R., & Varlagin, A. (2010). *Influence of spring and autumn phenological transitions on forest ecosystem productivity.* Philosophical Transactions - Royal Society. Biological Sciences, 365(1555), 3227–3246. https://doi.org/10.1098/rstb.2010.0102

Rita, A., Bonanomi, G., Allevato, E., Borghetti, M., Cesarano, G., Mogavero, V., Rossi, S., Saulino, L., Zotti, M., & Saracino, A. (2021). *Topography modulates near-ground microclimate in the Mediterranean Fagus sylvatica treeline.* Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-87661-6

Riviere, M., Caurla, S., & Delacote, P. (2020). *Evolving Integrated Models From Narrower Economic Tools: the Example of Forest Sector Models.* Environmental Modeling & Assessment, 25(4), 453–469. https://doi.org/10.1007/s10666-020-09706-w

Rötzer, T., Dieler, J., Mette, T., Moshammer, R., & Pretzsch, H. (2010). *Productivity and carbon dynamics in managed Central European forests depending on site conditions and thinning regimes.* Forestry: An International Journal of Forest Research, 83(5), 483–496. https://doi.org/10.1093/forestry/cpq031

Ruffault, J., Pimont, F., Cochard, H., Dupuy, J.-L. & Martin-StPaul, N. (2022). *SurEau-Ecos v2.0: A trait-based plant hydraulics model for simulations of plant water status and drought-induced mortality at the ecosystem level*. Geoscientific Model Development, 15, 5593–5626.

Skrk, N., Martinez del Castillo, E., Serrano-Notivoli, R., Luis, M. De, Novak, K., Merela, M., Cufar, K. (2023). *Spatial and temporal variation of Fagus sylvatica growth in marginal areas under progressive climate change*. Dendrochronologia 81. https://doi.org/10.1016/j.dendro.2023.126135

Schmied, G., Pretzsch, H., Ambs, D., Uhl, E., Schmucker, J., Fäth, J., Biber, P., Hoffmann, Y. D., Šeho, M., Mellert, K. H., & Hilmers, T. (2023). *Rapid beech decline under recurrent drought stress: Individual neighborhood structure and soil properties matter.* Forest Ecology and Management, 545, 121305. https://doi.org/10.1016/j.foreco.2023.121305

Simonin, K., Kolb, T., Montes-Helu, M., & Koch, G. (2007). *The influence of thinning on components of stand water balance in a ponderosa pine forest stand during and*

after extreme drought. Agricultural and Forest Meteorology, 143(3–4), 266–276. https://doi.org/10.1016/j.agrformet.2007.01.003

Sperry, J. S., Adler, F. R., Campbell, G. S., & Comstock, J. P. (1998). *Limitation of plant water use by rhizosphere and xylem conductance: results from a model.* Plant, Cell & Environment/Plant, Cell and Environment, 21(4), 347–359. https://doi.org/10.1046/j.1365-3040.1998.00287.x

Sperry, J.S., Venturas, M.D., Anderegg, W.R.L., Mencuccini, M., Mackay, D.S., Wang, Y., et al. (2017). *Predicting stomatal responses to the environment from the optimization of photosynthetic gain and hydraulic cost.* Plant, Cell & Environment, 40, 816–830. https://doi: 10.1111/pce.12852.

Taylor, A. R., Chen, H. Y. H., & VanDamme, L. (2009). *A Review of Forest Succession Models and Their Suitability for Forest Management Planning*. Forest Science, 55(1), 23–36. https://doi.org/10.1093/forestscience/55.1.23

Tegel, W., Seim, A., Hakelberg, D., Hoffmann, S., Panev, M., Westphal, T., Büntgen, U. (2014). *A recent growth increase of European beech (Fagus sylvatica L.) at its Mediterranean distribution limit contradicts drought stress.* Eur. J. For. Res. 133, 61–71. https://doi.org/10.1007/s10342-013-0737-7

Testolin, R., Dalmonech, D., Marano, G., Bagnara, M., D'Andrea, E., Matteucci, G., Noce, S., Collalti, A. (2023). *Simulating diverse forest management options in a changing climate on a Pinus nigra subsp. laricio plantation in Southern Italy.* Sci. Total Environ. 857, 159361. https://doi.org/10.1016/j.scitotenv.2022.159361

Thom, D., Buras, A., Heym, M., Klemmt, H. J., & Wauer, A. (2023). *Varying growth response of Central European tree species to the extraordinary drought period of 2018 – 2020.* Agricultural and Forest Meteorology, 338, 109506. https://doi.org/10.1016/j.agrformet.2023.109506

Tognetti, R., Lasserre, B., Di Febbraro, M., & Marchetti, M. (2019). *Modeling regional drought-stress indices for beech forests in Mediterranean mountains based on tree-ring data.* Agricultural and Forest Meteorology, 265, 110–120. https://doi.org/10.1016/j.agrformet.2018.11.015

Vacchiano, G., Magnani, F., & Collalti, A. (2012). *Modeling Italian forests: state of the art and future challenges. IForest*, *5*(1), 113–120. https://doi.org/10.3832/ifor0614-005

Vangi, E., Dalmonech, D., Cioccolo, E., Marano, G., Bianchini, L., Puchi, P. F., Grieco, E., Cescatti, A., Colantoni, A., Chirici, G., & Collalti, A. (2024a). *Stand age diversity and climate change affects forests' resilience and stability, although unevenly.* bioRxiv (Cold Spring Harbor Laboratory). https://doi.org/10.1101/2023.07.12.548709

Vangi, E., Dalmonech, D., Cioccolo, E., Marano, G., Bianchini, L., Puchi, P. F., Grieco, E., Cescatti, A., Colantoni, A., Chirici, G., & Collalti, A. (2024b). *Stand age diversity (and more than climate change) affects forests' resilience and stability, although unevenly.* Journal of Environmental Management, 366, 121822. https://doi.org/10.1016/j.jenvman.2024.121822

Verbeeck, H., Samson, R., Granier, A. A., Montpied, P., & Lemeur, R. (2008). *Multi-year model analysis of GPP in a temperate beech forest in France.* Ecological Modelling, 210(1–2), 85–103. https://doi.org/10.1016/j.ecolmodel.2007.07.010

Waring, R. H. and S. W. Running (2007). *Forest Ecosystems: Analysis at Multiple Scales*. San Francisco, CA, Elsevier Academic Press.

Yu, X., Orth, R., Reichstein, M., Bahn, M., Klosterhalfen, A., Knohl, A., Koebsch, F., Migliavacca, M., Mund, M., Nelson, J. A., Stocker, B. D., Walther, S., & Bastos, A. (2022b). *Contrasting drought legacy effects on gross primary productivity in a mixed versus pure beech forest.* Biogeosciences, 19(17), 4315–4329. https://doi.org/10.5194/bg-19-4315-2022

Zuccarini, P., Delpierre, N., Mariën, B., Peñuelas, J., Heinecke, T., Campioli, M. (2023). *Drivers and dynamics of foliar senescence in temperate deciduous forest trees at*

their southern limit of distribution in Europe. Agric. For. Meteorol. 342, 109716. https://doi.org/10.1016/j.agrformet.2023.109716