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Simulating diverse forest management options in a changing climate on a *Pinus nigra* subsp. *laricio* plantation in Southern Italy

Abstract

Mediterranean pine plantations provide several ecosystem services but are vulnerable to climate change. Forest management might play a strategic role in the adaptation of Mediterranean forests, but the joint effect of climate change and diverse management options have seldom been investigated together. Here, we simulated the development of a Laricio pine (*Pinus nigra* subsp. *laricio*) stand in the Bonis watershed (southern Italy) from its establishment in 1958 up to 2095 using a state-of-the-science process-based forest model. The model was run under three climate scenarios corresponding to increasing levels of atmospheric CO_2 concentration and warming, and six management options with different goals, including wood production and renaturalization. We analysed the effect of climate change on annual carbon fluxes (i.e., gross and net primary production) and stocks (i.e., basal area, standing and harvested carbon woody stocks) of the autotrophic compartment, as well as the impact of different management options compared to a no management baseline. Results show that higher temperatures (+3 to +5 °C) and lower precipitation (–20% to –22%) will trigger a decrease in net primary productivity in the second half of the century. Compared to no management, the other options had a moderate effect on carbon fluxes over the whole simulation (between –14% and +11%). While standing woody biomass was reduced by thinning interventions and the shelterwood system (between –5% and – 41%), overall carbon stocks including the harvested wood were maximized (between +41% and +56%). Results highlight that management exerts greater effects on the carbon budget of Laricio pine plantations than climate change alone, and that climate change and management are largely independent (i.e., no strong interaction effects). Therefore, appropriate silvicultural strategies might enhance potential carbon stocks and improve forest conditions, with cascading positive effects on the provision of ecosystem services in Mediterranean pine plantations.

Keywords

Mediterranean forests; Climate change; Forest management; Process-based model; 3D-CMCC-FEM; Autotrophic response; Laricio pine

1. Introduction

Temperate forests play an important role in the Earth system Carbon (C) cycle by absorbing and storing a considerable amount of C in their aboveground and belowground compartments (Keith et al., 2009). In Europe, Mediterranean forests account for 30% of the forest cover and represent a net C-sink (FAO, 2018; Morán-Ordóñez et al., 2020). The Mediterranean basin is also a global biodiversity hotspot (Myers et al., 2000; Noce et al., 2016), with its forests harbouring three times the number of tree species as the rest of Europe in a fourfold smaller area (Fady-Welterlen, 2005). These ecosystems play a key role in the livelihoods of local communities by providing food, timber, clean water, protection against soil erosion and micro-climatic regulation (Mazza et al., 2018; Morán-Ordóñez et al., 2021, 2020). At the same time, the Mediterranean basin is one of the main climate change hotspots on the planet (Diffenbaugh and Giorgi, 2012; Noce et al., 2017; Tuel and Eltahir, 2020). Indeed, the area is warming up 20% faster than the global average, precipitations are projected to decrease up to 20%, and extreme climatic events (e.g., heatwaves and droughts) are likely to increase both in frequency and intensity (D'Andrea et al., 2020; Lionello and Scarascia, 2018; Santini et al., 2014). These changing conditions could potentially reduce forest growth and prompt changes in forest dynamics (i.e., mortality and extensive dieback episodes) that, together with other disturbances, might limit the C-uptake capacity and the productivity of Mediterranean forests (Gentilesca et al., 2017; Klein et al., 2019; Matteucci et al., 2013; Resco De Dios et al., 2007). By the end of this century, the cumulative effect of climate and land use change in the Mediterranean basin could reduce the C absorption capability of the forests' autotrophic compartment, with inevitable and profound consequences on the persistence and dynamics of these ecosystems (Morales et al., 2007; Nolè et al., 2013; Pausas and Millán, 2019).

In this context, there is a high expectation towards the sustainable management of Mediterranean forests to counterbalance possible climate-change induced C-losses by preserving the sequestration capability of stands (Jandl et al., 2019; Reyer et al., 2015; Ruiz-Peinado et al., 2017; Vilà-Cabrera et al., 2018). Indeed, sustainable forest management practices can mitigate greenhouse gas emissions and contribute to climate change adaptation, while providing long-term livelihoods for communities by maintaining and enhancing ecosystem services (IPCC, 2019). This is especially critical for European and, particularly, Mediterranean forests, as they have already undergone several millennia of human influence which resulted in the prevalence of mixed forest stands and conifer plantations (Naudts et al., 2016; Ruiz-Benito et al., 2012). Among the latter, pine plantations were mainly established during the 20th century to restore overexploited land, foster soil protection, and increase the production of existing forest stands, resulting in multiple forest restoration projects on a vast scale (Maestre and Cortina, 2004; Pausas et al., 2004). Despite the typical fast-growing performances, Mediterranean pine plantations are particularly sensitive to the adverse effect of climate change and related disturbances (e.g., wildfires, drought, insect outbreaks) (González-Sanchis et al., 2015; Martin-Benito et al., 2011; Navarro-Cerrillo et al., 2019; Resco De Dios et al., 2007; Ruiz-Benito et al., 2012), which might be further exacerbated by the lack or the total abandonment of silvicultural treatments. The latter is particularly relevant in those mountainous areas characterized by limited accessibility and overall low economic revenue due to high forest exploitation costs (Lerma-Arce et al., 2021; Proto et al., 2020). Therefore, management interventions in Mediterranean pine plantations aimed at promoting the progressive evolution of these stands towards more diverse and species-rich forests should be advanced to ensure forest functioning and the future provision of ecosystem services in a changing climate (Nocentini et al., 2022).

Management strategies for climate change adaptation in Mediterranean forests can be mainly translated into different thinning schemes – both in terms of intervention frequency and removal intensities – and ultimately through adjusted rotation periods (Resco De Dios et al., 2007). These adaptation measures: (i) modulate C-stocks and C-uptake capacity, (ii) increase drought-stress resistance by reducing competition for water, and (iii) reduce losses of C use efficiency (net vs. gross primary production) by contrasting the aging of Mediterranean forests in the short-term, compared to the absence of management (del Río et al., 2017; González-Sanchis et al., 2015; Navarro-Cerrillo et al., 2019; Vilà-Cabrera et al., 2018). Despite the potential benefits of silvicultural practices aimed at enhancing the resilience of Mediterranean forests to future climate change impacts, the effects of diverse management alternatives on the long-term forest adaptation have been seldom investigated (Manrique-Alba et al., 2020; Vilà-Cabrera et al., 2018), with most existing studies carried out in central and northern Europe (Collalti et al., 2018; Dalmonech et al., 2022; Duveneck et al., 2014).

Process-based forest models provide a fundamental experimental framework to track the future responses of forest ecosystems to management strategies under a changing climate (Gupta and Sharma, 2019; Keenan et al., 2011; Maréchaux et al., 2021; Reyer et al., 2015; Ruiz-Benito et al., 2020). Such models incorporate both empirical and mechanistic relations of the main ecophysiological processes which drive the response of forest stand development over decadal time periods (Gupta and Sharma, 2019; Keenan et al., 2011; Mäkelä et al., 2000) and can therefore help quantify the impacts of climate change and management on forest fluxes and stocks under changing environmental conditions. In an integrated scenario-analysis framework, process-based forest models can inform both the scientific and policy-making communities of the forestry sector, thus supporting adaptation and mitigation strategies in the Mediterranean basin (Keenan et al., 2011; Morán-Ordóñez et al., 2020; Vilà-Cabrera et al., 2018). Yet, simulation studies aimed at assessing the crossed effect of climate change and of diverse management options on forest biomass and productivity have been mostly carried out outside the Mediterranean basin and are limited in the number of simulated climate scenarios (e.g., Borys et al., 2016; Fürstenau et al., 2007; Garcia-Gonzalo et al., 2007; Jönsson et al., 2015; Lexer et al., 2008; Shanin et al., 2011) and management options (e.g., Pussinen et al., 2009; Schelhaas et al., 2015).

By means of a state-of-the-science process-based forest model (3D-CMCC-FEM; Three Dimensional - Coupled Model Carbon Cycle - Forest Ecosystem Model) we simulated the development of a Laricio pine stand in the Bonis experimental watershed (southern Italy) with the aim of providing insights on future management strategies for Mediterranean pine plantations. We designed a wide portfolio of forest management options based on different schemes which are currently applied in the study area and tested their effects on the development of forest carbon stocks and fluxes under different climate scenarios. Thus, we assessed the relative impact of climate change and different silvicultural practices on the autotrophic response of one of the southernmost European pine plantations up to the end of the 21st century.

2. Materials and methods

2.1. Study area and stand data collection

The Bonis experimental watershed is located in the mountain area of Sila Greca (39°28’49’’ N, 16°32’07’’ E; from 975 to 1330 m a.s.l.) in the Calabria region, southern Italy, and represents one of the southernmost long-term experimental forest research sites in Europe. The catchment has a surface of 1.39 km^2, a mean elevation of 1131 m a.s.l. and was firstly instrumented for hydrological monitoring in 1986. Almost 93% of the total area is covered by forests, dominated by ~60 years old Laricio pine stands, whose origin is mainly artificial (Callegari et al., 2003; Caloiero et al., 2017). The stands were planted in 1958 with an average density of 2425 saplings ha^{-1} (Nicolaci et al., 2015) and underwent a thinning treatment in 1993 with a basal area (BA) removal of 25% (Callegari et al., 2003). The climate is typically Mediterranean, with average annual precipitation of 915 mm and average temperature of 12.2 °C. The geological substrate is mainly composed of acid plutonic rocks and gravelly sands (Callegari et al., 2003). To study forest structure and development, 14 circular 12 m-radius plots were established in 1993 before the thinning interventions. In each plot, for all trees with diameter at breast height (DBH; 1.3 m) > 2.5 cm, total height, crown insertion height and vitality were recorded (Collalti et al., 2017). The plots were resurveyed in 1999 and 2016. As part of the Euroflux-Carboitaly network, a tower for the measurement of eddy fluxes was installed in 2003 in one of the Laricio pine plantation stands within the study area (39°28’40’’ N, 16°32’05’’ E; Marino et al., 2005). The tower was regularly operated between 2005 and 2009. The plot data have been used to parameterize and, together with the eddy fluxes data, to validate the model.

2.2. Vegetation model and species parameterization

The 3D-CMCC-FEM forest model (v.5.6 BGC) is a biogeochemical, biophysical, and physiological process-based forest model developed to predict C, energy, and water fluxes coupled with stand development processes that determine relative stock changes in forest ecosystems (Collalti et al., 2019; Dalmonech et al., 2022). The model is designed to simulate the main physiological and hydrological processes at daily, monthly, and annual scales and at the species-specific level. The model requires data on initial forest stand conditions including species composition, average tree DBH, height, stand age and tree density (number of trees per hectare). Both structural and non-structural tree C-pools are initialized at the beginning of the simulation and updated daily, monthly, or annually, depending on the processes. Furthermore, the model allows the simulation of different management scenarios by defining the intensity and the interval of removals, as well as the length of rotation periods and artificial replanting schemes, which can be varied through the simulation time. For a full description of key model principles and theoretical framework see also Collalti et al. (2020a, 2019, 2018, 2016, 2014), Dalmonech et al. (2022), Engel et al. (2021), and Marconi et al. (2017).

The model was parameterized to simulate the development of a Laricio pine stand based on published literature (Lapa et al., 2017; Lebourgeois et al., 1998; Patenaude et al., 2008). When published information on the species was unavailable for a given ecophysiological parameter, we used the values reported for ecologically-close species following this order: other subspecies of *Pinus nigra* (Grossoni, 2014; Margolis et al., 1995; Móricz et al., 2018; Navarro-Cerrillo et al., 2016; Van Haverbeke, 1990), *Pinus pinaster* (Chiesi et al., 2007; Delzon et al., 2004; Mollicone et al., 2002), *Pinus sylvestris* (Collalti et al., 2019; Yuste et al., 2005) or, more generally and in few cases, other evergreen species (Arora and Boer, 2005; Dewar et al., 1994; Poulter et al., 2010). All parameter values and sources are reported in Supplementary Information Table S1.

2.3. Climate and atmospheric CO_2 data

The 3D-CMCC-FEM requires as climatic inputs daily values of solar radiation (MJ m^{-2}), temperature (°C), precipitation (mm) and vapor pressure deficit (hPa). Such data, from 1958 to 2016, were derived for the Bonis watershed using the mountain microclimate simulation model MT-CLIM (Thornton and Running, 1999) forced by temperature and precipitation series measured by the nearby Cecita meteorological station (39°23’51’’ N, 16°33’24’’ E; 1180 m a.s.l.). This dataset was used to perform historical simulations for model validation.

To simulate the development of the Laricio pine stand up to the end of the 21st century, we employed a set of climate data covering the 1976 - 2095 period at 0.0715° spatial resolution (~8 km) (Bucchignani et al., 2016; Zollo et al., 2016). This highly resolved climate data are based on the regional climate model COSMO-CLM (Rockel et al., 2008) driven by the CMCC-CM global model (Scoccimarro et al., 2011) using the 20C3M forcing (i.e., observed emissions) for the period 1976 - 2005, and two IPCC emission scenarios from 2006 onwards: the intermediate emission scenario RCP4.5 and the high emission scenario RCP8.5 (Moss et al., 2010; van Vuuren et al., 2011). The RCP4.5 scenario assumes that the total radiative forcing is stabilized, shortly after 2100, to 4.5 Wm^{-2} (approximately 650 ppmv CO_2-equivalent) by employing various technologies and strategies to reduce greenhouse gas emissions. The RCP8.5 is characterized by increasing emissions and high greenhouse gas concentration levels, leading to 8.5 Wm^{-2} in 2100 (approximately 1370 ppmv CO_2-equivalent). Modeled temperature and precipitation data were bias-corrected following the approach adopted and described in Sperna Weiland et al. (2010), starting from the observed series of the same variables. As an observational dataset for the bias correction the downscaled daily E-OBS dataset (v 10.0) at 1 km resolution (Maselli et al., 2012) was used. Additionally, we simulated a current climate (CUR) dataset as a benchmark scenario for the period 2006 - 2095 by randomly sampling each day in sequence from the bias-corrected COSMO-CLM dataset between 1990 and 2005. As the COSMO-CLM data were only available starting from 1976, we used the MT-CLIM climatic dataset described above for the 1958 - 1975 period.

Measured values of global annual atmospheric CO_2 concentration (ppmv) were derived from Meinshausen et al. (2011), while values consistent to the abovementioned emission scenarios were provided by Dlugokencky and Tans (2014). The atmospheric CO_2 concentrations for the CUR scenario were simulated by randomly sampling each year in sequence between 1990 and 2005 from Meinshausen et al. (2011).

To assess the departure of projected climate change from the baseline CUR scenario, we calculated the mean relative change in temperature, precipitation, vapor pressure deficit and atmospheric CO_2 concentration for the two RCP scenarios within two different time windows: near future (NF; 2025 - 2055) and far future (FF; 2065 - 2095). Confidence intervals (95%) were estimated as ± 1.96 times the standard error.

2.4. Model evaluation

Model performances were evaluated by simulating the development of a representative Laricio pine stand in the Bonis watershed from its establishment in 1958 to the last field measurements occurred in 2016, which includes the thinning in 1993. The model was initialized in 1958 with an initial density of 2425 saplings per hectare (DBH: 1 cm, height: 1.3 m, age: 4 years; Nicolaci et al., 2015), considering the average elevation of the watershed (1131 m a.s.l.), the average soil texture (clay: 20%; silt: 26%; sand: 54%) and depth (100 cm) (Buttafuoco et al., 2005; Moresi et al., 2020). The evaluation was carried out by comparing the resulting simulated mean annual DBH and tree density to the values measured at the field plots in 1993 (before thinning), 1999 and 2016, as well as to the estimations provided by Callegari et al. (2003) for low and high density Laricio pine plantations in the Bonis watershed for 1986, 1993 (before and after thinning) and 1999. Additionally, a micrometeorological validation of daily gross primary productivity (GPP) was carried out by comparing the simulated values to those obtained by the eddy covariance tower. As described in Collalti et al. (2018), we excluded years with major gaps (i.e., 2009), as well as all days with a quality control flag of eddy data lower than 0.6. The comparisons were carried out for each year, as well as for the daily averages, by calculating root mean squared error (RMSE), coefficient of determination (R^2) and modelling efficiency (ME). The latter index provides information about modelling performance on a relative scale: ME = 1 indicates a perfect fit, ME = 0 reveals that the model is no better than a simple average, while negative values indicate poor performance (Bagnara et al., 2015; Vanclay and Skovsgaard, 1997).

2.5. Forest management scenarios

For each of the three climate scenarios (i.e., CUR, RCP4.5, RCP8.5) we simulated forest management by mimicking six different silvicultural options reflecting different goals (Table 1), resulting in a total of 18 different model runs. All the options were simulated to take place after 2016, i.e., the last year of field measurements. The scenarios cover several management objectives including both wood production and renaturalization and reflect the state-of-the-science of management options applied to this region of the Italian Apennines (Cantiani et al., 2018). The first option (*'no management'*) represents the natural development of the forest left without human intervention. Such option also mimics land abandonment, that represents a relatively widespread occurrence in Mediterranean mountains. Two options simulating different thinning intensities – *'light'* and *'heavy'*, corresponding to a 28% and 35.5% reduction of BA, respectively – at an interval of 15 years are proposed in order to reproduce silvicultural interventions aimed at favouring natural forest dynamics. Indeed, at intermediate stages of stand development, pine forests can benefit from thinnings aimed specifically at improving their degree of stability (Cantiani et al., 2005; Cantiani and Piovosi, 2008). Selective thinnings also favor structural diversity, and reduce inter-tree competition for water, light, and nutrients (del Río et al., 2017; Marchi et al., 2018). However, tending and thinning interventions still represent a major passive management item in terms of net costs and are often avoided in public forests resulting in a progressive degeneration of stand structure (Ahtikoski et al., 2021; Niskanen and Väyrynen, 2001). An additional, production-oriented option (*'patch clearcut'*) simulating a complete harvest followed by replanting 80 years after the establishment of the plantation is also included. Nevertheless, the shelterwood system represents a more sustainable alternative to clear-cutting and patch cuttings by ensuring continuous forest cover and an adequate light availability to the forest floor and protection from soil erosion. The practice favours regeneration while modulating the competition for light and water resources with herbs and shrubs, and allows higher revenues (Brichta et al., 2020; Cantiani et al., 2018; Montoro Girona et al., 2018). Therefore, we simulated two shelterwood options: *'shelterwood A'*, consisting of two light thinnings (20% reduction of BA) with a 10 year interval, followed by a seed-favouring cut after 80 years from the original planting (80% reduction of BA) and a removal cut 10 years later; *'shelterwood B'*, defined by a delayed seed-favouring cut after 90 years, preceded by three heavier thinnings (28.5% reduction of BA) and followed by a removal cut after 10 years. In both cases, the seed-favouring cut is followed by natural regeneration of the same species. The regeneration is simulated as a prescribed replanting, with density of saplings derived from the estimated tree density of natural Laricio pine stands in 1986 (see Callegari et al., 2003) by going backwards to 1958 and assuming a 1% annual mortality rate (Andrus et al., 2021).

2.6. Analysis of simulation outputs

To assess the response of the autotrophic component of the stand to climate change and management, we considered the tree biomass compartment, whose C-stocks and fluxes are the most affected by forest management due to a modulation of stand density as a consequence of thinning and harvesting (D'Amato et al., 2011). Specifically, we evaluated the temporal trends of stand-level GPP, net primary productivity (NPP), potential C-woody stocks (pCWS; i.e., the sum of standing woody biomass and harvested woody stocks, assuming no decay) and BA. We chose these variables among all model outputs as they are key components of the forest C-budget and forest structure, representing the physiologically and structurally inherent capacity of trees to sequester and stock atmospheric CO_2 on the short- (i.e., GPP and NPP) to long-term (i.e., pCWS and BA). At the same time, these outputs are key variables relevant to decision makers to assess stand growth changes and current standing biomass, as well as to make appropriate management decisions. Notably, we considered pCWS as potential values representative of the maximum attainable C-stock capacity (i.e., the yield in woody biomass and timber), to quantify the inherent capability of trees to sequester and store C over medium- to long-time periods. Temporal trends of standing woody biomass and harvested woody stocks were also presented separately to facilitate the interpretation of pCWS. Likewise, trends of autotrophic respiration and biomass production (i.e., the fraction of NPP that is used for the biomass increment only; Collalti et al., 2020b) were evaluated to assess the relationship between productivity and C-stocks.

We analysed the crossed effect of climate change and management by calculating the relative change of the abovementioned outputs from the baseline '*no management*' option under CUR climate for each combination of management option and climate scenario. The results were averaged within the NF and FF time windows, as well as for the whole simulation starting from 2006 (i.e., the starting year of the climatic scenarios; ALL time window). All data analyses and visualization were performed with R (R Core Team, 2021).

3. Results

3.1. Model evaluation

The simulated mean stand DBH of Laricio pine plantations in the Bonis watershed was 18.1 cm in 1986, 20.5 cm in 1993 before the thinning, 21 cm in 1993 after the thinning, and 24.3 cm in 1999. In the same years, Callegari et al. (2003) reported a mean stand DBH range of 18 - 20.2 cm, 19.8 - 21.8 cm, 20.8 - 22.8 cm and 23.8 - 27.4 cm, respectively, for high- and low-density plantations. At the forest plots, a mean stand DBH of 22.2 ± 2.4 cm was estimated in 1993 before the thinning, which increased to 25.9 ± 3.7 cm in 1999 and to 33.7 ± 3.3 cm in 2016. The simulated value for in 2016, was 33.6 cm (Table 2; Figure S1). As for tree density, the model simulated 1620 trees ha^{-1} in 1986, 1276 trees ha^{-1} in 1993 before the thinning, 948 trees ha^{-1} in 1993 after the thinning, 894 trees ha^{-1} in 1999 and 474 trees ha^{-1} in 2016. The values measured at the forest plots were 1491 ± 382 trees ha^{-1}, 975 ± 376 trees ha^{-1} and 522 ± 231 trees ha^{-1} in 1993 before the thinning, 1999 and 2016, respectively. Similarly, Callegari et al. (2003) reported a range of 1250 - 2200 trees ha^{-1}, 1162 - 1701 trees ha^{-1}, 800 - 1150 trees ha^{-1} and 775 - 1102 trees ha^{-1} in 1986, 1993 before thinning, 1993 after thinning and 1999, respectively (Table 2; Figure S1).

Goodness-of-fit metrics of the four-year average trend of simulated daily GPP against values derived by the eddy covariance tower were RMSE = 1.38 gC m^{-2} d^{-1}, R^2 = 0.69 and ME = 0.6 (Figure 1 a,b). As for the daily GPP of each year, the model reproduced the annual trends, albeit with different accuracy (Figure S2).

3.2. Climate scenarios

On average, atmospheric CO_2 concentration will increase to 461 - 494 ppmv in NF and to 530 - 761 ppmv in FF, according to the RCP4.5 and RCP8.5 scenarios, respectively. At the same time, mean temperatures at the Bonis watershed under the RCP4.5 scenario are projected to increase by 1.2 °C (9%) in NF and 3 °C (23%) in FF, compared to CUR. According to the RCP8.5 scenario, the increase will be by 1.8 °C (14%) and 5 °C (39%). Vapor pressure deficit will also increase by 13% in NF and 31% in FF under the RCP4.5 scenario compared to CUR, while the increase will be by 18% and 59% under the RCP8.5 scenario. No significant change in precipitation is predicted in NF for both scenarios, while a reduction of 20% and 22% is predicted in FF, respectively for the RCP4.5 and RCP8.5 scenarios, compared to CUR (Table S2; Figure S3).

3.3. Crossed effects of climate change and management

Within the NF period, the *'no management'* option showed the highest values for GPP (1591 - 1677 gC m^{-2} y^{-1}), NPP (570 - 552 gC m^{-2} y^{-1}), and BA (42 m^2 ha^{-1}) under all climate scenarios, while the *'patch clearcut'* option showed the lowest values of the same variables (GPP: 1172 - 1269 gC m^{-2} y^{-1}, NPP: 450 - 455 gC m^{-2} y^{-1}, BA: 24 - 25 m^2 ha^{-1}). As for pCWS, the highest values were for the *'shelterwood B'* option (167 - 169 tC ha^{-1}), while *'no management'* exhibited the lowest (114 - 115 tC ha^{-1}). The *'shelterwood A', 'shelterwood B'* and *'patch clearcut'* options showed a similar decrease in GPP (between –12% and –26%) and BA (between –30% and –42%) compared to *'no* *management'* under CUR climate, while the *'light'* and *'heavy thinning'* options presented a more limited decrease (between –1% and –6% for GPP; between –11% and –16% for BA). As for NPP, the decrease was negligible for *'light'* and *'heavy thinning' (*between –2% and –5%); *'shelterwood A'* and *'shelterwood B'* exhibited intermediate values between –6% and –11% of NPP while the 'patch clearcut' presented the greatest decrease (between –19% and –20%) compared to *'no management'* under CUR climate. Increases in pCWS were between 37% and 47% for thinning and shelterwood options, while the *'patch clearcut'* option exhibited a 3% to 4% increase compared to *'no management'* under CUR climate. No large differences in the output variables were observed among different climate scenarios across all management options (Table 3; Figure 2 and 3).

As for the FF time window, mean GPP was the highest under the *'shelterwood B'* option (1833 - 1937 gC m^{-2} y^{-1}), while mean NPP was the highest under the *'shelterwood A'* option (465 - 604 gC m^{-2} y^{-1}). Mean pCWS was maximized with *'heavy thinning'* (265 - 275 tC ha^{-1}), while the highest simulated BA was found under the *'shelterwood A'* option (42 m^2 ha^{-1}). The *'heavy thinning'* option led to the lowest mean values for GPP (1334 - 1374 gC m^{-2} y^{-1}), NPP (353 - 490 gC m^{-2} y^{-1}) and BA (36 - 37 m^2 ha^{-1}), while the lowest mean values for pCWS were found under the *'no management'* simulation (138 - 141 tC ha^{-1}) (Table 3; Figure 2 and 3). Overall, *'patch clearcut'*, *'shelterwood A'* and *'shelterwood B'* options exhibited a similar change in GPP (between 25% and 37%) with very limited effect on BA (between –3% and 1%), compared to *'no management'* under CUR climate. Conversely, '*light'* and '*heavy thinning'* showed a slight decrease both in GPP (between –1% and –6%) and BA (–3% and –14%). pCWS increased between 61% and 94% under the thinning and shelterwood options and showed a 28% - 30% increase with *'patch clearcut'*. Even in the FF time window, no large differences in GPP, pCWS and BA emerged among different climate scenarios across the different management options. On the contrary, NPP was more strongly affected by climate change: it decreased by 14% and 25% under the RCP4.5 and RCP8.5 scenarios in the *'no management'* option compared to the baseline under CUR climate. As for the *'patch clearcut'*, *'shelterwood A'* and *'shelterwood B'* options NPP showed to increase between 1 and 18% under the CUR and RCP4.5

scenarios, and a to decrease under the RCP8.5 scenario (between –8% and –12%), compared to *'no management'* under CUR climate. As for the '*light'* and '*heavy thinning'* options, NPP decreased between 2% and 4% under CUR climate, 16% and 18% under RCP4.5, and between 28% and 30% under the RCP8.5 scenario, compared *'no management'* under CUR climate (Table 3; Figure 2 and 3).

Between 2006 and 2095, GPP was maximized under the *'patch clearcut'*, *'shelterwood A'* and *'shelterwood B'* options (1552 - 1695 gC m^{-2} y^{-1}), corresponding to a 1% to 11% increase compared to *'no management'* under CUR climate (1544 gC m^{-2} y^{-1}), while the thinning options showed the lowest values (1460 - 1530 gC m^{-2} y^{-1}) and a decrease between 1% and 5%. NPP showed a similar trend, with the *'shelterwood A'* and *'shelterwood B'* options exhibiting the highest values (509 - 569 gC m^{-2} y^{-1}), corresponding to a change between –6% and 4%, compared to *'no management'* under CUR climate (551 gC m^{-2} y^{-1}). The *'patch clearcut'*, *'light thinning'* and *'heavy thinning'* simulations had lower NPP (474 - 541 gC m^{-2} y^{-1}) than *'no management'* (491 - 551 gC m^{-2} y^{-1}) for the same climate scenarios, corresponding to a 2% - 14% decrease compared to the value obtained under CUR climate (Table 3; Figure 2 and 3). The same pattern was observed for biomass production – ranging between 502 - 557 gC m^{-2} y^{-1} with the shelterwood options and between 467 - 529 gC m^{-2} y^{-1} with the other active management options – and autotrophic respiration, which was maximized under the *'patch clearcut'*, *'shelterwood A'* and *'shelterwood B'* options (996 - 1177 gC m^{-2} y^{-1}) and minimized under the thinning options (928 - 1048 gC m^{-2} y^{-1}) (Table S4; Figure S4 and S5). All management options showed lower BA values (34 - 38 m^{2} ha^{-1}) compared to *'no management'*, corresponding to a relative change between –7% and –8% (*'light thinning'*), and –19% (*'shelterwood B'*). As for pCWS, all options led to greater values than *'no management'* (121 - 122 tC ha^{-1}), with the thinning and shelterwood options showing similar values (181 - 196 tC ha^{-1}), corresponding to a 45% to 56% increase (Table 3; Figure 2 and 3). The increase in pCWS under all active management options was explained by the larger harvested woody stocks (between 377% and 710%) compared to the *'no* *management'* option, while standing woody biomass decreased between –5% (*'light thinning'*) and –41% (*'shelterwood A'*) (Table S5; Figure S6 and S7).

4. Discussion

4.1. Model evaluation

The 3D-CMCC-FEM reproduced well the development of a Laricio pine stand in the Bonis watershed over a 58-year span. Our evaluation of stand attributes showed that, starting from the establishment of the plantation in 1958, the simulated mean stand DBH and tree density fell within the measured range of two independent datasets: average values for low and high density Laricio pine plantations in the area between 1986 and 1999 (Callegari et al.; 2003), and the forest plots surveyed between 1993 and 2016. The model was also able to simulate historical management activities and their effects on forest development. Indeed, the simulation included a thinning of 25% of stand BA that took place in 1993, which was reflected by the reduction in tree density in that year and a slight increase in the growth rate of mean stand DBH in the following years (0.6 cm y^{-1} after the thinning vs. 0.3 cm y^{-1} before the thinning).

Furthermore, the model was able to reproduce the mean seasonal cycle of daily GPP as obtained by the eddy covariance tower with sufficient accuracy, supporting previous assessments of model performance (Collalti et al., 2014, 2016, 2018, 2020a; Dalmonech et al., 2022; Engel et al., 2021; Mahnken et al., 2022; Marconi et al., 2017). The R^2 of 0.69 is in line with previous evaluations of simulated daily GPP across northern European forest sites (average R^2 across three sites = 0.73; Collalti et al., 2018), while the ME of 0.61 is within the range found for daily GPP simulated with other process-based models (0.42 - 0.84 in Bagnara et al., 2015; 0.61 - 0.98 in Minunno et al., 2016).

4.2. Impacts of climate change

In the first half of the 21st century, both RCPs projected similar increments in mean annual temperature and vapor pressure deficit with no significant changes in the amount of precipitation for the Bonis watershed. However, these trends had little effect on the considered forest variables within the NF time window. Conversely, in the second half of the 21st century, a reduction in precipitation and an increase in temperature – in line with previous estimates for the Mediterranean basin (see Lionello and Scarascia, 2018; Santini et al., 2014) – were probably responsible for the observed decrease in NPP across all management options. The changes were more pronounced under the most emission-intensive scenario and toward the end of the century, negatively affecting the ability of Laricio pine stands to absorb and to store C. Indeed, the decline in water availability is likely responsible for an increased water stress, which could offset the positive effects of higher atmospheric CO_2 concentrations and the lengthening of the growing season (Cinnirella et al., 2002), while higher temperatures favour autotrophic respiration and photorespiration (Dusenge et al., 2019; Gea-Izquierdo et al., 2017; Lindner et al., 2010), leading to a reduction in biomass production because of increased allocation to non-structural carbon pools (Collalti et al., 2020b). Yet, the observed climate change-driven decreases in C-fluxes were only marginally mirrored by lower C-stocks at higher atmospheric CO_2 concentrations. This is likely due to a temporal lag induced by a smaller magnitude of the fluxes compared to the stocks, with changes of the latter observable only over longer simulation timeframes.

Previous studies already highlighted the negative effect of high temperature and soil moisture scarcity on leaf development and tree growth for forests in general and, more in particular, for Laricio pines, although the emergence of pervasive acclimation mechanisms (e.g., changes in C-allocation for reserve accumulation) in this species could reduce forest vulnerability to extreme events, thus preventing extensive dieback episodes (Cinnirella et al., 2002; Mazza et al., 2018). Nonetheless, indirect effects of climate change, including increased vulnerability of trees to pathogen attacks, could lead to higher mortality rates irrespective of physiological adaptations (Gentilesca et al., 2017; Resco De Dios et al., 2007). Recent studies have shown the ambiguity in the responses of forests to both warming and enriched atmospheric CO_2 concentration (Rezaie et al., 2018), probably related to site-specific factors (e.g. forest age, forest structure, soil nutrient availability and microclimate). While Central and Northern Europe seem to show a general increase in both C-sequestration and C-stocks in the short- to medium-term (Reyer et al., 2015), the impact of increasing droughts and disturbance risk will likely outweigh any positive trends in Southern Europe induced by CO_2-fertilization, with an expected decline in the productivity of the Mediterranean region (Lindner et al., 2010; Reyer et al., 2014; Simioni et al., 2020). In this respect, the Bonis watershed represents a unique experimental site with mountain climate at the center of the Mediterranean basin. These features make it particularly exposed to the effects of climate change, hence its likely role as sentinel of future changes in forest dynamics for the whole region.

4.3. Impacts of forest management

Regardless of the short- to long-term changes in productivity, the effect of management on forest attributes largely outplays that of climate change, in line with previous findings for Mediterranean pine forests (del Río et al., 2017) and other European forests (e.g., Akujärvi et al., 2019; Gutsch et al., 2018). Therefore, the choice of far-sighted management options is key to the future of pine plantations, particularly in the case of Laricio pine stands in the Bonis watershed, with the aim of preserving and enhancing primary production and carbon storage capacity over time, improving forests resilience to biotic and abiotic stresses, as well as promoting their structural complexity and the multiple ecosystem functions (Scarascia-Mugnozza et al., 2000). The present study aimed at reducing the knowledge gap about the potential benefits of diverse forest management options for Mediterranean pine plantations under climate change and, to our knowledge, provides the most complete overview on the subject to date. Assessing the crossed effects of forest management and climate in these environments is of paramount importance for areas close to the geographical limit of the distribution of pine species like the Bonis watershed (Navarro-Cerrillo et al., 2019), as well as for the whole European continent given the ubiquity of conifer plantations (Naudts et al., 2016).

Our simulations showed that, in the first half of the 21st century, the lack of management interventions led to higher C-fluxes (i.e., GPP and NPP) and BA, as opposed to production-oriented management strategies involving clear-cutting or the shelterwood system, which abruptly slowed down C-fluxes because of the strong reduction in leaf area and in situ standing biomass. Yet, such commercial, forestoriented options showed to maximize C-fluxes in the second half of the 21st century as a response to regeneration or replanting. Despite these fluctuations, the overall effect on C-fluxes of different management options under different climate scenarios over the 2006 - 2095 period was modest, with a relative change range between –14% and +11% compared to *'no management'* under the CUR climate scenario. These results might allude that either forest management is counterbalancing the effects of warming and increasing atmospheric CO_2 concentration, or that the Laricio pine has already reached its suitability optimum for this particular geographic area.

Our results indicate that, in the long term, active management practices can effectively increase both pCWS and NPP. However, as defined in this paper, C-stocks in the harvested woody biomass are just a potential value and do not account for decay rates. Thus, our modelling outcomes tend to favour the options that maximize C-sequestration efficiency and storage into wood tissues, despite the observed reduction in standing woody biomass. Yet, even though the predicted total pCWS are probably on the optimistic end of the wide spectrum of possible outcomes (i.e., overestimated), the proactive management of Mediterranean pine plantation likely remains beneficial. Indeed, it has been previously demonstrated that the lack of forest management in pine plantations might increase inter-tree competition, hence vulnerability to drought stress (Manrique-Alba et al., 2020; Martín-Benito et al., 2010; Navarro-Cerrillo et al., 2019). Furthermore, unmanaged pine plantations of the Mediterranean basin are simplified ecosystems composed of high-density, even-aged stands with arrested succession and at risk of events like wildfires and pest outbreaks (Ruiz-Benito et al., 2012; Scarascia-Mugnozza et al., 2000). As these destructive events represent an increasingly likely outcome in Mediterranean pine plantations under climate change, forest managers should prioritize active management options aimed at reducing fire risk by decreasing the fuel load. Among these options, thinning interventions are particularly promising, as they have demonstrated to reduce fireline intensity while avoiding emissions from prescribed burning (Rabin et al., 2022)

Previous studies highlighted the role of management strategies targeting a reduction of tree density (i.e., thinning and shelterwood) in improving overall forest health in the Mediterranean region

(Brichta et al., 2020; del Río et al., 2017; Manrique-Alba et al., 2020; Martín-Benito et al., 2010; Navarro-Cerrillo et al., 2019; Prévosto et al., 2011; Ruiz-Benito et al., 2012). In particular, moderate to heavy thinning interventions (between 25% to 50% reduction of stand BA) have been recommended as a drought adaptation measure for Mediterranean pine forests with long-lasting positive effects (Manrique-Alba et al., 2020). Furthermore, heavy thinning was found to increase the C-sequestration potential of these environments by compensating the on-site loss of C with an increased total C-stock when harvested woody stocks are taken into account (del Río et al., 2017). Similarly, in the shelterwood system, stand density is reduced to increase light availability, with positive effects on the growth of naturally established seedlings (Prévosto et al., 2011). Shelterwood regeneration of pine species was found to be more favourable with respect to microsite characteristics and of greater quality compared to replanting after clear-cut, especially after a heavy reduction of initial stand density. Thus, the shelterwood system represents a potentially useful management option to mitigate the negative effects of climate change (Brichta et al., 2020) and to reduce the impacts of replanting operations on soils. While in the present study we did not explicitly assess the effect of management options on water-use efficiency, we found that *'heavy thinning'* represented the best option for maximizing the pCWS, in line with previous findings. At the same time, the shelterwood options performed halfway between patch clearcut and thinnings and can be used to renaturalize Laricio pine forests while enhancing potential C-stocks and productivity.

4.4. Assumptions and caveats

The 3D-CMCC-FEM allowed to simulate several management options for Laricio pine plantations at Bonis watershed under different climate scenarios considering biogeochemical, biophysical, physiological and stand development processes. In the present study, we considered only the autotrophic response to climate change and management, namely those primary stand attributes related to C-fluxes and C-stocks of the standing and harvested biomass. Despite we acknowledge the non-negligible contribution of other compartments like soil (Navarrete-poyatos et al., 2019) and deadwood (del Río et al., 2017) our aim was to provide an indication of the joint effect of climate change and management on the main C inputs and stocks of a Mediterranean pine plantation, which are the most affected by silvicultural activities (D'Amato et al., 2011) and the main target of management planning. In addition, the model is most suitable for medium-term simulations, as it currently does not incorporate complex regeneration and mortality-related dynamics, which are known to likely exert a greater effect than climate on C-stocks and might play an important role in post-disturbance recovery and resilience especially in the Mediterranean environments (Oberpriller et al., 2022). Thus, further studies including other ecosystem compartments and dynamics are required to obtain a complete picture of the overall C-balance in Mediterranean forests and project its changes under future climate.

In our approach, we did not consider the decay of the harvested woody biomass, as the main focus of the present study was to quantify the maximum potential capacity of trees to sequester C in woody tissues and, in turn, to provide products under the proposed robust modelling approach and portfolio of interventions. A life-cycle assessment with the quantification of the overall climate change mitigation contribution of the forestry sector would require the definition of context-specific scenarios of final use and displacement of harvested wood (e.g., Valade et al., 2017), as well as the full greenhouse gas budget. The analysis would however be highly influenced by the wood market, as well as the energy and manufacturing-construction sectors (Howard et al., 2021; Leskinen et al., 2018), potentially adding high uncertainty to the modelling outcome.

Furthermore, the current model version is not set to simulate some forest disturbances that are likely to impact our study area like recurrent wildfires and pest outbreaks. However, simulating such events was beyond the scope of the present study as they are better represented under simulations conducted at the landscape scale. We also recognize that more management options than the ones we simulated are available. Yet, our scenarios cover several objectives including biodiversity enhancement, wood production and re-naturalization and reflect the state-of-the-practice of management portfolios applied to this region of the Italian Apennines (Cantiani et al., 2018). Moreover, the model currently does not account for the effect of soil nutrients on tree growth, site conditions being equal in all simulations. Yet, nutrient availability is generally considered a secondary driver of tree growth in Laricio pine forests, which are usually mainly limited by soil moisture (Mazza et al., 2018). Indeed, Laricio pines and other *Pinus nigra* subspecies were widely employed in large-scale afforestation projects in the Italian Apennines for their pioneer species features, being able to thrive on depleted and overexploited soils (Cantiani et al., 2018). We acknowledge, however, that this low sensitivity of tree growth to soil nutrients is specific to this study and should be reconsidered when performing simulations on other forest ecosystems. Finally, the simulations did not include species replacement due to competition and colonization. However, the forests at the Bonis watershed are dominated by Laricio pines, both natural and artificial, which are likely to recolonize gaps in the absence of proactive replanting of other tree species.

5. Conclusions

Overall, our 137-year simulation showed that climate change will affect the productivity of Laricio pine plantations in the Bonis watershed, especially in the second half of the 21st century. However, the choice of current and future management will exert an even stronger effect on the C-sink and C-stock capacity of such forests. Therefore, an appropriate planning over a set of management options aimed at maintaining and enhancing forest functionality is key to allow the future provision of forest ecosystem services in the Mediterranean area. Among the investigated options, different thinning regimes and shelterwood represent the most promising management practice. The present work provided the most complete overview to date of the crossed effect of climate change and management on one of the southernmost European pine plantation sites, with direct implications for the planning of diverse management strategies in Mediterranean pine forests. Yet, further studies are required to assess the impact of recurrent stand disturbances, changes in soil nutrient availability and species replacement on multiple ecosystem services, possibly including the soil and heterotrophic fraction of the ecosystem C-balance.

Figure captions

Figure 1. Evaluation of the average simulated daily GPP against the values obtained by the eddy covariance tower at the Bonis watershed in the years 2005 - 2008 (a, b). The solid line represents the mean simulated value. The points represent the mean values derived by eddy covariance measurements in different years. Shaded areas (a) and error bars (b) are the interval between the minimum and maximum values for a given day.

Figure 2. Relative change of modeled outputs according to six different management options (no management, light thinning, heavy thinning, patch clearcut, shelterwood A, shelterwood B) and three climate scenarios (CUR, RCP4.5, RCP8.5) compared to the baseline 'no management' option under the CUR climate scenario within the NF, FF, and ALL time windows. The error bars are the 95% confidence intervals.

Figure 3. Simulated GPP (a), NPP (b), pCWS (c) and BA (d) according to six management options (no management, light thinning, heavy thinning, patch clearcut, shelterwood A, shelterwood B) and three climate scenarios (CUR, RCP4.5, RCP8.5). Black lines are the historical simulations from 1958 to 2005. Solid lines from 2006 are the outputs produced by different management options for each climate scenario.

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Tables

Table 1. Summary of simulated management options. Abbreviations: r = rotation period; thBA = basal area removed with thinning; thINT = time interval between thinnings.

Option	Detail	Objective	r	thBA	thINT	replanting	Description
			year	%	year	n saplings ha^{-1}	
No management	No interventions	-	-	-	-	-	This option simulates only the documented thinning in 1993 (25% of BA).
Light thinning	Multiple thinning interventions	Biodiversity / Renaturalization	-	28	15	-	4 light thinnings (years: 2017, 2032, 2047, 2062).
Heavy thinning	Multiple thinning interventions	Biodiversity / Renaturalization	-	35.5	15	-	4 heavy thinnings (years: 2017, 2032, 2047, 2062).
Patch clearcut	Clearcut + artificial regeneration (replanting)	Production / Commercial forest	80	-	-	2425	Complete harvest after 80 years from plantation establishment (year: 2038). After that, the same number of trees as in 1958 is replanted.
Shelterwood A	Thinnings	Production / Commercial forest	-	20	10	-	2 light thinnings (years: 2017, 2027), 1 heavy thinning (seed-favoring cut) in 2038 followed by natural regeneration, harvest (removal cut) in 2048.
	Seed-favoring cut		80	80	-	5013	
	Removal cut		90	100	-	-	
Shelterwood B	Thinnings	Production / Commercial forest	-	28.5	10	-	3 light thinnings (years: 2017, 2027, 2037), 1 heavy thinning (seed-favoring cut) in 2048 followed by natural regeneration, harvest (removal cut) in 2058.
	Seed-favoring cut		90	80	-	5013	
	Removal cut		100	100	-	-	

Table 2. Simulated values of mean stand DBH and tree density (in bold) against those reported by Callegari et al. 2003 (range between low and high density plantations) and measured at the sampling plots (mean and standard deviation). The reported simulated values for 1993 (before thinning) and 1993 (after thinning) are for the years 1992 and 1993, respectively.

	1986	**1993 (before thinning)**	**1993 (after thinning)**	**1999**	**2016**
Mean stand DBH (cm)					
Simulated	**18.1**	**20.5**	**21**	**24.3**	**33.6**
Callegari et al. 2003	18 - 20.2	19.8 - 21.8	20.8 - 22.8	23.8 - 27.4	-
Plot data	-	22.2 ± 2.4	-	25.9 ± 3.7	33.7 ± 3.3
Tree density (n trees ha^{-1})					
Simulated	**1620**	**1276**	**948**	**894**	**474**
Callegari et al. 2003	1250 - 2200	1162 - 1701	800 - 1150	775 - 1102	-
Plot data	-	1491 ± 382	-	975 ± 376	522 ± 231

Table 3. Mean values (rounded to unity) of selected model outputs for six management options, three climate scenarios and three time windows. Relative changes (rounded to unity) between each option and the baseline '*no management*' scenario with CUR climate are reported in brackets. The highest and lowest values when compared to the baseline are in bold and highlighted in grey.

		Near future (2025 - 2055)				**Far future (2065 - 2095)**				**All (2006 - 2095)**			
		GPP (gC m^{-2} y^{-1})	**NPP (gC m−–2 y^{-1})**	**pCWS (tC ha^{-1})**	**BA (m^2 ha^{-1})**	**GPP (gC m^{-2} y^{-1})**	**NPP (gC m^{-2} y^{-1})**	**pCWS (tC ha^{-1})**	**BA (m^2 ha^{-1})**	**GPP (gC m^{-2} y^{-1})**	**NPP (gC m^{-2} y^{-1})**	**pCWS (tC ha^{-1})**	**BA (m^2 ha^{-1})**
No management (baseline)	CUR (baseline)	**1591**	**570**	**115**	**42**	1421	513	**141**	41	1544	551	**122**	**42**
	RCP4.5	**1639 (3)**	**553 (–2)**	**114 (-)**	**42 (-)**	1427 (1)	439 (–14)	**139 (–2)**	41 (-)	1572 (2)	511 (–7)	**120 (–1)**	**41 (-)**
	RCP8.5	**1677 (6)**	**552 (–2)**	**115 (-)**	**42 (-)**	1396 (–2)	377 (–25)	**138 (–2)**	41 (–1)	1581 (2)	491 (–10)	**120 (–1)**	**41 (-)**
Light thinning	CUR	1528 (–4)	558 (–2)	158 (37)	37 (–11)	1407 (–1)	502 (–2)	254 (79)	40 (–3)	1499 (–3)	541 (–2)	184 (47)	38 (–7)
	RCP4.5	1572 (–1)	544 (–3)	158 (37)	37 (–11)	1408 (–1)	427 (–16)	249 (76)	39 (–5)	1524 (–1)	502 (–8)	182 (46)	38 (–8)
	RCP8.5	1608 (1)	545 (–3)	158 (37)	37 (–11)	1376 (–3)	363 (–28)	247 (74)	39 (–6)	1530 (–1)	482 (–12)	181 (45)	38 (–9)
Heavy thinning	CUR	1488 (–6)	550 (–3)	167 (44)	35 (–16)	**1374 (–3)**	**490 (–4)**	**275 (94)**	**37 (–10)**	**1460 (–5)**	**532 (–4)**	**196 (56)**	36 (–13)
	RCP4.5	1533 (–4)	537 (–5)	166 (44)	35 (–16)	**1369 (–3)**	**415 (–18)**	**268 (89)**	**36 (–12)**	**1482 (–4)**	**494 (–10)**	**193 (54)**	36 (–14)
	RCP8.5	1567 (–1)	539 (–4)	167 (44)	35 (–16)	**1334 (–6)**	**353 (–30)**	**265 (87)**	**36 (–14)**	**1487 (–4)**	**474 (–14)**	**192 (53)**	35 (–15)
Patch clearcut	CUR	**1172 (–26)**	**454 (–20)**	119 (4)	**24 (–42)**	1777 (25)	588 (14)	184 (30)	42 (1)	1559 (2)	539 (–2)	141 (14)	35 (–15)
	RCP4.5	**1221 (–23)**	**450 (–20)**	119 (3)	**24 (–42)**	1855 (31)	514 (1)	180 (28)	42 (1)	1617 (6)	504 (–7)	140 (13)	35 (–15)
	RCP8.5	**1269 (–20)**	**455 (–19)**	120 (4)	**25 (–41)**	1848 (30)	444 (–12)	180 (28)	42 (-)	1639 (7)	484 (–11)	140 (14)	35 (–15)
Shelterwood A	CUR	1300 (–18)	520 (–8)	158 (37)	26 (–37)	1797 (26)	**604 (18)**	231 (63)	**42 (2)**	**1606 (5)**	**569 (4)**	177 (42)	36 (–14)
	RCP4.5	1353 (–15)	517 (–8)	157 (36)	26 (–37)	1885 (33)	**533 (5)**	228 (61)	**42 (2)**	**1670 (9)**	**536 (–1)**	175 (41)	36 (–14)
	RCP8.5	1402 (–12)	528 (–6)	159 (38)	26 (–37)	1884 (33)	**465 (–8)**	230 (63)	**42 (1)**	**1695 (11)**	**518 (–5)**	177 (42)	36 (–14)
Shelterwood B	CUR	1306 (–18)	506 (–11)	**167 (45)**	29 (–31)	**1833 (29)**	590 (15)	261 (85)	40 (–2)	1552 (1)	557 (1)	191 (53)	**34 (–19)**

	RCP4.5	1366 (–14)	505 (–10)	**168 (46)**	29 (–30)	**1932 (36)**	526 (4)	261 (84)	40 (–4)	1620 (6)	530 (–2)	191 (53)	**34 (–19)**
	RCP8.5	1396 (–12)	510 (–9)	**169 (47)**	29 (–30)	**1937 (37)**	456 (–10)	261 (85)	39 (–5)	1637 (7)	509 (–6)	192 (54)	**34 (–19)**

Figure 1

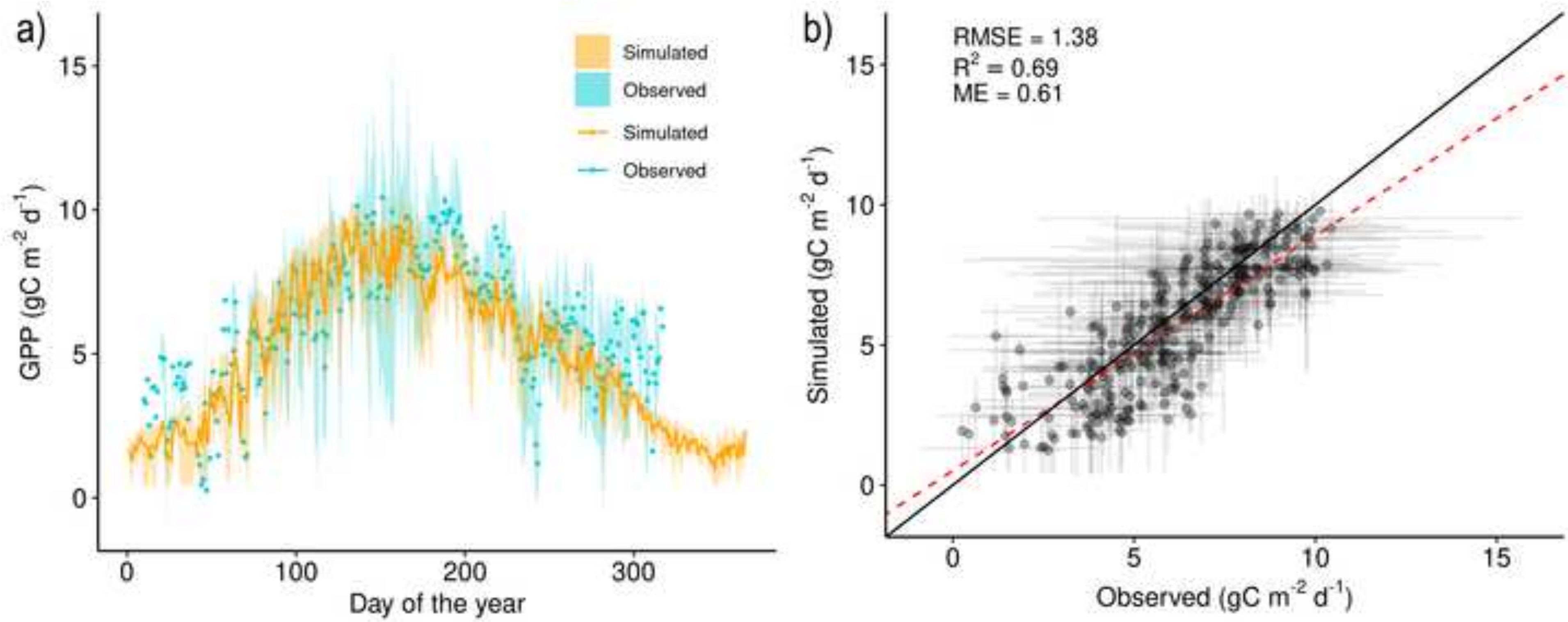
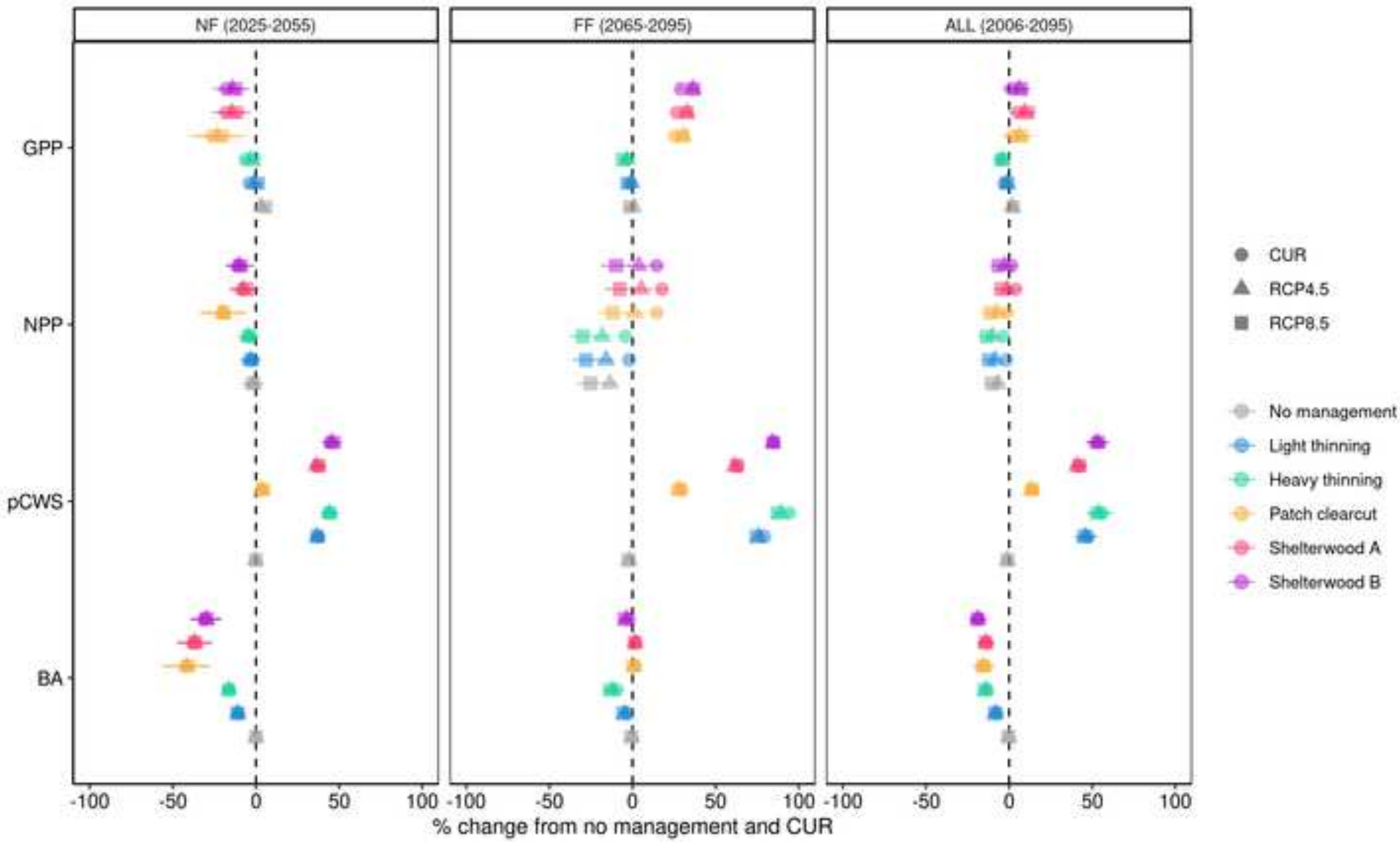
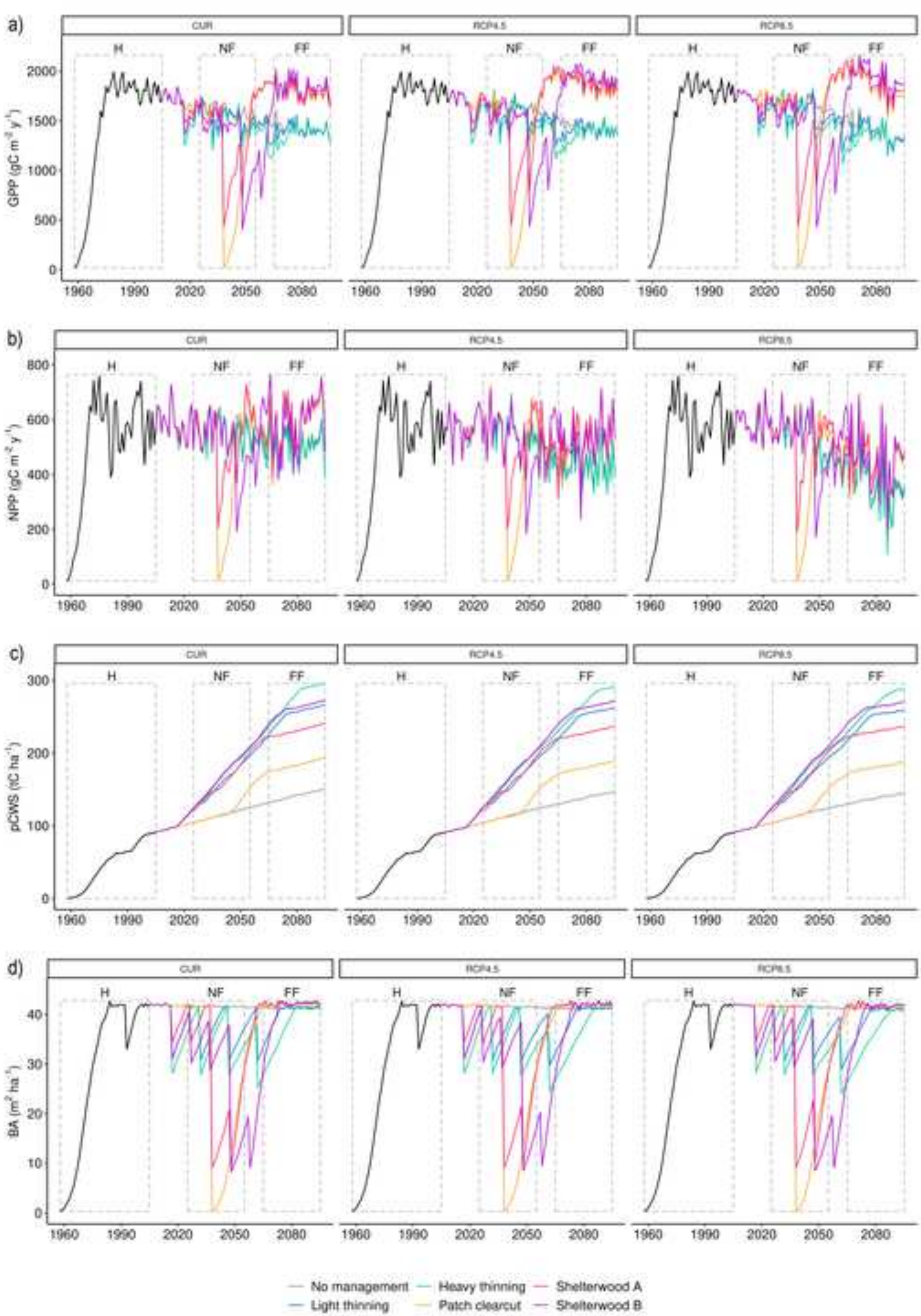

a)
Simulated
Observed
Simulated
Observed
GPP (gC m-2 d-1)
15
10
5
0
0
100
200
300
Day of the year
b)
RMSE = 1.38
R2 = 0.69
ME = 0.61
Simulated (gC m-2 d-1)
Observed (gC m-2 d-1)
15
10
5
0
0
5
10
15

Figure 2



NF (2025-2055)
FF (2065-2095)
ALL (2006-2095)
GPP
NPP
pCWS
BA
-100
-50
0
50
100
% change from no management and CUR
CUR
RCP4.5
RCP8.5
No management
Light thinning
Heavy thinning
Patch clearcut
Shelterwood A
Shelterwood B

Figure 3


a)
b)
c)
d)
CUR
RCP4.5
RCP8.5
H
NF
FF
GPP (gC m^{-2} y^{-1})
NPP (gC m^{-2} y^{-1})
pCWS (tC ha^{-1})
BA (m^2 ha^{-1})
1960
1990
2020
2050
2080
No management
Light thinning
Heavy thinning
Patch clearcut
Shelterwood A
Shelterwood B