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

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

3
4

5 **Abstract**

6 Mediterranean pine plantations provide several ecosystem services but are vulnerable to climate
7 change. Forest management might play a strategic role in the adaptation of Mediterranean forests, but
8 the joint effect of climate change and diverse management options have seldom been investigated
9 together. Here, we simulated the development of a Laricio pine (*Pinus nigra* subsp. *laricio*) stand in
10 the Bonis watershed (southern Italy) from its establishment in 1958 up to 2095 using a state-of-the-
11 science process-based forest model. The model was run under three climate scenarios corresponding
12 to increasing levels of atmospheric CO₂ concentration and warming, and six management options
13 with different goals, including wood production and renaturalization. We analysed the effect of
14 climate change on annual carbon fluxes (i.e., gross and net primary production) and stocks (i.e., basal
15 area, standing and harvested carbon woody stocks) of the autotrophic compartment, as well as the
16 impact of different management options compared to a no management baseline. Results show that
17 higher temperatures (+3 to +5 °C) and lower precipitation (−20% to −22%) will trigger a decrease in
18 net primary productivity in the second half of the century. Compared to no management, the other
19 options had a moderate effect on carbon fluxes over the whole simulation (between −14% and +11%).
20 While standing woody biomass was reduced by thinning interventions and the shelterwood system
21 (between −5% and −41%), overall carbon stocks including the harvested wood were maximized
22 (between +41% and +56%). Results highlight that management exerts greater effects on the carbon
23 budget of Laricio pine plantations than climate change alone, and that climate change and
24 management are largely independent (i.e., no strong interaction effects). Therefore, appropriate
25 silvicultural strategies might enhance potential carbon stocks and improve forest conditions, with
26 cascading positive effects on the provision of ecosystem services in Mediterranean pine plantations.

27 **Keywords**

28 Mediterranean forests; Climate change; Forest management; Process-based model; 3D-CMCC-FEM;

29 Autotrophic response; Laricio pine

30

31 **1. Introduction**

32 Temperate forests play an important role in the Earth system Carbon (C) cycle by absorbing and
33 storing a considerable amount of C in their aboveground and belowground compartments (Keith et
34 al., 2009). In Europe, Mediterranean forests account for 30% of the forest cover and represent a net
35 C-sink (FAO, 2018; Morán-Ordóñez et al., 2020). The Mediterranean basin is also a global
36 biodiversity hotspot (Myers et al., 2000; Noce et al., 2016), with its forests harbouring three times the
37 number of tree species as the rest of Europe in a fourfold smaller area (Fady-Welterlen, 2005). These
38 ecosystems play a key role in the livelihoods of local communities by providing food, timber, clean
39 water, protection against soil erosion and micro-climatic regulation (Mazza et al., 2018; Morán-
40 Ordóñez et al., 2021, 2020). At the same time, the Mediterranean basin is one of the main climate
41 change hotspots on the planet (Diffenbaugh and Giorgi, 2012; Noce et al., 2017; Tuel and Eltahir,
42 2020). Indeed, the area is warming up 20% faster than the global average, precipitations are projected
43 to decrease up to 20%, and extreme climatic events (e.g., heatwaves and droughts) are likely to
44 increase both in frequency and intensity (D'Andrea et al., 2020; Lionello and Scarascia, 2018; Santini
45 et al., 2014). These changing conditions could potentially reduce forest growth and prompt changes
46 in forest dynamics (i.e., mortality and extensive dieback episodes) that, together with other
47 disturbances, might limit the C-uptake capacity and the productivity of Mediterranean forests
48 (Gentilesca et al., 2017; Klein et al., 2019; Matteucci et al., 2013; Resco De Dios et al., 2007). By the
49 end of this century, the cumulative effect of climate and land use change in the Mediterranean basin
50 could reduce the C absorption capability of the forests' autotrophic compartment, with inevitable and
51 profound consequences on the persistence and dynamics of these ecosystems (Morales et al., 2007;
52 Nolè et al., 2013; Pausas and Millán, 2019).

53 In this context, there is a high expectation towards the sustainable management of Mediterranean
54 forests to counterbalance possible climate-change induced C-losses by preserving the sequestration
55 capability of stands (Jandl et al., 2019; Reyer et al., 2015; Ruiz-Peinado et al., 2017; Vilà-Cabrera et
56 al., 2018). Indeed, sustainable forest management practices can mitigate greenhouse gas emissions

57 and contribute to climate change adaptation, while providing long-term livelihoods for communities
58 by maintaining and enhancing ecosystem services (IPCC, 2019). This is especially critical for
59 European and, particularly, Mediterranean forests, as they have already undergone several millennia
60 of human influence which resulted in the prevalence of mixed forest stands and conifer plantations
61 (Naudts et al., 2016; Ruiz-Benito et al., 2012). Among the latter, pine plantations were mainly
62 established during the 20th century to restore overexploited land, foster soil protection, and increase
63 the production of existing forest stands, resulting in multiple forest restoration projects on a vast scale
64 (Maestre and Cortina, 2004; Pausas et al., 2004). Despite the typical fast-growing performances,
65 Mediterranean pine plantations are particularly sensitive to the adverse effect of climate change and
66 related disturbances (e.g., wildfires, drought, insect outbreaks) (González-Sanchis et al., 2015;
67 Martín-Benito et al., 2011; Navarro-Cerrillo et al., 2019; Resco De Dios et al., 2007; Ruiz-Benito et
68 al., 2012), which might be further exacerbated by the lack or the total abandonment of silvicultural
69 treatments. The latter is particularly relevant in those mountainous areas characterized by limited
70 accessibility and overall low economic revenue due to high forest exploitation costs (Lerma-Arce et
71 al., 2021; Proto et al., 2020). Therefore, management interventions in Mediterranean pine plantations
72 aimed at promoting the progressive evolution of these stands towards more diverse and species-rich
73 forests should be advanced to ensure forest functioning and the future provision of ecosystem services
74 in a changing climate (Nocentini et al., 2022).

75 Management strategies for climate change adaptation in Mediterranean forests can be mainly
76 translated into different thinning schemes – both in terms of intervention frequency and removal
77 intensities – and ultimately through adjusted rotation periods (Resco De Dios et al., 2007). These
78 adaptation measures: (i) modulate C-stocks and C-uptake capacity, (ii) increase drought-stress
79 resistance by reducing competition for water, and (iii) reduce losses of C use efficiency (net vs. gross
80 primary production) by contrasting the aging of Mediterranean forests in the short-term, compared to
81 the absence of management (del Río et al., 2017; González-Sanchis et al., 2015; Navarro-Cerrillo et
82 al., 2019; Vilà-Cabrera et al., 2018). Despite the potential benefits of silvicultural practices aimed at

83 enhancing the resilience of Mediterranean forests to future climate change impacts, the effects of
84 diverse management alternatives on the long-term forest adaptation have been seldom investigated
85 (Manrique-Alba et al., 2020; Vilà-Cabrera et al., 2018), with most existing studies carried out in
86 central and northern Europe (Collalti et al., 2018; Dalmonech et al., 2022; Duveneck et al., 2014).

87 Process-based forest models provide a fundamental experimental framework to track the future
88 responses of forest ecosystems to management strategies under a changing climate (Gupta and
89 Sharma, 2019; Keenan et al., 2011; Maréchaux et al., 2021; Reyer et al., 2015; Ruiz-Benito et al.,
90 2020). Such models incorporate both empirical and mechanistic relations of the main
91 ecophysiological processes which drive the response of forest stand development over decadal time
92 periods (Gupta and Sharma, 2019; Keenan et al., 2011; Mäkelä et al., 2000) and can therefore help
93 quantify the impacts of climate change and management on forest fluxes and stocks under changing
94 environmental conditions. In an integrated scenario-analysis framework, process-based forest models
95 can inform both the scientific and policy-making communities of the forestry sector, thus supporting
96 adaptation and mitigation strategies in the Mediterranean basin (Keenan et al., 2011; Morán-Ordóñez
97 et al., 2020; Vilà-Cabrera et al., 2018). Yet, simulation studies aimed at assessing the crossed effect
98 of climate change and of diverse management options on forest biomass and productivity have been
99 mostly carried out outside the Mediterranean basin and are limited in the number of simulated climate
100 scenarios (e.g., Borys et al., 2016; Fürstenau et al., 2007; Garcia-Gonzalo et al., 2007; Jönsson et al.,
101 2015; Lexer et al., 2008; Shanin et al., 2011) and management options (e.g., Pussinen et al., 2009;
102 Schelhaas et al., 2015).

103 By means of a state-of-the-science process-based forest model (3D-CMCC-FEM; Three Dimensional
104 - Coupled Model Carbon Cycle - Forest Ecosystem Model) we simulated the development of a Laricio
105 pine stand in the Bonis experimental watershed (southern Italy) with the aim of providing insights on
106 future management strategies for Mediterranean pine plantations. We designed a wide portfolio of
107 forest management options based on different schemes which are currently applied in the study area
108 and tested their effects on the development of forest carbon stocks and fluxes under different climate

109 scenarios. Thus, we assessed the relative impact of climate change and different silvicultural practices
110 on the autotrophic response of one of the southernmost European pine plantations up to the end of
111 the 21st century.

112

113 **2. Materials and methods**

114 **2.1. Study area and stand data collection**

115 The Bonis experimental watershed is located in the mountain area of Sila Greca (39°28'49'' N,
116 16°32'07'' E; from 975 to 1330 m a.s.l.) in the Calabria region, southern Italy, and represents one of
117 the southernmost long-term experimental forest research sites in Europe. The catchment has a surface
118 of 1.39 km², a mean elevation of 1131 m a.s.l. and was firstly instrumented for hydrological
119 monitoring in 1986. Almost 93% of the total area is covered by forests, dominated by ~60 years old
120 Laricio pine stands, whose origin is mainly artificial (Callegari et al., 2003; Caloiero et al., 2017).
121 The stands were planted in 1958 with an average density of 2425 saplings ha⁻¹ (Nicolaci et al., 2015)
122 and underwent a thinning treatment in 1993 with a basal area (BA) removal of 25% (Callegari et al.,
123 2003). The climate is typically Mediterranean, with average annual precipitation of 915 mm and
124 average temperature of 12.2 °C. The geological substrate is mainly composed of acid plutonic rocks
125 and gravelly sands (Callegari et al., 2003). To study forest structure and development, 14 circular 12
126 m-radius plots were established in 1993 before the thinning interventions. In each plot, for all trees
127 with diameter at breast height (DBH; 1.3 m) > 2.5 cm, total height, crown insertion height and vitality
128 were recorded (Collalti et al., 2017). The plots were resurveyed in 1999 and 2016. As part of the
129 Euroflux-Carboitaly network, a tower for the measurement of eddy fluxes was installed in 2003 in
130 one of the Laricio pine plantation stands within the study area (39°28'40'' N, 16°32'05'' E; Marino
131 et al., 2005). The tower was regularly operated between 2005 and 2009. The plot data have been used
132 to parameterize and, together with the eddy fluxes data, to validate the model.

133 **2.2. Vegetation model and species parameterization**

134 The 3D-CMCC-FEM forest model (v.5.6 BGC) is a biogeochemical, biophysical, and physiological
135 process-based forest model developed to predict C, energy, and water fluxes coupled with stand
136 development processes that determine relative stock changes in forest ecosystems (Collalti et al.,
137 2019; Dalmonech et al., 2022). The model is designed to simulate the main physiological and
138 hydrological processes at daily, monthly, and annual scales and at the species-specific level. The
139 model requires data on initial forest stand conditions including species composition, average tree
140 DBH, height, stand age and tree density (number of trees per hectare). Both structural and non-
141 structural tree C-pools are initialized at the beginning of the simulation and updated daily, monthly,
142 or annually, depending on the processes. Furthermore, the model allows the simulation of different
143 management scenarios by defining the intensity and the interval of removals, as well as the length of
144 rotation periods and artificial replanting schemes, which can be varied through the simulation time.
145 For a full description of key model principles and theoretical framework see also Collalti et al. (2020a,
146 2019, 2018, 2016, 2014), Dalmonech et al. (2022), Engel et al. (2021), and Marconi et al. (2017).

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

156 **2.3. Climate and atmospheric CO₂ data**

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

163 To simulate the development of the Laricio pine stand up to the end of the 21st century, we employed
164 a set of climate data covering the 1976 - 2095 period at 0.0715° spatial resolution (~ 8 km)
165 (Bucchignani et al., 2016; Zollo et al., 2016). This highly resolved climate data are based on the
166 regional climate model COSMO-CLM (Rockel et al., 2008) driven by the CMCC-CM global model
167 (Scoccimarro et al., 2011) using the 20C3M forcing (i.e., observed emissions) for the period 1976 -
168 2005, and two IPCC emission scenarios from 2006 onwards: the intermediate emission scenario
169 RCP4.5 and the high emission scenario RCP8.5 (Moss et al., 2010; van Vuuren et al., 2011). The
170 RCP4.5 scenario assumes that the total radiative forcing is stabilized, shortly after 2100, to 4.5 Wm^{-}
171 2 (approximately 650 ppmv CO₂-equivalent) by employing various technologies and strategies to
172 reduce greenhouse gas emissions. The RCP8.5 is characterized by increasing emissions and high
173 greenhouse gas concentration levels, leading to 8.5 Wm^{-2} in 2100 (approximately 1370 ppmv CO₂-
174 equivalent). Modeled temperature and precipitation data were bias-corrected following the approach
175 adopted and described in Sperna Weiland et al. (2010), starting from the observed series of the same
176 variables. As an observational dataset for the bias correction the downscaled daily E-OBS dataset (v
177 10.0) at 1 km resolution (Maselli et al., 2012) was used. Additionally, we simulated a current climate
178 (CUR) dataset as a benchmark scenario for the period 2006 - 2095 by randomly sampling each day
179 in sequence from the bias-corrected COSMO-CLM dataset between 1990 and 2005. As the COSMO-
180 CLM data were only available starting from 1976, we used the MT-CLIM climatic dataset described
181 above for the 1958 - 1975 period.

182 Measured values of global annual atmospheric CO₂ concentration (ppmv) were derived from
183 Meinshausen et al. (2011), while values consistent to the abovementioned emission scenarios were
184 provided by Dlugokencky and Tans (2014). The atmospheric CO₂ concentrations for the CUR
185 scenario were simulated by randomly sampling each year in sequence between 1990 and 2005 from
186 Meinshausen et al. (2011).

187 To assess the departure of projected climate change from the baseline CUR scenario, we calculated
188 the mean relative change in temperature, precipitation, vapor pressure deficit and atmospheric CO₂
189 concentration for the two RCP scenarios within two different time windows: near future (NF; 2025 -
190 2055) and far future (FF; 2065 - 2095). Confidence intervals (95%) were estimated as ± 1.96 times
191 the standard error.

192 **2.4. Model evaluation**

193 Model performances were evaluated by simulating the development of a representative Laricio pine
194 stand in the Bonis watershed from its establishment in 1958 to the last field measurements occurred
195 in 2016, which includes the thinning in 1993. The model was initialized in 1958 with an initial density
196 of 2425 saplings per hectare (DBH: 1 cm, height: 1.3 m, age: 4 years; Nicolaci et al., 2015),
197 considering the average elevation of the watershed (1131 m a.s.l.), the average soil texture (clay:
198 20%; silt: 26%; sand: 54%) and depth (100 cm) (Buttafuoco et al., 2005; Moresi et al., 2020). The
199 evaluation was carried out by comparing the resulting simulated mean annual DBH and tree density
200 to the values measured at the field plots in 1993 (before thinning), 1999 and 2016, as well as to the
201 estimations provided by Callegari et al. (2003) for low and high density Laricio pine plantations in
202 the Bonis watershed for 1986, 1993 (before and after thinning) and 1999. Additionally, a
203 micrometeorological validation of daily gross primary productivity (GPP) was carried out by
204 comparing the simulated values to those obtained by the eddy covariance tower. As described in
205 Collalti et al. (2018), we excluded years with major gaps (i.e., 2009), as well as all days with a quality
206 control flag of eddy data lower than 0.6. The comparisons were carried out for each year, as well as

207 for the daily averages, by calculating root mean squared error (RMSE), coefficient of determination
208 (R^2) and modelling efficiency (ME). The latter index provides information about modelling
209 performance on a relative scale: ME = 1 indicates a perfect fit, ME = 0 reveals that the model is no
210 better than a simple average, while negative values indicate poor performance (Bagnara et al., 2015;
211 Vanclay and Skovsgaard, 1997).

212 **2.5. Forest management scenarios**

213 For each of the three climate scenarios (i.e., CUR, RCP4.5, RCP8.5) we simulated forest management
214 by mimicking six different silvicultural options reflecting different goals (Table 1), resulting in a total
215 of 18 different model runs. All the options were simulated to take place after 2016, i.e., the last year
216 of field measurements. The scenarios cover several management objectives including both wood
217 production and renaturalization and reflect the state-of-the-science of management options applied to
218 this region of the Italian Apennines (Cantiani et al., 2018). The first option (*'no management'*)
219 represents the natural development of the forest left without human intervention. Such option also
220 mimics land abandonment, that represents a relatively widespread occurrence in Mediterranean
221 mountains. Two options simulating different thinning intensities – *'light'* and *'heavy'*, corresponding
222 to a 28% and 35.5% reduction of BA, respectively – at an interval of 15 years are proposed in order
223 to reproduce silvicultural interventions aimed at favouring natural forest dynamics. Indeed, at
224 intermediate stages of stand development, pine forests can benefit from thinnings aimed specifically
225 at improving their degree of stability (Cantiani et al., 2005; Cantiani and Piovosi, 2008). Selective
226 thinnings also favor structural diversity, and reduce inter-tree competition for water, light, and
227 nutrients (del Río et al., 2017; Marchi et al., 2018). However, tending and thinning interventions still
228 represent a major passive management item in terms of net costs and are often avoided in public
229 forests resulting in a progressive degeneration of stand structure (Ahtikoski et al., 2021; Niskanen
230 and Väyrynen, 2001). An additional, production-oriented option (*'patch clearcut'*) simulating a
231 complete harvest followed by replanting 80 years after the establishment of the plantation is also
232 included. Nevertheless, the shelterwood system represents a more sustainable alternative to clear-

233 cutting and patch cuttings by ensuring continuous forest cover and an adequate light availability to
234 the forest floor and protection from soil erosion. The practice favours regeneration while modulating
235 the competition for light and water resources with herbs and shrubs, and allows higher revenues
236 (Brichta et al., 2020; Cantiani et al., 2018; Montoro Girona et al., 2018). Therefore, we simulated two
237 shelterwood options: '*shelterwood A*', consisting of two light thinnings (20% reduction of BA) with
238 a 10 year interval, followed by a seed-favouring cut after 80 years from the original planting (80%
239 reduction of BA) and a removal cut 10 years later; '*shelterwood B*', defined by a delayed seed-
240 favouring cut after 90 years, preceded by three heavier thinnings (28.5% reduction of BA) and
241 followed by a removal cut after 10 years. In both cases, the seed-favouring cut is followed by natural
242 regeneration of the same species. The regeneration is simulated as a prescribed replanting, with
243 density of saplings derived from the estimated tree density of natural Laricio pine stands in 1986 (see
244 Callegari et al., 2003) by going backwards to 1958 and assuming a 1% annual mortality rate (Andrus
245 et al., 2021).

246 **2.6. Analysis of simulation outputs**

247 To assess the response of the autotrophic component of the stand to climate change and management,
248 we considered the tree biomass compartment, whose C-stocks and fluxes are the most affected by
249 forest management due to a modulation of stand density as a consequence of thinning and harvesting
250 (D'Amato et al., 2011). Specifically, we evaluated the temporal trends of stand-level GPP, net
251 primary productivity (NPP), potential C-woody stocks (pCWS; i.e., the sum of standing woody
252 biomass and harvested woody stocks, assuming no decay) and BA. We chose these variables among
253 all model outputs as they are key components of the forest C-budget and forest structure, representing
254 the physiologically and structurally inherent capacity of trees to sequester and stock atmospheric CO₂
255 on the short- (i.e., GPP and NPP) to long-term (i.e., pCWS and BA). At the same time, these outputs
256 are key variables relevant to decision makers to assess stand growth changes and current standing
257 biomass, as well as to make appropriate management decisions. Notably, we considered pCWS as
258 potential values representative of the maximum attainable C-stock capacity (i.e., the yield in woody

259 biomass and timber), to quantify the inherent capability of trees to sequester and store C over medium-
260 to long-time periods. Temporal trends of standing woody biomass and harvested woody stocks were
261 also presented separately to facilitate the interpretation of pCWS. Likewise, trends of autotrophic
262 respiration and biomass production (i.e., the fraction of NPP that is used for the biomass increment
263 only; Collalti et al., 2020b) were evaluated to assess the relationship between productivity and C-
264 stocks.

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

271

272 **3. Results**

273 **3.1. Model evaluation**

274 The simulated mean stand DBH of Laricio pine plantations in the Bonis watershed was 18.1 cm in
275 1986, 20.5 cm in 1993 before the thinning, 21 cm in 1993 after the thinning, and 24.3 cm in 1999. In
276 the same years, Callegari et al. (2003) reported a mean stand DBH range of 18 - 20.2 cm, 19.8 - 21.8
277 cm, 20.8 - 22.8 cm and 23.8 - 27.4 cm, respectively, for high- and low-density plantations. At the
278 forest plots, a mean stand DBH of 22.2 ± 2.4 cm was estimated in 1993 before the thinning, which
279 increased to 25.9 ± 3.7 cm in 1999 and to 33.7 ± 3.3 cm in 2016. The simulated value for in 2016,
280 was 33.6 cm (Table 2; Figure S1). As for tree density, the model simulated 1620 trees ha⁻¹ in 1986,
281 1276 trees ha⁻¹ in 1993 before the thinning, 948 trees ha⁻¹ in 1993 after the thinning, 894 trees ha⁻¹
282 in 1999 and 474 trees ha⁻¹ in 2016. The values measured at the forest plots were 1491 ± 382 trees ha⁻¹
283 ¹, 975 ± 376 trees ha⁻¹ and 522 ± 231 trees ha⁻¹ in 1993 before the thinning, 1999 and 2016,

284 respectively. Similarly, Callegari et al. (2003) reported a range of 1250 - 2200 trees ha⁻¹, 1162 - 1701
285 trees ha⁻¹, 800 - 1150 trees ha⁻¹ and 775 - 1102 trees ha⁻¹ in 1986, 1993 before thinning, 1993 after
286 thinning and 1999, respectively (Table 2; Figure S1).

287 Goodness-of-fit metrics of the four-year average trend of simulated daily GPP against values derived
288 by the eddy covariance tower were RMSE = 1.38 gC m⁻² d⁻¹, R² = 0.69 and ME = 0.6 (Figure 1 a,b).
289 As for the daily GPP of each year, the model reproduced the annual trends, albeit with different
290 accuracy (Figure S2).

291 **3.2. Climate scenarios**

292 On average, atmospheric CO₂ concentration will increase to 461 - 494 ppmv in NF and to 530 - 761
293 ppmv in FF, according to the RCP4.5 and RCP8.5 scenarios, respectively. At the same time, mean
294 temperatures at the Bonis watershed under the RCP4.5 scenario are projected to increase by 1.2 °C
295 (9%) in NF and 3 °C (23%) in FF, compared to CUR. According to the RCP8.5 scenario, the increase
296 will be by 1.8 °C (14%) and 5 °C (39%). Vapor pressure deficit will also increase by 13% in NF and
297 31% in FF under the RCP4.5 scenario compared to CUR, while the increase will be by 18% and 59%
298 under the RCP8.5 scenario. No significant change in precipitation is predicted in NF for both
299 scenarios, while a reduction of 20% and 22% is predicted in FF, respectively for the RCP4.5 and
300 RCP8.5 scenarios, compared to CUR (Table S2; Figure S3).

301 **3.3. Crossed effects of climate change and management**

302 Within the NF period, the '*no management*' option showed the highest values for GPP (1591 - 1677
303 gC m⁻² y⁻¹), NPP (570 - 552 gC m⁻² y⁻¹), and BA (42 m² ha⁻¹) under all climate scenarios, while the
304 '*patch clearcut*' option showed the lowest values of the same variables (GPP: 1172 - 1269 gC m⁻² y⁻¹
305 ¹, NPP: 450 - 455 gC m⁻² y⁻¹, BA: 24 - 25 m² ha⁻¹). As for pCWS, the highest values were for the
306 '*shelterwood B*' option (167 - 169 tC ha⁻¹), while '*no management*' exhibited the lowest (114 - 115
307 tC ha⁻¹). The '*shelterwood A*', '*shelterwood B*' and '*patch clearcut*' options showed a similar
308 decrease in GPP (between -12% and -26%) and BA (between -30% and -42%) compared to '*no*

309 *management*' under CUR climate, while the *'light*' and *'heavy thinning*' options presented a more
310 limited decrease (between -1% and -6% for GPP; between -11% and -16% for BA). As for NPP,
311 the decrease was negligible for *'light*' and *'heavy thinning*' (between -2% and -5%); *'shelterwood*
312 *A*' and *'shelterwood B*' exhibited intermediate values between -6% and -11% of NPP while the
313 *'patch clearcut*' presented the greatest decrease (between -19% and -20%) compared to *'no*
314 *management*' under CUR climate. Increases in pCWS were between 37% and 47% for thinning and
315 shelterwood options, while the *'patch clearcut*' option exhibited a 3% to 4% increase compared to
316 *'no management*' under CUR climate. No large differences in the output variables were observed
317 among different climate scenarios across all management options (Table 3; Figure 2 and 3).

318 As for the FF time window, mean GPP was the highest under the *'shelterwood B*' option (1833 - 1937
319 $\text{gC m}^{-2} \text{y}^{-1}$), while mean NPP was the highest under the *'shelterwood A*' option (465 - 604 $\text{gC m}^{-2} \text{y}^{-1}$)
320 1). Mean pCWS was maximized with *'heavy thinning*' (265 - 275 tC ha^{-1}), while the highest simulated
321 BA was found under the *'shelterwood A*' option (42 $\text{m}^2 \text{ha}^{-1}$). The *'heavy thinning*' option led to the
322 lowest mean values for GPP (1334 - 1374 $\text{gC m}^{-2} \text{y}^{-1}$), NPP (353 - 490 $\text{gC m}^{-2} \text{y}^{-1}$) and BA (36 - 37
323 $\text{m}^2 \text{ha}^{-1}$), while the lowest mean values for pCWS were found under the *'no management*' simulation
324 (138 - 141 tC ha^{-1}) (Table 3; Figure 2 and 3). Overall, *'patch clearcut*', *'shelterwood A*' and
325 *'shelterwood B*' options exhibited a similar change in GPP (between 25% and 37%) with very limited
326 effect on BA (between -3% and 1%), compared to *'no management*' under CUR climate. Conversely,
327 *'light*' and *'heavy thinning*' showed a slight decrease both in GPP (between -1% and -6%) and BA
328 (-3% and -14%). pCWS increased between 61% and 94% under the thinning and shelterwood options
329 and showed a 28% - 30% increase with *'patch clearcut*'. Even in the FF time window, no large
330 differences in GPP, pCWS and BA emerged among different climate scenarios across the different
331 management options. On the contrary, NPP was more strongly affected by climate change: it
332 decreased by 14% and 25% under the RCP4.5 and RCP8.5 scenarios in the *'no management*' option
333 compared to the baseline under CUR climate. As for the *'patch clearcut*', *'shelterwood A*' and
334 *'shelterwood B*' options NPP showed to increase between 1 and 18% under the CUR and RCP4.5

335 scenarios, and a to decrease under the RCP8.5 scenario (between -8% and -12%), compared to ‘*no*
336 *management*’ under CUR climate. As for the ‘*light*’ and ‘*heavy thinning*’ options, NPP decreased
337 between 2% and 4% under CUR climate, 16% and 18% under RCP4.5, and between 28% and 30%
338 under the RCP8.5 scenario, compared ‘*no management*’ under CUR climate (Table 3; Figure 2 and
339 3).

340 Between 2006 and 2095, GPP was maximized under the ‘*patch clearcut*’, ‘*shelterwood A*’ and
341 ‘*shelterwood B*’ options ($1552 - 1695 \text{ gC m}^{-2} \text{ y}^{-1}$), corresponding to a 1% to 11% increase compared
342 to ‘*no management*’ under CUR climate ($1544 \text{ gC m}^{-2} \text{ y}^{-1}$), while the thinning options showed the
343 lowest values ($1460 - 1530 \text{ gC m}^{-2} \text{ y}^{-1}$) and a decrease between 1% and 5% . NPP showed a similar
344 trend, with the ‘*shelterwood A*’ and ‘*shelterwood B*’ options exhibiting the highest values ($509 - 569$
345 $\text{gC m}^{-2} \text{ y}^{-1}$), corresponding to a change between -6% and 4% , compared to ‘*no management*’ under
346 CUR climate ($551 \text{ gC m}^{-2} \text{ y}^{-1}$). The ‘*patch clearcut*’, ‘*light thinning*’ and ‘*heavy thinning*’ simulations
347 had lower NPP ($474 - 541 \text{ gC m}^{-2} \text{ y}^{-1}$) than ‘*no management*’ ($491 - 551 \text{ gC m}^{-2} \text{ y}^{-1}$) for the same
348 climate scenarios, corresponding to a $2\% - 14\%$ decrease compared to the value obtained under CUR
349 climate (Table 3; Figure 2 and 3). The same pattern was observed for biomass production – ranging
350 between $502 - 557 \text{ gC m}^{-2} \text{ y}^{-1}$ with the shelterwood options and between $467 - 529 \text{ gC m}^{-2} \text{ y}^{-1}$ with
351 the other active management options – and autotrophic respiration, which was maximized under the
352 ‘*patch clearcut*’, ‘*shelterwood A*’ and ‘*shelterwood B*’ options ($996 - 1177 \text{ gC m}^{-2} \text{ y}^{-1}$) and minimized
353 under the thinning options ($928 - 1048 \text{ gC m}^{-2} \text{ y}^{-1}$) (Table S4; Figure S4 and S5). All management
354 options showed lower BA values ($34 - 38 \text{ m}^2 \text{ ha}^{-1}$) compared to ‘*no management*’, corresponding to
355 a relative change between -7% and -8% (‘*light thinning*’), and -19% (‘*shelterwood B*’). As for
356 pCWS, all options led to greater values than ‘*no management*’ ($121 - 122 \text{ tC ha}^{-1}$), with the thinning
357 and shelterwood options showing similar values ($181 - 196 \text{ tC ha}^{-1}$), corresponding to a 45% to 56%
358 increase (Table 3; Figure 2 and 3). The increase in pCWS under all active management options was
359 explained by the larger harvested woody stocks (between 377% and 710%) compared to the ‘*no*

360 *management*' option, while standing woody biomass decreased between -5% (*'light thinning*') and -
361 41% (*'shelterwood A*') (Table S5; Figure S6 and S7).

362 **4. Discussion**

363 **4.1. Model evaluation**

364 The 3D-CMCC-FEM reproduced well the development of a Laricio pine stand in the Bonis watershed
365 over a 58-year span. Our evaluation of stand attributes showed that, starting from the establishment
366 of the plantation in 1958, the simulated mean stand DBH and tree density fell within the measured
367 range of two independent datasets: average values for low and high density Laricio pine plantations
368 in the area between 1986 and 1999 (Callegari et al.; 2003), and the forest plots surveyed between
369 1993 and 2016. The model was also able to simulate historical management activities and their effects
370 on forest development. Indeed, the simulation included a thinning of 25% of stand BA that took place
371 in 1993, which was reflected by the reduction in tree density in that year and a slight increase in the
372 growth rate of mean stand DBH in the following years (0.6 cm y⁻¹ after the thinning vs. 0.3 cm y⁻¹
373 before the thinning).

374 Furthermore, the model was able to reproduce the mean seasonal cycle of daily GPP as obtained by
375 the eddy covariance tower with sufficient accuracy, supporting previous assessments of model
376 performance (Collalti et al., 2014, 2016, 2018, 2020a; Dalmonech et al., 2022; Engel et al., 2021;
377 Mahnken et al., 2022; Marconi et al., 2017). The R² of 0.69 is in line with previous evaluations of
378 simulated daily GPP across northern European forest sites (average R² across three sites = 0.73;
379 Collalti et al., 2018), while the ME of 0.61 is within the range found for daily GPP simulated with
380 other process-based models (0.42 - 0.84 in Bagnara et al., 2015; 0.61 - 0.98 in Minunno et al., 2016).

381 **4.2. Impacts of climate change**

382 In the first half of the 21st century, both RCPs projected similar increments in mean annual
383 temperature and vapor pressure deficit with no significant changes in the amount of precipitation for
384 the Bonis watershed. However, these trends had little effect on the considered forest variables within

385 the NF time window. Conversely, in the second half of the 21st century, a reduction in precipitation
386 and an increase in temperature – in line with previous estimates for the Mediterranean basin (see
387 Lionello and Scarascia, 2018; Santini et al., 2014) – were probably responsible for the observed
388 decrease in NPP across all management options. The changes were more pronounced under the most
389 emission-intensive scenario and toward the end of the century, negatively affecting the ability of
390 Laricio pine stands to absorb and to store C. Indeed, the decline in water availability is likely
391 responsible for an increased water stress, which could offset the positive effects of higher atmospheric
392 CO₂ concentrations and the lengthening of the growing season (Cinnirella et al., 2002), while higher
393 temperatures favour autotrophic respiration and photorespiration (Dusenge et al., 2019; Gea-
394 Izquierdo et al., 2017; Lindner et al., 2010), leading to a reduction in biomass production because of
395 increased allocation to non-structural carbon pools (Collalti et al., 2020b). Yet, the observed climate
396 change-driven decreases in C-fluxes were only marginally mirrored by lower C-stocks at higher
397 atmospheric CO₂ concentrations. This is likely due to a temporal lag induced by a smaller magnitude
398 of the fluxes compared to the stocks, with changes of the latter observable only over longer simulation
399 timeframes.

400 Previous studies already highlighted the negative effect of high temperature and soil moisture scarcity
401 on leaf development and tree growth for forests in general and, more in particular, for Laricio pines,
402 although the emergence of pervasive acclimation mechanisms (e.g., changes in C-allocation for
403 reserve accumulation) in this species could reduce forest vulnerability to extreme events, thus
404 preventing extensive dieback episodes (Cinnirella et al., 2002; Mazza et al., 2018). Nonetheless,
405 indirect effects of climate change, including increased vulnerability of trees to pathogen attacks, could
406 lead to higher mortality rates irrespective of physiological adaptations (Gentilesca et al., 2017; Resco
407 De Dios et al., 2007). Recent studies have shown the ambiguity in the responses of forests to both
408 warming and enriched atmospheric CO₂ concentration (Rezaie et al., 2018), probably related to site-
409 specific factors (e.g. forest age, forest structure, soil nutrient availability and microclimate). While
410 Central and Northern Europe seem to show a general increase in both C-sequestration and C-stocks

411 in the short- to medium-term (Reyer et al., 2015), the impact of increasing droughts and disturbance
412 risk will likely outweigh any positive trends in Southern Europe induced by CO₂-fertilization, with
413 an expected decline in the productivity of the Mediterranean region (Lindner et al., 2010; Reyer et
414 al., 2014; Simioni et al., 2020). In this respect, the Bonis watershed represents a unique experimental
415 site with mountain climate at the center of the Mediterranean basin. These features make it
416 particularly exposed to the effects of climate change, hence its likely role as sentinel of future changes
417 in forest dynamics for the whole region.

418 **4.3. Impacts of forest management**

419 Regardless of the short- to long-term changes in productivity, the effect of management on forest
420 attributes largely outplays that of climate change, in line with previous findings for Mediterranean
421 pine forests (del Río et al., 2017) and other European forests (e.g., Akujärvi et al., 2019; Gutsch et
422 al., 2018). Therefore, the choice of far-sighted management options is key to the future of pine
423 plantations, particularly in the case of Laricio pine stands in the Bonis watershed, with the aim of
424 preserving and enhancing primary production and carbon storage capacity over time, improving
425 forests resilience to biotic and abiotic stresses, as well as promoting their structural complexity and
426 the multiple ecosystem functions (Scarascia-Mugnozza et al., 2000). The present study aimed at
427 reducing the knowledge gap about the potential benefits of diverse forest management options for
428 Mediterranean pine plantations under climate change and, to our knowledge, provides the most
429 complete overview on the subject to date. Assessing the crossed effects of forest management and
430 climate in these environments is of paramount importance for areas close to the geographical limit of
431 the distribution of pine species like the Bonis watershed (Navarro-Cerrillo et al., 2019), as well as for
432 the whole European continent given the ubiquity of conifer plantations (Naudts et al., 2016).
433 Our simulations showed that, in the first half of the 21st century, the lack of management interventions
434 led to higher C-fluxes (i.e., GPP and NPP) and BA, as opposed to production-oriented management
435 strategies involving clear-cutting or the shelterwood system, which abruptly slowed down C-fluxes
436 because of the strong reduction in leaf area and in situ standing biomass. Yet, such commercial, forest-

437 oriented options showed to maximize C-fluxes in the second half of the 21st century as a response to
438 regeneration or replanting. Despite these fluctuations, the overall effect on C-fluxes of different
439 management options under different climate scenarios over the 2006 - 2095 period was modest, with
440 a relative change range between -14% and +11% compared to 'no management' under the CUR
441 climate scenario. These results might allude that either forest management is counterbalancing the
442 effects of warming and increasing atmospheric CO₂ concentration, or that the Laricio pine has already
443 reached its suitability optimum for this particular geographic area.

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

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

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

481 **4.4. Assumptions and caveats**

482 The 3D-CMCC-FEM allowed to simulate several management options for Laricio pine plantations at
483 Bonis watershed under different climate scenarios considering biogeochemical, biophysical,
484 physiological and stand development processes. In the present study, we considered only the
485 autotrophic response to climate change and management, namely those primary stand attributes
486 related to C-fluxes and C-stocks of the standing and harvested biomass. Despite we acknowledge the
487 non-negligible contribution of other compartments like soil (Navarrete-poyatos et al., 2019) and
488 deadwood (del Río et al., 2017) our aim was to provide an indication of the joint effect of climate

489 change and management on the main C inputs and stocks of a Mediterranean pine plantation, which
490 are the most affected by silvicultural activities (D'Amato et al., 2011) and the main target of
491 management planning. In addition, the model is most suitable for medium-term simulations, as it
492 currently does not incorporate complex regeneration and mortality-related dynamics, which are
493 known to likely exert a greater effect than climate on C-stocks and might play an important role in
494 post-disturbance recovery and resilience especially in the Mediterranean environments (Oberpriller
495 et al., 2022). Thus, further studies including other ecosystem compartments and dynamics are
496 required to obtain a complete picture of the overall C-balance in Mediterranean forests and project its
497 changes under future climate.

498 In our approach, we did not consider the decay of the harvested woody biomass, as the main focus of
499 the present study was to quantify the maximum potential capacity of trees to sequester C in woody
500 tissues and, in turn, to provide products under the proposed robust modelling approach and portfolio
501 of interventions. A life-cycle assessment with the quantification of the overall climate change
502 mitigation contribution of the forestry sector would require the definition of context-specific
503 scenarios of final use and displacement of harvested wood (e.g., Valade et al., 2017), as well as the
504 full greenhouse gas budget. The analysis would however be highly influenced by the wood market,
505 as well as the energy and manufacturing-construction sectors (Howard et al., 2021; Leskinen et al.,
506 2018), potentially adding high uncertainty to the modelling outcome.

507 Furthermore, the current model version is not set to simulate some forest disturbances that are likely
508 to impact our study area like recurrent wildfires and pest outbreaks. However, simulating such events
509 was beyond the scope of the present study as they are better represented under simulations conducted
510 at the landscape scale. We also recognize that more management options than the ones we simulated
511 are available. Yet, our scenarios cover several objectives including biodiversity enhancement, wood
512 production and re-naturalization and reflect the state-of-the-practice of management portfolios
513 applied to this region of the Italian Apennines (Cantiani et al., 2018). Moreover, the model currently
514 does not account for the effect of soil nutrients on tree growth, site conditions being equal in all

515 simulations. Yet, nutrient availability is generally considered a secondary driver of tree growth in
516 Laricio pine forests, which are usually mainly limited by soil moisture (Mazza et al., 2018). Indeed,
517 Laricio pines and other *Pinus nigra* subspecies were widely employed in large-scale afforestation
518 projects in the Italian Apennines for their pioneer species features, being able to thrive on depleted
519 and overexploited soils (Cantiani et al., 2018). We acknowledge, however, that this low sensitivity of
520 tree growth to soil nutrients is specific to this study and should be reconsidered when performing
521 simulations on other forest ecosystems. Finally, the simulations did not include species replacement
522 due to competition and colonization. However, the forests at the Bonis watershed are dominated by
523 Laricio pines, both natural and artificial, which are likely to recolonize gaps in the absence of
524 proactive replanting of other tree species.

525

526 **5. Conclusions**

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

540

541 **Figure captions**

542

543

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

549

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

555

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

561

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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
<i>Mean stand DBH (cm)</i>					
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
<i>Tree density (n trees ha⁻¹)</i>					
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 ($\text{gC m}^{-2}\text{y}^{-1}$)	NPP ($\text{gC m}^{-2}\text{y}^{-1}$)	pCWS (tC ha^{-1})	BA ($\text{m}^2 \text{ha}^{-1}$)	GPP ($\text{gC m}^{-2}\text{y}^{-1}$)	NPP ($\text{gC m}^{-2}\text{y}^{-1}$)	pCWS (tC ha^{-1})	BA ($\text{m}^2 \text{ha}^{-1}$)	GPP ($\text{gC m}^{-2}\text{y}^{-1}$)	NPP ($\text{gC m}^{-2}\text{y}^{-1}$)	pCWS (tC ha^{-1})	BA ($\text{m}^2 \text{ha}^{-1}$)
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)

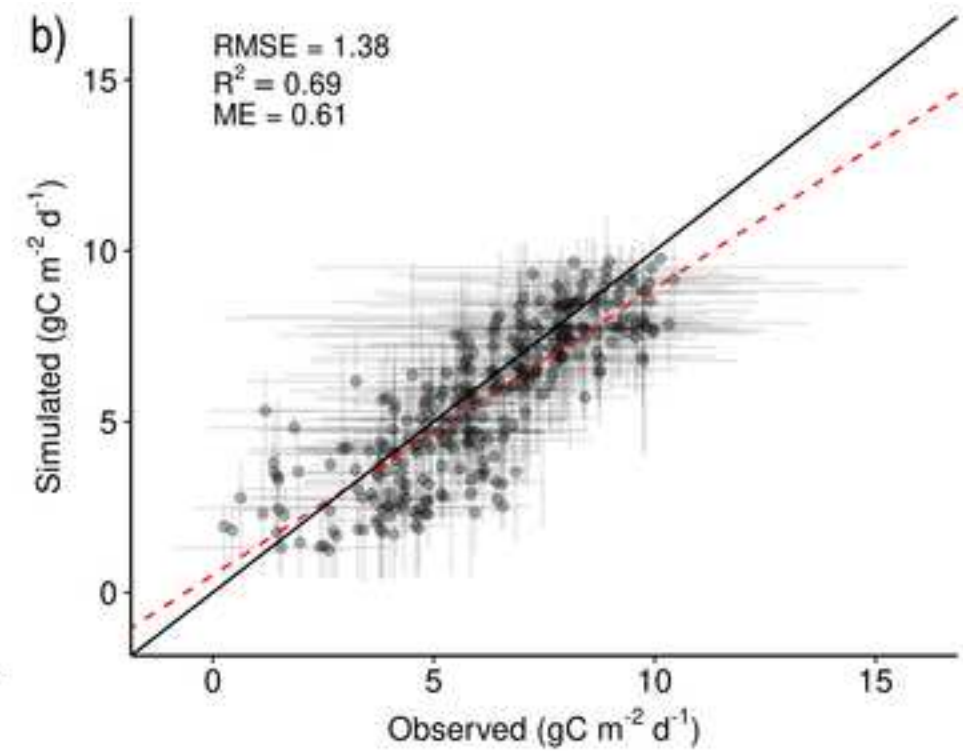
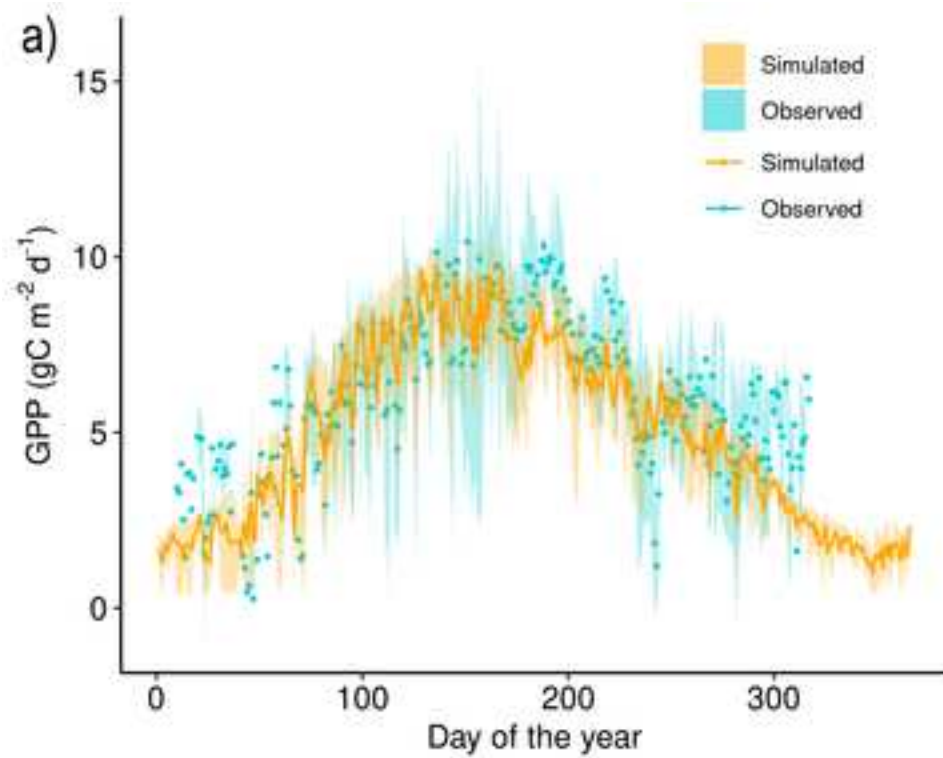


Figure 2

