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Climate change mitigation by forests: a case study on the role of management on carbon dynamics of a pine forest in South Italy

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Abstract

In the last decades, the problem of global changes has been of major importance, in particular the increase in CO_2 concentration in the atmosphere with the consequent rise in the average temperature of the planet. In this context forests and their rational/optimal management is very important to contribute to the mitigation of the effects of climate change. Studying in deep how forest management modifies the processes that control carbon dynamics during stand development and in response to climate change, is therefore key to improve our understanding of land-based climate mitigation. For these reasons, modelling tools are increasingly used by both forest ecologists, who face the challenge of transferring knowledge to stakeholders and the general community, and forest managers, who benefit from the development of scenario-based supports for decision-making. In particular, the objective of this study is to analyse the impact of the current and alternative forestry practices on carbon fluxes in a pine forest in South Italy under scenarios of climate change. This was done by simulating three different forest planning scenarios using the 3D-CMCC-CNR-FEM model, and evaluated over time with respect to carbon fluxes variables. The first part of thesis has focused its attention on analysis of dendrometric characteristics of the forest, sensitivity analysis and Bayesian calibration of the model. This has allowed to estimate the uncertainty of the model output in comparison with the measured data and its analysis, in response of the model outputs. The second part is focused, firstly, on analysing the different behaviour of the forest under management (reference management: rotation: 90 yrs; interval: 15 yrs; intensity: 25%), in comparison with the "not managed" forest in terms of temporal variation of Gross Primary Production (GPP), Autotrophic Respiration (RA), woody C-stock and Net Primary Production (NPP) under different climate scenarios. In this respect, results show that a progressive reduction in forest cover through thinning confers beneficial effects on the growth and development of the remaining plants. If management, on the one hand, due to a reduction in leaf area, determines a decrease in photosynthesis as a whole, on the other hand it creates better light conditions that contribute to increase and make the photosynthetic process of the remaining plants more efficient and consequently contribute to the enhanced NPP of forest ecosystems. Secondly, the analysis focused its attention on the woody C-stock and NPP dynamics by comparing different forest management options. The purpose is to analyse in detail how the variation of several management factors (rotation, interval, intensity), affect the forest development under different climatic scenarios. From the analysis it emerged that the factor that determines a greater weight on the productivity of the forest is the choice of rotation. In particular, it has been observed that an increase in rotation length has beneficial effects not only on the carbon stock but also on carbon sequestration. This would suggest the hypothesis that in conditions of climate change, in Mediterranean climate and for conifer forest, careful forest management characterized by rotations, intervals and intensities well calibrated on specific biotic and abiotic conditions may guarantee a carbon assimilation comparable in an undisturbed forest maximizing the total carbon stock at the same time. This confirms the importance of sustainable forest management, which not only provides for the optimal maximization of timber production, but also has the potential to guarantee the performance of various ecosystem services that are important for the community.

Keywords: *Carbon cycle, forest management, climate change, adaptation, mitigation*

1. INTRODUCTION

In the last decades, the problem of global changes has been of major importance, in particular the increase in CO_2 concentration in the atmosphere with the consequent rise in the average temperature of the planet. In this respect, initiatives for CO_2 emission control worldwide are mainly due to growing international concern over climate change that generated a series of binding negotiations aimed to limit and possibly halt the strong and progressive increase of CO_2 concentration.

This issue has been debated widely to identify causes of warming trends in global temperature. The Intergovernmental Panel on Climate Change (IPCC), reported as a conclusion that “It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2014).

Future conservation strategies and plans play a key role in preserving ecosystems against both natural hazards and human threats, in particular due to environmental resources’ exploitation and land-use changes (Noce *et al.*, 2017).

From this general and global trend, what is the specific status about the Mediterranean area?

Mediterranean region is located in a geographic area that is influenced by both the arid climate of northern Africa and the temperate and rainy climate of Central Europe. This dynamic scenario inevitably causes a deep influence on the Mediterranean climate, also related to shifts in the location of mid-latitude storms or high pressure conditions from sub-tropical areas (Ulbrich *et al.*, 2006).

In this context, the potential vulnerability to climate change for the Mediterranean basin area is connected both to the increasing concentration of greenhouse gases in the atmosphere (Ulbrich *et al.*, 2006) or, as has been reported by Luterbacher *et al.,* (2006), witnessed from the significant climate changes in the past. Furthermore, in addition to large-scale processes, the complex physiography of the Mediterranean area and the presence of the Mediterranean Sea has affected its climate over time. In addition, the Mediterranean climate is further influenced by the complex geography and presence of vegetation reducing the representativeness of large scale processes in favour of those at smaller spatial scales (Lionello *et al.*, 2006).

Still, Alpert *et al.,* (2006) has shown that Mediterranean climate is also influenced by anthropogenic and natural aerosols of European, African and Asian origin. Because of all these highly variable spatial and temporal interactions, the climate of the Mediterranean region is characterized by a wide variety of “local” climates and a high spatial variability (Lionello *et al.*, 2006).

Finally, Giorgi, (2006) has reported a general drying and warming of the Mediterranean region, particularly in the warm season with a decrease in precipitation larger than 20-30% and an increase in temperatures often above 4-5 ° C. Exceptions have been recorded in the Alpine region with an increase in precipitation during the winter. Also, the inter-annual variability has a tendency to increase and the likelihood of extreme heat and drought events too. These results are consistent with global and regional models projections and can be considered relatively robust and representative.

The Mediterranean basin is one of the most varied areas worldwide in terms of biodiversity and species richness due to its climatic and geomorphological features, and it is characterized by multi-faceted habitats where forests play a crucial role (Noce *et al.*, 2016). In this respect, the Mediterranean has been considered as one of the most important Hot-Spot for biodiversity, deserving particular attention in future investigation of impacts of changing climate (Giorgi, 2006). In this framework, forest ecosystems contributes significantly to the global carbon cycle, with the mitigation role of absorbing and storing CO_2, offsetting partially emissions from other sources (Ayres and Lombardero, 2000; Bachelet *et al.*, 2003; Lucht *et al.*, 2006; Scholze *et al.*, 2006; Lloyd and Bunn, 2007). Conversely, land use conversions and deforestation are contributing significantly (10-15%) to the anthropogenic emissions. In this respect, reforestation and reduced deforestation can contribute to the overall mitigation activity by forest ecosystems, as well as sustainable forest management. Transition from positive (absorption) to negative (emission) carbon balance in Mediterranean forest ecosystems, as a consequence of increasing environmental constraints, is a crucial process which might have profound consequences on forest persistence and forest vegetation dynamics (Nolè *et al.*, 2015).

In addition, forest fires, the progressive increase in vulnerability to pests and environmental conditions as temperature and precipitation (main effects of the climatic change) impact directly forest ecosystems' health, at a faster rate than that many ecosystems can naturally counteract through adaptation (i.e. exceeding threshold conditions for ecosystem adaptive capacity). Currently, the cumulative effects of all environmental drivers on forest ecosystems makes very difficult to determine to which level they are or will be affected by climate change, considering that these factors could act independently or in combination (Lucier *et al.*, 2009). However, there is a common point of view that climate change already has and will continue to have direct and indirect impacts on forest health (EEA, 2016).

In addition, currently as in the past, there is a gap between the forest management policies and the potential impact of climate changes on the long term physiological response of forest ecosystem. This is related to many reasons primarily linked to the necessary long monitoring periods, due to the slow forest ecosystem readjustment to the new ecological conditions created after disturbance, such as, for example, after forest harvesting. In this framework, the use of ecological simulation models is a tool to overcome this limitation, giving the possibility of simulating and forecasting which can be the dynamics of carbon\water fluxes in the future.

Wood productivity has traditionally been modelled using empirical growth models (e.g. Battaglia and Sands, 1997), but such models can only be parameterized using empirical datasets obtained under current growing conditions. These conditions therefore do not encompass future growing conditions expected under climate change (Kirschbaum *et al.*, 2012). Modelling tools are increasingly used both by forest ecologists, who face the challenge of transferring knowledge to stakeholders and the general community, and by forest managers, who benefit from the development of scenario-based supports for decision-making (Vacchiano *et al.*, 2012).

Simulation models of forest ecosystems answer two needs: clarifying the relationship between key ecosystem components, for a deeper understanding of their functioning (Kimmins, 2008), and predicting how the state variables of a dynamic system change due to processes in a forest stand or landscape (Brang *et al.*, 2002). The comparison with desired targets may then result in improved ecosystem management.

About 86% of European forests and about 52% of global forests are managed (Meyfroidt and Lambin, 2011; FAO, 2015). Studying in deep how forest management modifies the processes that control carbon dynamics during stand development and in response to climate change, is therefore key to improve our understanding of land-based climate mitigation (Nolè *et al.*, 2013, 2015; Bellassen and Luyssaert, 2014; Alkama and Cescatti, 2016; Naudts *et al.*, 2016).

In relation to the open debate on whether current forest management can increase forest yields and/or carbon sequestration under changing climate conditions (Bellassen and Luyssaert, 2014; Lindner *et al.*, 2014), currently there is a greater interest to represent the forest management through the modelling approach, relating it to the climate and consequently to the analysis of the climate scenarios (Schelhaas *et al.*, 2015; Yue *et al.*, 2017).

Furthermore, through the choice of different hypotheses of forest management and with an acceptable uncertainty degree, it is possible to evaluate for each simulated forest management option, how carbon fluxes and production will change. This may help us to understand in which direction we are going and will help formulate consistent hypotheses on sustainable forest management in the specific context analysed. In this respect, constructing future scenarios is not simply the mechanistic accumulation of data, but rather is an analytical process of defining interests, expectations, objectives and casual models, regain consensus on strategies and evaluating the potential outcomes.

1.1. Hypothesis and objectives of the research

This research move from the needs to analyse and understand the impact of the current and alternative forestry practices on carbon stocks and fluxes in a pine forest in South Italy under scenarios of climate change. In this context, it will be important to detect the effect on the carbon cycle response not only of different climate change scenarios but the weight of each component of forest management (rotation length, thinning intensity and interval) deriving several natural hypothesis such as:

- If is it varied the rotation, thinning intensity and interval, significant difference in carbon stock and carbon uptake is observed?
- If the first aspect is true, is it possible to maximize both carbon stock and carbon uptake?
- What is the most important component of the forest management to take mainly into account to manage the carbon cycle in forest?
- The climate change scenarios affects the probable effectiveness of management presence?
- There are significant differences between forest managed and unmanaged?

This was done by simulating three different forest planning scenarios using the 3D-CMCC-CNR FEM (Collalti *et al.*, 2014, 2016, 2017; Marconi *et al.*, 2017) and evaluated over time with respect to carbon dynamics variables.

Research objectives:

1. analyse the likely impacts of Climate Changes (CC) on a Mediterranean forest located in South Italy in relation to climate change scenarios
2. assess which are the functionalities of forests in carbon fluxes and what are the likely impacts of climate variability on carbon changes in one of the most southern European forests equipped with eddy covariance flux measurements
3. determine the future prediction’s uncertainty through Bayesian modelling approach and analysing the uncertainty results
4. evaluate, through a modelling approach, how, if and to what extent different silvicultural practices (scenarios management) can affect the carbon fluxes in the next years

5. discuss which would be the best way to manage forests to optimise carbon stock and carbon assimilation, in relation to modelling results

The work has been performed through: i) selection of the proper model type; ii) parameterisation, sensitivity and uncertainty analysis and validation of the model of the selected model; iii) collection of site level data and acquisition of scenarios for future climate; iv) definition of possible forest management scenarios; v) simulations.

The research results are planned to be implemented within the Integrated Information System of Forest Resources of Calabria (SIRFOR). A system based on the integration of various environmental data technologies from various sources such as remote sensing, regional environmental monitoring networks and modelling analysis. Furthermore, the position of Calabria Region, at the centre of the Mediterranean, will open up perspectives for transferring technology to other countries in the Mediterranean basin.

2. STATE-OF-THE-ART

2.1. Forests: likely impacts under climate change

2.1.1. Temperature, precipitation and CO_2 concentration effects

There are several processes in forest ecosystems that are related to and affected by climate and climate change.

The gradual change in temperature and precipitation is expected to produce a strong impact on natural or managed forests. In light of this, several bio-geographical models have identified a polar ward shift of potential vegetation of about 500 km, especially for the boreal areas (Walther *et al.*, 2002; Parmesan and Yohe, 2003).

In this context, forest migration could lead to a substantial loss of forest areas where migration takes place at a much slower pace than climate change (Peters and Darling, 1985), while in particular contexts migration rates may be faster (Weinstein DA., 1992). Specifically, managed forests could sometime guarantee faster migration rates than natural forests.

Furthermore, every bioclimatic zone in Europe is characterized by a different temperature variation rate and this has significant impacts on forest production. In this regard, in both boreal and temperate climates, an increase in temperature may have a beneficial effect on carbon stock (Kellomäki and Wang, 1996; Briceño-Elizondo *et al.*, 2006). In particular, in the northern latitudes, photosynthetic rate and length of the growing season may increase with higher temperatures. On the contrary, in the Mediterranean regions, an increase in temperature may have a negative effect on productivity and vitality of forestry systems mainly due to prolonged periods of drought with irregular rainfall (Loustau *et al.*, 2005).

In general, and in absence of concurring limiting factors (e.g. nutrients, water), we could observe a carbon "fertilization" effect that would lead to an increase in forest production (De Vries *et al.*, 2006; de Vries and Groenenberg, 2009; Solberg *et al.*, 2009; Rudel *et al.*, 2010), due essentially to a progressive increase in CO_2 concentration. For example, experiments which included an enrichment of CO_2 in free air (FACE), showed a positive effect on productivity. In fact, some studies have found an increase in net primary production of 23% in young trees (Loehle, 2003) due to a doubling of CO_2 concentrations. This tendency to increase the rate of growth in relation to the increase in CO_2 is not as direct as it might seem, since the effects of competition, disturbances, air pollutants, such as tropospheric ozone or nutrient limitation, could limit the effects (Kupfer and Cairns, 1996).

In certain conditions and geographic context, the climate scenarios projections will lead to a greater water scarcity in the soil, especially during the growing seasons with potential harmful impacts on ecosystems. In this context, in the Iberian Peninsula there was a significant defoliation of trees between 1990 and 2007, because of long period of drought that has caused an increment in tree mortality rates (Carnicer *et al.*, 2011).

If the prediction of precipitation decrease and the gradual increase in temperatures are considered simultaneously, the effects of drought would become more problematic, especially in the Mediterranean area as the evapotranspirative request by the atmosphere will increase, leading to more important drought effects.

2.1.2. Forest disturbances

Climate changes can lead to an increase in pathogenesis and spread of diseases, which inevitably may causes a progressive alteration of stand resistance, of plant nutritional quality and of community interactions. In this respect, the effects of climate change have caused, despite many uncertainties, a raise of pests and diseases in European forests, as reported in several studies (FAO, 2006; Desprez-Loustau *et al.*, 2007) with a sensible variation in spatial and temporal scales of insect attacks (Netherer and Schopf, 2010). In particular, the pine processionary caterpillar (*Thaumetopoea pityocampa*) is progressively expanding its habitat to higher altitudes and has been detected in the mountainous areas of the Sierra Nevada and Sierra Base in Spain (Hódar and Zamora, 2004) and in the Italian mountains (Petrucco-Toffolo and Battisti, 2009). Gypsy moth (*Lymantria dispar dispar*) is the responsible of tree defoliation for many species in temperate forest areas with negative influences in radial increments, and more in general the spread of other insect pests has lead to oak decline in central Europe (Muzika and Liebhold, 1999; Balci and Halmschlager, 2003). Furthermore, pest outbreaks may be more frequent (Williams and Liebhold, 1995; Volney and Fleming, 2000) and, at the same time, sporulation and diffusion of fungal pathogens may increase (Ayres and Lombardero, 2000; Desprez-Loustau *et al.*, 2006).

An increase in available fuel and consequently a greater risk and chance of forest fires may be related to the likely increase in insect infestations and diseases causing tree death (Lombardero and Ayres, 2011; Santolamazza-Carbone *et al.*, 2011; Lausch *et al.*, 2013).

However, forest pests may have impacts that could vary based on so many factors that interact with each other: in other words, there is no univocal response but the effects may be negative, positive (a decrease of attacks) or even stable in relations to the different cases (Netherer and Schopf, 2010).

2.2. Forest management effects under climate change

Carbon balance of forests is heavily influenced by management policies. Even though there are many differences in climate, soil, or anthropogenic factors that, over the centuries, have determined a significant diversification of forest types worldwide and so in their management, some characteristics are common to all forest ecosystems.

In many cases, the level of carbon stored is higher in unmanaged forests than that stored in short rotation plantations (Cannell and Milne, 1995; WBGU, 1998). However, if the harvest cycle is extended beyond the average length of the natural disturbance cycle, the carbon storage in managed forest can exceed that in unmanaged stands (Price *et al.*, 1997). Furthermore, in old growth forests where natural disturbances are relatively rare, a larger amount of carbon is stored compared to that in younger managed stands where frequently the net annual carbon sequestration rates are usually higher (Thornley and Cannell, 2000). In fact, the stand biomass C is directly influenced by several factors as rotation length, frequency and intensity of thinning, other disturbances (Liski *et al.*, 2001; Kaipainen *et al.*, 2004a).

In general, forest management practice allows to reduce living and dead biomass compared to unmanaged forests.

Figure 1 shows the different behaviour of forest development in relationship to management policies. In particular, different management regimes are compared with unmanaged forests over time, in terms of stand-level carbon accumulation. In young forest, the carbon sequestration rates are very high, while rates are progressively reduced as forests get older. In unmanaged stands, biomass carbon stocks increase constantly until they reach a maximum value. Aged forests are characterised by small annual increments and high carbon stocks (Cooper, 1983a; Vitousek, 1991). Management intensity generally interacts with carbon sequestration rates and causes temporal fluctuations in carbon stocks at the stand level. In other terms, biomass carbon results reduced in forest subject to management, from selective cutting to short rotation plantation. However, the overall carbon sequestered and stored depends also on the use of harvested wood.

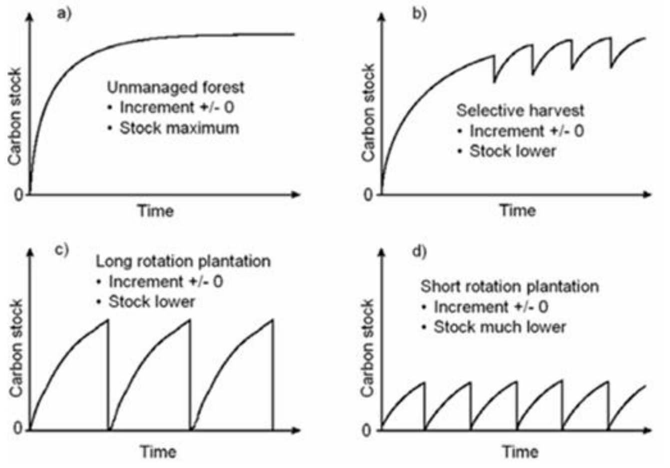

Figure 1. Schematic carbon stock development of aboveground biomass under different management system (redrawn from WBGU 1998)

However, long-term storage in the resulting wood products and the additional carbon fixed as the new forest becomes established are unlikely to offset the loss of carbon associated with harvest of the old growth forests (Harmon *et al.*, 1990; Vitousek, 1991; Schulze *et al.*, 2000). The substitution of old growth stands, with high carbon stocks and generally low C sequestration rates, is not a good strategy that would allow the removal of greenhouse gases from the atmosphere, because young, fast growing stands cannot compensate, for a relevant time interval the initial amount of removed carbon (Harmon *et al.*, 1990; Kurz *et al.*, 1998; Schulze *et al.*, 2000).

At present, active management of existing forests as carbon reservoirs does not guarantee suitable economic incentives. In this context, the Kyoto Protocol stipulates that converting mature forests in managed establishments will not benefit from carbon credits (IPCC, 2000). This condition may sometime pose problems to forest managers when developing their long-term forest management planning (Cairns and Meganck, 1994; Running *et al.*, 1999).

The overall scarcity of detailed field data, aimed at providing decision-making forest management support, has allowed the development of mathematical models with which it is possible to predict, on long term, the carbon storage in forest ecosystems. (Karjalainen, 1996; Apps *et al.*, 1999; Kimmins *et al.*, 1999).

Thinning is a common silvicultural practice targeted to allocate site resources to fewer individual trees and, when economical, allows for early revenues to forest owners. To increase the volume of individual timber compared to un-thinned stands, optimal thinning interval and intensity are two important factors (Wang and Nyland, 1996). This silvicultural practice reduces tree density, the remaining trees gradually gain in tree crown size to regain the cover of the removed trees (Assmann, 1968).

Another aspect is that the number of trees does not change between well-timed thinning practices. This aspect leads to reduced losses to natural decomposition and leaves more carbon for harvest, wood products and substitution.

2.3. Adaptation or mitigation strategies?

The strategies identified to address the impacts of climate change are classified into two potential routes that could be undertaken: adaptation and mitigation strategies.

In this context, there is an ever-increasing need for assessing how different silvicultural options affect ecophysiological responses of the forests and if a given management system is appropriate for supporting, in a sustainable way, the ecosystem services. To achieve these goals, adaptive management decisions are considered. In particular, the concept of adaptive forest management focuses in terms of adaptation to climate change (Wagner, 2004). This concept is essentially based on the general definition for which the adaptive management is ‘‘a dynamic approach to forest management in which the effects of treatments and decisions are continually monitored and used, along with research results, to modify management on a continuing basis to ensure that objectives are being met’’ (Canadian Forest Service, 2009).

Forest management can also provide a mean to reduce anthropogenic emissions of green house gasses (GHG) (mitigation of climate change). In this respect, promoting the mitigation effect resulting from forest management could maximize carbon sequestration and reduce GHG emissions in the atmosphere, but on the other hand, could have a negative impact on other sectors.

For example, stopping all forest harvest would increase the carbon stock, but at the same time would raise the use of other materials such as plastic, aluminium, steel and concrete products that cause more GHG emissions (Gustavsson and Sathre, 2006). Moreover, a forest expansion in new areas would lead to a reduction in areas available to agriculture. This would cause a transformation of other cropland into intensive management that could cause higher GHG emissions (e.g. more fertilizer use) or an increase in imports/exports activities (McCarl and Schneider, 2001).

2.3.1. Adaptation options

In line with this definition, the adaptive management allows to support forest system stress resistance and the ecological resilience and can be used as an important gunpoint to check at different time-step the answers to climate impacts. These characteristics are important to define and estimate the restoration capacity after disturbance (Loreau and Behera, 1999).

Adaptive management takes into account learning through acquired experiences ("learning by doing"), by analysing the physiological responses of forests, systematically and linking them to climate change (Millar *et al.*, 2007). In this context, managers play a key role because they not only need to be able to make flexible and sometimes risky decisions, but they have to be willing to change forest management types based on registered changes (Hobbs and Hilborn, 2006).

However, in the forest community, there is currently a lack of awareness of the risks of climate change (Williamson *et al.*, 2005). In fact, the potential impact of climate change on forests is not sufficiently considered by Institutions and policy Government. For example, only the current climate regime is considered for seed planning zones, reforestation and water sector policies.

In the future, the effects of climate change on forests could affect (Lindner *et al.*, 2014) :

1) growth and productivity;
2) species suitability;
3) disturbance responses of different tree species.

Considering the effect of climate change on forest, adaptation strategies can undergo significant changes in relation to how climate change would affect the three factors listed above. Specifically, adaptation strategies can be grouped into two types, the first promotes resilience, while the second "enables" the forest to respond to change. In particular the promotion of resilience to change is the most used strategy to counteract the effects of climate change in forest stands (Spittlehouse and Stewart, 2004).

Resilient forests have the property of getting acclimatized earlier to changes and, at the same time, they have the capacity to return to their original condition after disturbances, both naturally and with the support of programmed forest management actions (Millar *et al.*, 2007). Furthermore, in relation of climate change, the resilience of forests can be favoured in several ways, such as additional seed sowing or intensive management, especially during the early stages of the stands, to ensure the perpetuity of the desired species even if the climatic conditions gradually moved away from the optimum (Spittlehouse and Stewart, 2004). In addition, the resilience of a forest system can be guaranteed by maintaining a multi-layered multi-specific structure or, when needed, through prescribed fire treatment or sanitation harvesting (Drever *et al.*, 2006).

As the effects of climate change are cumulative over time, many physical and economic efforts will be needed to maintain and improve the future resilience of existing forests (Millar *et al.*, 2007).

Instead, another approach is to adapt forest management to the evolution of natural physiological processes due to climate change over time, in other words, it tends to "enable" forests to respond to change such as species dispersal and migration, trees mortality, colonization and changes in species dominances and community composition (Millar *et al.*, 2007).

The most important aspect is to avoid rapid and deep transformations in very tight timeframes and to favour management that ensures gradual adaptations and promotes, at the same time, transition processes that could be stable over time. In particular, management actions in this adaptive strategy include modifying harvest planning, modifying thinning in intensity and interval time, introducing different and more suitable tree species, moving tree species to new locations, and assisted migration to promote ongoing natural adaptive process (Briceño-Elizondo *et al.*, 2006; Millar *et al.*, 2007).

These changes are gradually applicable only if scientific research knowledge increases the confidence on the eco-physiological behaviours of the most important species. In fact, modifying the management policies or changing the tree species areas more suitable in the future than in the past, requires knowledge of the tree species and can be applied only to tree species of particular interest or in case of emerging problems.

Although there would be enough knowledge about the effects of climate on species and their origin, the uncertainty on the spatial and temporal distribution of climate limits somehow the prediction capacity. In this framework, the risk analysis has been an useful tool to scrutinise the possible adaptive actions (Davidson *et al.*, 2003; Ohlson *et al.*, 2005).

An important step to know in deep the adaptive choices is to identify and promote the following points in the forest community (Spittlehouse and Stewart, 2004):

- adaptation to climate change has to enter into the awareness and education of all forest communities
- the society has to reflect on how it intends to use its forest resources in the future, identifying concrete objectives to be achieved
- methodologies need to be established to estimate the vulnerability of forest ecosystems, communities and society (sensitivity, adaptive capacity)

- forest management should have the primary role of incorporating future responses (physiological, ecological, social, economic), to reduce vulnerability and add new knowledge to the future situation
- critical thresholds of forest systems need to be periodically detected to determine their health state
- periodic and regular forest management is needed to ensure a reduction in vulnerability and support a progressive recovery after the occurrence of disturbances.

Forest managers have many options for mitigating the effects of climate change and adapting to that change (Duinker, 1990; Papadopol, 2000; Dale *et al.*, 2001) and several of them have been discussed in the last decade (Spittlehouse and Stewart, 2004).

Generally, they can be grouped into three categories:

- **study and assessment of the vulnerability of ecosystems to change**: this first step is directly related to the adaptations of society and institutions (e.g., forest policy to encourage adaptation, revision of conservation objectives, changes in expectations).
- **Forest adaptation management today**: this step is important because it is a precondition for the foreseen future actions. It targets forests on the eco-physiological aspect but also on the regulation side through the introduction, in current forest management planning, of specific mitigation measures to climate change (e.g., species selection, tree breeding, stand management, fire smart landscapes, conserve biodiversity, develop models with climate variables, etc.).
- **Forest adaptation management tomorrow**: this step specifies concrete actions after careful research and forest planning. This action provides to modify the previous forest management policies. (e.g., change rotation age, use more salvage wood, modify wood processing technology, sanitation thinning, etc.).

The first point will be crucial to review our forestry policies, as a reformulation of management policies or forest conservation and protection actions may have positive effects for the community (Volney and Hirsch, 2005). In addition, there will also be changes in the quality of wood and supplies that will lead to the need for a new redistribution of available resources that are not evenly distributed globally (Sohngen and Sedjo, 2005).

Practices such as disease and insect control, stand management and monitoring and control of undesirable species, fire protection can be considered as important options for adapting the forest to future changes (Dale *et al.*, 2001; Volney and Hirsch, 2005). Forest management decisions will need to consider the carbon balance more concretely and above all will have to encourage carbon sequestration to cope with the anthropogenic emissions of carbon dioxide (Pollard, 1991; Spittlehouse, 2002). In this sense, forest certification could provide a valuable contribution to include adaptation to forest planning as a risk management strategy.

2.3.2. Mitigation options

Taking into account climate change related risks, reasonable options may be identified to reduce GHG emissions and increase the efficiency of forest ecosystems for carbon sequestration (Nabuurs *et al.*, 2007).

- **Reducing the deforestation and degradation actions**: this option can be with immediate carbon stock impact in the short term per globally because large carbon stocks are not destroyed when deforestation is prevented. The declining fraction of total emissions coming from deforestation and degradation raises the question of whether management of forests, and particularly REDD+[1], can play a significant role in reducing anthropogenic emissions, thereby helping to avoid climatic disruption.
- **Promoting afforestation/reforestation practices**: these actions could allow up to a 25% reduction in CO_2 in the atmosphere (Niles *et al.*, 2002). These activities could find two great obstacles to overcome, in future. On the one hand, unclear policy regulations, on the other the profitability and forest policies of management actions that is very variable from country to country (Barker *et al.* 2007). Availability of land is another issue of consideration.
- **Increasing the carbon stock with a rational forest management:** To promote CO_2 reduction in the atmosphere, the development of sustainable forestry practices is an effective mitigation strategy. Several studies confirmed that sustainable forest management not only preserve and enriches the biodiversity but also increase carbon stocks especially in degraded production forests.
- **Increasing the use of wood biomass in substitution for products with fossil fuel requirements:** essentially, it consists in the progressive reduction in the use of fossil products with the consequent replacement of products based on re-growing resources. This mitigation effects is cumulative over time, because it is added progressively to each harvest and then to the product use. In this contest, biomass plays a crucial role in reducing climate impacts (Gustavsson and Sathre, 2006). However, wood use may not be always compatible

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[1] REDD+ - Reducing Emissions from Deforestation and Degradation of forests - is a climate finance tool able to attract a series of public and private investment on the environment for sustainable management of natural resources.

with the role of forests as carbon sinks. For this important aspect, model simulations of different forest management scenarios (different rotation lengths or thinning intensities) and their effects have already been investigated (Schlamadinger and Marland, 1996; Eriksson and Berg, 2007; Hennigar *et al.*, 2008).

These mitigation actions could introduce and enhance the CO_2 sink role of forests by promoting it as an atmospheric carbon mitigation service. Carbon can be stored in biomass, litter, dead wood, organic soil material. Moreover, these mitigation measures may, on the one hand, minimize emissions in atmosphere and, on the other hand, increase the resistance of the forest to fire, parasites and diseases.

The promotion of mitigation in forests can also favour increased resistance with options such as preliminary detection of areas with high risk of fire, the creation of perimeter fire lines with the purpose of stopping the expansion of fires, high intensity first thinning to increase the resistance to storms up to biological control of parasitic spread.

Improving existing strategies and making them more effective for mitigation of climate change is the most important challenge for forest management today (Lundmark *et al.*, 2014). In recent studies in Sweden, it has been calculated that with current forestry practices, it is possible to capture 60 million tonnes of atmospheric CO_2, which is comparable to the annual GHG emissions of the country (Lundmark *et al.*, 2014).

2.3.3. Integrated strategy

Adaptation and mitigation are two different approaches whose combined effect is multiplied than the single effects when implemented separately (Klein *et al.*, 2007).

In fact, the triangle diagram (Figure 2) represents the combination of mitigation, adaptation and no action options. The corners of the triangle represent 100% of each one of these three options. The area in the centre represents the combination of approaches. Furthermore, there are costs associated with mitigation and adaptation. The effect of not taking any action has very high costs due to the fact that we will be not prepared to face the likely consequences that climate change will generate over time.

Considering the uncertainty related to the future physiological behaviours in forests and future climate projections, focusing on a single approach would not ensure effective management actions (Spittlehouse and Stewart, 2004; Hobbs and Hilborn, 2006). In this context, the combination of different management practices, progressively adapted to changing conditions, would be the approach that would ensure greater effectiveness in addressing climate change.

Most of the known strategies to address climate change such as the Global Environmental Facility (GEF) or the Clean Development Mechanism (CDM) refer to either mitigation or adaptation policies individually treated. Instead, mitigation and adaptation options should be considered together in synergic way, to make more effective the contrast to climate change.

The spatial and temporal dimension and the costs for the implementation of management are factors that will influence the strategic decisions in the forestry sector.

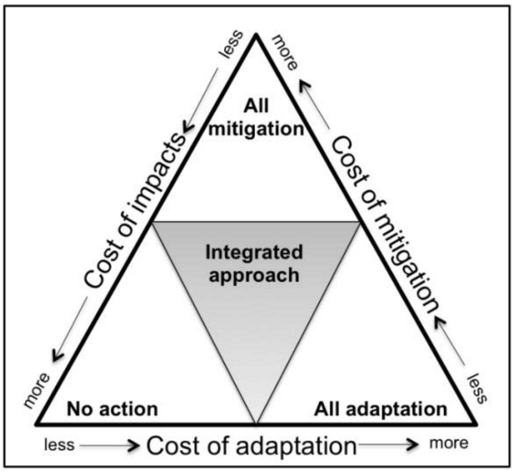

Figure 2. Schematic depiction of an integrated approach to sustainable forest management (Klein et al.,2007).

For example, adaptation strategies are more suitable at regional scale, while mitigation strategies are more appropriate to provide global benefits (Klein *et al.*, 2005).

Regional and stand scale approaches have two different uncertainty levels and types in forest management actions. Integrated management approaches for mitigation or/and adaptation to climate change should not endanger other major ecosystem services for human and forest ecosystems such as biodiversity, water quality and cultural and social services (McDermott *et al.*, 2010). For these reasons, carbon sequestration in the forest ecosystem should be favoured by integrated management that would simultaneously improve the functionality and health state of other ecosystem services related to forests. This implies a thorough knowledge of the likely future conditions of ecosystems. This can be appropriately investigated through the implementation of forest models capable of predicting future physiological responses with estimated uncertainty thresholds.

Furthermore, it is necessary to define clearly where and what will be the activities to be done, on a case-by-case basis, starting from the knowledge of the current physiological conditions of the forest.

2.4. Multiple ecosystem services in a changing environment

In the last decades, the forest area in Europe has increased considerably, reaching today almost 40% of the continental area. Most of the forests are destined for wood production but at the same time they offer a multitude of benefits in terms of human health, recreational activities, refuges, fresh water supply and many others. In this context, there is a growing need to preserve the woodland heritage through the sustainable management of its resources, thus guaranteeing its perpetuity over time.

To achieve these goals, forest and biodiversity are two strongly related concepts. Through the preservation and promotion of the forest biodiversity it is possible to guarantee a good state of vitality and health of the wooded areas, thus maintaining their production levels. All this is made possible by applying sustainable forest management aimed at supporting the supply of forestry goods and services and improving biodiversity levels.

Therefore, the main objective of the EU Forest Strategy is to improve existing levels of biodiversity in forestry. In this respect, the EU has set goals in its Biodiversity Strategy 2020. This has enabled more attention to identify the many ecosystem services that the forest offers and above all to evaluate the presence of the anthropogenic threats.

In particular, the functions of the forest ecosystem provide important ecosystem services to humans, contributing directly and indirectly to human well-being. In the light of this, it is important to contribute to the research for more effective management strategies that focus not only on the wood production aspect but also on all services that the forest system is able to offer to human society.

Duraiappah and Naeem, (2005) classified ecosystem functions in 4 main categories with the related goods and services:

- **Supporting services**: These functions collect all the services needed to produce all other ecosystem services and contributes to the conservation of biological and genetic diversity and evolutionary processes. Ecosystem services for this ecosystem function are: soil formation and the nutrient cycle, that is, the availability of mineral elements such as nitrogen, phosphorus and potassium essential for the growth and development of organisms. In addition, ecosystem services support reproductive, nutrition, shelter for stationary and migratory species and maintain evolutionary processes (on a phenotypic and / or genetic basis).

- **Regulating services**: In addition to maintaining the health and functioning of ecosystems, regulatory functions collect many other services that have direct and indirect benefits to humans (such as climate stabilization, waste recycling), usually not recognized when they are not lost or degraded. Examples of ecosystem services for this function are: modulation of gas concentrations, climate, water and erosion, protection from hydrogeological disasters, regulation of pollination and habitats to support the biodiversity.
- **Provisioning services**: These functions collect all the supplying resources that natural and semi-natural ecosystems produce. Ecosystem services for this ecosystem function are: food, raw materials (timber, metals, textile fibres), biological variability, fresh water.
- **Cultural services**: Natural ecosystems provide an essential "consultation function" and contribute to the maintenance of human health through the provision of opportunities for reflection, spiritual enrichment, knowledge development, recreational and aesthetic experiences. Ecosystem services for this ecosystem function are: inspiration for culture, arts, educational and spiritual values, sense of identity, recreational values, aesthetic values.

Over the last 50 to 80 years, man has changed ecosystems at a speed and strength that had never been observed in previous periods; the main causes were the growing need for food, fresh water, timber, fibre and energy sources: this impact caused and is still causing irreversible loss of biodiversity throughout the planet and in particular, it was estimated that 60% of the ecosystem services of the planet has been compromised.

Therefore, it has become crucial to integrate the concept of ecosystem services and functions into land management and planning decisions so that local administrators can control the pressures that threaten the ecosystem and their functionality, improve their effectiveness and "build" a governance model that is based on tools such as payments for ecosystem services.

2.5. Forest modelling classifications

The importance of understanding the carbon balance of forest ecosystems is due to the need to predict long-term forest ecosystem responses (e.g. stand, regional, global scale) in relation to ongoing climate change.

In this respect, in recent years, the use of forest models and their diffusion has made it possible to deepen the knowledge of forest ecosystems and their understanding through the simulation of eco-physiological behaviours in relation to the variation of abiotic and biotic factors. If, on the one hand, this feature is strong as it makes possible to represent a phenomenon in detail, on the other hand, could be a weak point because determines difficulties to use and evaluate them (Van Oijen *et al.*, 2005).

In recent years, however, new family of models can be applied in changing environmental conditions such as the dynamic space-state approach (Nord-Larsen and Johannsen, 2007; Nord-Larsen *et al.*, 2009), or models based on the process (Tyler *et al.*, 1996; Seynave *et al.*, 2005). The latter explicitly simulate processes that directly or indirectly affect long-term forest dynamics. Specifically, they take into account abiotic and biotic factors responsible for growth, mortality and tree rejuvenation. Many of these models envisage the explication of processes such as photosynthesis and respiration.

This family of models are probably the most suitable for supporting the understanding of the current and future growth dynamics of forestry systems, because the physiological processes on which they are based are heavily dependent on environmental conditions.

Nevertheless, the scaling-up of small scale measurements (e.g. individual tree measurements) to stand or canopy-level is difficult for different reasons (Parker et al. 1995):

- ecological and physiological differences among species;
- leaf-to-leaf variation within a species through the canopy;
- influences of canopy architecture on leaf microclimate;
- non-linearity in the response of photosynthesis to resource levels.

Especially in the last 40 years, ecological processes are represented by a growing number of increasingly complex mathematical models that require ever-greater computational power; through their use, it is possible to evaluate behaviour at large spatial domains but also to predict the future behaviour of forest ecosystems (Running *et al.*, 1999; White *et al.*, 2000; Rastetter *et al.*, 2003). Furthermore, modelling allows to gain insights into the behaviour of forest ecosystems and their evolutionary dynamics in relation to the progressive change of the monitored environmental variables (Magnani *et al.*, 2002; Grassi and Magnani, 2005; Oulehle *et al.*, 2011; Grant *et al.*, 2012).

There are many different modelling approaches used in Forest Ecology. They can be divided into various typologies, spatial scales and time scales, depending on the methods used, but above all by the application purposes, each with its own potentialities and limits (Idso, 1978; Hunt, 1982; Makela *et al.*, 2000).

In this context, several attempts have been made to put order among all forest models trying to catalogue them by categories. Each review takes into account different aspects of classification:

- Nightingale, Phinn and Held, (2004) divided the models in 4 organizational levels (Leaf–tree, Plot/stand, Ecosystem, Regional);
- Landsberg (2003) catalogued the models on the base of the type of user groups at which they refer (models relating to industry, to the broader public community, to the academic world)
- Pretzsch *et al.*, (2007) gave an historical division, based on model complexity and aims (maps and yield tables, growth- and yield simulators, individual tree-orientated management models, gap and hybrid models, matter-balance models, landscape models, visualization models);
- Makela *et al.*, (2000) classified, in particular, the process-based models focusing on their application to forest management.

However, there is still scientific debate about which are the physiological processes that may considered to limit long-term forest dynamics. In fact, one of the major obstacles to overcome is to identify key physiological processes that are limiting for future forestry dynamics (Bugmann and Martin, 1995; Körner, 1998, 2006; Braun *et al.*, 2010; Bugmann and Bigler, 2011), and to develop them so that they can be easily implemented in forest models for operational management.

In addition, a certain amount of uncertainty remains, deriving from the possibility that the simulated physiological processes may be influenced by external factors not considered in the current models and which could be linked to climate change. In fact, these interferences could act as disturbing agents such as fires, storms, parasites etc (Hanewinkel *et al.*, 2010).

2.6. In summary

Starting from the evidence that climate change and forests are closely linked and the increase in annual average temperatures, the alteration of precipitation and the more frequent extreme meteorological events are already having an impact on forest ecosystems, the need to identify effective mitigation and adaptation strategies that could guarantee the perpetuity of the forest system and consequently of its ecosystem services is increasingly important.

In this context, it is important to deepen the understanding of the likely impacts of climate change on carbon fluxes and stocks of key forest ecosystem in the Mediterranean and to analyse the role of forest management options in regulating the response to climate and climate change. This can be done through the use of modelling coupled to uncertainty analysis, with the aim of satisfying not only the bioeconomical aspects deriving from wood products, but also considering the maintenance of the ecosystem efficiency over time in terms of carbon assimilation. Models need to be properly evaluated and calibrated, including uncertainty estimation.

The model will be used to analyse the behaviour of a selected forested basin in the Mediterranean, not only under different climate scenario but also under several forest management practices to understand how changes and disturbances (management) affect the forest and its future. Application will build on detailed data collected at the site, both historically on with specific surveys, targeting the whole 140 ha basin.

3. MATERIALS AND METHODS

3.1. Experienced difficulties

Most of the research in this field was conducted for temperate (mainly at mid latitudes) or boreal forests. In this respect, the Mediterranean region is characterized by more limited knowledge of future forests projections and to our knowledge, this research is one of the first to have been made at such low latitudes in Europe.

There are several reasons why the forests of the Mediterranean basin differ from those of the rest of Europe. Differences are related mainly to climate, the role and type of forest management and the long and intense human impact. These factors added to a more limited knowledge of the biology of many species in this area make the modelling approach quite complicated and also information from literature is often insufficient to parameterize a model for this specific situation (Kabat et al 1995; Metselaar 1999). Hence, a sensitivity analysis is implemented for investigation of the importance of the parameters in relation to model outputs (e.g. Baird, 1989).

From basic information on the biological parameters and on their importance, a Bayesian model calibration was implemented to know the most likely probability distribution of parameter values, comparing model outputs with the measured data..

Another difficulty encountered was to accurately detect growth rings in a Mediterranean pine species. This is due to the relatively slow growth rates of Mediterranean species and the frequently unseasonal growth of these species. Based on climatic conditions, plants may have different growth periods in one year especially for the evergreen species (Mitrakos, 1980). As consequence, several cores were read and then synchronized by both visual comparing and statistical methods.

3.2. 3D-CMCC-CNR Forest Ecosystem Model

The 3D-CMCC-CNR Forest Ecosystem Model (FEM) (Collalti *et al.*, 2014, 2016, 2017; Marconi *et al.*, 2017) is an hybrid model because is both an empirical and process-based model based on Light Use Efficiency (LUE) approach (Monteith, 1972; Monteith and Moss, 1977; Landsberg and Waring, 1997). This model is developed to simulate different aspects of forest ecosystems with different scales and it is subdivided into different sub-models that simulate the main eco-physiological processes of the forest and the key factors that control the carbon and water cycle (*Figure 3*).

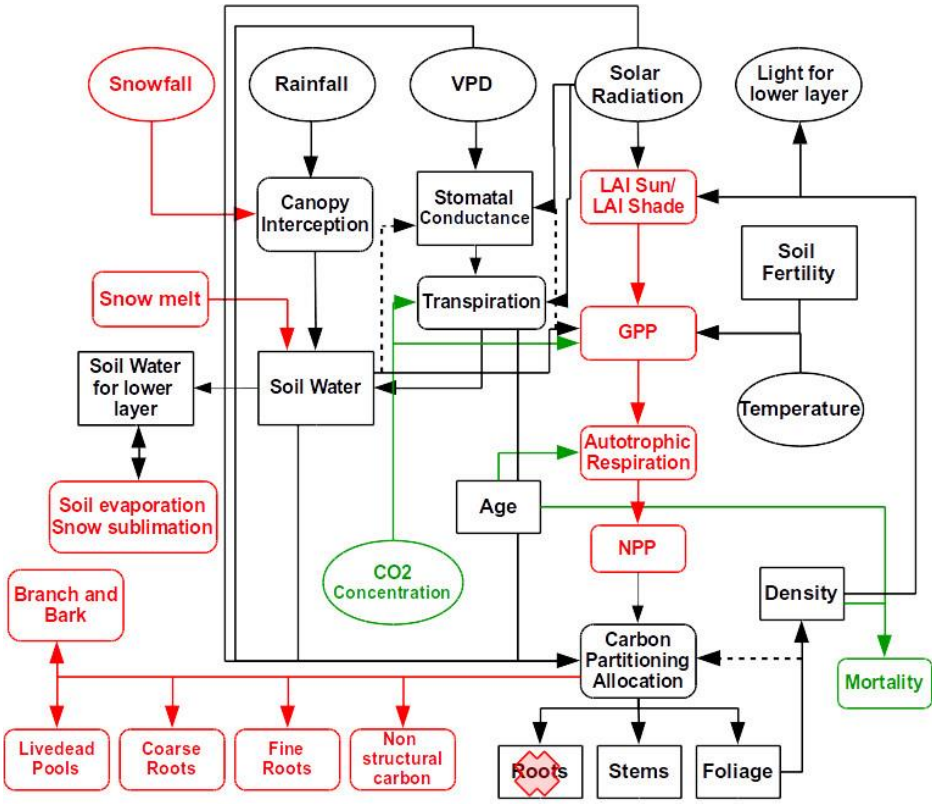

Figure 3. 3D-CMCC Forest Ecosystem Model structure flow chart (Collalti et al. 2017)

In particular, the representation of the forest occurs through a matrix composed of cells which can be of variable size from 100 to 10.000 m^2, following the approach of Klausmeier and Tilman, (2002), in which the forest is vertically divided into different levels (layers), based on the age classes, of diameter (DBH, diameter at breast height) and of height present on a species-specific basis, while the trees are at the spatial level uniformly distributed according to the density. The hierarchical position of a height class compared to the others is defined by the model according to the other height classes present within the plant community in a dynamic way, while the annual increments determine annually the possible transition from one layer to another from one hierarchical position to another.

Most of the processes are simulated at daily temporal resolution (e.g. photosynthesis) other at monthly (e.g. changes in stem diameter) or at annual scale (e.g. changes in forest structure). The simulated main eco-physiological processes are related to carbon and water fluxes, in heterogeneous and complex forest structure. Each variable (e.g. carbon pools, leaf area index, tree height) of the model output is referred to representative aggregation of tree classes that it is allowed by the model code structure. The model identifies these variables through four indices: species, diameter class, height class, and stand age class (i.e. cohort); with this preliminary information, it is possible to characterize the different typologies of forest ecosystems. This information along with those from physical and chemical soil characteristics (e.g. soil texture, soil depth and soil fertility) and stand topography (e.g. latitude and altitude), allow to initialize the model.

Furthermore, different forest ecosystems are represented with the species-specific parameterization for each species simulated.

In addition, the model takes into account all tree age classes. This allows to simulate a progressive reduction in net primary production due to senescence. This assumption is supported by numerous studies (Landsberg and Waring, 1997; Waring and McDowell, 2002) which show that the aging of a forest leads to a decrease in above ground net primary production for different reason (Ryan, 1991).

To simulate light interception, the model uses the general and well-known Lambert-Beer law, for exponential attenuation of incoming light, and the "Big leaf" approach from sun and shaded leaves (De Pury and Farquhar, 1997) developed for multi-stratified stands. These formulations are made possible by the explicit way in which the model considers the height classes and tree position within the vertical profile of the forest (Medlyn *et al.*, 2002; Collalti *et al.*, 2014), while horizontal canopy coverage is controlled by DBH and stand density (Collalti *et al.*, 2014). This computational strategy allows, on the one hand, to reproduce different combinations of uneven aged, multi-layered and multi species forests, on the other hand, makes the model flexible and suitable for a wide range of applications in different forest types. In addition, the 3D-CMCC-CNR FEM described in Collalti *et al.* (2014) has been advanced first to version 5.1 passing from monthly to daily meteorological data, site specific data and ecophysiological data (e.g. maximum canopy conductance, specific leaf area and it provided to improve the representation of forest processes, like phenology, canopy photosynthesis – including autotrophic respiration – tree carbon allocation and water dynamics.

In particular, several more detailed description of model implementations are listed below:

- **Photosynthesis process**: as in Collalti *et al.* (2014) the photosynthesis is still estimated in 3D-CMCC-CNR FEM with a Light Use efficiency approach. The gross primary productivity (GPP, gC m^2 day^{-1}) is defined like the speed to which radiant energy is transformed, by the photosynthetic activity, in organic substance. *Theoretical maximum quantum canopy efficiency* represents the parameter species-specific that describes the maximum ability of converting the electromagnetic radiation (in optimal conditions) in organic carbon. The *maximum quantum canopy* efficiency is reduced in *quantum canopy efficiency* by the influence of modifiers that determine the effect of the climate, fertility, site and, age of the forest on the daily productivity in not optimal conditions of growing. The interception of the radiation from the forest cover (APAR) is determined starting from the global radiation (MJ m^2 or W m^2), previously converted into PAR (mol PAR m^{-2}), from LAI that represents the index of leaf area (m2 of leaves on m2 of covered soil from vegetation) and from k (coefficient of extinction of the light) through the Lamber-Beer law.

- **Autotrophic respiration**: unlike the previous version where the autotrophic respiration was calculated as a constant fraction of GPP (Waring and Landsberg, 1998), with the 5.1 version it is explicitly simulated, in daily temporal resolution, discriminating in separate way, the Maintenance Respiration controlled by a Q10 type response function and Growth Respiration is represented by a fixed ratio (30%) of all newly living tissues produced (Larcher, 2003).
- **Water balance and water competition:** this process is simulated in the same way by the different model versions. In particular, the water enters in the cycle through the precipitation (mm_{H2O} $daily^{-1}$) a part leaves the system by evaporation from the ground (based on the radiation that reaches the ground) , and a part exits by evapotranspiration (ET), according to the covering degree of the cell layers. In particular, both in the dormant and growing season, soil evaporation (ES) is computed using the formula suggested by Penamn-Monteith equation while, only for vegetation season, evapotranspiration is modeled using the approach of Penman-Monteith equation (Campbell and Norman, 1998) as proposed by Feikema *et al.*, (2010) and Liu *et al.*, (2003). Excess water present in the soil is considered lost by runoff or by infiltration into the deep layers of the soil where it is no considered available for the roots.
- **Daily meteorological data:** With the 5.1 version the model implements the daily time step (we stress that it was monthly in the previous version), using several forcing data such as: daily maximum (Tmax; °C) and minimum air temperature (Tmin; °C), soil temperature (Tsoil; °C), vapour pressure deficit (hPa), global solar radiation ($MJm-^{2}$ day^{-1}) and precipitation amount (mm day^{-1}). Furthermore, the model takes into account the day-time and night-time average temperature and if the soil temperature is missing into the forcing data the model can simulate it for the first 10 cm of soil depth considering also, if present, the influence of the snowpack (Zheng *et al.*, 1993; Kimball *et al.*, 1997; Golinkoff, 2010).
- **Phenology and carbon allocation**: An important component to simulate realistically the eco-physiological aspects of the forest is the phenology that plays a crucial role in regulation not only of photosynthesis process but also other processes (Richardson *et al.*, 2012). In the 5.1 version, phenology and carbon allocation is related on six different carbon and nitrogen pools. Five pools represents the principal tree organs: foliage, (fine and coarse) roots, stem, branch and bark fraction. One pool represents the starch and sugar (non-structural carbon,

NSC) content in the whole plant. This last distinction is very important to simulate correctly the leaf phenology and carbon allocation by the NSC mobilization. Another features introduced in the 5.1 version is the estimation of LAI separately for sun and shaded leaves (De Pury and Farquhar, 1997; Thornton and Zimmermann, 2007; Wu *et al.*, 2015). This aspect allows to reduce the effects of the "Big-Leaf" in relation to the quantity to carbon stored to the leaf pool. The phenological mechanism, for deciduous species, follows five transitions phases (Arora and Boer, 2005) that are well described in Collalti *et al.*, (2016). For evergreen species the approach is similar but more simplified.

The carbon partitioning and allocation, instead, considers constant coefficients that are linked to the soil water content and light competition. These coefficients vary each month according to the phenological phase of the simulated forest species (Arora and Boer, 2005) and to the extension of the vegetative period. At the end of each vegetative month, the model calculates the amount of new biomass that is allocated, through variable partitioning ratios according to the availability of limiting resources (Friedlingstein *et al.*, 1999), in the different compartments of the tree (stem, root and foliage). Specifically, the model calculates the amount of NPP that is allocated separately in the three compartments following the Frankfurt biosphere model approaches (Ludeke *et al.*, 1994).

Then with the model version 5.3.3 has been introduced several function to simulate, in its complexity, the climate change aspect allowing:

- to simulate processes occurring in medium/long periods (more than 50 years), such as self-pruning, mortality related to stand age and competition for light and growth
- to consider the progressive future increase in atmospheric CO_2 concentration (i.e. the fertilization effect due to the increase in atmospheric CO_2 and at the same time the relative stomatal acclimatization)
- to consider the thermal acclimatization on autotrophic respiration by predicting a gradual decrease at increasing temperature
- the possibility to set different types of forest management.

3.3. Assumption of the model for climate change

3.3.1. Fertilization effects

The CO_2 enrichment is considered to produce a fertilization effect when the atmospheric CO_2 concentration ([CO_2curr], ppmv) is above the reference level for which the model has been parameterized ([CO_2ref], ppmv) (Veroustraete *et al.*, 2002; Nowak *et al.*, 2004; Ainsworth and Long, 2005; Medlyn *et al.*, 2011, 2015; De Kauwe *et al.*, 2013).

This concept has extensive scientific experimentation and has been demonstrated in controlled environmental conditions for a variety of C3 vascular plants including trees (Norby *et al.*, 1999; Ainsworth and Long, 2004; Huang *et al.*, 2007; Prentice and Harrison, 2009). For example, an increase in NPP of 23% in relation to an increase in CO_2 concentration in free air CO_2 experiments was observed (Norby *et al.*, 2005).

In light of these results and many other studies that have been done over time, (Chen *et al.*, 2000; Rathgeber *et al.*, 2000, 2003; Balshi *et al.*, 2007; Su *et al.*, 2007; Peng *et al.*, 2009), modellers have included the effects of CO_2 fertilization in their simulations of both past and future forest productivity projections, generally resulting in an increase of expected growth in forests under future atmospheric CO_2 concentrations. In this way it is possible to establish a direct link between climate and forest growth dynamics considering various CO_2 projections over time. Furthermore, this inclusion has an important impact on the prediction of carbon sequestration under different CO_2 emission scenarios.

In this context, CO_2 fertilization is taken into account by the 3D-CMCC-CNR FEM model, using a daily CO_2 modifier that increases the efficiency of converting light absorbed into photosynthetates due to increase of CO_2 and closely linked to the daily average temperature (Collatz *et al.*, 1991; Veroustraete *et al.*, 2002)

The formula of the CO_2 modifier (fCO_2) is the following:

$$f_{CO_2} = \frac{[CO_{2\,curr}] - \frac{[O_2]}{2\tau}}{[CO_{2\,ref}] - \frac{[O_2]}{2\tau}} \times \frac{K_m{}^{CO_2}\left(1 + \frac{[O_2]}{K_0}\right) + [CO_{2\,ref}]}{K_m{}^{CO_2}\left(1 + \frac{[O_2]}{K_0}\right) + [CO_{2\,curr}]} \qquad (1)$$

where $[O_2]$ is the atmospheric concentration(%), K_mCO_2 (ppmv CO_2) and K_O (%O_2) are the Michaelis-Menten Rubisco affinity coefficients for CO_2 and the Michaelis-Menten inhibition coefficient for O_2, respectively and τ is the CO_2/O_2 specificity ratio.

As shown by Veroustraete (1994) and Veroustraete *et al.* (2002), $KmCO_2$ and KO are controlled by daily average temperature according to an Arrhenius relationship.

The equation by which all 3D-CMCC-CNR FEM versions (Collalti *et al.*, 2018, under review) consider the dependency of photosynthesis to daily temperature, following Waring and McDowell, (2002), is given by:

$$f_T = \left(\frac{T_{avg} - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_{avg}}{T_{max} - T_{opt}}\right)^{(T_{max}-T_{opt})/(T_{opt}-T_{min})} \quad (2)$$

where f_T is a daily value (0-1) and T_{max}, T_{min}, T_{opt} are maximum, minimum and optimum temperatures for gross assimilation (fT = 0 if $T_{avg} \leq T_{min}$ or $T_{avg} \geq T_{max}$).

A strong relationship between CO_2, temperature and concentration has been shown (Sigurdsson *et al.*, 2002; Medlyn *et al.*, 2011). In particular, when these two modifiers (fCO_2 and fT) are considered at the same time, an optimum temperature increase for photosynthetic processes of about 1-2 ° C occurs (Collalti *et al.*, 2018, under review). This coupling are in line with the data shown by Battaglia *et al.*, (1996) and Kirschbaum, (2000) where the behaviour of fCO_2 is modulated downward causing a progressive deviation from the optimum temperature.

The general equation by which 3D-CMCC-CNR FEM versions (see Collalti *et al.*, 2014, 2016; Marconi *et al.*, 2017) computes the gross primary productivity (gC m^{-2} day^{-1}) is:

$$GPP = \alpha_c \times APAR \quad (3)$$

where:

$$\alpha_c = \alpha_x \times f_n \times (f_T \times f_{CO_2}) \quad (4)$$

α_c and α_x are the current and maximum canopy quantum efficiencies respectively (molC $molPAR^{-1}$), APAR is the Absorbed Photosynthetically Active Radiation (PAR, MJ m^{-2} day^{-1}) from the canopy, and normalized modifiers (f_n) are physiological (i.e. age effect) and environmental scalars (e.g. vpd, soil water) with values between 0 and 1 (for a full description see Landsberg and Waring, (1997)).

3.3.2. Thermal acclimation of respiration

Temperature is considered to be one of the most important regulators of many biological processes including respiration process. Generally in models, when the short-term temperature increases there is, at the same time, an exponential increase in respiration rate. This mechanism essentially depends on an increase in cellular maintenance demand, which is associated an increase in protein turnover and a loss of high temperature membrane (Amthor, 1984; Ryan, 1991). Starting from the general equation:

$$R = R_{\mathrm{REF}} \times Q_{10}^{\left[\frac{T - T_{\mathrm{REF}}}{10}\right]} \quad (5)$$

The respiration dependence on T is therefore the function of basal respiration and Q_{10}, respectively describing the intercept and the degree of curvature of the exponential function that best describes the trend of the respiration between the reference temperature and the temperature choice. The eq. n.6 allows to calculate the respiration to different temperatures, also in absence of experimental data.

Temperature responses of respiratory CO_2 efflux rates from plants, soils, and ecosystems are frequently modelled though exponential functions with a constant Q_{10} value (Reich *et al.*, 2016). This fixed Q_{10} parameter (usually 2.0; Essery *et al.*, 2001; Mäkelä *et al.*, 2006; Golinkoff, 2010; Chen and Zhuang, 2013; Smith and Dukes, 2013) implies that respiration increases exponentially with temperature leading to a gross over- or underestimation larger at local scale rather than at global scale (Atkin *et al.*, 2008; Kattge *et al.*, 2009). To date, this considered not completely realistic since it means that respiration has to constantly increase to increasing temperature.

To obviate to this 'modelling problem of realism', the model adopted the formulation proposed by Atkin and Tjoelker, (2003) and Smith and Dukes, (2012) in considering the thermal responses of plants to increasing temperature i.e. the "Type I" or "short-term acclimation" and the "Type II" or "long-term acclimation".

Therefore, we included the Q_{10} modification proposed by Tjoelker, *et al.,* (2001), Atkin and Tjoelker, (2003) and recently by Smith and Dukes, (2013) that more closely matches the instantaneous response of maintenance respiration (R_{mTx}, gC m^{-2} day^{-1}) (i.e. 'Type I' or 'short-term' acclimation *sensu* (Atkin and Tjoelker, 2003; Atkin *et al.*, 2005, 2008) within the calculation expressed by the two following equations:

$$Q_{10} = 3.22 - 0.046T_x \quad (6)$$

$$R_{T_x} = R_{ref} Q_{10}^{\left(\frac{T_x - T_{ref}}{10}\right)} \quad (7)$$

where, R_{ref} is the basal respiration rates (0.218 gC gN^{-1} day^{-1}; Ryan, 1991; Thornton *et al.*, 2007) at the reference temperature Tref (20°C; Thornton *et al.*, 2007; Reich and Oleksyn, 2008; Collalti *et al.*, 2016), T_x is the temperature for each of the five respiring (live tissues or substrates) pools considered by the model: daily average daytime and night-time air temperature for leaves, daily average air temperature for stem and branch, and daily average soil temperature for fine and coarse root pools, respectively. Maintenance respiration for each pool x is computed as in Cox (2001) based on tissue Nitrogen amount (N_x, gN m^{-2}) within each live biomass pool such that:

$$R_{mTx} = R_{T_x} N_x \quad (8)$$

Hence, when respiration is assessed on a proportional basis all species, exhibit similar degrees of change while, on an absolute basis, the degrees of change is higher for species with the highest N concentration.

The implementation introduced with maintenance respiration leads to a decreasing response of respiration to an increase in temperature (at a peak temperature of 35 °C as in Smith & Dukes, 2012) via a sixth-degree polynomial function and reflects an instantaneous response of respiration to temperature as a biochemical adjustment to this stimulus (Atkin and Tjoelker, 2003).

The second modification implemented within the model represents the likely result of a biogeochemical plant adjustments and/or biogeochemical feedbacks in the long-term response of respiration rates to temperature (R_{Maccl}, gC m^{-2} day^{-1}) (i.e. ‘Type II’ or ‘long-term’ acclimation Atkin and Tjoelker, 2003; Atkin *et al.*, 2005, 2008) through:

$$R_{M_{accl}} = R_{mT_x} 10^{A(T_{10days} - T_{Ref})} \quad (9)$$

where A represents a constant temperature correction factor for acclimation (-0.00794, Atkin *et al.*, 2008, Smith and Dukes, 2012), T_{10days} the preceding 10 days weighted average daily temperature (Campbell *et al.*, 2007; Lombardozzi *et al.*, 2015). This equation leads to a decrease in the temperature-mediated basal rate response curve with increasing temperature as described by Smith and Dukes (2012) and Collalti *et al.*, (2018, under review).

3.3.3. CO_2 control on stomatal conductance

Acquisition of CO_2 by the leaves is accompanied by the loss of water vapour through stomata (Keenan *et al.*, 2013). In the 3D-CMCC-CNR FEM, the effects of increasing CO_2 concentration on the water balance are modelled by a control of stomatal closure. Wang and Nyland, (1996) as well as (Harmon *et al.*, 1990) demonstrated a similar dependence of stomatal conductance on ambient CO_2 from hourly to geological time scales and the high sensitivity of stomata at anatomical level, which translates to a shift in maximum leaf diffusive conductance.

As in Hidy *et al.*, (2016), which is inspired by Franks *et al.*, (2013), 3D-CMCC-CNR FEM includes a CO_2 dependent modifier (f_{CO2st}) based on an empirical power function to describe the quantitative relationship between the relative change of stomatal conductance compared to increased CO_2 concentration and standard conditions through equation 10:

$$f_{CO_2st} = 39.43 \times [CO_{2\,curr}]^{-0.64} \qquad (10)$$

The scalar explicitly controls the maximum species-specific stomatal conductance parameter (g_x, g_{x1} when modified for CO_2 concentration, m sec^{-1}, Booth *et al.*, 2012) annually reduces the g_x value as CO_2 concentration increases with the following equation 11:

$$g_{x_1} = \frac{f_{CO_2st}}{0.9116} \times g_x \qquad (11)$$

This involves reducing current stomatal conductance under elevated CO_2 concentrations, or increasing it under reduced CO_2 concentrations, and varying with air temperature as widely observed (Ainsworth and Rogers, 2007; Keenan *et al.*, 2013).

It is thereby highlighted that assimilation, as in other LUE family models (e.g. Landsberg and Waring, 1997), is not directly coupled to stomatal conductance calculations (*sensu* (Collatz *et al.*, 1991), but is indirectly coupled by the multiplicative method applied for daily assimilation calculation both using the same environmental scalars (fn) (at daily scale for VPD, soil water content, light and temperature) following the (Jarvis, 1976) method as in Thornton *et al.*, (2007) including also the tree age effect (Irvine *et al.*, 2004).

3.3.4. Limitation of the model and uncertainties

The model selected for the simulations, could overestimate or underestimate the process rates that have been described in the previous paragraphs.

In addition, analysing the underlying model assumption in using the Rubisco limitation for CO_2 fertilization effects (rather than RuBP-regeneration limitation), places model outcomes at the ‘optimistic’ end of the spectrum of possible CO_2 responses.

In 3D-CMCC-CNR FEM, differently from the assumptions of other models (Landsberg and Waring, 1997; Lasch *et al.*, 2005; Nemani *et al.*, 2009; Friend, 2010; Reyer *et al.*, 2014) that consider the respiration as a fixed ratio of photosynthesis, autotrophic respiration is explicitly computed and is directly related to climate change (through temperature and its acclimation). The fixed ratio method, could misrepresent respiration rates, since it is regulated only by the photosynthetic process (Mäkelä and Valentine, 2001; Smith and Dukes, 2012).

The fixed ratio NPP:GPP has been amply discussed and analysed (Hunt *et al.*, 1999; Mäkelä and Valentine, 2001; Pruyn *et al.*, 2002; Atkin *et al.*, 2007; Campbell *et al.*, 2007; De Lucia *et al.*, 2007; Smith and Dukes, 2012; Campioli *et al.*, 2016) and, it could lead to unrealistic results considering it depends heavily on age (Gratani *et al.*, 2008; Way and Sage, 2008; Vicca *et al.*, 2012). This approach could lead to an estimate of the autotrophic respiration which proportionally could be higher than that obtained considering the fixed ratio.

The 3D-CMCC-CNR FEM does not take into account the concept of efficiency in the use of nitrogen. In fact, this process too could probably have a very important influence by climate change and (Medlyn *et al.*, 2011, 2015; Smith and Dukes, 2012; Lombardozzi *et al.*, 2015). In addition, the model doesn’t represent the nitrogen deposition and nutrient availability (Luo and Al-Dahhan, 2004; Smith *et al.*, 2014; Walker *et al.*, 2015), land use change, changes in species composition, ozone (Anav *et al.*, 2011; Seidl *et al.*, 2011; Reichstein *et al.*, 2013).

3.4. The study site

The Bonis experimental watershed is located in the mountain area of Sila Greca (39°25’15’’ N, 16°12’38’’ E), in the Calabria region (southern Italy). The catchment has a surface of 1.39 km^2, a mean elevation of 1131 m a.s.l. and it was firstly instrumented in 1986. Almost 93% of the total area is covered by forest stand, dominated by 50-60 year old Calabrian pine (*Pinus laricio* Poiret) forests, whose origin was both natural artificial. There are also small stands of chestnut (*Castanea* *sativa* Mill.) and riparian forests of common alder (*Alnus glutinosa* L.). Finally, a small proportion of the catchment (about 6% of the area) has no tree cover and is largely devoid of vegetation. The forest cover characterization has been identified by photographic surveying and by mapping resolution at 1:2000 scale.

The climate is typically Mediterranean, with average annual precipitation of 1124 mm, average temperature of coldest and hottest month of 1°C and 17.1 °C, respectively (Table 1). The annual average temperature is 8.7 °C (data measured at the meteorological station of Cecita, 39°23'1.26" N, 16°32'55.01" E). According to Pavari phytoclimatic classification (1916) the pine forest is located in the warm sub-zone of Fagetum. Geological substrate is constituted by granitic rocks. Soils are characterized by a clay horizon, with illuvial foils clay (Dimase & Iovino, 1996; Castrignanò & Buttafuoco, 2004).

Weather variables	**Values**
Annual Average (T°C)	8.7°
Coldest month (T°C)	1° *(January)*
Hottest month - (T°C)	17.1° *(July)*
Precipitation (mm)	1124

Table 1. Summary of the most important climatic variables for "Bonis" basin.

As a part of the Euroflux-Carboitaly network, in May 2003 a tower for measurement of eddy fluxes was installed at an altitude of 1100 m a.s.l, on a 54 years old plantation of Laricio pine.

The eddy covariance station has been running for 4-5 years, After a detailed analysis of each year recorded, checking data gaps for sensor malfunctions and power failure, year 2007 was chosen for both sensitivity analysis and Bayesian calibration of the model.

3.5. Characteristics of Laricio pine

3.5.1. Geographical distribution

In Italy, the natural area of diffusion of the laricio pine from South to North extends from Sicily to Calabria. In Sicily, the laricio pine grows in some areas of Etna, irregularly distributed on the volcano areas from 1,000 to 2,000 m altitude, on an area of about 4,000 hectares.

In Calabria, the laricio pine forests can be found on the southern slopes of the Aspromonte, distributed between 1250 and 1600 meters above sea level and, above all, on the Sila massif where it significantly characterizes the forest landscape. Overall, according to the data of the National Forest Inventory (INFC, 2007), in Calabria the laricio pine occupies a little over 74.000 hectares, of which only about 5% in Aspromonte. On Sila massif this pine do not constitute a single and homogeneous forest, but they form jagged complexes, i.e. interrupted by pastures, arable land and beech forests, in some areas sometimes mixed with white fir. These forests cover a vast area of the plateau almost to 1600 m of altitude and part of the slopes that branch off in the four cardinal directions (Ciancio *et al.*, 2002). From altitude 900 and up to 1200 - 1300 m a.s.l. almost all pine forests are of artificial origin, planted between 1950 and 1970. The pine forests, like many of the current forest ecosystems, do not have any natural features.

In fact, this species were also used in wood arboriculture plants (Arcidiaco *et al.*, 2000) and is the species most used in reforestation in all the Calabrian reforestations (Sila Greca, western slopes of the Sila Grande, the eastern ones of the Sila di Crotone and Sila Piccola, large areas of the Coscile and Battendiero basin and to a lesser extent on the Coastal Chain, on the Serre and in Aspromonte). The highest planting densities reaches about 3200 plants per hectare, while the most reforestation densities are ranged for about 1000/2500 (Mercurio, 2002).

Their structure, composition and stability, is linked to the continuous interference of forest management, which with the silvicultural interventions can accelerate, or delay, to annul the evolution towards more complex forest systems (Iovino and Menguzzato, 1996).

The data of the surface underline the importance that the laricio pine assume in the Sila's territory of which they represent, as previously said, the characterizing element of the landscape which, although shaped by man, constitutes the most apparent and enjoyable peculiarity of the Sila plateau. The conditions of extreme degradation of the mountainside, following the soil erosion, have allowed the spread of the species that for its eco-physiological characteristics (distinctly heliophilous, xerotollerants, frugal) managed to colonize large areas damaged by fire, cultivated and then abandoned.

3.5.2. Ecological characteristics of species

The Calabrian pine finds optimal conditions with average annual temperature from 10° to 6.9°C, that of the coldest month from 2.4° to -2°C and that of the hottest month from 18.4 ° to 16.3 ° C. The annual precipitation is between 1200 mm and 1800 mm, the summer one between 140 and 200 mm; in this season, in Calabria, the drought periods are attenuated by the presence of mists and nocturnal condensations, while the persistence of snow in the winter period makes it possible to constitute a valuable water reserve.

The Calabrian pine is a pioneer species that requires full light from above, relatively thermo-xerophilous. Calabrian pine begins to produce fruit abundantly at 25-30 years with abundant seed production every 2 years. The anemochory seed dispersal begins in March. The germination capacity is 75-80% and remains high up to 140-150 years. The natural regeneration occurs in the presence of "natural" disturbances (landslides, erosions, fires) or induced by man (cultural techniques). Optimal conditions are in open areas, on mineral soils, in the absence of grassy layers, in these cases there are 9000-10000 seedlings per hectare (Caminiti *et al.*, 2003), while Anzillotti (1950) after 3 years from the fire reports of 40-50 seedlings per m^2. The passage of fire facilitates the renewal that takes place in groups (Del Favero, 2008) but on large areas or following the repeated passage of fire there is the introduction and presence of the poplar species. An obstacle to renewal consists of a very consistent herbaceous or shrub layer. according to some observations made in Sila, Calabrian pines of about 400-500 years old are generally observed (Avolio and Ciancio,1985), but it can be much higher.

3.5.3. Parameterization of species and study site

The data required by the model for parameterization’s step of the species are parameters that represent several eco-physiological factors that can be obtained from the existing literature or from field surveys (see Table 1 in *supplementary material*).

3.6. Weather data

3.6.1. Historical climate data

The 3D-CMCC-CNR FEM model utilises daily time series of meteorological input data related to the area of interest (in this case the Bonis basin). The main weather variables required by the model are precipitation (mm/day), minimum and maximum air temperature (°C), global solar radiation ($MJ/m^2/day$), vapour pressure deficit (mBar) (alternatively, relative air humidity) and annual atmospheric CO_2 concentration (ppmv).

For weather data, the choice of the reference weather station is accomplished taking into account the availability, quality and completeness of the recorded time series. It was initially examined the possibility of using the data recorded by the weather station of the Eddy Covariance Tower. However, this station has recorded data for a time interval extended to four years, between 2005 and 2008. Hence, in order to obtain a sufficiently long series of daily weather dataset suitable to model the forest stand in the basin area has directed the choice of reference station to that of Cecita, located a few kilometres away from the Bonis basin. For that station precipitation records are available from 1923 to 2016, while mean, minimum and maximum temperature from 1955 to 2016, global radiation and air humidity from 2000 to 2016, although with some gaps. In order to verify that the Cecita station (CS) was representative of the climatic variability of the Bonis, the correlation between the two stations was analysed through the comparison of the recorded data in the 2005-2008 period. The comparison was made for each of the measured meteorological quantities, calculating R^2 (Table 2).

Weather parameters	**R^2**
Precipitation (mm)	0.61
Mean temperature (°C)	0.95
Min. temperature (°C)	0.82
Max temperature (°C)	0.93
Global radiation (MJ/m2/day)	0.85
Relative humidity (% rel.)	0.73

Table 2. R^2 values of the correlation between the weather stations at Cecita and the Eddy Covariance tower.

In order to complete the daily time series of meteorological parameters related to Cecita station, it was decided to use a Weather Generators; MT-CLIM (Thornton and Running, 1999). MT-CLIM, a mountain of microclimate simulation model, developed in the past years by the United States Department of Agriculture (USDA) was selected as a suitable weather generator (Thornton and Running, 1999). The choice was made mainly based on the simplicity of use of the model, the type of data required as input and results provided as output. This choice allowed the generation of missing meteorological data series, based on the characteristics of the measured data, relating to weather variables required as input from the 3D-CMCC-CNR FEM. The data generated by MIT-CLIM were then compared to the available time series, in order to assess the quality of the reproduced weather data. For a single year of simulation, the MT-CLIM model generates daily values of global solar radiation and vapour pressure deficit starting from precipitation and air temperature. The model requires input parameters on the "reference site", i.e. the station for which the time series of the input meteorological parameters are available (Cecita), and the "site", that is, the area for which we want to generate data output (Bonis). The starting parameters are: latitude, altitude, slope, slope exposure, gradient of minimum and maximum air temperature, mean annual precipitation. In addition, the average daily values of precipitation, maximum and minimum temperature recorded by the "base station" at a specific year are also required.

3.6.2. Climate scenarios

The bias corrected daily climate projections provided by the "*Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici*" (CMCC). Data were generated by the ISC Division and bias-corrected by the IAFENT division at Viterbo, Italy (http://www.cmcc.it/it/divisions).

Original climate projections come from COSMO-CLM simulations performed under the project GEMINA (Project Italian MIUR/MATTM n. 232/2011), at ca. 0.0715° grid resolution and for the period 1971-2100. COSMO-CLM was forced by the global model CMCC-CM (Scoccimarro *et al.*, 2011), using 20C3M forcing (i.e. GHGs as observed in the 20th century; http://www.ipcc-data.org/ar4/scenario-20C3M.html) from 1971 to 2005 and two IPCC-AR5 emission scenarios from 2006 to 2100: Representative Concentration Pathways 4.5 and 8.5 (hereafter RCP).

The RCP4.5 assumes that total radiative forcing is stabilized, shortly after 2100, to 4.5 W m^{-2} (approximately 650 ppmv CO_2-equivalent) by employing various technologies and strategies to reduce GHG emissions. The RCP8.5 is characterized by increasing GHG emissions and high GHG concentration levels, leading to 8.5 W m^{-2} in 2100 (approximately 1370 ppmv CO_2-equivalent).

The bias correction approach adopted is described in Sperna Weiland *et al.,* (2010, Eqs. 1 and 3), and it uses an additive correction for temperatures and a multiplicative factor for precipitation, starting from observed series of the same variables.

3.7. Scenarios of forest management

Several researches, especially in recent years, have proven the role of the forest management for mitigating the increase of CO_2 in atmosphere. (Johnson and Curtis, 2001; Guo and Gifford, 2002). In particular, forest management influences carbon pools, fluxes and productivity, evapotranspiration rate. This modifies can be instantaneous (thinning) or slowly with fertilization activity (Nabuurs *et al.*, 2007).

In particular, it is used the scenario-technique to provide decision makers with various options of possible developments in the future (von Gadow and Puumalainen, 2000) and as a helpful tool to allow overcoming the limits of long-term effects of forest management (for an overview see e.g. (Nabuurs *et al.*, 1998)

In the context of this study, management scenarios are used to analyse the effects of alternative silvicultural management regimes and climate change on a set of ecosystem services (timber production, carbon storage, carbon fluxes), employing a simulation-based scenario approach.

The 3D-CMCC-CNR FEM the variables considered are:

- thinning intensity (percentage of stand basal area to be removed based on total stand basal area)
- thinning interval (years between operations)
- rotation length and no rotation option (NR)

Each variable is considered and then parameterized at the species-specific stand level by the user.

After the rotation practice, the stand is replanted with 1.100 plants/hectare for all cases.

The different scenarios are chosen for reflecting different degree of forestry management. In particular, it is possible to assume a long-term scenarios (e.g. 90 years), for studying patterns of fluxes and stock carbon. The experimental design has been the following (Table 3):

a) without Practice (WP): this scenario does not include any type of forest management
b) reference management (BAU): is based taking into account the usual density, rotation length and interval according to the local forest regulations (PMPF, 2007).

Following an adaptive approach, different management factors combinations were chosen:

Thinning Intensity (%)	**Thinning Interval (year)**			**Rotation length**			
25	10	15	20	70	90	110	NR
20							
15							

Table 3. Forest management options used in the simulations

“No rotation” is a scenario of “continuous cover forestry”: further to being an option that is more and more frequently applied in European forestry, the scenario was chosen also because the model does not allow for intermediate levels of final harvest. In particular, considering that laricio pine is a light-demanding and frugal species with a close to thermoxerophile adaptation, the most appropriate form of silvicultural treatment would be represented by clear-cut on small surfaces or in groups or patches (Carullo, 1931; Anzillotti, 1950, Pavari, 1953; Meschini and Longhi, 1953), leaving. 50-100 plants ha^{-1} as “reserves” (and seed trees).

3.8. Site data

The model has been validated by comparing growth rates with the historical data coming from several data sources and comparing the output model to 2007 forest state. With this strategy, it is possible to reconstruct the whole history of the forest.

In particular, 3D-CMCC-CNR FEM, before using simulations under different scenarios and data management strategies, is applied to "Bonis" basin for the period 1965-2007. The historical situation of the forest is rebuild using these information:

- **afforestation in 1965**: in the second half of the last century, a huge reforestation action was carried out in Calabria, with a predominantly protective purpose. An important preliminary step to the execution was the choice of conifers to be used in the sub-mountain areas. Particular attention has been concentrated to the indigenous and exotic coniferous indicated in 1952 by Pavari (Maiolo, 1998) as potentially suitable for ensuring effective and fast forest cover of the soil or to improve and diversify wood production. The main purpose was, as mentioned, the fulfilment of essentially protective tasks. The plant was planted on terraces (gradoni) traced along the level curves, spaced on average 4 m, inside which holes of 40x40x40 cm were opened every 1.5-2 m to plant seedlings of 2- 3 years. The mean value, therefore, was 1100 plants per hectare (n ha-1), with variations (1050-1250 n ha-1) determined by the degree of the soil slope.
- **Thinning in 1993**: The Bonis basin was interested by a thinning with high intensity (Table 4), which provided for the removal of 15% of basal area equal to about half of the trees present (Callegari *et al.*, 2003). This silvicultural action was simulated with the 3D-CMCC-CNR FEM model for the validation model approach.

YEAR	Variables	Values
1986	Plant number (N/ha)	1120
	Basal area (m^2/ha)	43.2
	DBH (cm)	20.2
1993*	Plant number (N/ha)	1100
	Basal area (m^2/ha)	46.6
	DBH (cm)	21.8
1993**	Plant number (N/ha)	700
	Basal area (m^2/ha)	32.4
	Diameter (cm)	22.8
1999	Plant number (N/ha)	690
	Basal area (m^2/ha)	45.8
	DBH	27.4

Table 4. Historical dendrological analysis. 1993 represents the dendrological measure before the thinning, while 1993** the dendrological data right after the thinning (DBH = diameter at breast height).*

- **Plots in 2016**: The surveys have been performed on 36 circular permanent plot (Figure 4), with dimensions of 20 m radius and centred on the point of sampling to the ground, distributed in the basin area, selected also in order to characterise the different stand type in the basin.

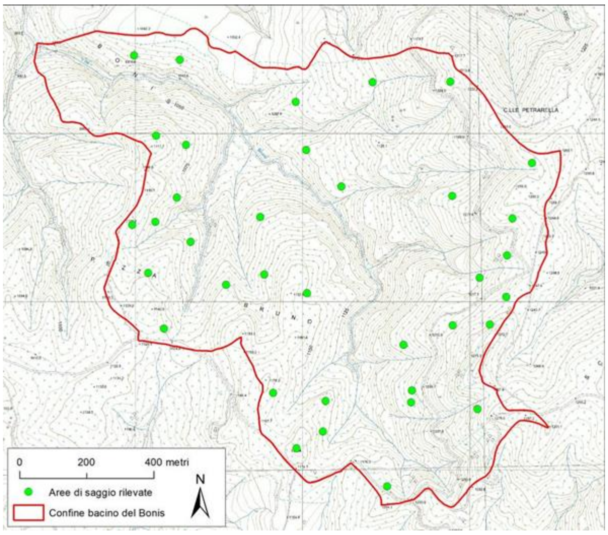

Figure 4. Spatial distribution of plots detected within the experimental basin of Bonis

For each test area a site description (silvicultural treatment, population structure, recent management practice, natural forest renewal types, coverage and damage, evidence of fire passage, abundance of dead wood on the ground), and the classical dendrometric measurements (position of trees, species, diameter at breast height, total height and height of crown insertion, vitality, morphological damage) was carried out.

Moreover, from 10 dominant or co-dominant trees with good shape of the stem, canopy and without wounds, 2 incremental sample were extracted with the Pressler increment borer at about 1.30 m from the ground. The sampling was performed in a perpendicular direction to the tilting of the land surface, considering the hypothetical formation of reaction wood (Fritts, 1972) and aiming at reaching the marrow. The choice of plants has been made to reduce, in the anular amplitudes, the presence of disturbance caused, for example, by scar tissue due to mechanical wounds, by torsion of stem that makes it difficult to read every annual amplitude, to the intra-specific competition (typical of the plants dominated and / or co-dominated). Sample preparation was carried out according to the standard procedures used in dendrochronology (Fritts, 1976).

3.8.1. Dendrological and dendrochronological analysis

From the performed surveys it is possible to rebuild the history of the forest within the Bonis Basin and moreover, it is possible to find a solid relationship between diameter and height using 140 model tree taking into account all the present diameter classes (Figure 5). The height vs. diameter curve was fitted with the Prodan function (1944). In particular, the coefficients found for the Prodan formula are: b_0:8.9, b_1:-0.2 and b_2: 0.04

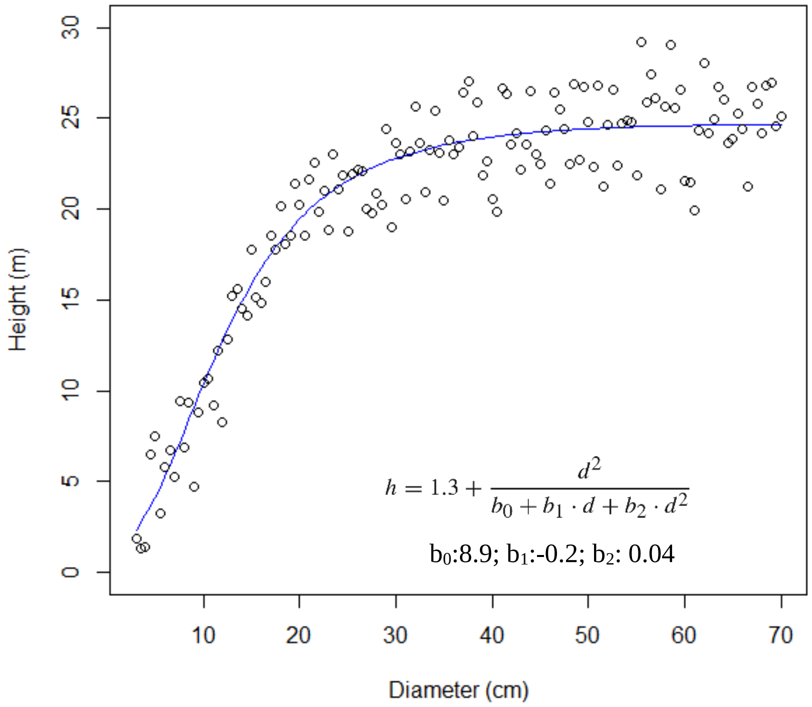

Figure 5. relationship between diameter and height of 140 tree model tree within the basin.

The wood volume was determined by the allometric equations developed for Mediterranean pines for the National Inventory of Forests and Forest Carbon pools (Tabacchi *et al.*, 2011). Below (*Table 5*) the summary of the main dendrologic characteristics of the stand at 2016.

Variable	**Values**
n/ha	670
Average tree height	24 m
Average DBH	33 cm
Volume	670 m^3/ha

Table 5. Dendrologic characteristics of the pine stand at 2016

For the dendrochronological data, cross sections and cores were stored in a fresh-air drying chamber and sanded a few months later, before ring-width measurements were carried out. Ring-width measurements were executed using LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany), read with a Leica MS5 stereomicroscope, and analyzed with the TSAP software package. The ring-width series were plotted and visually synchronized for identification of errors during the measurements and of potential missing or double rings (Fritts, 1976). In particular, cross-dating and correction of any measurement errors were made with both skeleton plot and statistical approach, through the "dplR" R package. The synchronization was performed by visual and statistical method using the Cross Date Index (CDI), a synchronization index calculated by TSAPWin and resulting from the combination of a non-parametric Glk-Gleichlaeufigkeit function (Eckstein and Bauch, 1969) that represents the overall measure of similarity between series, and Student's (Rinntech, 2003) test both used to evaluate the correlation between the series of ring width. Synchronization is considered acceptable with CDI> 10 (Rinntech, 2003).

Based on the results obtained from these measurements it was possible to average the 15 individual series into a mean stand chronology (54±4 years old) and consider it representative for the forest involved in the study.

Below is reported a summary graph (Figure 6) that represents, year-by-year, the growth dynamics of diameter, height and Current Annual Increment (CAI in m^3 ha^{-1}) representing the entire monitored stand.

After the thinning in 1993, a slightly increase of diameter growth rate is registered but not so much for the height.

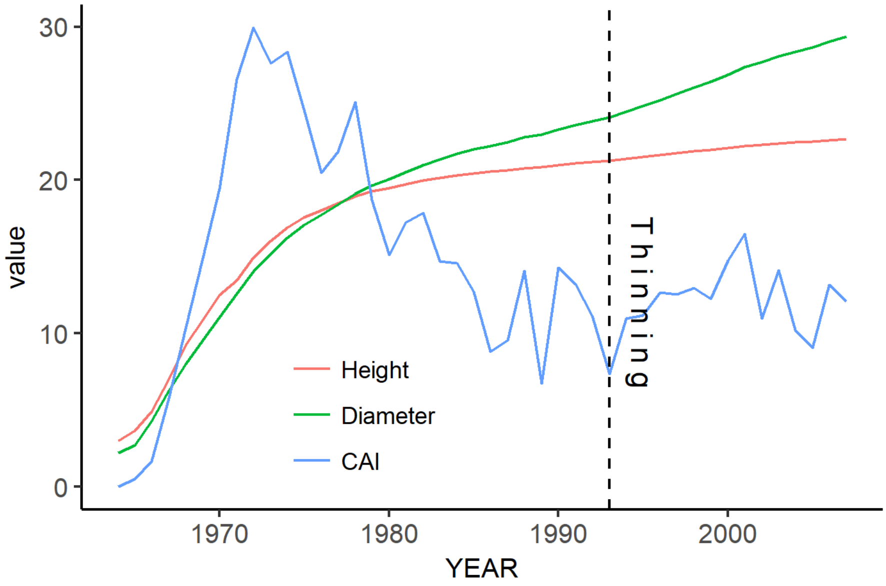

Figure 6. growth development of the stand: CAI (m^3 ha^{-1})- red line, DBH (cm)- green line and tree height (m) – blue line

For validation of the model and for simulations of scenarios three different time periods are considered:

- validation under measured climate: the time window for validation is from 1965 to 2008
- validation under modelled climate scenario: the time window is from 1976 to 2008
- forecast simulation: the time window is from 2006 to 2095. For analysis of results, this time window is then divided in “Near Future” (NF, 2020 to 2050) and Far Future (FF, 2050 to 2095).

For each of these growth phase the model is initialized by different values of diameter, height and number of plant as reported in Table 6

Year start	DBH (cm)	Height (m)	N. plants/ha	Age
1965	1.5	2	1100	2
1976	16.8	17.5	1100	31
2006	22.9	30.1	680	42

Table 6. Dendrological data used for initializing the model at different time step

3.9. Model evaluation and methods of analysis

3.9.1. Sensitivity analysis.

A model sensitivity analysis has been performed to determine for which eco-physiological parameters the 3D-CMCC-CNR FEM was more sensitive (Nicholson and Possingham, 2007; Naujokaitis-Lewis *et al.*, 2009; Fullerton *et al.*, 2010).

The sensitivity analysis lets to know in deep, which is the importance of different modelling processes and at the same time allows to determine the most influential parameters involved.

In a complex ecological model, like 3D-CMCC-CNR FEM, the application of “one-parameter-at-a-time” sensitivity methods is an inadequate choice (Saltelli and Annoni, 2010). First, while a single parameter value varies, the problem is to know the values of the other parameters that should be kept constant. This could have significant consequences on the results of the analysis (Wagner, 1995). Secondly, ecological models are very complex and the interactions among factors are often nonlinear. Changing two or more parameters at the same time may produce a strong variations in output results compared with an one-at-a-time parameters variation (Ciannelli *et al.*, 2004).

For this reasons for the sensitivity analysis the 3D-CMCC-CNR FEM is considered as a black-box, where it is not known a priori neither what it contains nor how it behaves. With this assumption, it is possible to study its behaviour solely by analysing the responses (*output*) produced according to the *input* it receives. In other words, it is possible to consider the ecological model as it is, without any specific hypothesis about its structure (Pappas *et al.*, 2013).

First, it is important to select the variable of interest. The 3D-CMCC-CNR FEM model has many output variables because several processes are implemented. For this study, the sensitivity analysis is conducted on GPP (Gross Primary Production) and LE (Latent Heat) variable. This choice comes from the intention of studying in detail the carbon and water cycles in the Laricio pine forest selected.

3.9.1.1. Screening approach: Elementary effects (Morris method)

For this analysis, a screening test was applied to select a group of the most important model parameters.

One of the most widely used and recognized methods in scientific literature is the method of Morris (1991), also called the Elementary Effect (EE, Saltelli *et al.*, 2007).

This method aims at determining the importance of input parameters on the basis of the effects on the model outputs. In particular, it is possible to determine which are the input parameters with a i) negligible, ii) linear and additive, iii) non-linear effect or involved in interactions with other parameters. This is possible because the method calculates two kind of sensitivity magnitudes, the mean (μ) and the standard deviation (σ) for parameter ranking. In particular, the μ indicator assesses the overall influence of one parameter and the resulting effects on a single variable in model output. The higher μ is, the more the input contributes to the dispersion of the output values. The σ estimates the non-linear and/or interaction effects between parameters on the outputs, and the parameter's higher order effects, such as interactions with other parameters or non-linear effects on the outputs. If σ is small, elementary effects have small interaction with other. Otherwise, the larger σ is, the less likely the linearity hypothesis is and in addition the parameter can be considered having non-linear effects, or being implied in an interaction with other, one or more, variables (Saltelli *et al.*, 2004). Low values of both σ and μ correspond to a non-influent input.

Campolongo *et al.*, 2007 contributed to improving the estimation of μ with the introduction of μ* (absolute value of mean). This change allows a robust metric sensitivity especially for non-monotonic functions and avoid minimising the inverse effects on the mean.

In this study Global Index (GI) is calculated to facilitate the interpretation of the results and the ranking of parameters, according to the Euclidian distance (Campolongo *et al.*, 2007; Saltelli and Annoni, 2010; Ciric *et al.*, 2012). GI is defined as:

$$GI = \sqrt{\left(\mu_i^*\right)^2 + (\sigma_i)^2} \qquad (12)$$

the computational cost of this analysis is calculated by this formula:

$$r \times (p + 1) \qquad (13)$$

where, r is the number of elementary effect computed per parameter, and p is the number of parameters, involved in this analysis.

3.9.2. Quantifying uncertainties: a Bayesian Approach

In 3D-CMCC-CNR FEM, different tree species are represented, by the same eco-physiological parameters but obviously with different values, reflecting the different species traits. Overall, it follows that the accuracy of the investigated variables is strongly influenced by the reliability of eco-physiological parameterization.

In this context, the evaluation of variables of interest through the use of a Process-Based Model is strongly connected to the complex parameterization phase.

In this regard, Bayesian statistic allows to overcome this complexity by allowing the estimation of the uncertainty associated with both input parameters and output variables (Van Oijen *et al.*, 2005).

The method involves estimating the uncertainties associated with input parameters considering them as a prior probability distribution. In turn, output simulated data are compared with the measured data and the result obtained will be used to update the distribution probabilities of the parameters, providing updated posterior parameter distribution. In this way, the Bayesian statistical method combines probability distributions of input parameters and observed output variables to quantify uncertainty in parameters. To perform a simulated output analysis with the associated uncertainty, the method uses the step-by-step updated parameter uncertainty.

From the reasons above discussed the Bayesian statistical method was then used to calibrate 3D-CMCC-CNR FEM.

During calibration, measured independent data from different sources were used to update the probability distribution of input parameters. In particular, as above described, both GPP and LE were considered for the Bayesian calibration.

3.9.3. The Bayesian calibration framework

Bayesian calibration is a method based on probability theory to parameter evaluation (Jaynes, 2003; Sivia, 2006). In the method, both the input parameters and the output variables do not have single values but as probability distribution.

This characteristic limited its spread in the past (Svensson *et al.*, 2008). However, recently, the development of Markov Chain Monte Carlo techniques has overcome the computational problems. In particular, this approach is currently used in ecological modelling (to estimate directly parameter uncertainty in terms of probabilistic distributions density for possible parameter values (Ghazoul and McAllister, 2003; Van Oijen *et al.*, 2005; Hartig *et al.*, 2014)

Based on the assumption that the knowledge of some of the eco-physiological parameter (and mostly for Pinus laricio) is very weak, the purpose of the calibration is to know the most likely probability distributions (called posterior), within an initial range and distribution well defined (called prior). The probability distributions are calculated in relationship to the likelihood of the model output being equal to the measured data (Svensson *et al.*, 2008).

For this work a version of Markov Chain Monte Carlo (MCMC) known as the Metropolis-Hastings random walk is used (Robert and Casella, 2004) with the aim to obtain the posterior distribution investigating the total parameter space. Bayes' theorem is written below in a simplified form for GPP:

$$p(\theta|GPP) \propto p(GPP|\theta)p(\theta) \tag{14}$$

Where GPP is the Gross Primary Production observations, $p(\theta|GPP)$ is the posterior distribution of the parameter value θ, $p(GPP|\theta)$ is the likelihood function for θ and the factor $p(\theta)$ is the prior distribution for θ (Van Oijen *et al.*, 2005). In other words, the likelihood function modifies the prior assumptions and computes the probabilistic distribution density of observed data. The estimation of the posterior distribution is usually also performed using Markov Chain Monte Carlo method (MCMC).

3.9.3.1. Prior distribution

This step is very crucial because the knowledge about the parameter value, before calibration, should be translated in prior probability distribution $p(\theta)$ and should be based on observations, literature survey and/or experience.

However, there is not always enough knowledge about the parameter values, moreover the parameters are not only species-specific but, sometimes, also site-specific. These features make their estimate not only very difficult, but labours and time expensive. For this reasons, it is generally better to choose a wider range of the prior parameter, because the posterior distribution can have uniquely the same upper and lower bounds of the prior distribution.

Regarding the parameter distribution, the uniform Probability Density Function (PDF) is chosen when priori information is not available. This approach can be found in many studies (Box and Tiao, 1992; Medlyn *et al.*, 2005; Bernardo and Smith, 2008; Wramneby *et al.*, 2008; Bagnara *et al.*, 2015). There are some weak points regards the uniform distribution: first, it may cause an overestimation of model uncertainty and of the sensitivity process, as parameter combinations may also include "unrealistic" values. In order to overcome this problem some parameters values were calculated by maintaining a constant ratio between them (Pappas *et al.*, 2013).

3.9.3.2. The likelihood function

The likelihood function represents a measure of model performance, that is, how well the model is able in reproducing the physical phenomenon. It can take any form of probability distribution, in accordance with the trend of differences between observations and simulated data.

In our case, the likelihood function (eq. 15) takes into account that the model error, i.e. the difference between the observed GPP (Oj) vs. simulated GPP (Sj) is normally distributed, M is the standard deviation of the model error, and n is the number of observations (sample points).

$$\log L = \sum_{i=1}^{n} \left(-0.5 \left(\frac{O_i - S_i}{M_i} \right)^2 - 0.5 \log(2\pi) - \log(M_i) \right) \qquad (15)$$

This assumption is quite useful, because it considers several output variables and error estimates. Further discussions about choice of likelihood function and error models can be found in Engeland, Xu and Gottschalk, (2005), Gallagher and Doherty, (2007) and Yang, Reichert and Abbaspour, (2007).

In particular, to avoid rounding errors due to probability values that can easily become very small, it is strongly recommended to use the logarithmic transformation of the likelihood function. For this reason, the term usually found in technical language "summed log-likelihood" is sometimes used as a synonym for "log of the data likelihood".

3.9.3.3. Posterior distribution

The main result of Bayesian calibration is the estimation of parameters uncertainty and consequently of variables uncertainty that does not derive from analytical formulas but it is an extraction of a large sample of parameters values from the posterior distribution. This sample is used for the phase of scenarios simulation. The maximum log-likelihood represents the value of the parameter vector at which the posterior probability distribution has its maximum.

The number of candidate parameter sets in the sample is equal to 10% of the length of the Markov Chain, not considering the burn-in phase.

To calculate the model results, the parameter set with maximum log-likelihood was used as the main result of the model, while the model uncertainty was calculated at 5% and 95% percentile (Levy *et al.*, 2017) for the GPP and LE distribution resulting from the model calculations for each parameter set in the MCMC sample.

3.9.3.4. Algorithm used

The algorithm used to estimate the posterior distribution combine two methods that are apparently very different but in reality are complementary. In particular, it was used both the genetic algorithm called Differential Evolution (DE) (Price *et al.*, 1997) and Markov Chain Monte Carlo (MCMC) for global optimization over real parameters space (Gilks *et al.*, 1996).With the use of MCMC it was possible to generate a sample from target distribution of parameters. The use of DE and MCMC in a synergistic way is used often in many sectors, particularly for their versatility and adaptability to several cases. Many researchers explored the solution to combine both genetic algorithms with MCMC (Liang and Wong, 2001; Liang, 2002; Laskey and Myers, 2003) and always in a more efficient way adopting for example, in the early 1990s, replica exchange MCMC and direction sampling (Gilks and Roberts, 1996).

In addition, an important problem in MCMC was solved with the combination of DE and MCMC, namely adaptation in scale and progressive orientation for the jumping distribution (Braak, 2006).

In the present study, the Bayesian Tools R package was used (Hartig *et al.*, 2017).

The convergence of the MCMCs was assessed through the Gelman-Rubin diagnostic that was proposed to measure the degree of convergence of the calibration by analysing the difference between multiple Markov chains (Gelman and Rubin, 1992). In particular, the degree of convergence was estimated through the comparison of between-chains and within-chain variances. The reference value for considering that the chains are converged is <1.1. No convergence is indicate by a number greater than 1.1 (Gelman and Rubin, 1992; Brooks and Gelman, 1998).

3.10. Validation strategy

The validation phase of the model did not only affect the variables involved in Bayesian calibration at daily timescale, but included the year by year dynamics of tree growth starting from the planting date (1965) to eddy covariance monitoring date (2008), and accounted, as above specified, for the forestry treatment that occurred in 1993. In particular, other variables are involved in model validation process:

- Mean tree height;
- Mean DBH;
- Current annual increment (CAI);

With diameter at breast height (cm) and tree height (m) it is possible to reconstruct the volume of the stand and the current annual increment. This methodological approach allows to obtain the carbon accumulation both at the tree level and at stand level. We assume that the carbon content of biomass is approximately the 50% of the wood mass (Joosten *et al.*, 2004).

CAI (m^3 ha^{-1}) represents the annual increase in volume, of a particular tree or stand age. It is determined by annual measurements/estimations of standing volume and it is a fundamental information to support forest management and planning.

In this scenario, the validation approach is executed by the result of the Bayesian inference, in which the goodness of fit is usually evaluated via posterior predictive simulations. This concept is important because the model simulates the new data exploring the parameters values estimated from posterior distributions, and subsequently the simulated result are compared to the measured data.

To obtain a range of uncertainty, 1000 draws (runs of model's simulation) from the posterior distribution were simulated, not considering the burn-in phase. In particular, the model results are calculated by parameter set with maximum likelihood. while the model uncertainties were calculated between the 5% and 95% quantiles of the variable distribution resulting from the model calculations for each parameter set in the MCMC sample. In addition, to calculate the uncertainty, the Normalized Root Mean Square Error (NRMSE) and Percent Bias (PBIAS) are applied to the data obtained from the calibration compared to the measured data. NRMSE is expressed as a percentage, where lower values indicate less residual variance. In many cases, especially for smaller samples, the sample range is likely to be affected by the sample size which may hamper comparisons. PBIAS index measures the average tendency of simulated values to be higher or lower than the observed data. In particular, a value close to zero indicates high model accuracy, positive values indicate overestimation bias, while negative values indicate a model's underestimation.

3.11. Simulation experimental design under climate and management scenarios

For Bonis site, 108 combined forest management options and 1000 runs each has been performed, from 2006 to 2095.

In particular:

1. three different forcing scenarios (reference climate, RCP4.5, RCP8.5)
2. three CO_2 concentration options: stable CO_2 after 2006 or varying consistently with RCPs
3. two management options: no management (i.e. leaving the stand to develop without thinning after 2006) or the Business-As-Usual (BAU) management scenarios
4. two alternative thinning intensities (±5%) combined with two different thinning intervals (±5 years).
5. three alternative rotation and a case without rotation (continuous cover forestry).

The uncertainty analysis is performed by comparing forest management scenarios against the no management case. In particular, we analysed the dynamic development of a suite of modelled key variables that are needed to understand some aspects of the eco-physiological factors of the forest, such as: gross primary productivity (GPP), net primary productivity (NPP), autotrophic respiration (Ra) and C-woody stock that is the aboveground wood and coarse roots, to which the harvested aboveground wood is added.

In addition, the analysis is organised in a full factorial analysis design to assess the effects of forest management and with alternative management schemes taking into account CO_2, thinning intensity, thinning interval, rotation, climate scenario. The aim of this analysis is that to identify the most influential results that explain the variability of the results (Mason *et al.,* 2003).

4. RESULTS AND DISCUSSION

4.1. Sensitivity analysis results

In accordance with Pareto's principle, only 5 parameters, out of 52 originally examined, were selected for detailed assessment after the "complete" sensitivity analysis (Figure 7). Those are the parameters for which Gl is above 0.25.

In particular, from *SAP_B* (one of the two parameter involved in the computation of tree sapwood area), the most influential parameter, down to *GrowthOpt* (the optimal temperature at which photosynthesis occurs at the maximum rate for pine), the model has shown to be more sensitive for GPP and LE.

Specifically, sapwood area is responsible to conduct water and nutrients to the foliage, and stores water (e.g., Waring & Running 1998) and into the model it is used to calculate the annual maximum attainable Leaf Area Index (LAI, m^2m^{-2}) following the 'Pipe model' theory (Shinozaki, 1990). Another important parameter is the *Alpha_max* (maximum quantum canopy efficiency, $molC\ molPAR^{-1}$), which represents the maximum capacity of the species to convert the absorbed PAR (Photosynthetically Active Radiation) into phosynthetates under unstressed conditions. We stress that the 3D-CMCC-CNR FEM simulates GPP uses the light use efficiency method of Monteith for photosynthesis (1972, 1977).

Another important parameters is *GrowthOpt*, which represents a species-specific optimum temperature for photosynthesis. In fact, temperature distant from this optimum may lead to a slowdown of metabolism due to the alteration of enzyme activity, especially under conditions of high or low temperatures for prolonged periods (Davidson and Janssens, 2006).

Two other parameters to which modelled GPP and LE showed to be sensitive are *maxcond* (i.e. maximum canopy conductance under unstressed conditions) that is used to calculate the actual maximum stomatal conductance (Jarvis's method) and *Blcond* that represents the canopy boundary layer conductance. Both parameters are involved into the canopy evapotranspiration process.

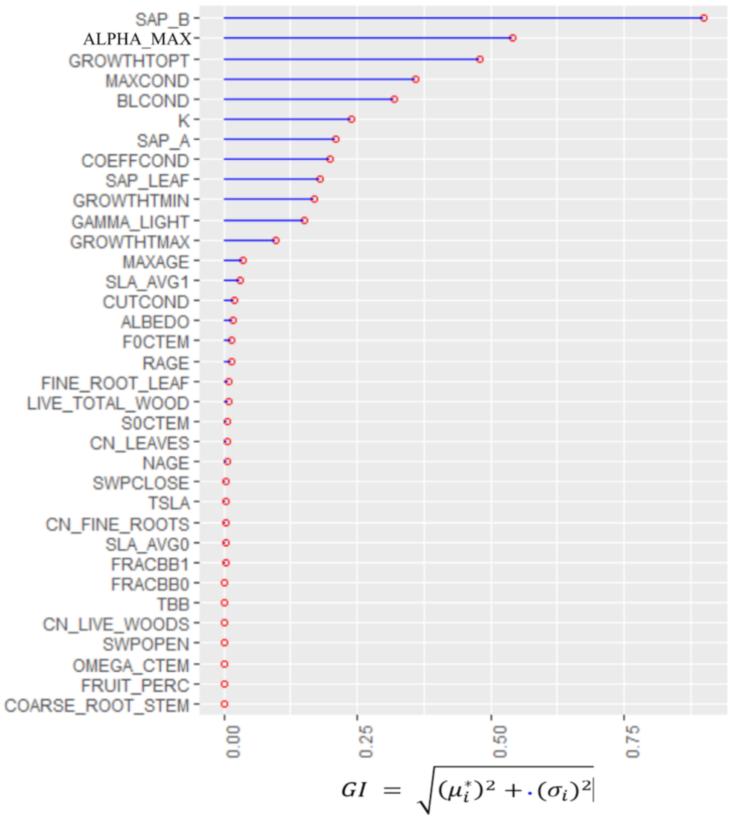

Figure 7. In order of decreasing relevance, the parameters for which GPP and LE are more sensitive

4.2. Calibration results

4.2.1. Convergence of the Markov chains

As a general result, the trace plots (Figure 8) shows a stationary pattern. The trajectories of the chains for each parameter are stable over time and their distribution appears appropriately normal in all cases. Clearly, the uncertainty connected to all five calibrated parameters is reduced and the ranges of plausible values were significantly narrowed through the good convergence of calibration process.

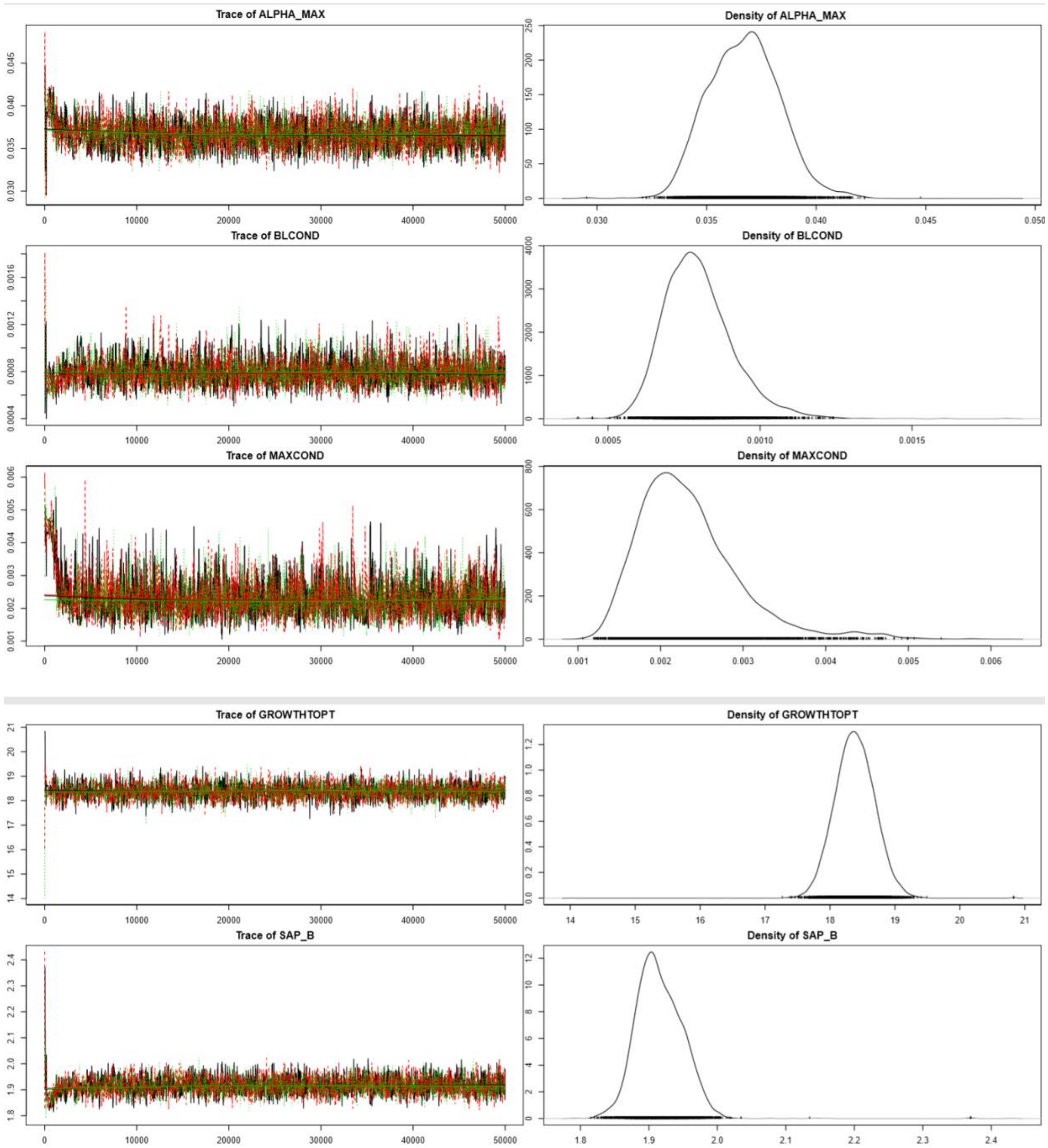

Figure 8. Trace plot on the left (in x axes the number of runs in y axes the range value of the parameters calibrated) and on the right the parameter distribution probability (in x axes the parameters value and in y axes the probability related to)

Moreover, the MCMC (Markov chain Monte Carlo) convergence was evaluated by analysing the difference between multiple Markov chains. The convergence is assessed by comparing the between-chains and within-chain estimated variances for each model parameter. Large differences between these variances indicate non-convergence. The Gelman diagnostic gives the scale reduction factors for each parameter. A factor of 1 means that between variance and within chain variance are equal, larger values mean that there is still a notable difference between chains (see Table 7).

The multivariate value of Gelman/Rubin PSRF (1.01) and for each parameter obtained in the calibration was close to one and this result confirms a very good convergence of Bayesian calibration for the selected parameters.

.PARAMETERS	Gelman index
Alpha_max	1
Blcond	1.01
Maxcond	1
Growthtopt	1
Sap_b	1
Multivariate PSRF	**1**

Table 7. Gelman Rubin potential scale reduction factor (PSRF) of each 3D-CMCC-CNR FEM parameter selected for calibration.

The Gelman plots (Figure 9) show the development and stability of the scale-reduction over time (chain steps). The Gelman plot shows also from which point on the chains values seem to fairly converge and to estimate after how many iterations the MCMC reached convergence.

For all parameters investigated and for all calibration the convergence occurred at ~5000 iterations showing a very fast convergence. There are no cases of chain instability.

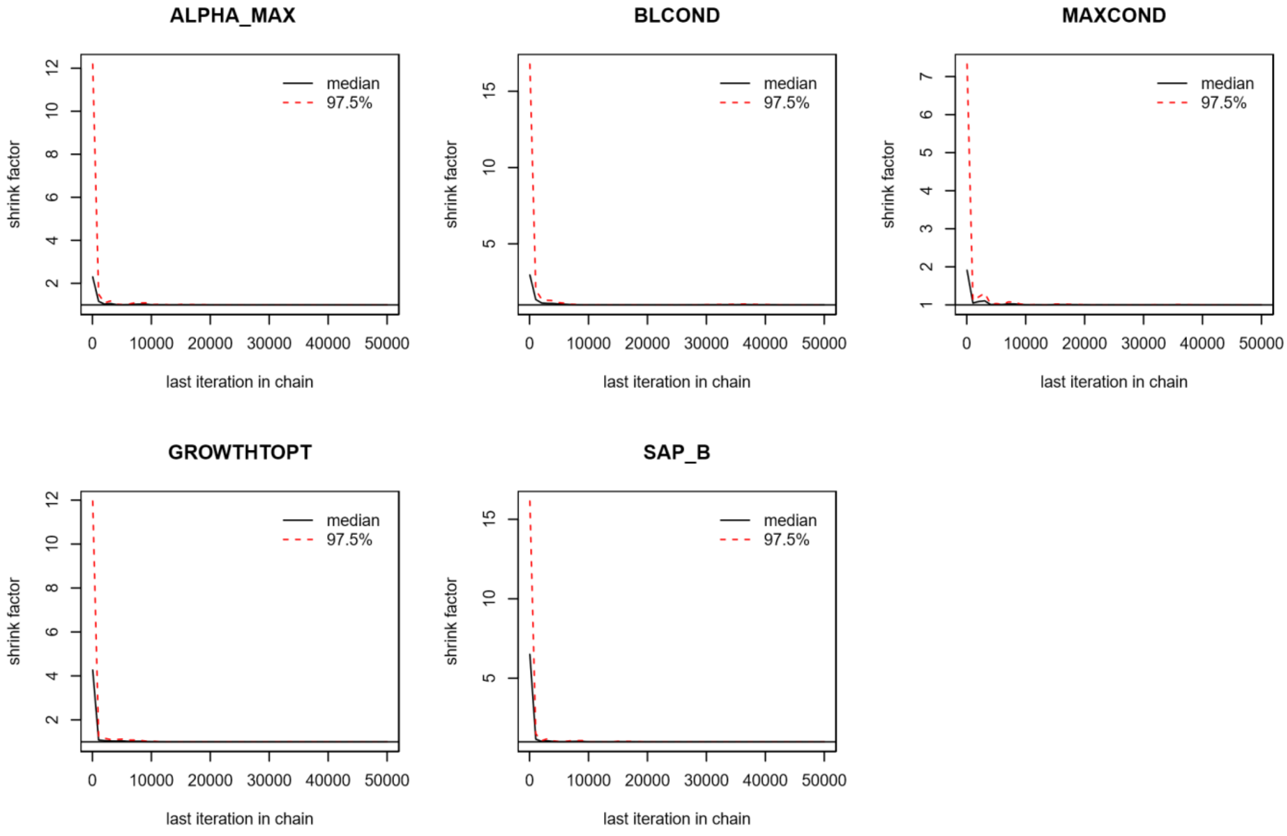

Figure 9. Graphical results of the Gelman diagnostic for each interested parameter

Another useful information of the calibration results is the prior/posterior comparison (Figure 10), which indicates how much the prior distribution is far or close to the posterior distribution. In this case, the prior distributions are all represented by a uniform distribution within the parameters space that is not particularly informative.

For many of the parameters interested by the calibration, the posterior distributions changed sensibly from the prior ones. The marginal posterior distribution of model parameters are presented in Figure 10 and Table 8.

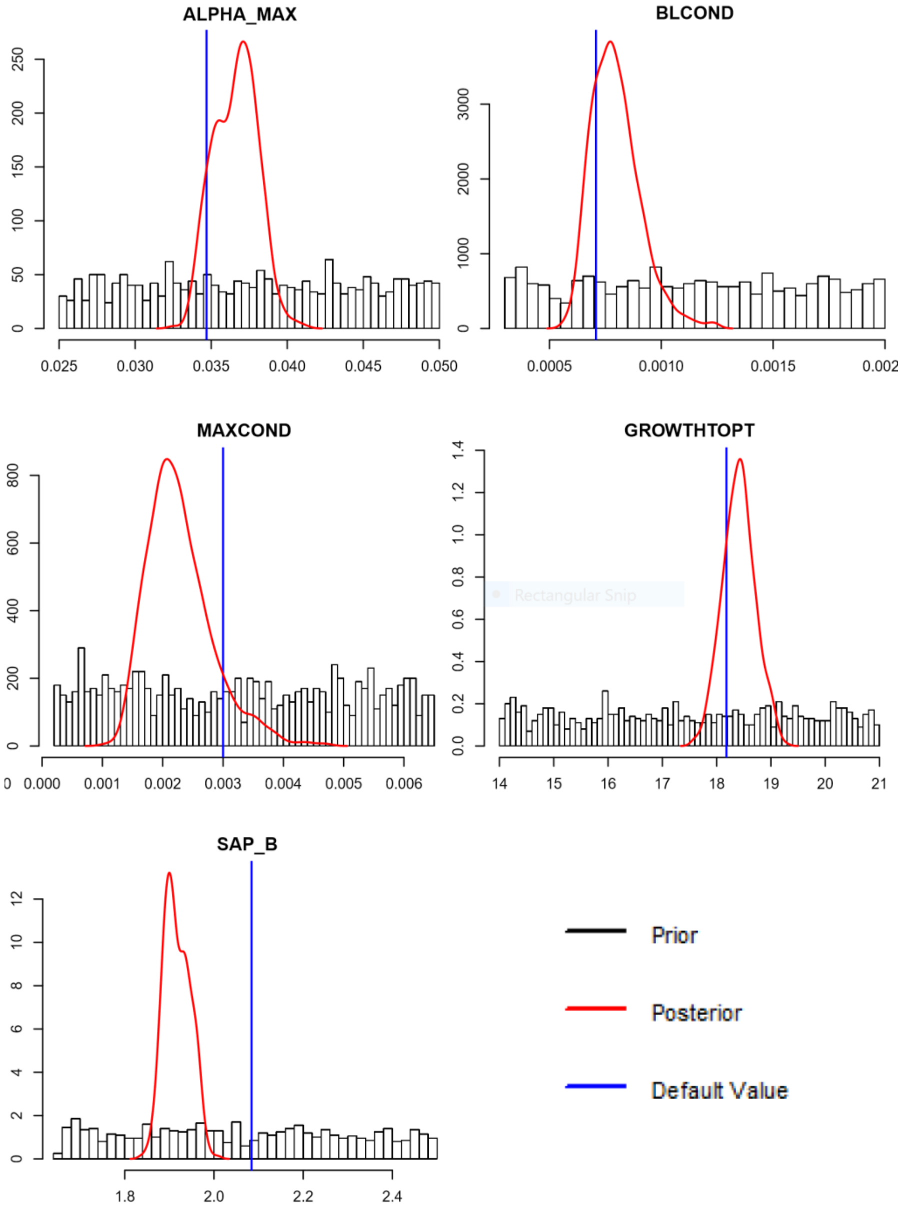

Figure 10.Graphical prior/posterior comparison (in x is reported the parameters values and in y the probability)

Parameter	MAP	2.50%	median	97.50%
ALPHA_MAX	0.036	0.034	0.037	0.04
BLCOND	0.0013	0.001	0.0012	0.0016
MAXCOND	0.0023	0.001	0.0028	0.004
GROWTHOPT	18.232	17.807	18.38	18.983
SAP_B	1.939	1.857	1.913	1.98

Table 8. Posterior parameter estimates, summarized by their quantiles. MAP represents the maximum likelihood of results.

The posterior correlations between pairs of calibration parameters are presented in Figure 11, where it is possible to see that two pairs of parameter are significantly correlated (*SAP_B* and *Alpha_max* with -0.89).

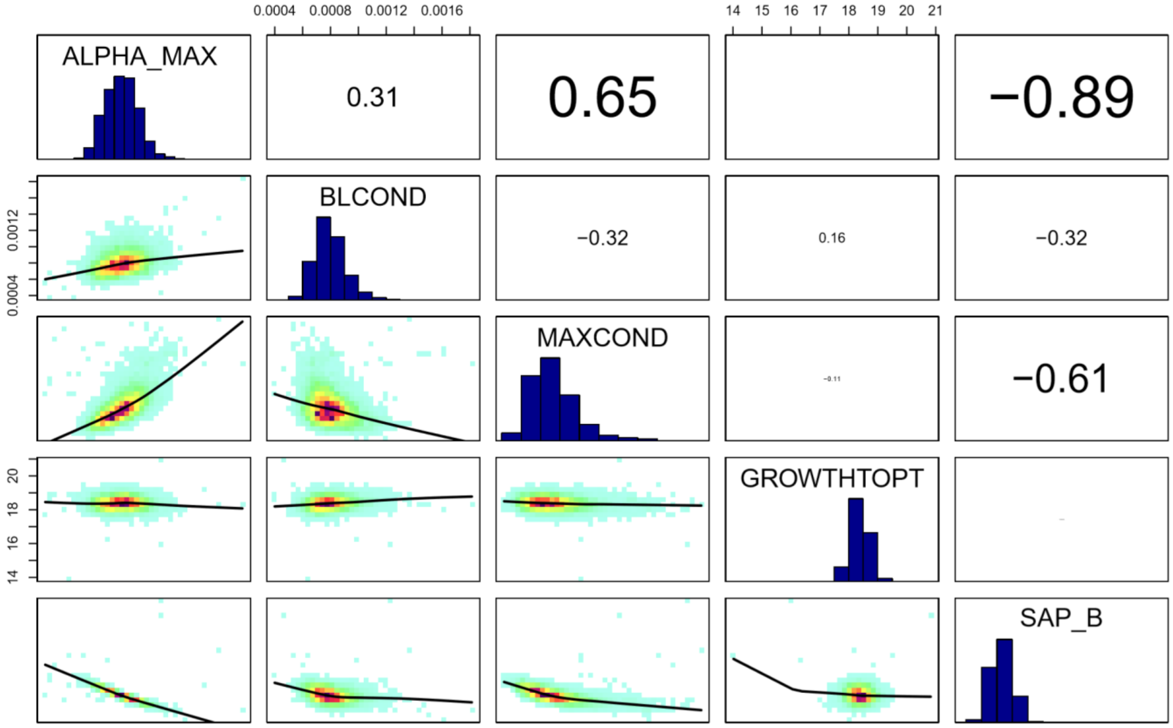

Figure 11. posterior correlation between pairs of parameters.

4.3. Model validation

4.3.1. Forcing model with measured climate data

Model showed to reproduce satisfactorily the observed patterns for each year for tree height, tree diameter and stand CAI (see Figure 12 and Table 9).

In particular, for tree height and tree diameter a correlation of 0.9 is observed, while it is 0.7 for CAI. In general, there is a slightly overestimation for all three variable for about 0.6 m, 2 cm, 5.5 $m^3 ha^{-1}$ for tree height, tree diameter and CAI, respectively. The average uncertainty is around 1 m, 2.5 cm and 3 $m^3 ha^{-1}$ corresponding to about 6, 11 and 20% of the best estimate for height, diameter and CAI, respectively, while NRMSE has registered 9.3, 8.5 and 60 for tree height, tree diameter and CAI.

Figure 13 shows the validation plots for GPP and LE with the measured data derived from eddy covariance station in daily resolution. A correlation of 0.63 and 0.40 for GPP and LE is observed, respectively. However, it was found a very good reproduction of seasonal pattern with a slightly underestimation for GPP and slightly overestimation for LE with -5.6 and 6.6, respectively.

For eddy covariance data, several data gaps are present in the time series considered for validation (2008). Especially, for Latent Heat the relatively limited validation sample may influence the goodness of fit, which is lower compared to the other parameters tested. Overall, for daily resolution of GPP and LE, uncertainty is around 0.5 gC m^{-2} yr^{-1} and 3.2 W m^2 corresponding to about 10% and 15%, respectively

	PERCENTAGE BIAS (%)	**NRMSE**
Tree height	0.6	9.3
DBH	2	8.5
CAI	5.5	60.1
Gross Primary Production	-5.6	70.7
Latent Heat	6.6	66.3

Table 9. Validation of all variable with percentage bias and NRMSE, under measured climate scenario

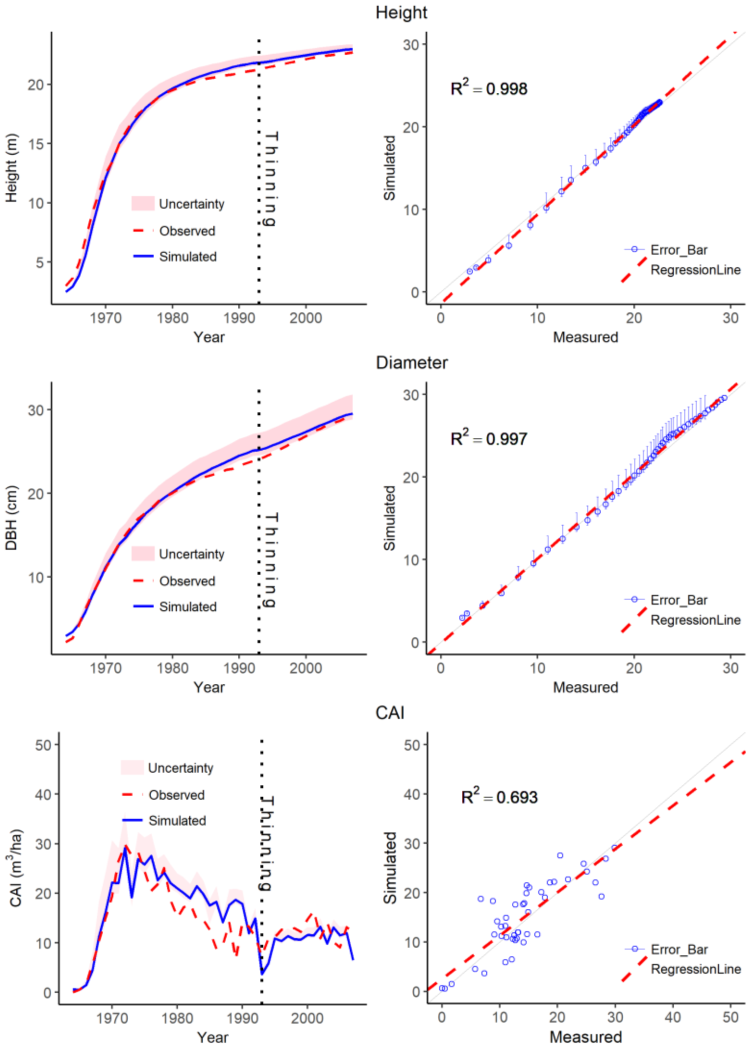

Figure 12. Validation 1964-2008 under measured climate scenario, for tree height, tree diameter and stand CAI showing the maximum a posteriori estimate (from Bayesian calibration results) and the 95 % credibility interval.

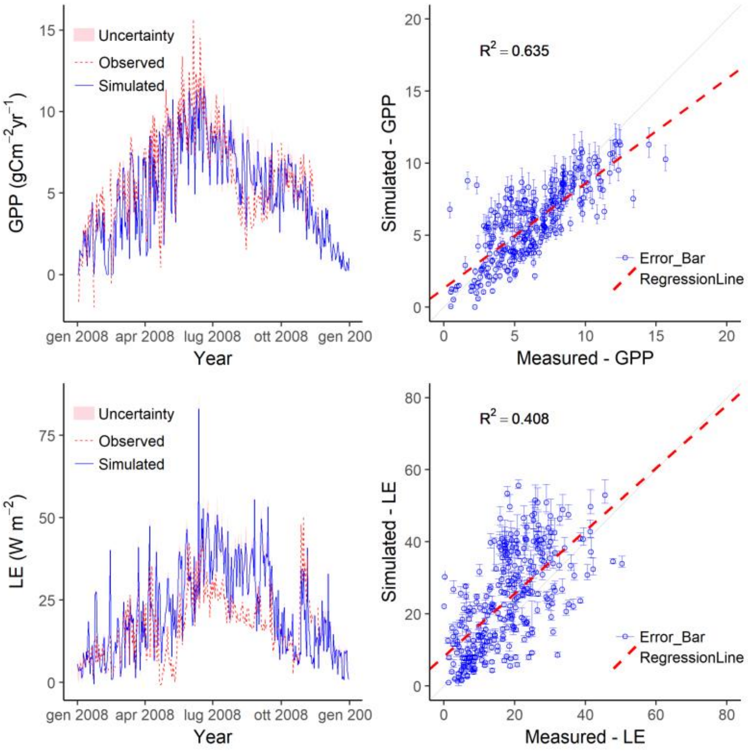

Figure 13 Validation for the year 2008 for GPP and LE: modelling vs. eddy covariance dataset at daily resolution under measured climate scenario. The maximum a posteriori estimate (from Bayesian calibration approach) and the 95 % credibility interval are shown.

4.3.1. Forcing model with modelled climate data

Another validation of the model outputs against tree height, tree diameter and CAI has been performed under the modelled climate derived from Cosmo-CLM, for the period 1976-1995 and for daily GPP and LE in 2008 (Figure 14) to test how the modelled climate forcing was still able to replicate within the 3D-CMCC_CNR FEM the aforementioned observed trends.

Similarly to the measured climate, also using the modelled climate data the validation shows a correlation of 0.9 for both tree height and DBH and of 0.65 for CAI. There is a slightly underestimation of f -3.7% for CAI. Furthermore, NRMSE has registered 11.3, 10.7 and 72 for tree height, tree diameter and CAI, respectively (Table 10).

In addition, the uncertainty is around ±0.5 m, ±1.5 cm ±4 m^3 ha^{-1} corresponding to about 5, 9 and 25% of the best estimate for height, DBH and CAI, respectively.

Figure 15 shows the validation for GPP and LE against the measured data derived from eddy covariance station at daily resolution. The correlation is relatively low (0.3 and 0.2 for GPP and LE, respectively) and, particularly, it is lower compared to that found when using the measured climate data. These low correlations were partially expected since often the use of lower resolution climate forcing data in high resolution (8 km) forest models may be the cause of biases.

However, a good reproduction of seasonal pattern with a slightly underestimation for GPP and overestimation for LE with -15% and 32%, respectively, can be observed (figure 14) and at daily resolution of GPP and LE, the uncertainty is more or less the same compared to the simulation under the measured climate scenario (around 0.5 gC m^{-2} yr^{-1} for GPP and 3 W m^2 for LE, corresponding to about 10% and 14%, respectively).

	PERCENTAGE BIAS (%)	NRMSE
Tree height	0.5	11.3
DBH	-0.7	10.7
CAI	-3.8	72
Gross Primary Production	-15	105
Latent Heat	32	138

Table 10. Validation of all variable with percentage bias and NRMSE, under measured climate scenario

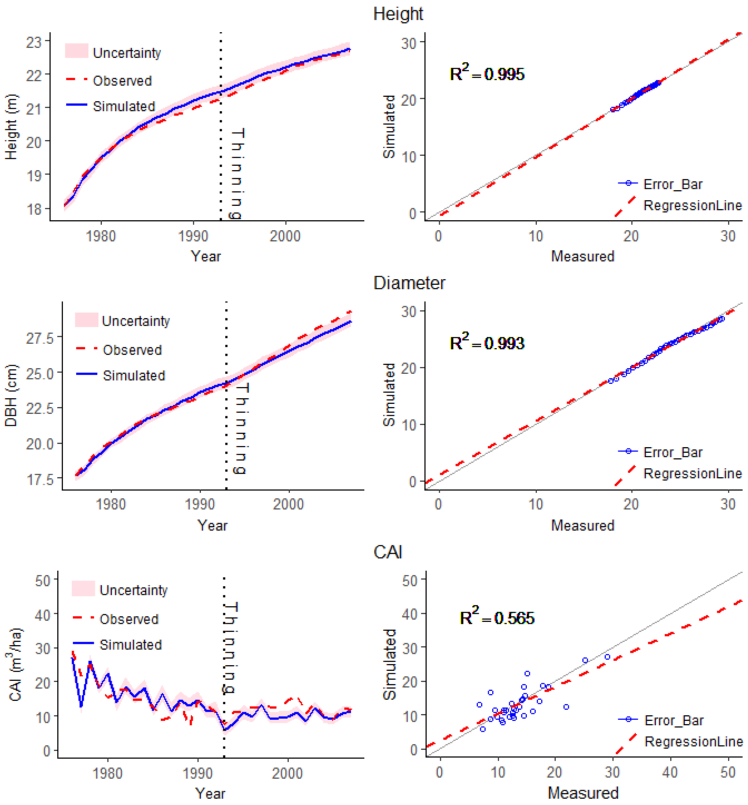

Figure 14. Validation of the model for the period 1964-2008 under modelled climate scenario, for tree height, tree diameter and stand CAI showing the maximum a posteriori estimate (from Bayesian calibration results) and the 95 % credibility interval.

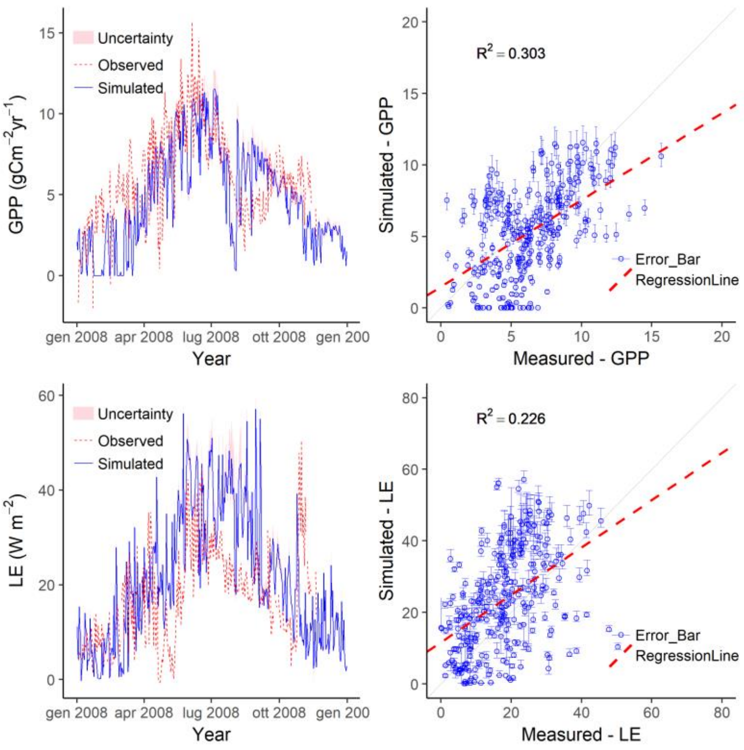

Figure 15. Validation for 2008 for GPP and LE: modelling vs eddy covariance dataset at daily resolution under modelled climate scenario. The maximum a posteriori estimate (from Bayesian calibration approach) and the 95 % credibility interval are shown

4.4. Climate analysis

For evaluating the model responses to changing climate conditions, two different climate scenarios have been used to drive the 3D-CMCC-CNR FEM (Figure 16).

An additional baseline climate scenario (or control scenario) was generated from ten years (1995-2005) data from the same Cosmo-CLM dataset and repeated recursively and randomly, hence avoiding any hidden climate trend. More precisely, these ten years climate data were, at first, detrended in a conventional manner (e.g. McQuigg *et al.*, 1973; Sakamoto, 1978) using a simple linear regression model (with time as the independent predictor for all variables) and then, the ten years period was replicated and sampled from 2006 up to 2095 (the corresponding atmospheric CO_2 concentrations was detrended similarly for consistency).

As described, the scenario RCP 4.5 presents at the Bonis site for the first 40 years a general increase of both maximum and minimum air temperature of about 1°C (corresponding to +6% and +10% over the present), a reduction of about 14 mm in annual rainfall (corresponding to approximately -2% of current annual precipitation) no appreciable trend for VPD is detected. During the subsequent thirty years (2066-2095), the increase of the simulated maximum and minimum temperatures is about +2 and +1.8 ° C (corresponding to +12 and + 18% compared to the present), a further reduction of the annual rainfall of about 124 mm annually (corresponding to -14%), and VPD increase of about 2 kPa (corresponding to ~28% of the current VPD value).

The RCP 8.5 scenario shows even more alarming changes at Bonis site, with a rise in temperatures of about 1.5°C over the first thirty years (corresponding to approximately +8 and + 12% over the present), a fall in precipitation of around 99 mm per year (corresponding to - 11%) and VPD increase of about 0.9 kPa (corresponding to ~11% of the current VPD value). For the last thirty years the average increases of the maximum and minimum daily temperatures are about 3.5 ° C (corresponding to +22 and + 35%), precipitation is reduced by about 185 mm per year (-21%) while VPD increase of about 3 kPa (corresponding to ~34% over the present).

The carbon emission in RCP4.5 peak around 2040 (corresponding to ~450 ppmv), then decline, while under RCP8.5 the emission continue to rise progressively throughout the 21st century up to ~950 ppmv.

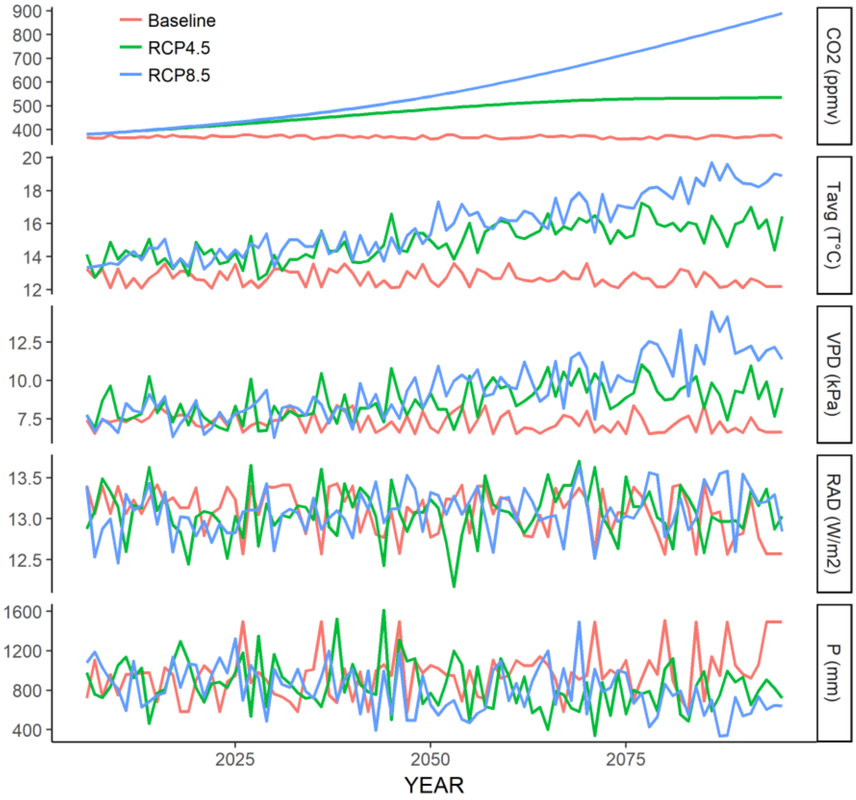

Figure 16. Comparison of three climate scenarios.

Figure 17 shows the differences in mean values of main climate variables under different scenarios at the end of the simulation period.

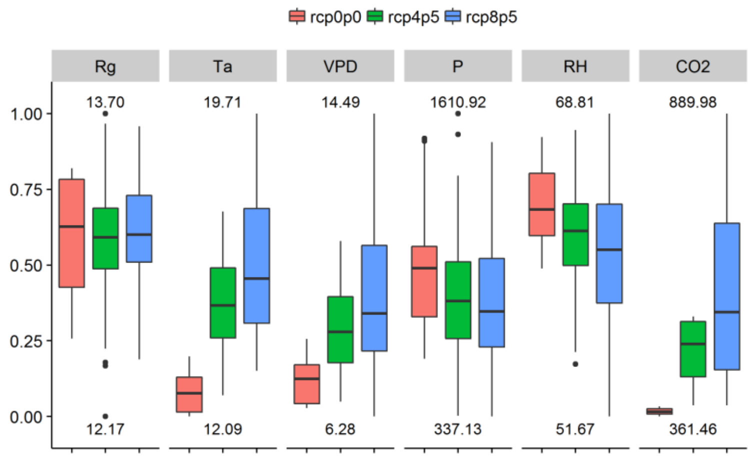

Figure 17. Climate comparison among baseline climate, RCP 4.5 and RCP 8.5. The original climate values are normalised between 0 to 1, with zero representing the absolute minimum and one the absolute maximum values in the dataset for each variable, while the numbers at the top represent the average of the maximum and the numbers below the average of the minimum.

4.5. Response to step change in climatic conditions

4.5.1. Effects of climate change on management and un-management case

In this section, the ecophysiological dynamics of the forest will be analysed taking into account the climatic component and disturbance factors (natural development vs. management scenarios), splitting the scenarios in two time windows: Near Future (NF, 2020-2050) and Far Future (FF, 2070-2095). This comparison helps to analyse more clearly the effects of climate warming, in the medium and long term.

As a reference for forest management, the Business As Usual (BAU) scheme implies a rotation of 90 years, a thinning intensity of 15% of the present stand basal area every 15 years (PMPF, 2007).

For this analysis, the following variables will be considered: Gross Primary Production (GPP), Net Primary Production (NPP), Autotrophic respiration (RA) and carbon stock in wood (C-stock). The latter is considered as the sum of the standing (live) wood biomass (stem + branches + coarse root) summed up to the harvested wood biomass, the latter not separated into the final uses. This variable, hence, represents the potentiality of the forest to stock C inside or outside the stand for medium to long time period.

To test the assumptions of the model and to interpret the behaviour under climate change, the forest responses and sensitivity under warming and rising CO_2 concentration in comparison with baseline climate are analysed.

In particular, this experiment is implemented for:

- analysing the effect of temperature only (“warming effect”): assuming a constant CO_2 ($[CO_2]_{fixed}$) at the concentration level registered in 2006 (year of simulation start) with CO_2 concentration at 368.865 ppmv in comparison with the baseline climate. This experiment is conducted only for the “no management” case in “undisturbed” condition to highlight the warming effect without other interferences;
- analysing the rise of CO_2 concentration only (“fertilization effect”): using the baseline climate along the whole period but with CO_2 concentrations derived from the RCP4.5 and RCP8.5. Also in this case the simulation is conducted only under “undisturbed” condition;
- analysing the complete climate change effects (“combined effect”) taking into account the coupled effects of both increasing $[CO_2]$ (fertilization) and temperature (warming): comparison of RCP4.5 and RCP8.5 scenarios against the baseline climate (we stress that each scenario has its own CO_2 concentration); this experiment is implemented for both “undisturbed” condition (no management) and management case and it is analysed separately before and then in comparison between the two cases;

To summarize and compare the behaviour of each variable in NF and FF, the variables values are also normalised between 0 to 1. Zero represents the absolute minimum value and one the absolute maximum for each of the examined cases.

Simulation with both climate and CO_2 concentration changes are labelled as RCP4.5 and RC8.5.

4.5.1.1. *Effects of temperature only (“warming effect”)*

The Figure 18 shows the simulations where only temperature (climate) are considered, comparing RCP4.5 and RCP8.5 climate with fixed CO_2 with baseline climate.

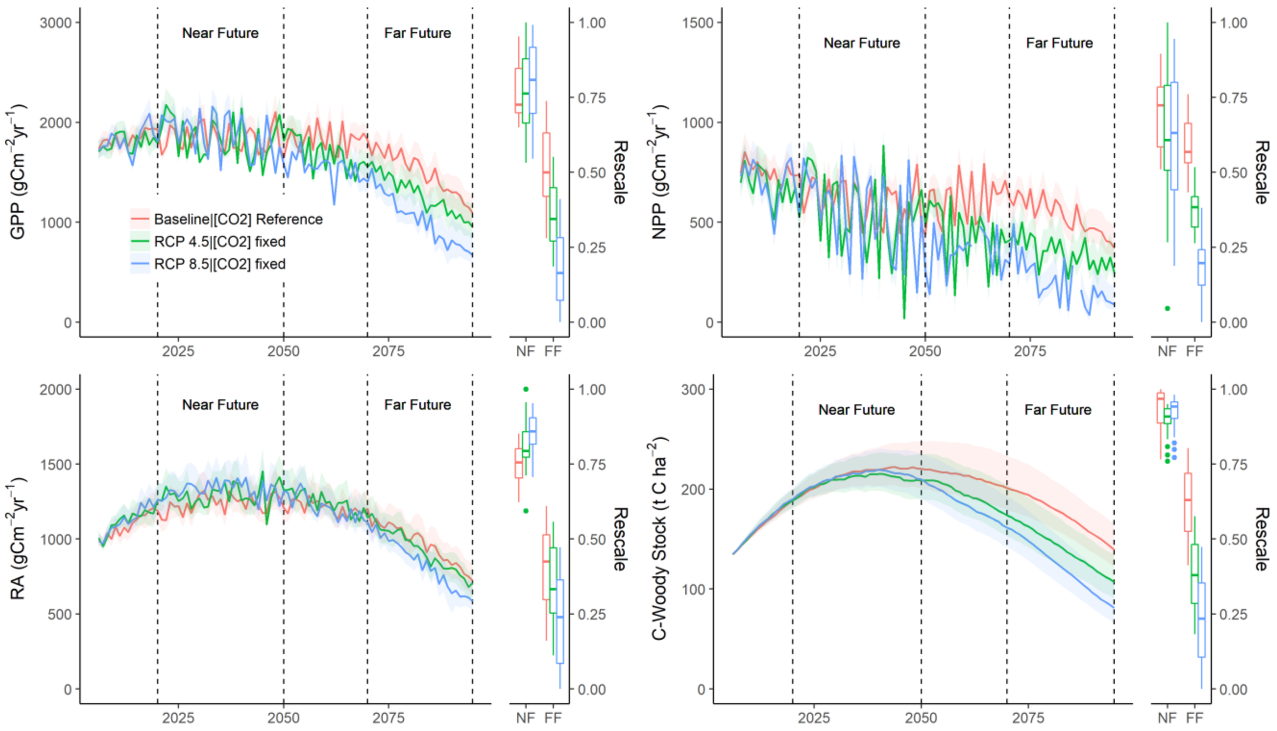

Figure 18. Gross Primary Production (GPP, gC m^{-2} yr^{-1}), Net Primary Production (NPP, gC m^{-2} yr^{-1}), Autotrophic respiration (Ra, gC m^{-2} yr^{-1}) and C-woody stock (t C ha^{-1}) over 2006-2095, for the forest in unmanaged condition under two climate scenarios (RCP4.5 and RCP8.5 with fixed CO_2 concentration), showing the maximum a posterior estimate (from Bayesian calibration approach) and the 95 % credibility interval. Right panel, normalization of variables for the near future (NF, 2020-2050) and the far future (FF, 2070-2095) time period. The box plot shows the average of variables value derived from the time series on the left.

Analysing the output variables considered (GPP, Ra, NPP, C-woody stock), the effect of temperature change only simulated by model is more or less negligible in the NF and becomes more evident in the FF where climate change effects are more pronounced.

In particular, under FF, RA shows higher values under baseline climate for about 6 and 16% than RCP4.5 and RCP8.5 with $CO_{2[\text{fixed}]}$, respectively.

In addition, a generalized negative trend is detected after year 2065 for both scenarios. This decline in autotrophic respiration is mainly due to a progressive decrease the amount of standing ‘respiring’ biomass that is controlled by an increase in forest mortality, which is in turn controlled by forest ageing. In addition, a reduced biomass accumulation is due to a reduced (at stand level) photosynthetic rate that reduces one of the two components of autotrophic respiration, that into the model are maintenance and growth respiration.

Moreover, under baseline we observe higher values on GPP (16, 34%), NPP (35, 70%), C-woody stock (20, 32%) than RCP 4.5 and RCP8.5, respectively.

In other words, under RCP4.5 higher levels of photosynthesis and similar level of respiration allows higher levels of productivity and C-woody stock over time

The behaviour of the model is due to the difference between the average temperature in FF and the optimum temperature for physiological processes (model's parameter): the greater the difference between these two temperatures, the greater is the reduction of photosynthesis rate. In fact in far future, the average daily temperature under RCP8.5 and RCP4.5 is 19.8 and 17.5°C, respectively, while the optimum temperature at which the model is calibrated (through the Bayesian approach) is around 18.2°C (with 10% of uncertainty). Both photosynthesis and transpiration are processes directly dependent on temperature (Kirschbaum, 2004) and plants acclimate their ecophysiological mechanisms to the temperature conditions in which they grow (Slatyer, 1978; Battaglia *et al.*, 1996). At the same time NPP has an optimum temperature above which it could be reduced. Furthermore, the response of photosynthesis and respiration to temperature is different, causing a consistent variation in their ratio as temperature increase, affecting, at the end, net productivity.

In addition the model seems to detect no effects of drought in summer seasons. The reason could be related to the climate of the "Bonis" watershed, being located at 1100 m a.s.l. where average precipitation is 1100mm.

4.5.1.2. Effects of CO_2 fertilization only ("fertilization effect")

The effect of rising in CO_2 concentrations on modelled forest eco-physiology is shown in Figure 19.

Under baseline climate with CO_2[reference], all variables present lower values than in the same climate but forced with CO_2[4.5] and CO_2[8.5].

In particular, especially in FF, under baseline climate forced with CO_2[8.5] values of GPP, NPP, RA and C-woody stock are higher for 80, 110, 60 and 52% compared to baseline climate with CO_2[reference]. These differences are sensibly reduced when comparing baseline climate forced with CO_2[4.5] with baseline climate and CO_2[reference]. As a result, high levels of photosynthesis rate and, in proportion, lower autotrophic respiration levels lead to higher productivity and C-woody stock over time. This increase in autotrophic respiration, being the climate the same in the three scenarios presented in Figure 19, it is controlled by the higher amount of living biomass produced at elevated [CO_2] scenarios (Amthor, 1989; Ryan, 1991).

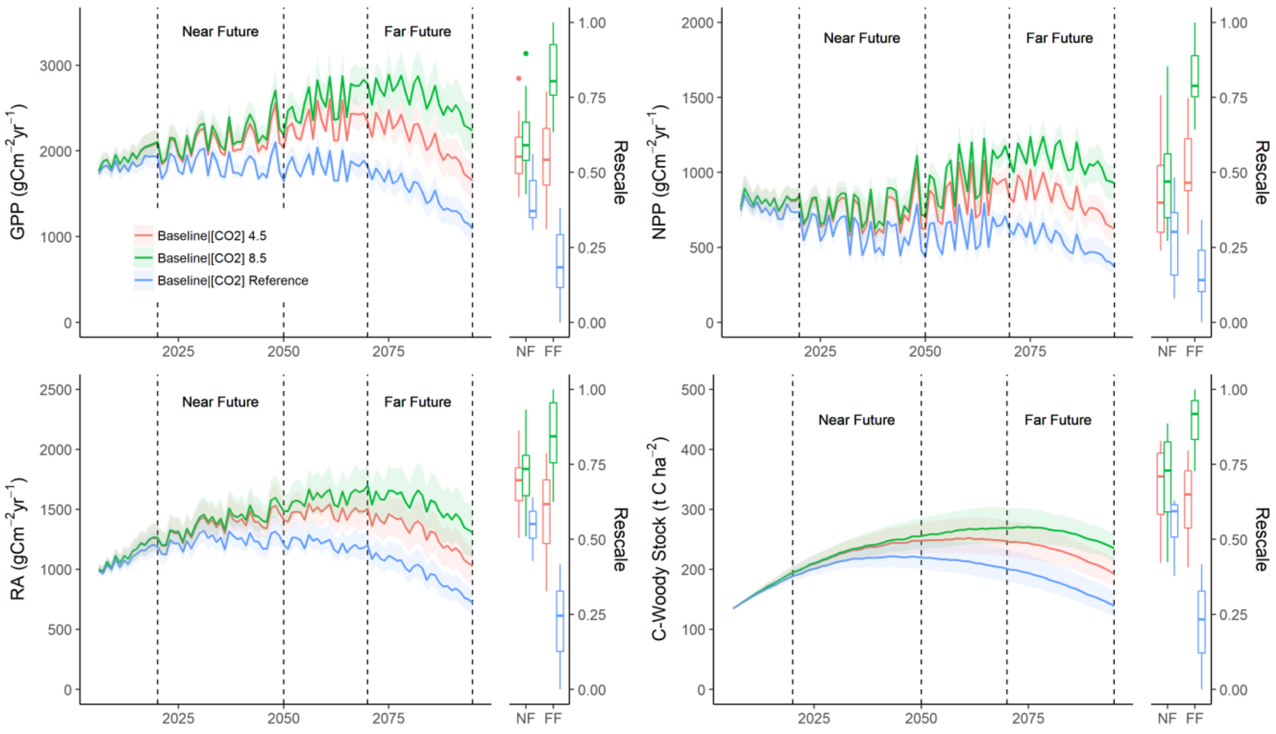

Figure 19. Gross Primary Production (GPP, gC m^{-2} yr^{-1}), Net Primary Production (NPP, gC m^{-2} yr^{-1}), Autotrophic Respiration (Ra, gC m^{-2} yr^{-1}) and C-woody stock(t C ha^{-1}) over 2006-2095, for the forest in unmanaged condition under three climate scenarios(Baseline climate forced by CO_2[4.5] and CO_2[8.5]), showing the maximum a posteriori estimate (from Bayesian calibration approach) and the 95 % credibility interval. Right panel, normalization of variables for the near future (NF, 2020-2050) and the far future (FF, 2070-2095) time period. The box plot shows the average of variables value derived from the time series on the left.

In general, the photosynthesis rate response to increasing CO_2 in the model may be considered "optimistic", as the Light Use Efficiency approach considers a slow saturation to increasing CO_2. In reality, photosynthesis could be affected by limitation in nutrients (nitrogen content) that may cause a down-regulation of photosynthesis rate, especially in far future (Medlyn *et al.*, 2011).

This results is a combined effect of several model assumptions. In particular, the CO_2 enrichment is consider to produce a fertilization effect that increase progressively the photosynthesis rate (Collatz *et al.*, 1991; Veroustraete *et al.*, 2002). At the same time, also the water cycle is influenced, allowing an increase in water use efficiency in relation to rising in [CO_2] through an empirical power function that describes the quantitative relationship between the relative change of stomatal conductance compared to standard conditions (Hidy *et al.*, 2016) (see also paragraph 3.2.3).

Also in this case it may be taken into account the non-presence of drought during the summer season for the same reasons set out in the previous paragraph.

4.5.1.3. *Climate change effects on no management and management cases*

Figure 20 presents the trends of the selected variables under coupled climate and [CO_2] changes and for both management and no management case.

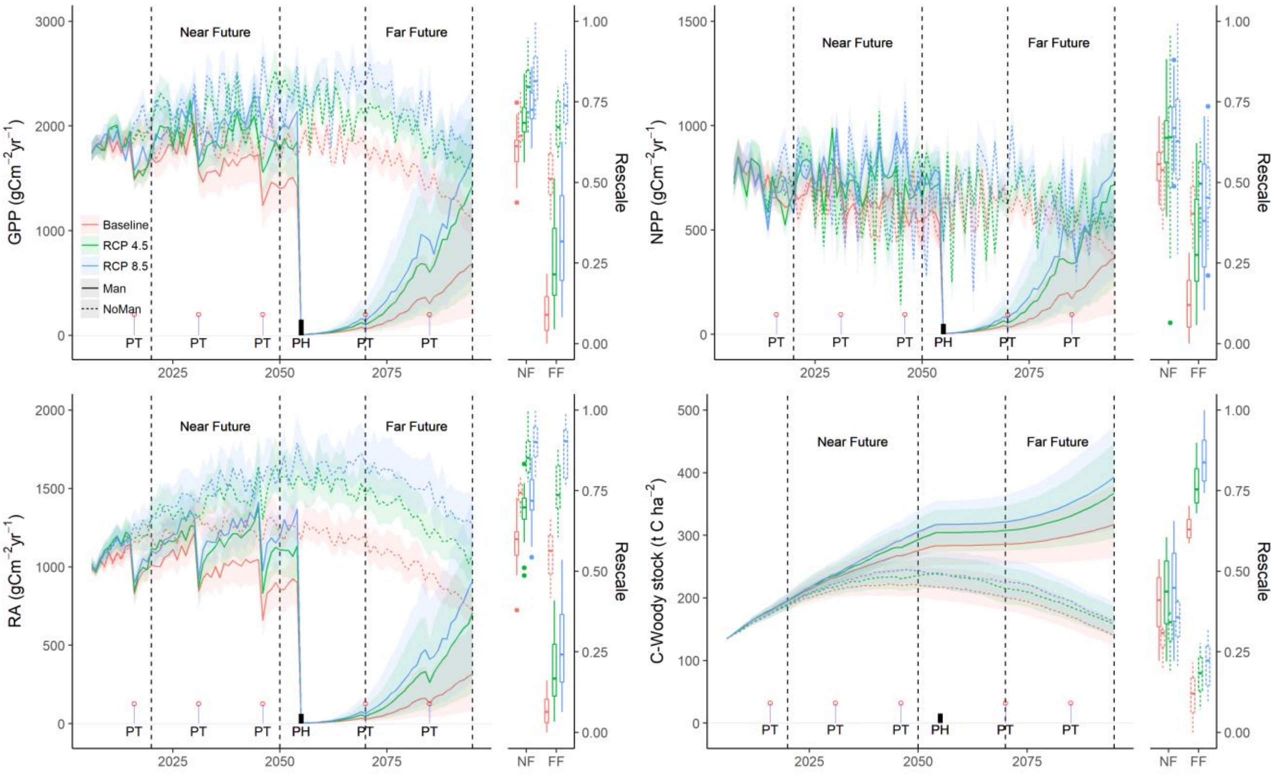

Figure 20. Gross Primary Production (GPP, gC m^{-2} yr^{-1}), Net Primary Production (NPP, gC m^{-2} yr^{-1}), Autotrophic respiration (RA, gC m^{-2} yr^{-1}) and C-woody stock(t C ha^{-1}) over 2006-2095, for the forest in unmanaged and managed condition under three climate scenarios (Baseline climate, RCP4.5 and RCP8.5), showing the maximum a posterior estimate (from Bayesian calibration approach) and the 95 % credibility interval (PT = prescribed thinning, PH = prescribed harvesting). Right panel, normalization of variables for the near future (NF, 2020-2050) and the far future (FF, 2070-2095) time period. The box plot shows the average of variables value derived from the time series on the left.

Generally, over the whole period and both with and without forest management, model results show higher values for all variables under the most extreme scenario (RCP 8.5), compared to the RCP 4.5 scenario and Baseline climate.

This difference is on average higher in FF than NF but not for all variables. In particular, productivity levels (NPP) in NF is slightly higher under RCP8.5 than both RCP4.5 and baseline climate for about 7 and 17% (40 and 130 gC m^{-2} yr^{-1}), respectively. Conversely, in FF and in no management case, the productivity is higher under RCP4.5 than RCP8.5. This behaviour is due to higher respiration rate under warmest climate (RCP8.5) for about 11% (200 gC m^{-2} yr^{-1}) than medium climate scenario (RCP4.5). This occurs despite the photosynthesis rate is higher under

RCP8.5 for about 10% (180 gC m^{-2} yr^{-1}) than under RCP4.5. The respiration rate is due to higher level of C-woody stock under RCP8.5 for about 7% (8 tC ha^{-1}) than medium climate (RCP4.5) and 12% (23 tC ha^{-1}) than reference climate with productivity being slight higher under RCP4.5 than RCP8.5.

It could be useful to recall that in the model, growth respiration is assumed to decrease progressively with ageing, from 35% to 25% of the daily net photosynthesis (Ryan, 1991; Waring and Running, 1998).

Analysing wood C stock under no management, a decreasing, especially in far future is projected. This behaviour depends on mortality phenomenon. In fact, the model takes into account, in addition to the mortality of the dependent age, the mortality for competition (Collalti *et al.*, 2014) that it is much more likely to occur in condition with high population density (no management).

In the management case, mortality is almost null or much lower, as thinning is focused to “anticipate” and avoid mortality, favouring growth of the remaining trees. In the model, C-woody stock is the summation over time of aboveground wood and coarse roots growth, to which the portion of harvested aboveground wood is added. To this summation, eventual mortality will result in a slight decrease.

When management is considered in the simulations, in NF the effect of climate change is more or less similar than un-management case, while in FF the response of the simulation is totally different. This derives from the harvest related to the rotation, that removes totally the remaining trees at the age of 90 years.

In particular, under RCP8.5 the simulation results in higher values of GPP, NPP, RA and C-woody stock for about 60, 55, 63 and 15% (565, 260, 305 gC m^{-2} yr^{-1}, 55 tC ha^{-1}) compared to the reference climate, while under RCP4.5 the difference with the baseline is slightly for the flux variables (GPP, NPP, RA, 15%) and a third for C-woody stock. Generally, management reduces the variability among the considered cases and, in synergy with climate change, has a positive effects on fluxes and carbon stock.

The influence of management on simulated variables (between 8 and 20%) starts in NF (presence of only thinning), already in condition of moderated climate change. The impact of management becomes more important in FF after the rotation harvest.

In FF the presence of rotation at year 2065 affects the comparison between management and no management. In RCP 8.5 average fluxes are lower in no management (565, 304, 260 gC m^{-2} yr^{-1}

and 53, 67, 19% for GPP, RA and NPP, respectively), but wood stock is higher for about 80% (54 tC ha^{-1}). Under RCP4.5, differences between management and no management are similar for GPP and C-woody stock, while higher for NPP (33%).

Overall, when management is considered, autotrophic respiration presents a positive trend and, at regular time intervals undergoes a sharp decrease, in other words autotrophic respiration shows the classical trend with saw-tooth oscillation patterns with different magnitude. Also, after the harvest that took place in 2065-2066, there is a progressive increase in the NPP, RA, GPP mainly due to: i) the young age of the stand and the high rates of growth respiration, ii) the increase in biomass which is faster under warmer and CO_2 concentrations rich scenarios and iii) fast-growing canopies in a short-time. Specifically, the thinning causes regular sudden drops of autotrophic respiration (mostly in the maintenance respiration component) due to a sharp decline in the standing biomass combined with a reduction in GPP (Woodward *et al.*, 2010). However, these different contributions tend to compensate each other and they are very difficult to determine individually.

The effect of thinning allows to reduce the forest canopy, allowing an improvement in the light and water availability for the remaining trees, favouring a reduction in the natural mortality rate and this is in line with several other works (Thornley and Cannell, 2000; Dore *et al.,* 2012; Saunders *et al.,* 2012; Wilkinson *et al.,* 2016).

These processes have also been confirmed for other forest sites and they are simulated by the model (Kolari *et al.*, 2004; Vesala *et al.*, 2005).

After the clear cut in 2065, while the C-woody stock of the un-managed forest shows a decreasing trend under all scenarios, the trend for the managed forest, after a stable phase of approximately 25 years, increases significantly, particularly for the scenarios that include an increase in CO_2. This behaviour depends on i) the young age of the stand and ii) decreased competition related to thinning.

Hence, C-woody stock are sensitive to forest management practice, as reported in other studies comparing managed vs. natural forest (Richter *et al.*, 1994; Masera *et al.*, 2003; Markewitz, 2006). This is in line with Ruiz-Peinado *et al.* (2011) that reported higher accumulated carbon stock in managed vs. unmanaged forests, when the offsite carbon stock (harvested biomass) is included in the balance.

However, as the effects of thinning on the accumulation of carbon stock can be very different, it is very useful to investigate the different impact that the classic components of forest management (intensity and frequency of thinning, rotation length) have on stand productivity (Nilsen and Strand, 2008). For this reason, estimates of changes in C-woody stock in relation to different experimental designs regarding forest management will be studied in-depth (see paragraph 4.7.1).

4.5.2. Uncertainty analysis

The uncertainty analysis of the results just discussed is an important issue that deserves to be treated separately. Uncertainty of the simulations is reported as shaded areas in Figure 18, 19, 20. The corresponding uncertainty boundaries are represented with an area of the same colour of the same trend line. The credibility interval is set at 95%.

Before the analysis, an ANOVA is implemented to verify the significance differences considering the management, climate scenarios and near future / far future factors.

	Df	Sum Sq	Sq	F value	Pr(>F)	
Management	1	122053	122053	285.814	< 2e-16	***
Climate Scenarios	2	2652	1326	3.106	0.15515	
NF/FF	2	348709	174355	48.29	< 2e-16	***

Significance codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

Table 11. Anova results

The results (Table 11) shows a significance difference within management factor and NF/FF time and not for climate scenarios.

Starting to analyse the uncertainty in the Near Future, there is generally a different degree of uncertainty between scenarios including or not management.

For GPP, an average uncertainty of 253.1 gC m^{-2} $yr^{-1}$and 391.8 gC m^{-2} yr^{-1} is observed corresponding to about 12% and 23% of the best estimate for no management and management case, respectively. For Ra uncertainty average levels are similar at 230 gC m^{-2} $yr^{-1}$and 260 gC m^{-2} yr^{-1} respectively for no management or management but still at a larger percentage for the simulations when management is considered (28% vs. 18%). While, for NPP a noticeably larger uncertainty is observed if compared to the GPP and RA, although very similar between management and no management (193 gC m^{-2} yr^{-1}, 33.5%; 207.5 gC m^{-2} yr^{-1}, 34.5%). Interestingly, for carbon stock the overall uncertainty is lower compared to the other variables at 15.8% (35 tC ha^{-1}) and 17.1% (41.5 tC ha^{-1}), for no management and management cases, respectively.

The dynamics of uncertainty changes considerably during Far Future, where for GPP there is an uncertainty of 383.8 gC m^{-2} $yr^{-1}$and 1048.8 gC m^{-2} yr^{-1}corresponding to about 22% and 160% of the best estimate under no management and management scenarios, respectively.

The change is also relevant for Ra (no management: 284 gC m^{-2} yr^{-1}, 23.5%; management:556 gC m^{-2} yr^{-1}, 170%) and for NPP (no management: 189.8 gC m^{-2} yr^{-1}, 35%; management: 495 gC m^{-2} yr^{-1}, 154%) of the best estimate. Also in this case, the uncertainty for the simulated wood carbon stock is lower, particularly for the management case (no management: 52.2 tC ha^{-1}, 28.7%; management: 108.9 tC ha^{-1}, 64.4%).

Uncertainty shows to be significantly higher in management than no management, this may depend on the presence of disturbing factors (i.e. management practices) that could affect the probability distribution of the investigated variables. Furthermore, there is a greater uncertainty during the FF when compared to the NF simulations, and this result is extended to all the examined cases, both without and with management. This distribution may depend essentially on the fact that narrow uncertainty, observed in the initial part of the time series, cause, through a series of iterate approximations, year-by-year, a progressive increase in uncertainty. This trend is even more evident when there are disturbances such as thinning and harvesting.

4.6. Forest management: targeting a balance between carbon stock and carbon assimilation

Forest management is targeted to multiple objectives, that can be overall synthesised in maximizing social and ecosystems values, when both market and nonmarket outputs are considered. In this respect, the impact of a particular type of proposed management depends essentially on the type of management practices (e.g. thinning, prescribed burning, rotation length), on how the practice influences the “allocation” of carbon between the different carbon pools, on the time period between disturbances or management practices (frequency of intervention) and the area of forests under management. In particular, different management regimes can perturb the stand in different ways. On the other hand, the integration of the potential effects of climate change on disturbance and species composition may reveal additional opportunities and risks.

Moreover, the response time of forest stands to the different types of forest management is usually long, which would make difficult to analyse changes in carbon storage yields directly in the field. In this context, modelling offers a way to evaluate the changes after a particular management practice.

In this context, many studies, based on forest model simulations, have focused on several management options (several rotation length, different age structures, several thinning options) (Liski *et al.*, 2001; Bravo *et al.*, 2008). This approach proved useful to detect the best management alternatives in terms of carbon sequestration or productivity, but it is very important to validate these results through empirical studies that take into account all forest carbon compartments. This aspect is particularly evident for Mediterranean forests because currently there are weak knowledge about empirical experiments on the importance and efficacy of forest management alternatives (de las Heras *et al.*, 2013; Ruiz-Peinado *et al.*, 2013, 2016; Bravo-Oviedo *et al.*, 2015).

Despite everything, climate change has direct effects on the functioning of forests, and management strategies should have aim to adapt forest ecosystems to change. In other words, the impact could be so much smaller as their adaptation to climate change will be better. This aspect is very important to understand because it is only by improving our understanding of forest drought adaptation, the effects of soil degradation, the loss of fertility or reduction of productivity in the Mediterranean area it will be possible to develop forest management policies and strategies adapted to changes and that combine both adaptation and mitigation (Verchot *et al.*, 2007; D’Amato *et al.*, 2011, 2013; Sohn *et al.*, 2016).

In this study, several management scenarios were chosen for reflecting different degree of forestry management.

In particular, it is possible to assume a long-term scenarios (e.g. 90 years), for studying patterns of fluxes and carbon stock. The experimental design has been the following (Table 12):

a) Without Practice (NP): this scenario does not include any type of forest management;
b) Reference management (BAU): is based taking into account the usual intensity, rotation length and interval according to the local forest regulations (PMPF, 2007).

Following an adaptive approach, different management factors combinations were chosen:

Thinning Intensity (%)	**Thinning Interval (year)**			**Rotation lenght**			
25	10	15	20	70	90	110	NR
20							
15							

Table 12. Forest management options. NR rotation scenario consider “continuous cover forestry” (i.e. no final clearcut)

4.6.1. Full factorial analysis

Taking into account the experimental modelling design, a factorial analysis to determine the contribution of each of the considered management factor, including their interactions has been performed. Results are presented in Figure 21.

A different behaviour of NPP and C-woody stock is observed. In particular, for NPP (net carbon assimilation) the most important factor is the rotation length contributing to 65% of the total variability, followed by thinning interval (20%) and intensity (12%), while the interactions among factors is not important.

For C-woody stock the most important factor is still rotation length but with a lower weight (40%) of the full variability, while very low are the effects of interval (5%) and intensity (6%) of thinning. For wood stocks, the interactions among factors is instead relevant, with interval:rotation influencing variability for 25% and interval:intensity for 15%.

Generally, the different climate scenarios do not affect in a strong way the importance of management factors on variability of carbon assimilation (NPP) and wood C-stock.

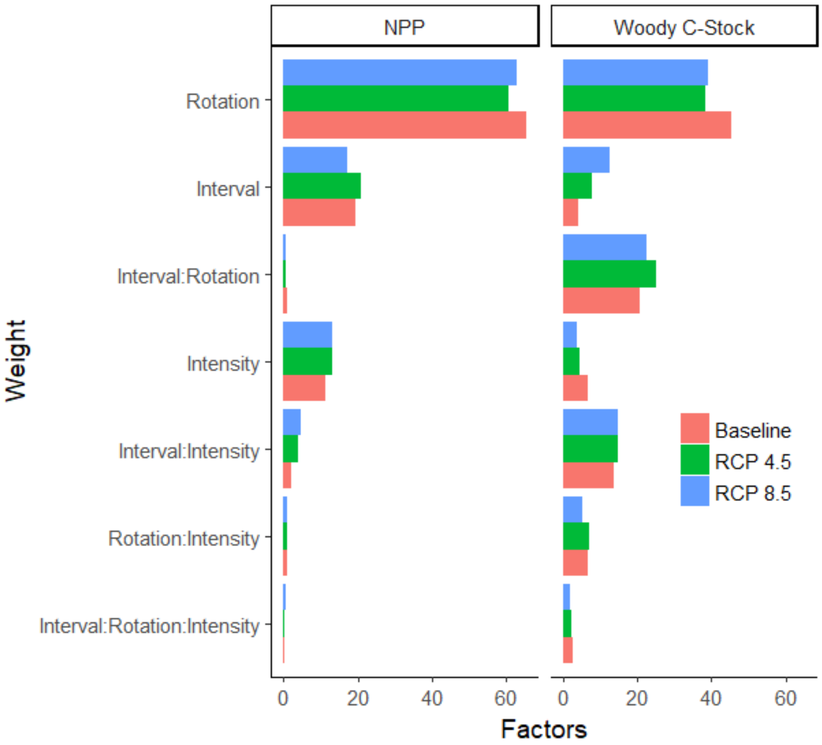

Figure 21. Importance of forest management factors on the changes in NPP and wood carbon stocks. Results show percent contribution of each factor to the total variability of the sample. Interactions are also included.

The different factors, singularly or in interaction, play a decisive role in both carbon assimilation and the carbon stock. In fact, harvesting operations alter significantly the conditions of the stand mainly due to the removal of the biomass and therefore of the stored carbon by the forest (Ruiz-Peinado *et al.*, 2017).

The choice of the rotation length may impacts on the ecophysiological response of forest (e.g. through ageing) can change the type of products that can be retrieved and the overall amount of exchanged and carbon stocked.

In this respect, a reasonable compromise among management factors could improve forest performance both from an environmental (C-uptake) and financial-economic (type of products) point of view.

As consequence of these results, the two key variables, the carbon assimilation process (NPP) and the carbon stocked (wood C-stock) are investigated in relation to the different factors that have a greater weight in the variability of the sample.

4.6.2. Carbon stock

Figure 22 shows average carbon stocks levels achieved among the different climate scenarios for the factors and interactions that resulted significant in the full factorial analysis. In particular, lower carbon stock values have been observed in the reference climate compared to the other climate scenarios.

Generally, a progressive increase of carbon stock with increasing rotation length is observed, with the highest value in the case of "no rotation" (NR – *continuous cover forestry*) with only thinning practices, which has an amount of stocks 30 tC ha^{-1} greater when compared to the shorter rotations. This increase is present irrespective of the climate scenarios considered.

These results are in line with several studies that have shown that carbon stock levels are influenced by the choice of the rotation length (Liski *et al.*, 2001; Pussinen *et al.*, 2002; Zhou *et al.*, 2013). In particular, it has been shown that longer rotation lengths are is effective in increasing carbon storage (Cooper, 1983b; Liski *et al.*, 2001; Seely *et al.*, 2002), which is helpful for the reduction of greenhouse gas emissions (Kaipainen *et al.*, 2004b).

Longer rotation are simulated using model such us CO2fix (Nabuurs and Schelhaas, 2002; Masera *et al.*, 2003), which have showed the achievement of higher level of carbon in the forest (Kaipainen *et al.*, 2004a; Kaul *et al.*, 2010; Nizami *et al.*, 2014; Prada *et al.*, 2016). But, actually, there aren't monitored real examples for allowing to confirm the model predictions.

For instance, Moreno-Fernández *et al.*, (2015) studied a chronosequence in two Scots pine stands in a Mediterranean mountain area, with the same thinning intensity but different rotation periods. One of the interesting conclusions of this research was that higher levels of carbon sequestration is observed in forest subjected to longer rotation period. In addition, the study remarks the role of increase in rotation length to improve structural biodiversity, activating the natural regeneration and at the same time increasing the resistance to drought.

In addition, a study based on the increment analysis in forests managed with the current rotation lengths in Europe, indicated that the average carbon stock is increased by 6-13% for pine forests and by 14-67% for spruce forests (Kaipainen *et al.*, 2004b). The study concluded by stating that the increase in the length of the rotation positively affects the cut biomass.

Furthermore, the effectiveness of management depends strongly on the diverse combination of factors involved in the forest management. Although the rotation length is the most influential factor on carbon stock, as also demonstrated in the present simulation study, the appropriate combination of intensity of thinning plays also a crucial role. It is hence important to consider the interaction between rotation length and thinning intervals even if the latter factor has a low influence on stored carbon when considered alone (see figure 21).

In particular, for the same rotation but with different thinning intervals it is possible to observe diversified behaviours on the accumulation of stocks (Figure 22). Specifically, for the shortest rotation (70 years) lower carbon stock is observed in response to short thinning intervals, then progressively increasing for longer intervals. This behaviour levels off at the rotation of 90 year after which stock values are poorly affected by interval variation. Under the no-rotation scenario, higher carbon stocks were observed at shorter thinning intervals. This result is in agreement with Lasch *et al.* (2005) where longer rotation length and lower thinning intensity allowed to maximise total carbon stock.

But for this observed point there are several contrasting results. In particular, similar levels of carbon stock is observed indifferently under heavier regimes (Powers et al., 2011; Ruiz-Peinado et al.,2013a; 2016; Bravo-Oviedo *et al.*, 2015). These results, from forest management point of view, provide a greater flexibility by forest manager allowing a greater focus on other environmental services beyond the carbon stock (Ruiz-Peinado *et al.*, 2017).

For example, Ruiz-Peinado *et al.* (2011) has conducted a study with a comparison of on-site carbon stocks among different thinning intensities. The results clearly showed higher level of carbon stock under lightly-thinned stand (151 MgC ha^{-1}) than un-thinned (145 MgC ha^{-1}) and heavily thinned stands (116 MgC ha^{-1}). At the same time, considering cumulating the harvested biomass to standing carbon stock, managed stands always present higher values of carbon stocks.

In this context, the simulation approach is implemented to understand better the dynamics of carbon sequestration behaviour in relationship to different thinning algorithms. For example, Rio *et al.* (2008a) observed that the best forest management strategy is to adopt heavy thinning regime to obtain highest carbon stock in maritime pine (*P. pinaster*) in central Spain (rotation period of 80 years)

In contrast with this results, Balboa-Murias *et al.* (2006) showed that the light thinning regimes in plantations of maritime pine is the best strategy to obtain highest level of carbon stocks on the Atlantic coast of the Spain. Furthermore, Coletta *et al.* (2016), for maximizing carbon stock levels (without include the harvested biomass) a selective light thinning regime was the optimal forest management strategy.

Another observed aspect is that high thinning intensities (30%) do not influence the carbon stock in relation to different intervals. Only at the lowest tested intensity, the carbon stock progressively decrease with increasing interval. Then, it seems that low intensities (20%) and short time intervals (10 year) ensure greater forest efficiency for carbon stock accumulation.

This result is due mainly to fill the gap in the forest cover causing less penetration of solar radiation affecting the photosynthesis process rate.

This behaviour is observed in several studies (D'Amato *et al.*, 2013; Sohn *et al.*, 2016; Bradford and Bell, 2017) in which is showed the decrease of thinning's benefits in relation to the increase of its time interval. This results are supported by recent studies in Mediterranean areas such as Ruiz-Benito *et al.* (2013) considering the thinning component an important way to contrast the climate change trough an adaptation strategy reducing the tree mortality. Furthermore, heavy thinning allows to increment the water availability per tree but could reduce carbon sequestration rates, while light thinning allow high carbon stocks but may increase their vulnerability with high risk of disturbance (D'Amato *et al.*, 2011).

In all cases simulation considering management, with different options, show higher values of carbon stock than simulation where management is not included. This confirms the role of management for carbon stock independently of the combination of factors (rotation length, interval and intensity of thinning.

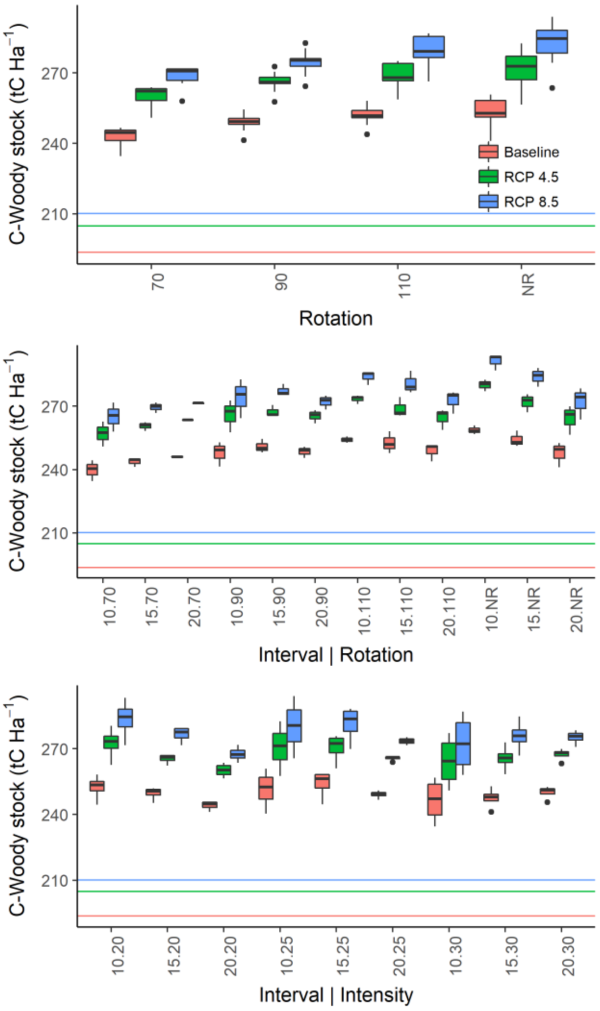

Figure 22. C-woody stock level under the different forest management options. The horizontal lines represent the average in carbon stock for no management cases (under the three scenarios). The boxplot shows in summarise way the minimum, first quartile, median, third quartile, and maximum C-woody stock values and the external points represents the outliers values.

4.6.3. Net Primary Production

Simulations show that also productivity is strongly influenced by the different climate and management scenarios (Figure 24). Higher NPP is observed in the warmer scenario (RCP 8.5) compared to baseline and milder scenario (RCP 4.5).

In term of management factor, the role of increasing rotation length is confirmed also for NPP, with higher NPP for longer rotations. In particular, a progressive increase in net carbon assimilation with increasing rotation is observed. The highest value is represented by no rotation case for which carbon assimilation values are 250 gC m^{-2} yr^{-1} higher than the shortest tested rotation. This trend remains constant in relation of all climate scenario. This behaviour of the model depend essentially by the reduction of the canopy cover that consequently determine a lower light competition for the remaining trees and a more efficient carbon uptake. Furthermore, lower thinning intensities allows to maintain almost the same carbon assimilation rate despite the number of trees are reduced. The rotation presence affect significantly the net carbon assimilation because from the year of the harvesting event needs several years so that the level of NPP returns to the same quantity modelled before the harvest contributing to destroying it for other uses, in a short time, will release a lot of carbon dioxide into the atmosphere. A Figure 23. represents this concept in a schematic way. In particular, a only thinned forest A maintain the level of carbon uptake less or more constant over the time while the rotation hinder high level of absorption for several years making a greater contribution to climate change.

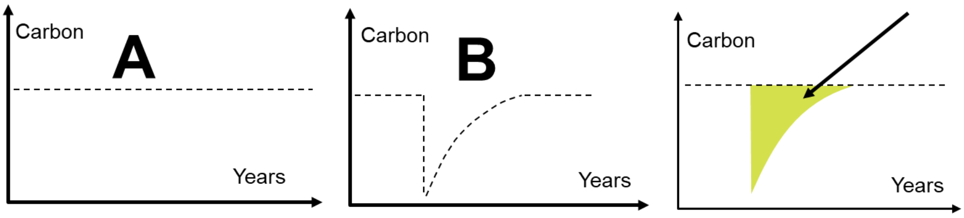

Figure 23. Forest management alternative for climate change mitigation. Only thinned forest (A), forest management with rotation length (B). difference about the carbon uptake between two types of management.

Similar results have been shown by several studies that affirm the effectiveness of different forestry practices on the amount of carbon stored and of harvested biomass, with particular importance on the careful adjusting of the rotation length (Pussinen *et al.*, 2002; Ranatunga *et al.*, 2008). Though sometime an increased rotation length may negatively impact carbon sequestration in the soil (Seely *et al.*, 2002; Lasch *et al.*, 2005) even with an increase in total carbon accumulation in the forest (Lasch *et al.*, 2005).

Furthermore, should be kept in mind that longer rotation periods as well as the decrease in NPP due an increase of mortality rate and age factor, it would lead to an increase in the likelihood of timber rot attacks such as the Mediterranean species Phellinus pini (Brot.) Bondartsev and Singer attacks Pinus pinea L. (Garcia Güemes and Montero, 1998), leading to a loss in the value of the wood.

Analysing the effect of thinning intensity, low intensities guarantee slightly higher levels of assimilated carbon, which decreases as the intensity increases (Figure 23). When considering intervals, a reduced frequency allow slightly greater carbon assimilation.

Differently from carbon stock, NPP levels are higher under no management compared to management.

However, under climate change scenarios (RCP 4.5 and RCP 8.5) thinning at low to medium frequency (15 and 20 years) and intensity (15 to 20%) result in NPP values closer to the "no rotation" option. Overall, the best performance for productivity is obtained from the optimal combination of all factors (rotation length, thinning intensity and interval).

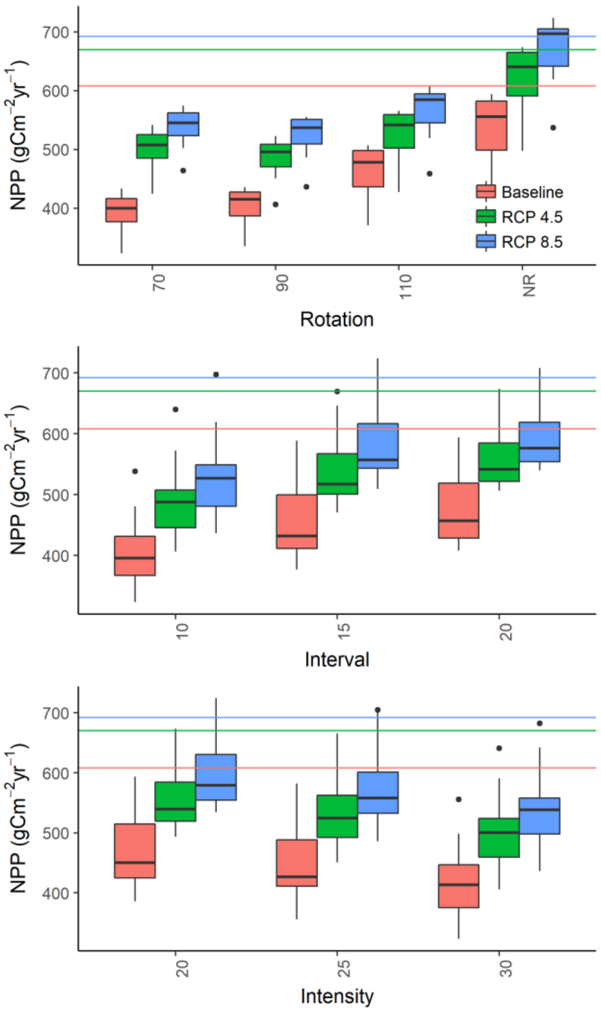

Figure 24. Carbon assimilation level with different forest management options. The horizontal lines represent the NPP values for no management cases. The boxplot shows in summarise way the minimum, first quartile, median, third quartile, and maximum NPP and the external points represents the outliers values.

In this context, Figure 25 show a detailed comparison of the effect of management options (interval and intensity of thinning) in the two longest rotation length and in the "No rotation" (i.e. *Continuous cover forestry*) case. In general, under no rotation case, higher values in carbon assimilation are attained compared to options with a rotation. In particular, choosing intense thinning practices lower values of carbon assimilation (NPP) compared to lower intensity and interval thinning. This is effective under all rotation cases.

In addition, under low thinning intensity with intermediate interval time and with the longest rotation length or without a fixed rotation, NPP is less or more similar to that achieved in the NR management case (0|0), specially under the warmest scenario, while values lower for about -20% are observed when short intervals and high thinning intensity options are used.

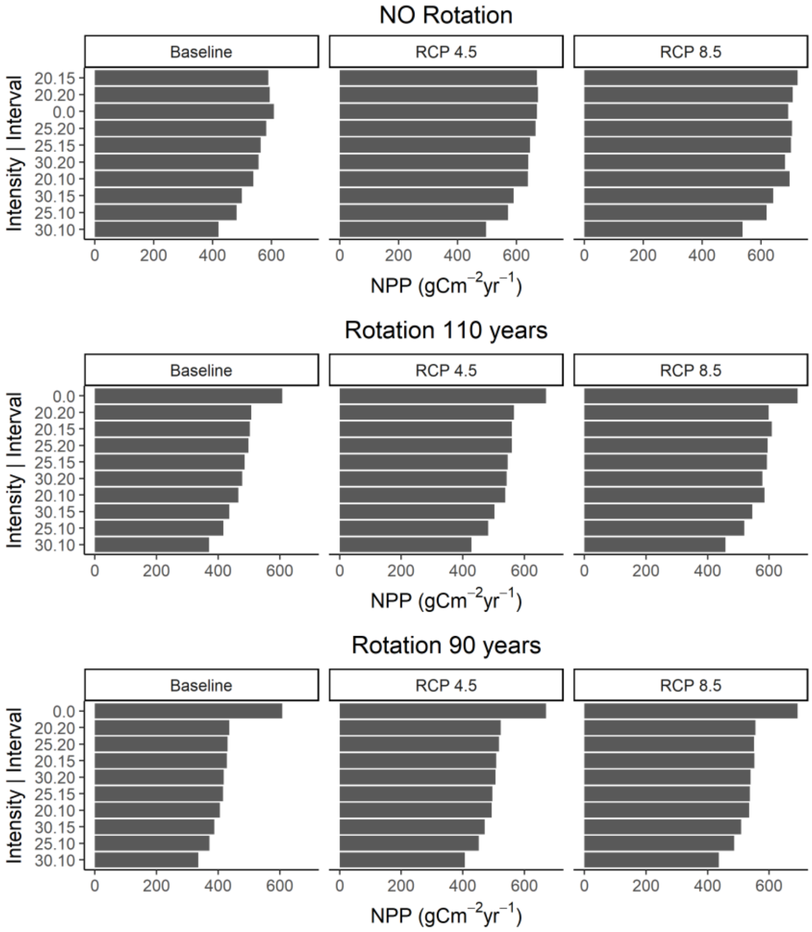

Figure 25. Representation of several forest management option in relation to rotation length in comparison with the 0|0 case (no management)

However, it is worth noting that, under climate change, assimilation of the regularly and sustainably thinned pine forests can be similar to that of the unmanaged forest. This can be related to the maintenance of an almost continuous coverage and of the LAI value that is little influenced by the weak intensity of thinning, keeping an efficient and almost constant light interception over time.

Average NPP over the simulation period is lower in management vs. no management scenario. This depends on the time needed for the harvested stand to attain again canopy closure and full photosynthetic capacity (Ballantyne *et al.*, 2012).

While under continuous cover forestry where thinning practises are computed, the remaining plants have a greater availability of light that they can use for their photosynthetic processes and at the same time lower autotrophic respirations is observed. In other words, similar levels on NPP between no rotation cases and no management is due by an increase in light use efficiency caused by decreasing competition (Saunders *et al.*, 2012) and by removing a part of standing biomass allowing a decreasing in respiration.

After thinning, trees generally benefit from better light availability and root nutrition conditions, which allow an increase in radial growth (Tullus, 1988). Furthermore, after thinning, a growth stimulating effect can be observed at 5-6 (Uri, 1994) or even 8-10 years (Tullus *et al.*, 1992) from the execution of the forest practice. Tree branches react to improved light conditions favouring a more intensive photosynthesis (Doruska and Burkhart, 1994). Furthermore, the thinned forest has lower biomass than an unmanaged stand, resulting in less maintenance respiration. In addition, the mortality rate is also lower in a managed forest, being thinning a tool to “anticipate” and avoid the natural mortality occurring in unmanaged forests.

When making management choices, rotation is hence a factor to be carefully considered. At the same time, thinning intensity and interval must also be determined judiciously, because it could weaken the productive capacity of the forest causing eco-physiological imbalances, as any intervention is to be considered a factor of external perturbation, to which forest responds with rebalancing its physiological functions over time.

5. CONCLUSION AND FUTURE PERSPECTIVES

This study was conducted for a fundamental reason: to deepen the knowledge of the carbon cycle dynamics in one of the most southern European experimental forest sites of the Mediterranean basin in a context in which the climate is expected to change at a pace that is even higher than in other regions of the globe.

Laricio pine (*Pinus nigra laricio* (Poir.) Maire) is one of the most representative species in the local forest context of Calabria and where most of the forests are managed. Hence, the study aimed at analysing the changes and dynamics in the main carbon cycle variables (GPP, NPP, RA) and in wood carbon stocks in relation to management practices in an increasing vulnerable context.

For this purpose, a modelling approach was chosen and the 3D-CMCC-CNR FEM was used to evaluate the effect of climate change, increasing CO_2 concentrations and management practices on forest ecophysiological processes and carbon stocks.

To date, the Mediterranean region is characterized by a limited knowledge of future projections for forests, as the most of the research in this field has been conducted for temperate or boreal forest. These situations are profoundly different than in the Mediterranean region, where climate, limiting factors, management options and objectives are much different and where the history of human impact is long and intense.

The study started from a detailed analysis of the studied forest and of its history, through the execution of surveys to obtain structural, dendrological and dendrochronological data to validate the model. At the same time, the model was parameterised in detail, in order to increase its reliability in the conditions of the study.

In particular, sensitivity analysis of the model was implemented and subsequently the Bayesian calibration made it possible to quantify the uncertainty of the output variables compared with the measured data.

Specifically, in this study the temporal variation of GPP, RA, C-woody stock and NPP under different climate scenarios was analysed and a reference management (rotation: 90 years; interval: 15 years; intensity: 25%) that was compared with no management case, to analyse in detail how management may influence a Mediterranean forest under climate change.

As literature shows also in the studied forest, a positive effect of management was observed on various eco-physiological aspects. In particular, a reduction in forest cover through thinning confers beneficial effects on the growth and development of the remaining plants, creating light conditions that makes more efficient their photosynthetic process, consequently contributing to enhance NPP, despite the decrease of Leaf Area Index.

Management, when sustainably applied, determines an overall increase in average total stock (including harvest), although the average NPP is still higher in the unmanaged forest.

Different management options were then considered in the modelling experiment, modulating rotation length, thinning intensity and interval compared to no management. Analysis was focused on total stock and NPP dynamics in response to management under climate change scenarios.

From the analysis, it emerged that the factor that has a greater weight on the productivity of the forest is the choice of rotation length. In particular, an increase in rotation length has beneficial effects not only on the carbon stock but also on average productivity. Under the same rotation, the combination of short intervals of thinning (10-15 years) with low intensity (10-15%) guarantee the best strategy.

New findings that emerged from the analysis concerns net productivity that resulted higher in the “undisturbed” forests vs. the BAU managed forest by 24.3%, 13.5% and 7.5% under baseline, RCP 4.5 and RCP 8.5 scenarios, respectively. Interestingly, when management is modulated, NPP values with a thinning intensity of 20% repeated every 15 years tend to be similar or even slightly higher (+6%) compared to NPP in the no management case. This result is reversed at high thinning intensity repeated at short intervals.

This confirms the importance of low intensity thinning at short and regular intervals over time. Indeed, an increase in rotation length could lead to greater biotic and abiotic risks (fungi, pests, wind, snow), which could compromise the sustainability of forests in the future.

This would suggest the hypothesis that in Mediterranean climate and for conifer forest, under climate change, careful forest management characterized by well calibrated rotation length, thinning intervals and intensities, based on specific biotic and abiotic conditions, may guarantee a carbon assimilation comparable to no management forest and, at the same time, maximizing the total carbon stock.

In particular, all three components (rotation length, intensity and interval of thinning) deserve attention, not only for the total stock that the forest is able to accumulate over time inside and outside the stand (harvested wood) but also to net carbon assimilation that can be comparable or sometimes even higher in a managed compared to an unmanaged forest. This would ultimately also allow for provision of multiple services. This confirms the importance of sustainable forest management, which not only provides for the maximization of timber production, but also has the potential to guarantee the performance of various ecosystem services that are important for the community.

In spite the carbon sequestration potential and human intervention in forests was identified as a research priority (Scarascia-Mugnozza *et al.,* 2000), there are, actually substantial gaps in our knowledge specially for Mediterranean forests.

In conclusion, multidisciplinary studies should be undertaken to investigate specifically the impact of forest management on carbon sequestration that include all components of forest carbon and especially its effects considering the long term. Based on the above, the most important challenge in the context of the Mediterranean basin is to undertake new experimental studies to compare long-term forest management alternatives.

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8. Supplementary material

DESCRIPTION	PARAMETERS	Unit	Value	Bibliography
Shadow tolerance degree	LIGHT_TOL	dim	3	
Types of species	PHENOLOGY	dim	1.2	
Canopy quantum efficiency	ALPHA	molC/molPAR	0.014	(Navarro-Cerrillo *et al.*, 2016)
Empirical parameter for light modifiers	GAMMA_LIGHT	dim	0.045	(Peltionemi *et al.,* 2012)
Extinction coefficient for absorption of PAR by canopy	K	dim	0.56	(Patenaude *et al*., 2008)
Albedo	ALBEDO	dim	0.12	(Navarro-Cerrillo *et al.*, 2016)
Max proportion of rainfall intercepted and Evaporated from canopy	INT_COEFF	dim	0.052	(Patenaude *et al*., 2008)
Average Specific Leaf Area (juvenile)	SLA_AVG0	m^2/KgC	5.2	(Nunes *et al*., 2014)
Average Specific Leaf Area (mature)	SLA_AVG1	m^2/KgC	4.5	(Nunes *et al*., 2014)
Age at which SLA_AVG=(SLA_AVG1+SLA_AVG0)/2	TSLA	dim	20	
Shaded to sunlit projected SLA	SLA_RATIO	dim	2	(Navarro-Cerrillo *et al*., 2016)
All-sided to projected leaf area ratio	LAI_RATIO	dim	2.6	(Navarro-Cerrillo *et al*., 2016)
Branch and bark fraction at juvenile age	FRACBB0	dim	0.33	(Navarro-Cerrillo *et al*., 2016)
Branch and bark fraction at mature age	FRACBB1	dim	0.1	(Navarro-Cerrillo *et al*., 2016)
Age at which TBB = (FRACBB0 + FRACBB)/2	TBB	year	10	(Navarro-Cerrillo *et al*., 2016)
Min basic density for juvenile tree	RHO0	t m^{-3}	0.45	(Navarro-Cerrillo *et al*., 2016)
Max basic density for older trees	RHO1	t m^{-3}	0.45	(Navarro-Cerrillo *et al*., 2016)
Age at which = (min +max)/2	TRHO	year	4	(Navarro-Cerrillo *et al*., 2016)
Form factor of trees	FORM_FACTOR	dim	0.45	
Defines stomatal response to VPD	COEFFCOND	mbar	0.01	(Navarro-Cerrillo *et al*., 2016)
Canopy boundary layer conductance	BLCOND	ms^{-1}	0.0013	Bayesian Calabration
Maximum canopy conductance	MAXCOND	ms^{-1}	0.0023	Bayesian Calabration
Cuticul conductance	CUTCOND	m/sec	4.4E-05	(Navarro-Cerrillo *et al*., 2016)
Determines rate of "physiological decline" of forest	MAXAGE	year	200	(Navarro-Cerrillo *et al*., 2016)
Relative age to give *fage* = 0.5	RAGE	dim	0.95	(Navarro-Cerrillo *et al*., 2016)
Power of relative age in *fage*	NAGE	dim	4	(Navarro-Cerrillo *et al*., 2016)
Minimum temperature for growth	GROWTHTMIN	°C	2	(Patenaude *et al*., 2008)
Optimum temperature for growth	GROWTHTMAX	°C	37	(Patenaude *et al*., 2008)
Maximum temperature for growth	GROWTHTOPT	°C	18.232	Bayesian Calabration
Average temperature for starting growth	GROWTHSTART	days	195	
Minimum soil water potential to keep stomata open	SWPOPEN	MPa	-0.5	(Cinnirella et al., 2002)
Minimum soil water potential to close stomata	SWPCLOSE	Mpa	-2.2	(Cinnirella et al., 2002)
Environmental dependent allocation factor	OMEGA_CTEM		0.5	(Navarro-Cerrillo *et al*., 2016)
Stem Allocation factor	S0CTEM	dim	0.45	(Navarro-Cerrillo *et al*., 2016)
Root Allocation factor	R0CTEM	dim	0.35	(Navarro-Cerrillo *et al*., 2016)
Foliage Allocation factor	F0CTEM	dim	0.2	(Navarro-Cerrillo *et al*., 2016)
Fraction of NPP allocated for reproduction	FRUIT_PERC	dim	0.15	Xiao et al., 2003
Life span for cones	CONES_LIFE_SPAN	year	3	
Allocation new fine root C:new leaf (ratio)	FINE_ROOT_LEAF	dim	0.85	(Nunes *et al*., 2014)
Allocation new coarse root C:new stem (ratio)	STEM_LEAF	dim	2.3	(Nunes *et al*., 2014)
allocation new coarse root C:new stem (ratio)	COARSE_ROOT_STEM	dim	0.294	(Nunes *et al*., 2014)

DESCRIPTION	PARAMETERS	Unit	Value	Bibliography
new live C:new total wood (ratio)	LIVE_TOTAL_WOOD	dim	0.045	(Nunes *et al.*, 2014)
CN of leaves	CN_LEAVES	kgC/kgN	50	(Nunes *et al.*, 2014)
CN of fine roots	CN_FALLING_LEAVES	kgC/kgN	125	(Nunes *et al.*, 2014)
CN of fine roots	CN_FINE_ROOTS	kgC/kgN	55	(Nunes *et al.*, 2014)
CN of live woods	CN_LIVE_WOODS	kgC/kgN	65	(Nunes *et al.*, 2014)
CN of dead woods	CN_DEAD_WOODS	kgC/kgN	1350	(Nunes *et al.*, 2014)
Leaf litter labile fraction	LEAF_LITT_LAB_FRAC	dim	0.26	(Cenciala and Tatarinov, 2006)
Leaf litter cellulose fraction	LEAF_LITT_CEL_FRAC	dim	0.49	(Cenciala and Tatarinov, 2006)
Leaf litter lignin fraction	LEAF_LITT_LIGN_FRAC	dim	0.25	(Cenciala and Tatarinov, 2006)
Fine root litter labile fraction	FROOT_LITT_LAB_FRAC	dim	0.23	(Cenciala and Tatarinov, 2006)
Fine root litter cellulose fraction	FROOT_LITT_CEL_FRAC	dim	0.41	(Cenciala and Tatarinov, 2006)
Fine root litter lignin fraction	FROOT_LITT_LIGN_FRAC	dim	0.36	(Cenciala and Tatarinov, 2006)
Dead wood litter cellulose fraction	DEAD_WOOD_CEL_FRAC	dim	0.7	(Cenciala and Tatarinov, 2006)
Dead wood litter lignin fraction	DEAD_WOOD_LIGN_FRAC	dim	0.3	(Cenciala and Tatarinov, 2006)
Days of bud burst at the beginning of growing season	BUD_BURST	days	0.3	
Average YEARLY leaves and fine root turnover rate	LEAF_FINEROOT_TURNOV	dim	0.33	(Nunes *et al.*, 2014)
Annual yearly live wood turnover rate	LIVE_WOOD_TURNOVER	dim	0.75	(Nunes *et al.*, 2014)
Maximum ratio DBH-crown diameter for low density	DBHDCMAX	dim	0.525	direct analysis
Minimum ratio DBH-crown diameter for high density	DBHDCMIN	dim	0.105	direct analysis
Sapwood Allometric Parameter	SAP_A	dim	0.298	direct analysis
Sapwood Allometric Exp Parameter	SAP_B	dim	1.939	Bayesian Calabration
Ratio Sapwood MaxLAI	SAP_LEAF	dim	1500	(Verbeeck *et al.*, 2007)
Sapwood-Reserve biomass ratio	SAP_WRES	dim	0.075	(Schwalm and Ek, 2004)
Allometric parameter to initialize stem biomass	STEMCONST_P	dim	0.00155	direct analysis
Allometric exp parameter to initialize stem biomass	STEMPOWER_P	dim	3.5	direct analysis
Chapman-Richards asymptotic maximum height	CRA	dim	26	(Pilli R, *et al.*,2006)
Chapman-Richards exponential decay parameter	CRB	dim	0.11	direct measure
Chapman-Richards shape parameter	CRC	dim	2.4	direct measure
Crown form factor	CROWN_FORM_FACTOR	dim	1	
Crown relationship with tree height	CROWN_A	dim	0.415	
Crown exponential with tree height	CROWN_B	dim	1	
Maximum number of seeds producted by plant	MAXSEED	dim	22500	
Year of abundant fruitification	MASTSEED	year	4	
Weight of seeds	WEIGHTSEED	g	0.02	
Age at sexual maturity	SEXAGE	year	28	
Geminability	GERMCAPACITY	year	0.65	
Forest Rotation for harvesting	ROTATION	year		
Thinning interval	THINNING	year		
Thinning regime (0 = above, 1 = below)	THINNING_REGIME	dim		
Thinning intensity (% of Basal Area/N-tree to remove)	THINNING_INTENSITY	m^2/ha		

Table 1. Parameters used for model parameterization.