Adaptive measures for mountain Mediterranean forest ecosystem services under climate and land cover change in the Mont-Ventoux natural Regional Park, France

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Abstract

Climate change (CC) and land use and land cover change (LULCC) threaten Mediterranean forests and the ecosystem services (ES) they provide. In complex socio-ecological systems and under high uncertainties, the resilience of ES has become the target objective for adaptive management strategies driven by decision makers and local stakeholders. This work develops an integrative and territorial approach to combining biophysical modeling and local managers' assessments to elaborate scenarios of LULCC in response to climate and socioeconomic changes. It also evaluates the impacts of forest ecosystem changes on coupled ES for different time horizons for a case study of the mountain Mediterranean forests of Mont-Ventoux Natural Regional Park. The results demonstrate first that the future ES provisions predicted by biophysical modeling in this area are less affected by CC than expected by local managers. Furthermore, LULCC increases the changes in ES provision and accentuates the difference between climate scenarios. These results originate from a combination of two effects: (1) pessimistic predictions by local managers and, as a consequence and (2) anticipatory actions that tend to reinforce or even accelerate the expected changes in the mountain Mediterranean forest area.

Key words: mountain Mediterranean forests, ecosystem services, climate change, adaptive scenarios, socio-ecological approach

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1. Introduction

Climate change (CC) and land use land cover change (LULCC) have become the two biggest threats to Mediterranean forests, profoundly altering the future of forest ecosystem services (ES) (Lamarque et al., 2014; Choe and Thornes, 2017). Awareness of CC and uncertainty modifies forest management and political decisions from sustainable management to the adaptive strategy perspective (von Detten, 2011; Hoogstra-Klein & Burger 2013; Lidskog & Löfmarck 2015, 2016). In the adaptive management perspective, three main issues must be considered: (1) the forest ecosystems will change as driven by climate and human decisions, (2) the demand on ES will change as driven by societal evolution and (3) the changes in forest ecosystems will have multiple impacts on multiple ES. The exploration of future delivery of ES in socioecological systems (SES) must integrate complex interrelations and feedback among economic activities (e.g., forestry), land use, local environmental conditions and ecological dynamics.

Currently considered as an interesting approach by the scientific and decision maker communities, the future delivery of ES has been increasingly studied through exploratory scenarios (Harmáčková and Vačkář, 2018; Berg et al., 2016; van Vuuren et al., 2011). Scenario construction relies on qualitative narratives (for example, the evolution of local management policies or social preferences) and their transcription into quantitative changes (input variations such as temperature, quality of soil, demand for renewable energy, etc.) (Martinez-Harms et al., 2017). Mediterranean forests provide good case studies of multifunctional SES (Croitoru, 2007; Masiero et al., 2016), as they are biologically and ecologically diverse, rapidly changing, and heterogeneous in ownership and management systems (FAO, 2014; Martinez de Araño et al, 2018).

In the case of Mediterranean forests, the expected impacts of global changes on future ecosystem functioning and sustainability have already been listed (FAO, 2014). The literature discusses several factors of changes (CC, LULCC, and ecosystem management policies) using different methods (statistical/correlation analysis and process-based modeling) to evaluate their impacts on ES production and value. A recent literature review on models and scenarios used to assess the future of the Mediterranean forest ES (Morán Ordóñez et al., 2018) showed that only a few studies used process-based models while the majority of studies evaluated only one driver of change, i.e., CC.

In particular, integrated prospective analyses of future ES delivery can be improved by a combined approach addressing three major challenges:

(i) Implementing biophysical modeling to better estimate the balanced effects of CC (e.g., longer growing season or increasing drought) and CO_2 fertilization on ecosystem functions;
(ii) Combining biophysical models and managers' expert assessments to elaborate scenarios of LULCC in response to climate and socioeconomic changes; and
(iii) Combining biophysical and economic approaches to evaluate the impacts of forest ecosystem changes on multiple-ES delivery at a territorial scale for different temporal horizons.

Such integrated assessment of ES is still largely missing due to integration complexity, implying different ecosystems, ES, values, temporal and spatial scales, stakeholders and disciplines (Tardieu, 2017).

The biophysical evaluation of ES is commonly based on empirical linear models (Lamarque et al., 2014, Martinez-Harms et al., 2017, Schirpke et al., 2017) that estimate the determinants of ES, including ecological processes and human practices. These relationships are first documented in different climate or land use contexts, accounting for current spatial and past temporal variations, then applied in future conditions. These empirical models assume a stable relationship between eco-physiological ecosystem characteristics and ES provision. As these effects are empirically estimated using past and present observations of the relationships between climate and ES, they do not account for complex and dynamic changes in forest functioning in the future climate context. Thus, they are considered unable to incorporate the effects of changing environmental conditions on tree and stand growth (Fontes et al., 2010). By contrast, process-based models have thus been considered particularly convenient for the investigation of forest dynamics under new environmental conditions (Fontes et al., 2010; Oddou-Muratorio et al., 2020).

Only few publications consider a combined approach for the study of global change impact on the future provision of ecosystem services at the landscape scale (Kubiszewski et al., 2017; Small et al., 2017; Costanza et al., 2011) or at a local scale (Ding et al., 2016; Bottalico et al., 2016; Masiero et al., 2016). However, integrated study of ES considering both supply side (ES provided by ecosystems according to ecological functions) and demand side (beneficiaries of ES) in spatially explicit terms is currently recognized as a powerful tool to help environmental and management planning decisions (Tallis and Polasky, 2009; De Groot et al., 2010; Garcia-Nieto et al., 2013). The economic valuation of CC and LULCC impacts on the production of ES is an important step to solving potential conflicts between beneficiaries or establishing guidelines for sustainable forest management considering the potential trade-offs or synergies between ES (Kubiszewski et al., 2017).

In this work, we studied Mont-Ventoux Natural Regional Park. We developed a methodology to explore the effects of different scenarios of forest policies and CC on changes in carbon sequestration (regulation and maintenance ES) and timber production (provisioning ES) in spatially sensitive and dynamic ways, combining biophysical and economic values. We designed different forest management options under climate scenarios to estimate the resilience of Mediterranean forest ES according to their ecological and economic trajectories in two time horizons, 2050 and 2100. We first used a stakeholder-based analysis to estimate the evolution of ES production according to the LULCC. This first step was based on the InVEST model and its stakeholder matrices tool (i.e., InVEST models; Kareiva et al, 2011). Then, we used a biophysical model to assess the future state and functions of different forest types (i.e., climate impact on ecosystem functions) using simulations on nine forest types at five altitude levels for three soil water depths, two canopy openness values and two aspects (i.e., CASTANEA model; Dufrêne et al., 2005; Davi and Cailleret, 2017). This combined model-based approach (i.e., LULC modeling and physiological assessment of forest functioning) allowed us to jointly explore the future effect of LULC and CC on forest ecosystems. Moreover, this approach combined a spatially explicit ES analysis and an economic valuation.

We used an integrated approach to investigate how climate and LULCC factors impact the different ES and to analyze whether the changes in ES are due to climate scenarios or LULCC scenarios (including adaptation) and whether some LULCC scenarios can offset the effect of climate.

2. Methodology

Figure 1 presents the four steps of our methodology.

2.1 Land cover map of the studied area

The case study is on Mont-Ventoux Natural Regional Park in France, a Mediterranean forest socio-ecological system. Located in the southern part of France (the Provence region), the current perimeter of the Mont-Ventoux park covers a total area of 987 km². Mont Ventoux peaks at 1,912 m a.s.l. The territory is occupied by 57.7% forest and semi-natural environments and hosts a great diversity of

natural habitats linked to a unique bioclimatic and geomorphological context (Barbero and Quezel, 1976). Because of its altitudinal gradient and its intermediate geographical location between the Alpine and Mediterranean regions, the Ventoux area presents a high diversity of environments.
We characterized our study territory according to a typology compatible with the ecological and land cover models, i.e., a mono-specific and spatially representative typology. We used two main geographic databases: the French forest database by the National Geographic Institute in 2012 (BDForêt©) and the Corine Land Cover database in 2012. Finally, we obtained 37 types of land covers comprising (see Fig. 2): nine locally predominant tree species (*Quercus pubescens, Quercus ilex, Fagus sylvativa, Pinus nigra, Pinus sylvestris, Pinus halepensis, Pinus unicinata, Abies alba, Cedrus atlantica*) and five bioclimatic stages (plain, Mediterranean, supra-Mediterranean, lower mountain, and higher mountain), five groups of companion species, moors, fire areas, and three aggregated LULCs (artificial areas, agricultural areas and various vegetation). This typology allowed us to work on mono-specific process-based and fine-scale (i.e., non-aggregated) LULC models. The spatial resolution was 25 m X 25 m grid (i.e., 1 ha = 16 pixels).

2.2 Exploratory scenario narratives

Our exploratory scenarios are based on two main drivers, CC and forest policy, defined over two time horizons: short term (2050) and long term (2100).

2.2.1 Establishment of a local stakeholder panel

The scenario construction started with the identification of the effects of the drivers of change on local forest ecosystems, which we achieved in close relationship with local stakeholders and managers (McKenzie et al., 2012). To do so, the first step was to identify a panel of stakeholders and managers to define and improve our scenarios and collect their knowledge on local forest resources and management. As recommended by the NatCap team in their InVEST guide and in the existing literature on this topic (Berg et al., 2016; Tallis et al., 2013), our stakeholder panel participated in four iterative meetings: scenario narrative construction (e.g., local forest policy orientation, biodiversity protection, and timber market evolution), data and inputs for the assessment (e.g., forestry planning by species and stage, harvest mass, cost of production and prices), future LULC and the transition matrix construction, and reviewing and improving the ES outputs. The stakeholder panel is presented in Appendix A.

2.2.2 Current local climate and downscaled climate change scenarios

We used the Safran meteorological analysis system (Durand et al., 1999), which provides past meteorological daily input data on a regular grid (8 × 8 km). Then, we used two points of the grid located in the Ventoux, one at the north and the other at the south, to calibrate the climatic clines used in the simulations. To account for altitudinal effects on climate, local measurements were taken at ten forest sites targeted in the study from local weather stations (2007-2015). The minimum, maximum, and average temperatures, rainfall and relative humidity were recorded with a Prosensor HOBO Pro (RH/Temp; Onset Computer Corporation, Bourne, MA 02532, USA). Regression coefficients were estimated between these local stations and the Safran climate data at the two grid points. These

regression coefficients were then used to generate daily climate data from 1959 to 2015 based on the long-term SAFRAN outputs using the equations described by Oddou-Muratorio and Davi (2014).
For the future climate, we used the Hadley Centre Global Environmental Model version 2 (HadGEM2) and the Coupled CNRM - CM/AOGCMs - atmosphere-ocean general circulation models. From all existing climate models, CNRM – CM5 is the coldest model that can also predict an increase in precipitation, and HadGEM2 - ES is the warmest model that can predict a decrease in rainfall (McSweeney et al., 2015). We considered two CC scenarios: RCP 4.5 (Representative Concentration Pathway[1]) and RCP 8.5. RCP 4.5 is the more optimistic scenario, and RCP 8.5 is the more pessimistic scenario. RCP 8.5 is estimated using the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (Moss et al., 2010) predicting a rising up to 1,370 ppm CO_2-eq in 2100. These climate predictions were downscaled at the two studied points of the Safran grid using the 1960–2015 period as a reference using the R-package 'meteoland' (De Cáceres et al., 2015). Both scenarios follow the same trend until 2050, but they strongly diverge between 2050 and 2100 (see Appendix B).

2.2.3 Global forest policy scenarios and local forest management options

The global forest policy scenarios are based on the plausible futures of the European forestry sector published by the UNECE FAO section (European Forest Sector Outlook Study II – EFSOS II; FAO, 2011). Among the four EFSOS scenarios, we selected the three most relevant forest policies in our study area: business as usual (BAU), promotion of wood energy (WE) and biomass and carbon sequestration maximization (BIO). The first corresponds to the evolution of land cover (i.e., LULCC) related to "as usual" forest management, without adaptation, whereas the latter two, BIO and WE, correspond to forest management policies for adaptation to global changes.
We adapted the EFSOS scenarios to our case study by translating them into a short narrative description that was then validated by the stakeholders. A brief description of the scenarios used in this work is in Appendix C (Table C1).
The three forest policy scenarios and their related forest management options affect forest management regimes (e.g., thinning, harvest period). The forestry planning is accurately described in Table 1.
These scenarios resulted in 12 combinations (2 time horizons × 2 RCP × 3 forest policies), producing our 12 scenarios (see Appendix C, Fig.2).

2.3 Models

As presented in Figure 1, our two global change drivers, climate change and forest policy, were then used as inputs for the LULC and process-based models. All data sources used in these methods are presented in Appendix D.

2.3.1 Land cover change model

The three forest policy scenarios and their related forest management options affect forest management regimes (e.g., thinning, harvest period). The forestry planning is accurately described in Table 1.

[1] The modeled climate scenario data follow the Representative Concentration Pathways (RCP).

For the construction of different potential futures, we used InVEST, which allows incorporation of complex scenarios combining climate, policy factors and local stakeholder expertise (Kareiva et al., 2011; Tallis et al., 2013). Forest management options under different climate change contexts are translated first into forest planning options, then into transition matrices and finally into maps. Stakeholder and manager interviews provided local information on tree species choices according to the potential mortality or adaptation of each species in a global change context. The methodology to express the transition probabilities from the corpus of information provided by the panel of stakeholders follows the recommendations of the InVEST guide. The transition probabilities depend on the percentage of change from one land cover type to another and the two surface areas of the original and final land covers. Given our 37 land cover types and 12 scenarios, the required information represents a complex overview. Stakeholders provided the rate of area change in each land cover for each scenario and at the two time horizons, given in matrix A, as follows:

To F'_j / From F_i	F'_1	…	F'_{37}	Current surface area S_i
F_1	$P_{1,1}$	…	$P_{1,37}$	S_1
$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
F_{37}	$P_{37,1}$	…	$P_{37,37}$	S_{37}
Future surface area S'_j	S'_1	…	S'_{37}	
Δ Surface area O_j	O_1	…	O_{37}	

with $F_{i,j}$ as the LULC categories, from type $i = 1, \dots, 37$ to type $j = 1, \dots, 37$. $P_{i,j}$ is the proportion, between 0 and 1, of the total surface of land cover type i that becomes a land cover type j. The current surface related to each LULC type is S_i; the future surface, S'_j, based on probabilities in matrix A, is computed as presented by equation (1); and O_j is the difference between S_i and S'_j:

$$S'_j = \sum_{j=1}^{37} P_{i,j}\, S_i \quad (1)$$

We finally obtained 12 future land cover maps (one per scenario).

2.3.2 Process-based model

CASTANEA is an eco-physiological process-based model used to predict water and carbon fluxes in forest stands (Dufrêne et al., 2005). The canopy is assumed to be horizontally homogeneous and is vertically subdivided into a variable number of layers, each with the same amount of leaf area. One averaged tree is assumed to be representative of the whole stand; therefore, each tree behaves as a dominant tree. In CASTANEA, the tree structure is assumed to be a combination of five different functional parts: stems, branches, leaves, coarse and fine roots (Davi et al., 2005). In addition, a carbohydrate storage section is included. The main simulated output variables are canopy photosynthesis, maintenance and growth respiration, tree carbon allocation, soil heterotrophic respiration, tree transpiration, and ecosystem evapotranspiration (Davi et al., 2005).

Species-specific parameters were defined using a literature review, remote sensing and forest inventory data (see Appendix F). The model was first evaluated at four FLUXNET sites, where some of the studied species are present, using growth data on all of the studied species (Davi et al., 2005; Davi et al., 2006; Guillemot et al., 2017; Lopez-Garcia, 2018). Then, the CASTANEA model was used to simulate the water and carbon fluxes across an elevation gradient for different types of stands (open vs. closed, three types of soil, and soil water content) under past and future climate conditions (two contrasted climate models, HADGEM2 and CNRM - CM/AOGCMs and two RCPs, 4.5 and 8.5) with or without silviculture (Appendix B).

Mortality is estimated in the model by accounting for both the mortality induced by hydraulic cavitation and the mortality related to carbon starvation (Adams et al., 2017). Adult mortality is due to either carbon starvation or hydraulic failure (Davi and Cailleret, 2017). We assumed that conifers die when the percentage of conductance loss is greater than 50% (Brodribb and Cochard, 2009) and that angiosperms die when the percentage of conductance loss is greater than 88% (Urli et al., 2013). We then estimated the average concentration of non-structural carbohydrates ($[NSC]_{threshold}$) per species below which trees die from past mortality data recorded in the IGN data. For Holm oak, this method generated an excessively high value for $[NSC]_{threshold}$; we then used the maximum value obtained for the other species.

2.4 Ecosystem services assessment

We studied two categories of ES, provisioning for timber production and regulating for carbon sequestration, at every time horizon and for all scenarios. To respect the specificity of each ES and the forest multifunctionality outputs, we selected adapted methods for the economic valuation. Thus, we used the price in euros in the French market for the timber production service, and we used a socioeconomic value, i.e., the social cost of carbon (SCC), for the carbon sequestration. In these two cases, the demand is commonly equal to the flow of ES: the biophysical amount of ES is directly converted into monetary units through market prices and costs. These methods are part of the market valuation methods (versus nonmarket valuation, for example, revealed and stated preference techniques), allowing for a better comparison and joint analysis of our pair of ES.

2.4.1 Carbon sequestration

At every time horizon, for every scenario and for each forest land cover type $(i = 1, \dots, 35)$, carbon sequestration, $Stock_i$, was assessed yearly using the CASTANEA model ($t_C.ha^{-1}.year^{-1}$) using the following equation:

$$Stock_i = GPP_i - Ra_i - Rh_i \tag{2}$$

where GPP_i is the gross primary production; Ra_i the sum of all autotrophic respiration of coarse and fine roots, branches, stem and leaves; and Rh_i is the heterotrophic respiration of soil.

The economic valuation is based on the social cost of carbon (SCC). It corresponds to the reduction of future damage, i.e., avoided damage, caused directly or indirectly by the emission of an additional ton of CO_2, by reducing theses emissions. We computed the economic value of carbon sequestration as follows:

$$Stock\_NPV_i = \frac{SCC \times Stock_i}{(1+r)^t} \quad (3)$$

$$Stock\_TNPV_i = Stock\_NPV_i \times S_i \quad (4)$$

where $Stock\_NPV_i$ and $Stock\_TNPV_i$ are the net present value (NPV) and the total net present value (TPNV) of carbon sequestration in euros, respectively, SCC is the current and fixed social cost of carbon, CC_i is the carbon sequestration (equation (2)), t is the total number of years during the studied period (to obtain the mean annual sequestration), and r is the discount rate. The surface of each forest land cover type i is given by S_i (or S'_i for the future).
The literature has proposed a large range of SCC. Then, as recommended in the literature on this topic (Bottalico et al., 2016), we simplified the analysis and selected only two values (expressed in €$_{2017}$), 44€/tCO2 in 2017 and 57€$_{2017}$/tCO2 in 2050 (Watkiss, 2006), and we assumed that those values remain constant between 2050 and 2100.

2.4.2 Timber production

Timber production depends on two main pieces of information, the wood volume in m^3.ha^{-1} and the forest planning (thinning, % of timber harvested, harvest frequency), which vary across time horizons, climate scenarios and policy scenarios.
In CASTANEA the wood volume per ha, Vha_i for forest land cover type i ($i = 1, \ldots, 35$), is estimated yearly using the following equation:

$$Vha_i = \frac{B_{stem_i}}{\rho_{wood_i} \times tc_i} \quad (5)$$

where B_{stem_i} is the stem biomass per ha, ρ_{wood_i} is the wood density, and tc is the carbon content of wood (the stem biomass in the model is in gC/m^2 of soil). We did not include new recruitment in our simulated stands.
Then, from the forest planning, we obtained the mass of wood harvested (m^3/ha), $ThinnedVha_i$, as follows:

$$ThinnedVha_i = Vha_i \times harv_{rate} \quad (6)$$

where $harv_{rate}$ is the percentage of wood harvested for each period studied (see Table 1).
The model used for the timber production net present value, NPV_i , and the total net present value, $TNPV_i$, in euros is the following:

$$ThinnedVha\_NPV_i = \frac{ThinnedVha_i \times (Price_i - Harv_{cost_i}) - Maint_{cost_i}}{(1+r)^t} \quad (7)$$

$$ThinnedVha\_TNPV_i = ThinnedVha\_NPV_i \times S_i \quad (8)$$

This model includes the mass of wood harvested (m^3/ha), $ThinnedVha_i$; the cost of wood harvesting (€/m^3/ha), $Harv_{cost_i}$; and the cost of maintenance of each plot (€/ha), $Maint_{cost_i}$. We then computed the TNPV, weighing the NPV by the total surface area (in ha). For the economic data, we used the marketplace value of the wood harvested from each plot, depending on the tree species (€/t) $Price_i$, and the market discount rate r (see Appendix E for all input details). Based on the literature (survey by Clark, 2001; Ding et al., 2016), we assumed that the timber selling price remains constant across the whole simulated period 2017-2100. We also justify this choice due to the very low impact of local shocks (supply or demand economic shocks resulting from the policy scenarios) on the timber marketplace.

2.4.3 Sensitivity analysis for the economic valuation

Economic forecasting analyses are characterized by a high level of uncertainty directly related to the selected level of discount rate applied to ES valuation. French legislation as well as many studies on land use planning projects recommend adopting a 4% discount rate (Lebègue Report, 2005; Quinet Report, 2013; Trivino et al.,2015). Other studies tested the effect of various discount rates: from 1% to 8% in Bottalico et al. (2016) or from 1% to 5% in Pukkala (2016). However, to account for the scarcity of natural resources and the strong and positive correlation between ecological growth and economic growth (Gosselin et al., 2011), the Stern Review and numerous studies recommend the use of a low discount rate of 1.5% (Weitzman, 1998; Stern, 2006; Weitzman, 2007; Gollier, 2010; Freeman and Groom, 2013).
The selected discount rate can significantly modify the results. Therefore, we tested discount rates ranging from 1% to 4%. However, in this work we only compare the effect of the scenarios on the ES values based on the reference year, 2017. Thus, even if the results are modified in level, they are not modified in relative terms. We finally selected a discount rate of 1.5%, as recommended by the specific literature on economic valuation of biodiversity and ecosystems services (Stern, 2006; Gollier, 2010).

3. Results

To disentangle the effects of LULCC and forest adaptation policies on the socio-ecosystem evolution in various CC contexts, we present the results in three steps: (i) without LULCC and forest policy scenarios, i.e., the baseline; (ii) with LULCC but no adaptation policy, i.e., the BAU scenario; and (iii) with LULCC and adaptation policies, i.e., the BIO and WE scenarios (see Appendix C, Fig.C2). The analysis of the results was therefore conducted within time horizons, and between the different scenarios (CC, LULCC and adaptation) in 2050 and then in 2100. Carbon sequestration ($t_C.ha^{-1}$) and timber production ($m^3.ha^{-1}$) in 2017 were computed from the past period, 1960-2017.

3.1 Baseline: climate change results

We defined the baseline changes as the CC effect alone under the climate scenarios used in the biophysical model. Figure 3 and Appendix I show the results in terms of biophysics and NPV for the climate change without LULCC and forest policy adaptation (BAU, BIO, and WE).
Figure 3 presents the results of carbon sequestration and timber production for the two main species in terms of surface area in Mont Ventoux: *Pinus halepensis* and *Quercus pubescens*. We observed a weak effect of climate scenario on ES until 2050 but a slightly more noteworthy effect for the timber production starting in 2080 and the carbon sequestration of *Quercus pubescens* starting in 2050. Indeed, for this last species from 2050, the carbon sequestration related to RCP8.5 is approximately 5%

higher than the carbon sequestration with RCP4.5. This is not the case for *Pinus halepensis*. Moreover, from 2080, the timber harvested is 5% to 10% higher with climate scenario 8.5. This is due to the fertilization effect of the CO_2 increase on photosynthesis and water use efficiency and to the higher increase in growing season under the 8.5 scenario. These effects counterbalance the higher mortality under the 8.5 scenario.

Assessing the mortality risk allows for more precisely including the effect of climate change on the future of species and therefore on the production of ES. Indeed, its variation is explained at 70-90% by climate scenarios and thus marginally explained by the LULCC and adaptation scenarios. More specifically, mortality on Mont Ventoux is on average 2% for RCP 4.5 and 4% for RCP 8.5 in 2050 and then 3% for RCP 4.5 and 5% for RCP 8.5 in 2100.

At the species level (Fig. 3 and Appendix I), the average difference between both RCPs is -/+ 15% for carbon sequestration and -/+ 5% for timber production. At the landscape level (Appendix J), the TNPV increases by 15% in 2050 from RCP4.5 to RCP8.5 and decreases by 15% in 2100. Finally, few effects of CC scenarios (RCP4.5 and RCP8.5) were found on ES production and their related TNPV both at the species and landscape levels.

3.2 Land cover changes

LULCC evolution differs according to CC and policy scenarios. Indeed, even if the signs of trends for all species remain stable across our scenarios, they strongly differ in terms of magnitude. For instance, the *Pinus nigra* surface increases from 22% to 134% according to the studied scenarios (Fig. 4).

Using the stakeholder transition matrices, we projected that the area covered by *Quercus pubescens* and the *Pinus sylvestris* will strongly decrease due to climate change. According to forest managers, these two species will not adapt to CC in their current location in the future; they cannot move to a higher altitude level, and the managers have already observed a strong drought-related mortality rate. For *Quercus ile*x, *Pinus halepensis*, and *Pinus nigra*, forest managers anticipated different dynamics in the Ventoux. Due to the resilience of these species regarding CC, the area covered by these species is expected to increase because they will replace *Quercus pubescens* and *Pinus sylvestris* in different locations. Moreover, a policy scenarios effect occurs; *Quercus ilex* and *Pinus nigra* are the two species most favored by alternative forest policy scenarios: the BIO scenario supports *Pinus nigra* and *Pinus halepensis* development, and the WE scenario supports *Quercus ilex* and *Pinus nigra*.

3.3 Socio-ecosystem evolution with land cover changes and adaptation strategies

In this section, we present the ES variations, first including LULCC only (i.e., BAU scenario) and then including LULCC and adaptation strategies (i.e., BIO and WE scenarios). This allows us to observe the isolated and cumulative effects of the different drivers of change.

Figure 5 (and Appendix J) summarizes the changes in ES economic values according to these different factors. LULCC and adaptation positively affect the aggregated total value of ES in 2050 and 2100, increasing the TNPV by 30% to 120%, 50% on average, compared with the baseline. Moreover, in three cases, RCP4.5 and RCP8.5 in 2100 and RCP4.5 in 2050, the best scenario in terms of ecosystem services production aimed at promoting biomass; in the fourth case, RCP8.5 in 2050, the best scenario targeted the production of wood energy (see Fig. 5). The role of adaptation strategies on ES changes is highly variable according to the time horizon and the ES considered. The effects of LULCC are significant but opposite for the two ES (Appendix J). LULCC and the new species distribution at the landscape scale

(see part 3.2) appear favorable for carbon sequestration but detrimental to timber production. The first effect is partly explained by the increase in *Pinus halepensis and Pinus uncinata*, and the second effect is partly explained by the decrease in *Quercus pubescens.* The effects of adaptation strategies, in addition to the LULCC, are significant and highly positive for the aggregated value of ES. However, each adaptation strategy affects ES differently. The biomass scenario is positive for carbon sequestration and negative for timber production, and the promotion of wood energy is positive for both ES but strongly favors timber production. As a result, the results vary according to the ES and the time horizons. The overall results are in line with the literature (Bottalico et al. 2016; Chiabai et al. 2011; Ding et al., 2016; Morán-Ordóñez et al., 2020).
Finally, combined with LULCC and adaptation strategies, a climate scenario effect on the ES results exists. Figure 5 shows higher TNPV for RCP8.5 than for RCP4.5 for both horizons, 2050 and 2100. Indeed, comparing the TNPV in the case of LULCC and adaptation strategies with the baseline, we can observe that positive effects in RCP 8.5 are almost twice those in RCP 4.5.
All of these results assume a contrasting effect of the scenarios on the two ecosystem services, which is confirmed by Pearson's correlation analysis (see Appendix K). In the case of the spatial correlation analysis of the BAU, the correlation between the two ES is positive (around 0.7) in 2050 and then negative in 2100 (around -0.1). For adaptation scenarios (BIO and WE), the spatial correlations between ES vary more strongly for the WE in 2100, with correlations decreasing from 0.9 to 0.5, but the correlations remain stable for the BIO scenario.

4. Discussion

In this paper, we developed a socioeconomic and ecological methodology co-constructed with stakeholders to explore the effect of different scenarios of forest policies and CC on future ES provision (carbon sequestration and timber production) in a spatially sensitive and dynamic way, combining biophysical and economic values. This methodology, organized around the co-construction of change scenarios and transition matrices according to the stakeholders' local expertise, allows for the replicability of the study (as structured by the Wayfinder guideline[2]).

Our contribution is threefold. First, our predictions of the effect of CC scenarios on ES evolution are rather optimistic. Indeed, process-based predictions rely on physiological mechanisms to predict future ecosystem functioning, which corresponds to the fundamental niche of the species (Keenan et al., 2011). By contrast, predictions based on correlative species distribution models are usually more pessimistic because they derive their predictions from the realized bioclimatic niche of the species, which can be much more restricted than the fundamental niche for some species. Second, LULCC has the effect of increasing the changes and accentuating the difference between climate change scenarios. This result combines two effects: (1) a more pessimistic prediction by managers (probably the result of previous works based on correlative models and more pessimistic conclusions - particularly maps - which have left their mark on foresters' management) and, as a consequence of this first point, (2) an anticipation action that tends to overanticipate and reinforce or even accelerate the expected changes. In this sense, the impact of adaptive actions, influenced by some models' predictions, can become

[2] « Wayfinder represents a new generation of resilience practice that will guide development practitioners, policymakers and other change-makers navigating towards better futures. »
https://graid.earth/projects/wayfinder/

greater than the impact of climate change itself. The action in adaptive strategy must be flexible and regularly reviewed according to the improvement of knowledge and scenario predictions. Third, even if the impact of economic choices is not major in our case study (we focus on a long-term management region rather than on short-term intensive management), our work shows that large-scale political orientations (i.e., adaptation strategies) impact ES. For the ES relationship, without adaptation scenarios, we can make wrong conclusions about synergy or conflict. Moreover, unlike the BIO scenario, which strengthens the synergies between ES, the WE scenario appears to weaken them considerably. In line with several previous case studies, LULCC and adaptation strategies appear to be decisive drivers of the future ES evolution (Morán-Ordóñez et al., 2020; Bréteau et al., 2019).

A few limitations and refinements of the study must be discussed to provide better modeling and policy orientations. First, rigorously comparing model and stakeholder results is difficult because simulation and forest management account for distinct elements. For example, managers not only anticipate the effect of CC on carbon sequestration but also the timber production and the future of the sectors. However, we can compare their global trends (upward/downward), and we can analyze what they are related to. Second, the NPV of carbon sequestration and the NPV of timber production (see Appendix J) differ by a hundred-fold. However, the "factor effect" is greatly attenuated in our analysis as we look at the results in terms of variations for each ES and then for the TNPV. Finally, regarding the use of process-based models, work still needs to be conducted in several directions. We may underestimate the tipping points in terms of hydraulic failure or the effects of multiple disturbances (drought, insects, and fire). In Davi et al. (2006), we showed that the main positive effect of climate change on the photosynthesis of evergreen species was due to the increase in atmospheric CO_2, whereas the increase in vegetation duration mainly has an effect on deciduous species. We therefore looked at the relationship between GPP and CO_2 simulated for pines by CASTANEA in this study and compared this relationship with the measurements obtained in the FACE experiments on a *Pinus ponderosa* forest at a Duke site (Appendix G). CASTANEA reproduces the increasing water use efficiency (WUE) well for pine trees but underestimates the GPP fertilization (+23% instead of 30% at the Duke forest). However, we may still overestimate the fertilizing effect of CO_2 by the absence of acclimatization of photosynthesis to CO_2 and feedback of the nitrogen cycle. Moreover, huge uncertainties exist regarding soil organic carbon simulations (Smith et al., 2020), but CASTANEA reproduces the ranges of soil carbon stock and soil respiration, the relative variations between species and the effect of altitude well (Appendix H).

5. Conclusion

We conclude with directions that can be taken in future research. First, this work is valid for the public forest sector and management, but it does not include specific private forest silviculture. One obvious difference between private and public forests, which tends to disappear over time, is relying on the ES integration in forest management: if ES are normally integrated in public forest management, some incentives need to be implemented for private owners as these goods are public goods for most of them. Another possible extension addresses how some local impacts on demand or supply sides can diffuse at a more global scale.

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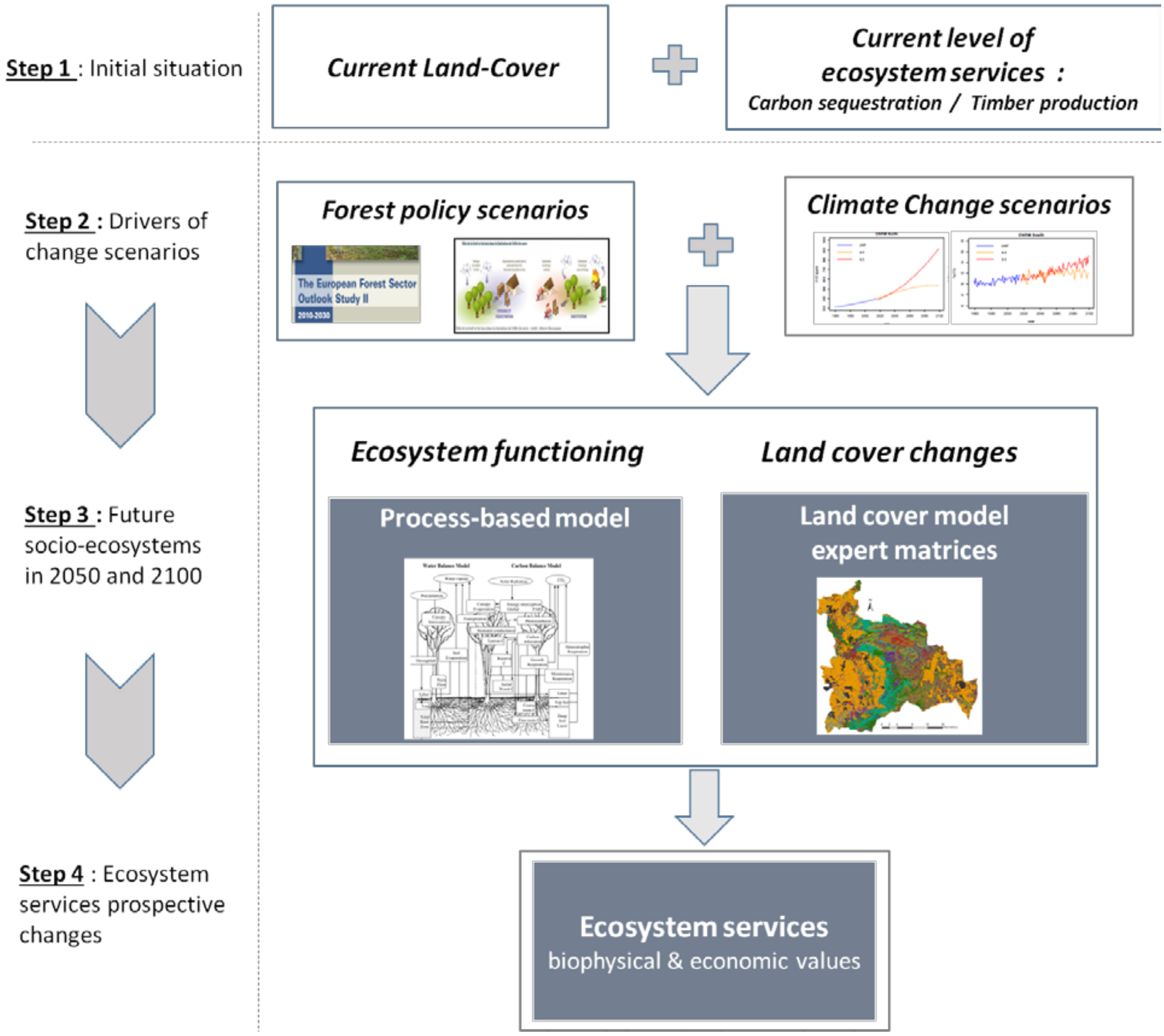
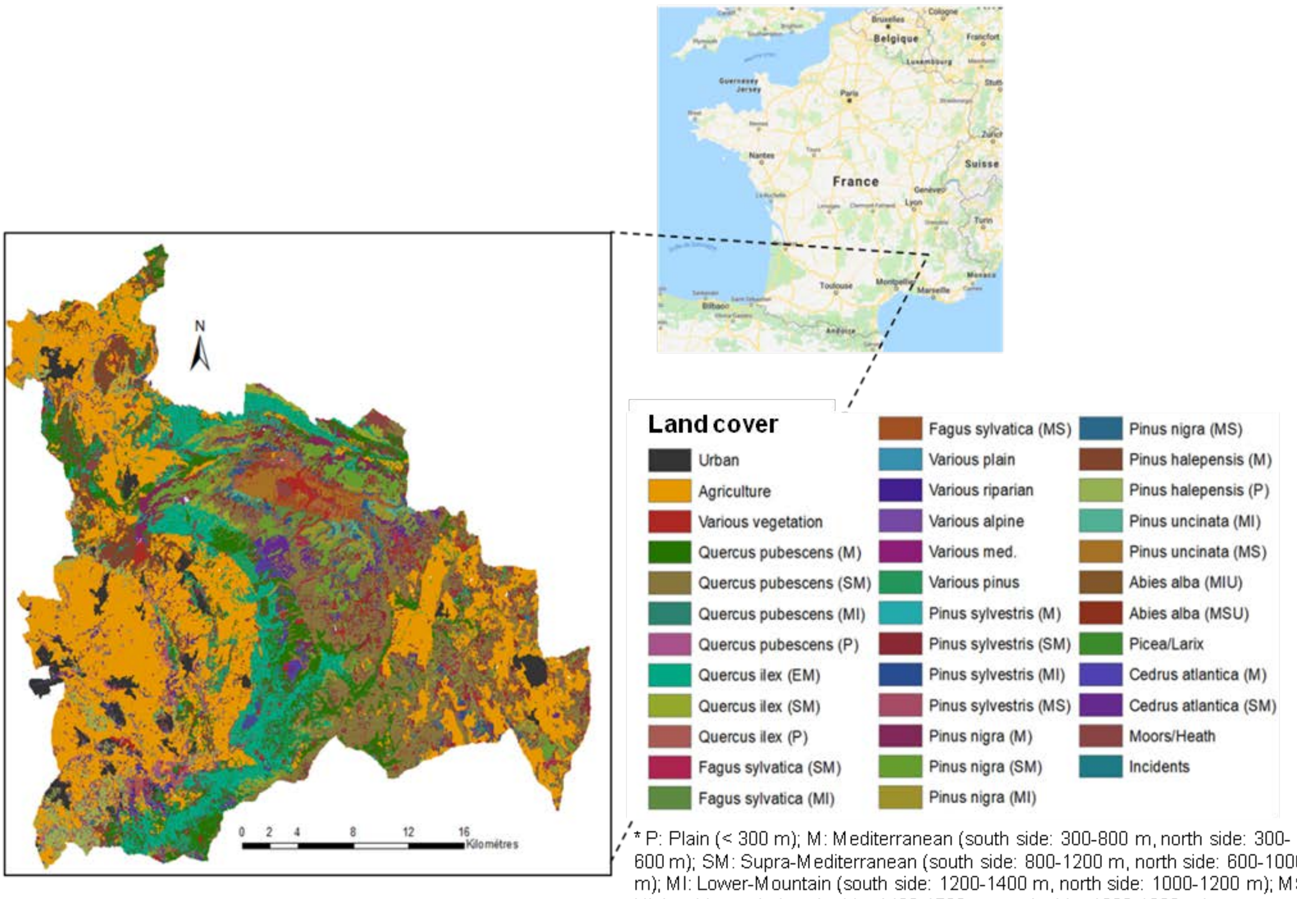


Fig.1. Snapshot of the methodology in four steps.



* P: Plain (< 300 m); M: Mediterranean (south side: 300-800 m, north side: 300-600 m); SM: Supra-Mediterranean (south side: 800-1200 m, north side: 600-1000 m); MI: Lower-Mountain (south side: 1200-1400 m, north side: 1000-1200 m); MS: Higher-Mountain (south side: 1400-1700 m, north side: 1200-1600 m)

Fig. 2. The Mont-Ventoux study site and its land cover typology.

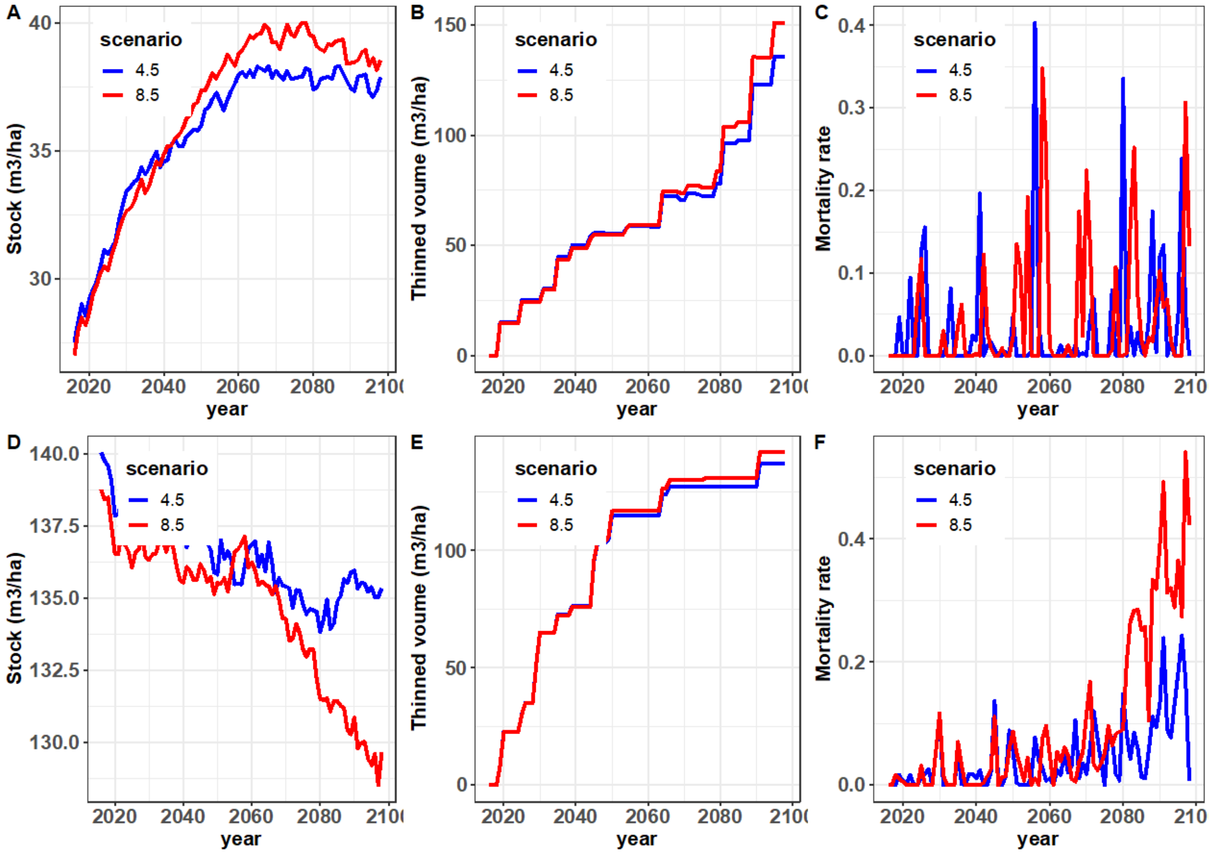


Fig. 3. Carbon stock ($t_C.ha^{-1}$), timber production ($m^3.ha^{-1}$) and mortality (in %) predictions in the 2017-2100 period under two climate scenarios (RCP4.5 and RCP8.5): the example of Quercus pubescens (A, B, C) and Pinus halepensis (D, E, F).

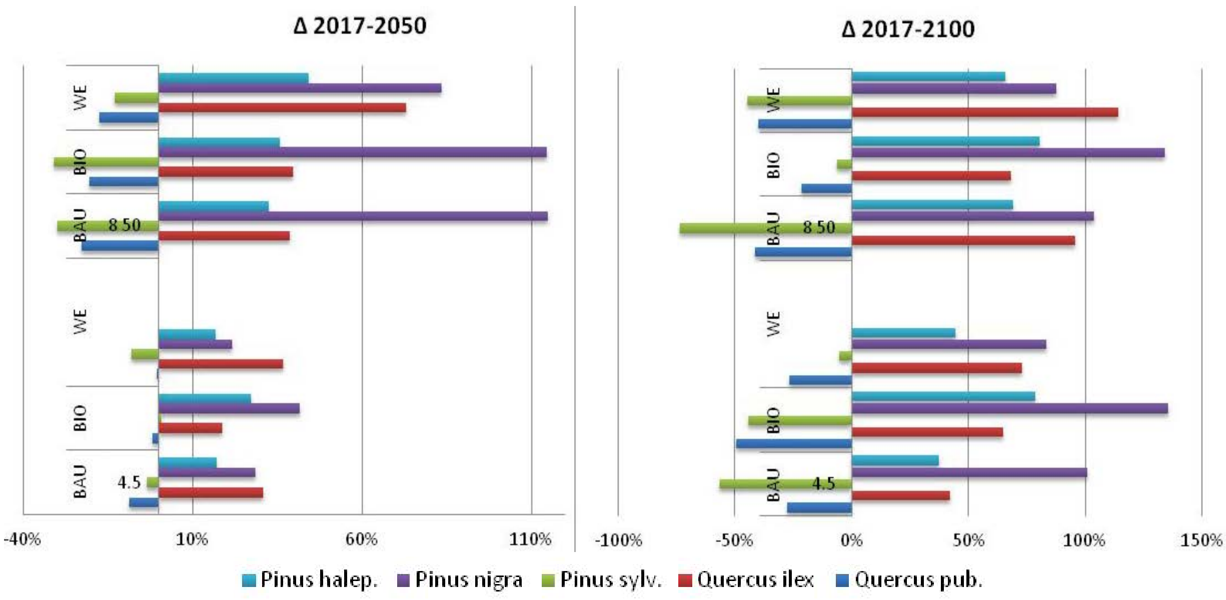


Fig. 4. Land cover variations (in %) between 2017 and the two time horizons, 2050 (left side) and 2100 (right side) and scenarios (business as usual (BAU), biomass (BIO), wood energy (WE)), according to the expertise of the stakeholder panel for the five main tree species: Pinus halepensis, Pinus nigra, Pinus sylvestris, Quercus ilex, and Quercus pubescens.

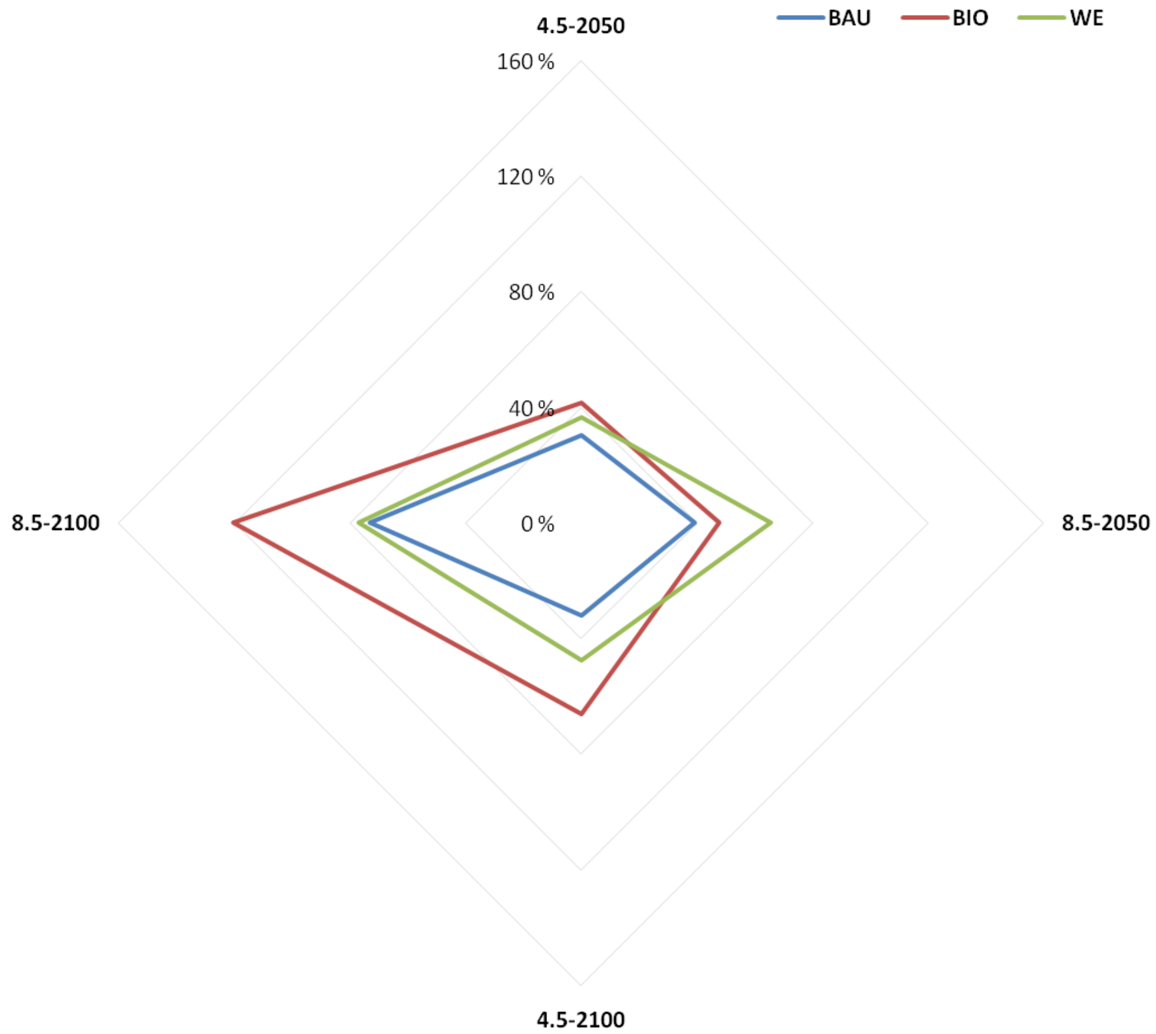


Fig. 5. Evolutions (rate of change in %) of the total net present value (sum of the carbon and timber economic values in euros) between the scenarios (business as usual (BAU), biomass (BIO), wood-energy (WE)) and the baseline for two Representative Concentration Pathways, 4.5 and 8.5, and two time horizons, 2050 and 2100.

Table. 1. Forestry planning (age and percentage harvested) according to three scenarios: business as usual (BAU), biomass (BIO), wood energy (WE).

	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested	Age	% Harvested
	Quercus ilex		Quercus pubescens		Fagus sylvatica		Cedrus		Pinus sylvestris		Pinus nigra		Pinus halepensis		Pinus uncinata		Abies alba	
Business as usual	70	100	70	100	50	100	50	45	15	82	15	82	30	46.6	70	50	50	51
	140	100	140	100	100	100	60	28	50	39	45	42	50	50	130	40	60	32
	210	100	210	100	150	100	75	26	70	36	60	35	80	35.7	140	100	70	25
							90	23	85	32	75	31	95	100			80	23
							105	18	100	48	90	27					90	17
							120	45	110	100	100	38					100	42
							130	100			110	100					110	52
																	120	100
Biomass carbon	70	100	50	50	70	50	50	45	15	82	15	82	30	46.6	70	50	50	51
	140	100	70	60	85	60	60	28	50	39	45	42	50	50	130	40	60	32
	210	100	90	60	100	60	75	26	70	36	60	35	80	35.7	140	100	70	25
			120	35	120	100	90	23	85	32	75	31	95	100			80	23
			125	45			105	18	100	48	90	27					90	17
			130	100			120	45	110	100	100	38					100	42
							160	100	-	-	140	100					110	52
																	120	100
Wood energy	70	100	70	100	50	100	50	45	15	82	15	82	15	82	70	50	50	51
	140	100	140	100	100	100	60	28	50	40	50	40	50	40	130	40	60	32
	210	100	210	100	150	100	75	26	70	60	70	60	70	60	140	100	70	25
							90	23	85	100	85	100	80	100			80	23
							105	18									90	17
							120	45									100	42
							130	100									110	52
																	120	100