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RESEARCH PAPER

A multi-criteria analysis of forest restoration strategies to improve the ecosystem services supply: an application in Central Italy

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Abstract

• ***Key message*** **A multi-criteria analysis can be an interesting tool to assess the effects of silvicultural treatments on ecosystem services supply. In the degraded forests, thinning has a positive effect on the provision of ecosystem services such as timber and bioenergy production, climate change mitigation, and recreational attractiveness.**

• ***Context*** The Millennium Ecosystem Assessment highlights the importance of the ecosystem services for human well-being and for maintaining conditions for life on Earth. Silvicultural treatments can improve the provision of ecosystem services to increase local communities' well-being.

• ***Aims*** The aim of this study is to understand the effects of two-forest restoration practices (selective thinning and thinning from below) on three ecosystem services (wood production, climate change mitigation, and recreational opportunities) in an Italian case study.

• ***Methods*** A multi-criteria decision analysis (MCDA) was performed to compare the effects of three forest restoration scenarios (baseline, selective thinning, thinning from below) on ecosystem services. Wood production was estimated considering the local market prices and the wood volumes harvested, while climate change mitigation was quantified through the C-stock and C-sequestration changes in carbon pools due to the silvicultural treatments. The recreational activities were assessed through a questionnaire survey. A sample of 200 visitors was interviewed face-to-face to estimate the impact of thinning on recreational activities.

• ***Results*** The results of the MCDA show that the selective thinning scenario is the optimal forest restoration practice to increase the recreational attractiveness and the wood production in the study area.

• ***Conclusion*** The results concerning the effects of the silvicultural treatments on ecosystem services supply are an important tool to support decision makers.

Keywords Biophysical assessment · Economic evaluation · Carbon stock · Carbon sequestration · Recreational activities · Multiple-criteria decision analysis (MCDA)

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Contribution of the co-authors Alessandro Paletto, Ugo Chiavetta, Isabella De Meo, and Alessandra Lagomarsino conceived and designed the study. Ugo Chiavetta, Gianluigi Mazza, Isabella De Meo, Paolo Cantiani, Alessandro Elio Agnelli, Alessandra Lagomarsino coordinated and performed the sample collections. Alessandra Lagomarsino, Alessandro Elio Agnelli performed the laboratory experiments. Alessandro Paletto and Elisa Pieratti analyzed the data and interpreted the results. Alessandro Paletto, Elisa Pieratti, and Isabella De Meo contributed equally to the writing, editing, and reviewing of the relevant literature.

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1 Introduction

In the last decades, the global interest for the ecosystem services (ESs) has rapidly grown, at first in the scientific researches, and later in the policy makers' agenda (Potschin et al. 2016). At international level, many initiatives—e.g., the Economics of Ecosystem Services and Biodiversity (TEEB), the Common International Classification of Ecosystem Services (CICES), and the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES)—analyzed and incorporated the ES framework in environmental policy targets (Santos-Martín et al. 2016). In Europe, the European Union (EU) Biodiversity Strategy to 2020 identified the need to maintain and restore ecosystems and their services emphasizing the importance to assess, evaluate, and map the state of ESs in the EU member countries (EC 2011). Many political documents at international and European level emphasized the importance of increasing the knowledge about the assessment and evaluation of ESs and the effects of land use changes and natural resource management on ES supply (de Groot et al. 2002; Vihervaara et al. 2010).

In literature, there are many definitions of the ES concept as emphasized by Häyhä and Franzese (2014) and La Notte et al. (2017). At the end of the 1990s, Daily (1997) defined the ESs as the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. Costanza et al. (1997) highlighted the importance of ESs from a monetary perspective, defining them as the benefits human populations derive, directly or indirectly, from ecosystem functions. "ESs are the benefits people obtain from ecosystems" is the most common ESs' definition used in the scientific literature, provided by The Millennium Ecosystem Assessment (MEA 2005), while in 2010, TEEB defined the ESs as the direct and indirect contributions of ecosystems to human well-being (TEEB 2010). In these definitions, different ES categories are included such as provisioning services (e.g., food, energy, raw materials), regulating services (e.g., climate regulation, water cycle regulation), supporting services (e.g., photosynthesis, biodiversity, soil production), and cultural services (e.g., recreation, historical, spiritual, and aesthetic value). Recently, the CICES reclassified the ESs into three categories to avoid double counts and overlaps: provisioning, regulation and maintenance, and cultural ecosystem services (Haines Young and Potschin 2017). An exhaustive definition and classification of ESs is the fundamental starting point for delimiting boundaries in the studies concerning assessment and evaluation of the ESs provided by nature (Häyhä et al. 2015).

In forestry, the ESs provided by natural, semi-natural, or planted forests include wood and non-wood forest products (provisioning services), protection against natural hazards, water cycle, and climate change mitigation (regulating services), habitat and biodiversity (supporting services), recreational opportunities, and spiritual and historical values of forests (cultural services) (Baral et al. 2016; Langner et al. 2017). In this context, the different forest management objectives and strategies have a great impact on forests' structure and consequently on the supply of the ESs in the long-term run (Rodríguez García et al. 2016).

Generally, in degraded forests, ES supply is sub-optimal and forest restoration can be the tool to regain functionality to ESs (Marchi et al. 2018). Forest restoration is a key issue to deliver a wide range of ESs provided by forest resources and to maintain biodiversity (Valasiuk et al. 2018). From the theoretical point of view, forest restoration is defined as the process of regaining ecological functionality and enhancing human well-being across degraded forests (Chazdon and Laestadius 2016). To implement a sustainable forest restoration, it is fundamental to apply a transdisciplinary, multi-stakeholder, and multi-dimensional approach able to integrate the traditional ecological knowledge in a scientific framework (Naveh 2005). Forest restoration requires an integrated analysis of ESs, able to consider from the biophysical to the socio-cultural and economic dimensions of this complex concept (Palomo et al. 2016). From the practical point of view, forest restoration can be implemented through silvicultural treatments (e.g., thinning in even aged stands or continuous cover silviculture) influencing one or more key variables related to forest structure such as tree species composition, structural diversity, stand density, age structure, and so on (Duncker et al. 2012a; Becagli et al. 2013). Silvicultural treatments can have direct effects on single ecosystem service but also indirect effects on the relationships between different ESs (Duncker et al. 2012b). These relationships between ESs might be synergistic—as the carbon sequestration and timber production through the transfer of carbon stocked from the forest to the wood products with a long lifetime (Ruddell et al. 2007)—or in trade-off such as the possible negative effect on timber production when wood is left in forest for biodiversity conservation (Boscolo and Vincent 2003). Therefore, the studies aimed at quantifying the effects of forest restoration on ES supply must be based on a transdisciplinary and multi-dimensional approach able to consider synergies and trade-offs between ESs (Lafond et al. 2017; Marchi et al. 2018).

In the international literature, there are many multiple criteria decision methods to provide information about trade-offs between ESs and to include them in forest planning and management (Tóth and McDill 2009). The multiple-criteria decision analysis (MCDA) is a useful tool to identify the optimum result/solution in complex scenarios, where many actors are involved, with multiple aspects—e.g., ecological, social, economic, technical, ethical—and interests not directly comparable (Pohekar and Ramachandran 2004; Grilli et al. 2017). Recently, MCDA has become a popular decision support tool for decision makers and stakeholders to bridge ESs into policy processes, due to its capacity to assess trade-off. It allows for comparison among decision alternatives based on a set of evaluation criteria to which different weights may be applied (Myšiak 2006). Several authors have successfully applied MCDA to forest management and planning (Saarikoski et al. 2016; Langemeyer et al. 2016). From a technical point of view, several MCDA approaches and techniques can be performed as emphasized by Borges et al. (2017): analytical hierarchy process (AHP), evaluation matrix (Evamix), ELECTRE III, goal programming (GP), and multi-objective programming (MOP). The choice of a specific method depends on the objectives of the study as well as on the complexity of the problem to be solved. Both AHP and GP methods have been applied in participatory forest planning and management to include stakeholders' objectives and needs concerning different forest functions or ESs (Nordström et al. 2009; Eyvindson and Kangas 2015; Garcia-Gonzalo et al. 2015).

Starting from these considerations, the main aim of the present study is to assess through a transdisciplinary and multi-dimensional approach the effects of two forest restoration practices (i.e., selective thinning and thinning from below) on three ESs (wood production, climate change mitigation, and recreational activities) provided by a degraded coniferous forest in Central Italy (Monte Morello forest). The study aims to investigate what changes in the provision of the above-mentioned ESs are generated by the implementation of different types of thinning. The main contribution of the present research is to provide new insights for the sustainable management of degraded coniferous forests in the Mediterranean region. To quantify the direct and indirect effects of thinning on ESs, the research was structured in three steps: (1) field measurements to quantify the ES supply before and after silvicultural treatments (selective thinning and thinning from below), (2) biophysical assessment and economic evaluation of ESs in three different forest restoration scenarios, and (3) multi-criteria analysis to identify the forest restoration scenario optimal to increase the ES supply.

2 Material and methods

2.1 Study area

The study area is Monte Morello forest (43°51′20″'N; 11°14′23″E) located near Florence and Sesto Fiorentino municipalities in the Tuscan Apennines (Central Italy). Monte Morello forest is the result of a program of reforestation carried out from 1909 to 1980 to improve hydrogeological stability over a surface of 1035 ha. The main tree species used in the reforestation program are black pine (*Pinus nigra* J.F. Arnold), Calabrian pine (*Pinus brutia* Ten. subsp. *brutia*), cypress (*Cupressus* spp.), and Turkey oak (*Quercus cerris* L.). Naturally regenerated flowering ash (*Fraxinus ornus* L.) is very frequent in the understory while Downey oak (*Quercus pubescens* L.) is sporadic.

The altitude is between 590 and 650 m a.s.l., and the climate is characterized by precipitations concentrated from autumn to early spring and a dry summer. July is the driest month, while October and November are the rainiest ones. During the last three decades, the total annual rainfall is 1003 mm and the average annual temperature is 13.9 °C.

The reforestation of Monte Morello was originally carried out with a density of about 2700 trees ha^{-1}, but during the rotation period the appropriate silvicultural treatments were not applied and Monte Morello forest stand has been largely abandoned. Forest abandonment generated important consequences on stands' stability, mortality, and increase of fire risk (Nocentini 1995). Currently, Monte Morello forest can be considered a degraded forest characterized by poor effective regeneration, marked susceptibility to adversities, huge quantity of deadwood, and a high degree of flammability. Nevertheless, the forest provides several ESs for the well-being of local communities. First, Monte Morello is highly frequented by visitors and especially by hikers from the province of Florence during all seasons of the year (Paletto et al. 2017). Secondly, in Monte Morello forest, there is a Natura 2000 network site (IT5140008). Thirdly, the forest cover plays an important role in soil protection and water regulation.

In the winter of 2016, two different forest restoration practices (two kinds of thinning) were applied in a pilot area of 16.4 ha representative of the average characteristics of Monte Morello forest. The pilot area is a black pine (*Pinus nigra* J.F. Arnold) and Calabrian pine (*Pinus brutia* Ten. subsp. *brutia*) dominated forest (vegetation type: EEA-EFTs code: 6.14.1) with a mean tree density of 980 tree ha^{-1}, a basal area of 62.9 m^2 ha^{-1}, and a mean height of 17.1 m. The stand age is between 55 and 65 years (Mazza et al. 2019). The average growing stock is around 560 m^3 ha^{-1}, while the deadwood volume is equal to 75.1 m^3 ha^{-1} thus distributed (De Meo et al. 2017): 59.9 m^3 ha^{-1} lying deadwood, 13.9 m^3 ha^{-1} standing dead trees, and 1.3 m^3 ha^{-1} in stumps.

2.2 Experimental design and field measurements

The data used to assess and evaluate the ESs were collected in field before thinning (October–December 2016) and after thinning (October–December 2018). Therefore, ES assessment was made considering the effects of thinning on forest ecosystems after 2 years. The implementation of thinning followed a completely randomized design with three replicates for each of the three experimented scenarios (Fig. 1). Each replicate had at least one hectare of area.

The field data were collected in two randomly located sampling plots for each replicate (Mazza et al. 2019). The sampling plots were circular with a fixed area of 531 m^2 (13 m of radius). In each sampling plot, the number of stems, height, and diameter at breast height (dbh) for all standing living trees with a dbh greater than 5 cm, canopy cover, length, and diameters of logs, snags, and stumps were collected during the field measurements. All logs, snags, and stumps with a diameter greater than 5 cm were recorded and classified indicating tree species and decay class, while those with a diameter less than 5 cm were considered as litter. The decay class was visually assessed by forest operators using the 5-decay class classification

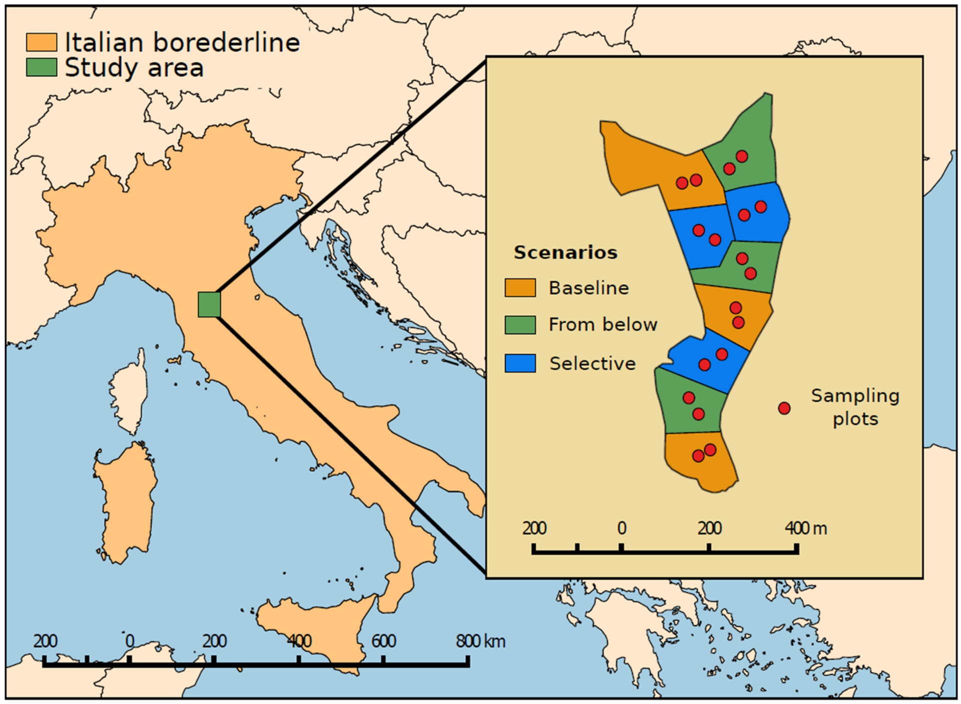

Fig. 1 Study area location and experimental design

system proposed by Næsset (1999): recently dead, weakly decayed, medium decayed, very decayed, and almost decomposed. The visual assessment of decay rate was conducted considering some key variables and visible characteristics (Næsset 1999; Paletto and Tosi 2010): structure of bark; presence of small branches with a diameter less than 3 cm; softness of wood; other visible characteristics such as rot extension and development of fungus mycelium, mosses, and lichens.

The standing living (stem) volume was estimated using the model elaborated by second Italian National Forest Inventory (NFI) (Tabacchi et al. 2011), while the deadwood volume was estimated using a different estimation method for each component in accordance with the protocol proposed by De Meo et al. (2017).

2.3 Forest restoration scenarios

In 2016, two silvicultural treatments (thinning from below and selective thinning) were applied to improve stand characteristics and forest multifunctionality of Monte Morello forest. The silvicultural treatments were implemented within the LIFE FoResMit project (LIFE14/CCM/IT/905) "Recovery of degraded coniferous Forests for environmental sustainability Restoration and climate change Mitigation" aimed to the sustainable management of degraded forests with a special emphasis on climate change mitigation.

With the application of the thinning, three restoration scenarios were developed in the pilot area:

(1) Baseline scenario (BU): no silvicultural treatments are implemented and deadwood (logs and snags) is not removed from the forest;
(2) Thinning from below scenario (TB): the choice of trees to be cut is based on a negative selection, and only small and leaned living trees and snags are harvested (thinned from below 15–20% of basal area). The logs are not removed during the harvesting operations;
(3) Selective thinning scenario (ST): the choice of the trees to be cut is based on a positive selection, and all crown-volume competitors are harvested (thinned 30–40% of basal area). Standing dead trees and logs of the first two decay classes with a diameter more than 20 cm are removed.

The three above-mentioned forest restoration scenarios were analyzed and compared considering the annual ES supply changes in a rotation period of 15 years (period between two thinning). Although we recognize the limitation of the short horizon, the 15-year rotation period is a hypothetical rotation period based on typical thinning in young planted coniferous forests, also prescribed by forest management plans. Moreover, a longer term could result in a higher error in wood and biomass growth estimate.

An analytical hierarchical process (AHP) was performed to evaluate the optimal forest restoration scenario aimed at maintaining and improving the ESs provided by the Monte Morello forest. AHP was applied to handle qualitative and quantitative criteria related to forest ESs. Blattert et al. (2017) accurately described the indicators for several ESs to construct an indicator-based analysis framework for the MCDA in mountain forest management and planning. In the present study, the indicators chosen for the three considered ESs—recreational activities, climate change mitigation, and wood production—are in accordance with the indicators suggested by Blattert et al. (2017), as described below (Fig. 2):

- I_1 for recreational activity, which is the current economic importance of recreational benefits in the study forest [€ ha^{-1} $year^{-1}$]
- I_{2b} for the C-stock removed due to the thinning action [tCO_2 ha^{-1}], and I_{2a} for the C-sequestration in above/below-ground biomass and soil [tCO_2 ha^{-1} $year^{-1}$]
- I_3 for wood production, calculated as the forest owner's average annual income from the sale of wood products [€ ha^{-1} $year^{-1}$]

An input standardized matrix (starting from the values of indicators) must be built to apply the AHP approach. The construction of the matrix is a fundamental part of the MCDA, since it is used for selecting management alternatives in forest planning. It is necessary to choose a standardization method that can be different for each indicator. When possible, it is better to define a value function for a specific indicator that would be valid across different type of forests. In this case, it is possible to use the goal or interval method for standardization and the standardized values of different areas/forest could be compared. Unfortunately, the definition of a threshold value and the function shape is often hard to be done; thus, the maximum method is more frequently applied since local values are used. Blatter et al. (2017) have listed the suggested/most common standardization methods applicable at a wide range of indicators of ESs. In the present study, the maximum method has been applied for all three indicators, considering that in the degraded coniferous forest, it is difficult to define an optimum value for the categories analyzed.

2.4 Ecosystem services assessment and evaluation

2.4.1 Wood production

Wood production was estimated considering the wood volume harvested with the thinning intervention and the local market prices (year 2018). In Monte Morello forest, the final wood products are influenced by the species—mainly cypress, black, and Calabrian pine—and by the wood characteristics. Therefore, in accordance with the local forest enterprises' opinions, all the standing living trees and the deadwood harvested were allocated for the woodchip production, because the quality was considered very low to produce timber.

The forest owner's average annual income (I) from the sale of wood products was calculated using the following equation (Eq. (Undefined control sequence \EUR1)):

$$I = \frac{a}{\text{surface}}[\text{€/ha}] \text{ with } a = \frac{P_m \cdot r}{(1+r)^n - 1} \quad (1)$$

where:

a = average annual income deriving from the sale of wood products (€)

Pm = net profit gain for year m

r = real interest rate

n = numbers of years among two subsequent thinning (15 years)

The period of 15 years among two thinning is derived from the forest management prescription by the LIFE CCM/IT/905 FoResMit project, while the current woodchip price of 37 € t^{-1} (with a moisture content of 45%) was obtained through interviews with the local forest enterprises. The

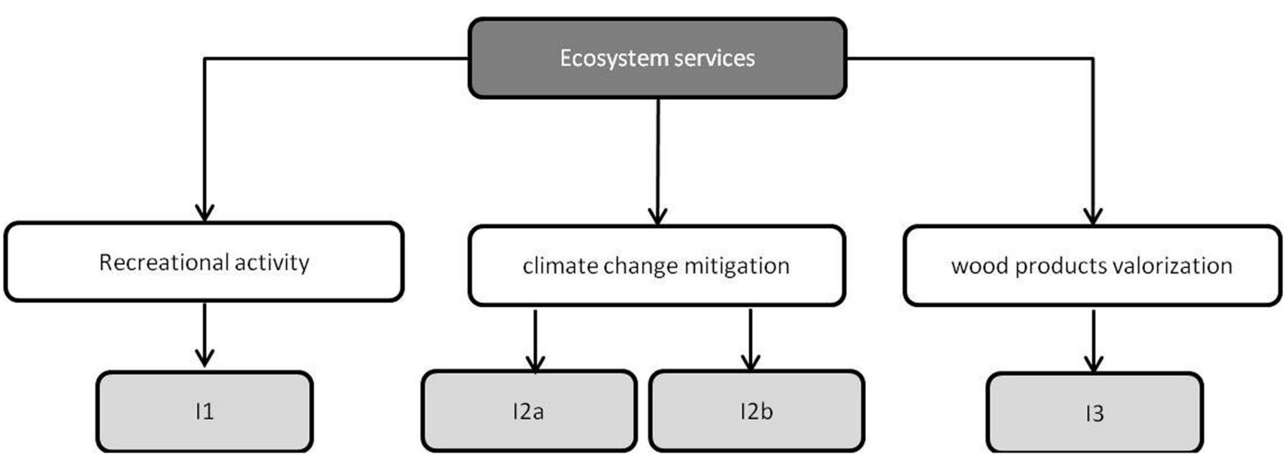

Fig. 2 Framework structure for multiple-criteria decision analysis (MCDA)

estimation was limited to 15 years of the after-life of the LIFE CCM/IT/905 FoResMit project considering the uncertainty of successive silvicultural treatments.

2.4.2 Climate change mitigation

According to the cap-and-trade schemes (carbon emission trading), carbon "credits" can be generated from forestry activities that reduce carbon dioxide (CO_2) emissions such as improved forest management (IFM) practices aimed to increase the carbon stocked in the forest or in the semi-finished and finished wood products (Deal et al. 2012; Vacchiano et al. 2018).

The two types of thinning applied in Monte Morello forest can be considered as IFM practices aimed to increase the carbon stocked in four carbon pools (above-ground and below-ground biomass, deadwood and soil) in the long-term period. In this study, the changes of C-stock due to the silvicultural treatments (before and after thinning) were estimated distinguishing between above-ground/below-ground biomass, deadwood and soil. The C-stock change in above-ground/below-ground biomass was calculated using the following equation (Eq. (2)):

$$C_{\text{stock-biomass}} = k \cdot \left[(1-b) \cdot \left(V_{\text{i,IFM}} - V_{\text{i,baseline}}\right) \cdot BEF \cdot WBD\left(1 + R_{\text{i}}\right)\right] \tag{2}$$

where:

$C_{\text{stock-biomass}}$ = carbon stock in above- and below-ground biomass (tCO_2 ha^{-1})

i = reference thinning method (i = thinning from below or selective thinning)

k = biomass to CO_2 conversion factor (1.833)

b = carbon lost from emissions due to unplanned natural disturbances

$V_{\text{i,IFM}}$ = volume in the post thinning scenario (m^3 ha^{-1})

V_{baseline} = volume in the baseline scenario (m^3 ha^{-1})

BEF = species-specific biomass expansion factor (1.33)

WBD = species-specific wood basal density (kg m^{-3})

R_{i} = species-specific root/shoot ratio (0.36)

The C-stock in the deadwood (logs and snags) was estimated considering the volume distribution by component and decay class. The C-stock change in deadwood was calculated using the following equation (Eq. (3)):

$$C_{\text{stock-deadwood}} = k \cdot \sum_{n} \left[\left(D_{\text{i,SFM}} - D_{\text{i,baseline}}\right) \cdot WBD\right] \tag{3}$$

where:

$C_{\text{stock-deadwood}}$ = carbon stock in deadwood (tCO_2 ha^{-1})

i = reference thinning method (i = thinning from below or selective thinning)

k = biomass to CO_2 conversion factor (1.833)

n = decay classes (5)

$D_{\text{i,IFM}}$ = deadwood volume post thinning (m^3 ha^{-1})

D_{baseline} = deadwood volume in the baseline scenario (m^3 ha^{-1})

WBD = wood basal density by decay class (kg m^{-3})

To increase the accuracy of C-stock estimation, the specific wood basal density of Calabrian pine deadwood for each decay class elaborated by De Meo et al. (2018) was used (Table 1).

The C-sequestration in the above-ground and below-ground biomass was estimated considering the annual increment of volume measured in the study area before and after the two types of thinning, according to the method proposed by Grilli et al. (2015). The changes in C-sequestration (Δ) before and after thinning have been calculated with the following two equations (Eqs. (4) and (5)):

$$\Delta_{C_t} = C_t - C_b \tag{4}$$

$$\Delta_{C_s} = C_s - C_b \tag{5}$$

where:

C_t = $tCO2$ sequestered by the annual increment after the thinning from below scenario

C_b = $tCO2$ sequestered by the annual increment in the baseline scenario (no IFM actions)

C_s = $tCO2$ sequestered by the annual increment after the selective thinning scenario

Table 1 Moisture content ($U\%$), wood basal density (WBD) of Calabrian pine deadwood by component and decay class

Decay class by Næsset (1999)/component	Logs		Snags		Stumps	
	$U\%$	WBD (g cm^{-1})	$U\%$	WBD (g cm^{-1})	$U\%$	WBD (g cm^{-1})
1- Recently dead	74.8	0.4470	78.3	0.4176	49.9	0.6349
2- Weakly decayed	154.7	0.2726	86.4	0.3767	92.7	0.3327
3- Medium decayed	143.3	0.2357	102.0	0.3113	100.4	0.2562
4- Very decayed	103.1	0.2048	187.0	0.2366	151.2	0.2163
5- Almost decomposed	126.8	0.1330	74.9	0.1503	111.8	0.1782

Source: modified from De Meo et al. (2018)

The C-sequestration in soil was calculated as difference between C accumulation in the soil organic and mineral layers after thinning and the quantity of CO_2 equivalents lost as emissions considering the sum of CO_2, CH_4, and N_2O. The formula used to estimate the C-sequestration in soil is the following Eq. (6):

$$C_{\text{sequestration-soil}} = k \cdot \left(C_{\text{soilpost}} - C_{\text{soilpre}}\right) - CO_{2\text{eq}}\text{emitted} \tag{6}$$

where:

$C_{\text{sequestration-soil}}$ = amount of CO_2 accumulated in the soil net of GHG emissions (tCO_2 ha^{-1} $year^{-1}$)

k = conversion factor from C to CO_2

$C_{\text{soil post}}$ = C-stock in the first 30 cm 2 years after thinning (t ha^{-1})

$C_{\text{soil pre}}$ = C-stock in the first 30 cm before thinning (t ha^{-1})

CO_{2eq} emitted = sum of annual cumulative emissions in the second year after thinning multiplied for specific coefficients: $CO_2 + 34 \times CH_4 + 298 \times N_2O$ (tCO_2 ha^{-1} $year^{-1}$)

Finally, the economic evaluation of climate change mitigation (changes in C-stock and C-sequestration) was estimated in the three restoration scenarios using carbon credits (CCs) selling price in the voluntary market referred to the IFM projects (2.1 €/tCO_{2eq}) (Hamrick and Goldstein 2018). The potential economic benefits related to the C-sequestration were estimated considering a constant annual increment and a period of 15 years as done for the wood production.

2.4.3 Recreational activities

The recreational activities were assessed through the administration of a semi-structured questionnaire to a sample of visitors. The questionnaire was administered face-to-face in situ by a trained interviewer in the period from April to July 2016.

The visitors to be interviewed were selected in a systematic way, selecting one out of two visitors who arrived in the previously identified sampling points (near refreshment areas and parking). The interviews were conducted both in the working days and in the weekend in order to include different types of visitors (e.g., tourists and residents) in the sample and to estimate the potential annual visitors of Monte Morello forest. The estimation of potential annual visitors was necessary to overcome the shortage in official statistics. The days of interviews were selected distributing them by month and day of the week. At the end, 30 days of interviews was spent (25% of potential days of the survey period) divided in 10 working days (from Monday to Friday), 10 Saturdays, and 10 Sundays. In addition, the days of interviews were distributed by month: 6 days in April, 8 days in May, in June, and in July. During each day, the average time spent at the sampling points was 4 h for a total of approximately 120 h.

The questionnaire focused on people's preferences towards the ESs provided by Monte Morello forest and visual-aesthetic impacts of the two forest restoration practices (thinning from below and selective thinning) implemented in the forest.

The respondents were asked to assess the importance of the three ESs considered in the present study—wood production, climate change mitigation, and recreational activities—using a 5-point Likert scale format (from 1 = very low importance to 5 = very high importance). Besides, the respondents assigned their visual-aesthetic preferences for the three forest restoration scenarios (baseline, thinning from below, and selective thinning scenarios) comparing in pairs images of Monte Morello forest representing the three scenarios (Fig. 3).

During the data processing, the image preferred by the visitors was identified with the calculation of the priority value of each image using the analytic hierarchy process (AHP) approach (Saaty 1987).

In the last part of questionnaire, the key information to estimate the recreational value of Monte Morello forest was collected such as visitors' home location, the number of times they visited the site in the past year, the length of the trip, the amount of time spent at the site (hours), the travel expenses (e.g., lodging, meals, and transportation), the reasons for visiting Monte Morello forest (i.e., hiking, sport activities, non-wood forest product collection, relaxing in the nature, picnicking, and eating local products), and the socio-demographic characteristics of respondents (age, gender, level of education). The recreational value was indirectly calculated using the travel cost method (TCM) and considering individual total cost expenditures

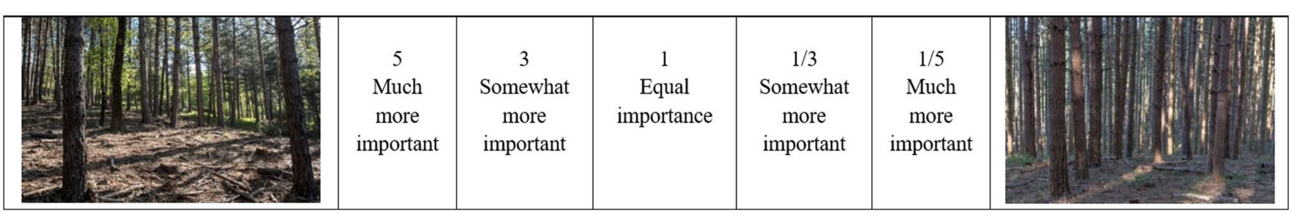

Fig. 3 Pairwise comparison between images of Monte Morello forest after different silvicultural treatments

for the trip to Monte Morello forest. The assumption of the TCM is that visitors are travel cost sensitive, meaning that the expected number of trips to a certain site is lower when the cost sustained to reach the destination increases (Hanley and Barbier 2009). The demand function, to model the number of trips Y_i an individual is likely to make in a certain time span, was calculated in the following way Eq. (7):

$$Y_i = f(TC_i, M_i, C_i) \tag{7}$$

where:
TC_i = cost sustained to reach the destination
M_i = vector of motivations to visit the area
C_i = vector of socio-demographic characteristics

The consumer surplus (CS)—estimated as the negative inverse of the travel cost coefficient (Ram et al. 2002) using a negative binomial regression (Martínez-Espiñeira et al. 2008)—was used as an indirect measure of the recreational value of Monte Morello forest.

The assumption is that in the 15 years (rotation period), the effects of the thinning remain unchanged in terms of recreational attractiveness. Probably, the visual-aesthetic value of forest stand will worsen year after year following the thinning, but with negligible levels perceived by visitors. Consequently, the potential economic benefits related to the recreational activities were estimated considering a constant number of visitors per year and a period of 15 years as done for the wood production and climate change mitigation.

2.5 Multiple-criteria decision analysis

A multiple-criteria decision analysis (MCDA) approach was implemented with the aim to support decision-making process for evaluating the optimal forest restoration scenario. Within the MCDA methods, the Analytic Hierarchy Process (AHP) method was adopted considering the three principles emphasized by Saaty and Alexander (1989): (1) the principle of constructing hierarchies, (2) the principle of establishing priorities, and (3) the principle of logical consistency.

In the present study, pairwise comparisons (comparing three ESs in pairs) are used for establishing priorities among ESs of the same hierarchical level. The visitors of the study area (Monte Morello forest) compared in pairs the importance of the three ESs (recreational opportunities, climate change mitigation, wood production). The results of the pairwise comparison are represented in a reciprocal matrix (A) where the relative weight is expressed as a_{ij} and it is located at the right side of the diagonal, whereas its reciprocal is defined as $1/a_{ij}$ and it is located in the opposite side of the diagonal.

$$A = (a_{ij}) = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{pmatrix} \tag{8}$$

In the matrix, the row indicates the relative weight of each activity with respect to the others. When $I = j$, then $a_{ij} = 1$. Next, the transpose of the vector of the weights w is multiplied by matrix A to obtain the vector represented by λ_{max}, which follows the principle (Saaty 1987):

$$(A - \lambda_{max} I) \cdot w = 0 \tag{9}$$

where:
λ_{max} = maximum Eigenvalue of matrix A
I = identity matrix of size n
n = number of rows or columns in the matrix
w = vector of the weights

In the AHP method, the maximum Eigenvalue of the matrix A of pairwise comparisons is computed for checking the degree of inconsistency. The value of λ_{max} is always positive, equal or higher than n. The consistency of the respondents' information depends on how much the value of λ_{max} deviates from the value of n. In the case where λ_{max} equals n, the responses are perfectly consistent. The matrix A is, thus, tested for consistency using the following formula:

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{10}$$

where:
CI = consistency index
CR = consistency ratio
RI = expected consistency index obtained from random generated comparisons of the same order n

Saaty (1987) has computed a list of RI estimates for positive reciprocal matrices of orders 2 to 14. The value of CR should be lower or equal to 0.1 (10%) for the matrix A to be consistent.

The final result is a ranking of the importance of ESs provided by Monte Morello forest useful to identify the optimal forest restoration scenario able to enhance the most important ESs.

3 Results

3.1 Wood production

The results show that after the silvicultural treatments, 24% of the growing stock was harvested through the thinning from below 134.7 m^3 ha^{-1} and 36% through the selective thinning (202.0 m^3 ha^{-1}). In the selective thinning, logs and snags of the first two decay classes, with a diameter greater than 20 cm, were removed (18.2 m^3 ha^{-1}), while, in the thinning from below, only snags of the first two decay classes were removed (9.5 m^3 ha^{-1}) while logs were left on the soil surface. All the wood collected in the field (144.2 m^3 ha^{-1} with the thinning from below, 220.2 m^3 ha^{-1} with the selective) was chipped and delivered to a combined heat and power (CHP) plant 12 km far from Monte Morello forest.

The forest owner's average annual income was estimated in 0 € $year^{-1}$ ha^{-1} for the baseline scenario (no forest management activities), 337.8 € $year^{-1}$ ha^{-1} for the thinning from below scenario, and 515.8 € $year^{-1}$ ha^{-1} for the selective scenario (Table 2). These values were estimated hypothesizing that the price of local woodchips does not vary substantially over the next 15 years.

3.2 C-stock and C-sequestration

The results show that after the thinning from below the C-stock decreases of 145 tCO_2 ha^{-1} (96% of changes are in the above-ground and below-ground biomass and 4% in deadwood), while after the selective thinning, the C-stock decreases of 220 tCO_2 ha^{-1} (95% of changes are in above-ground biomass and 5% in deadwood). Consequently, both thinning leads to a loss of C-stock in the short-term period (Table 3).

At the same time, the C-sequestration has been calculated using the annual volume increment measured in the study area (Table 3): 12.2 m^3 ha^{-1} in the baseline scenario (BU), 26.0 m^3 ha^{-1} after the thinning from below (TB), and 17.3 m^3 ha^{-1} after the selective thinning (ST). The results show that the range of C-sequestration in the forest restoration scenarios may vary from 17.7 tCO_2 ha^{-1} $year^{-1}$ in the BU scenario to 37.8 tCO_2 ha^{-1} $year^{-1}$ in the TB one. Starting from these values, the C-sequestration changes compared with the BU scenario are equal to 20.1 tCO_2 ha^{-1} $year^{-1}$ in the TB scenario and 7.5 tCO_2 ha^{-1} $year^{-1}$ in the ST scenario. Considering the current carbon credits (CCs) price, the potential economic benefit is of 42.6 € ha^{-1} $year^{-1}$ for the TB and 15.8 € ha^{-1} $year^{-1}$ for the ST scenario.

The data on the soil C-sequestration capacity, before and after the thinning implementation, show that the soil in the BU scenario has a C-accumulation capacity of 1.3 tCO_2 ha^{-1} $year^{-1}$ in organic and mineral layers, which increases up to 33.3 and 36.9 tCO_2 ha^{-1} $year^{-1}$ for the TB scenario and ST scenario, respectively. The CO_{2eq} emission values are comparable among the three scenarios, with an average value of 20.6 tCO_2 ha^{-1} $year^{-1}$.

Summing the C-sequestration capacity of the above- and below-ground biomass and the soil and subtracting the C lost due to the soil emissions, the recovering time of the C-stock lost as result of silvicultural treatments is 3 years in the TB scenario and 5 years in the ST scenario (Table 3).

3.3 Recreational activities

At the end of the questionnaire survey, 201 visitors on a total of 269 visitors filled out the questionnaire (response rate equal to 75%). The sample of respondents was composed of 120 males (59.7%) and 81 females (40.3%), while the age classes were distributed as follows: 4.5% less than 25 years old, 30.3% between 25 and 44 years old, 41.8% between 45 and 64 years old, and the remaining 23.4% more than 64 years old. Besides, the distribution of respondents by level of education was as follows: 26.9% of respondents had an elementary school degree, 40.8% a high school degree, 29.8% a University degree (Bachelor's or Master's degree), and the remaining 2.5% a post-University (PhD) degree. The target of visitors of the Monte Morello forest is mainly represented by local visitors: 68% of respondents comes from Florence and Sesto Fiorentino municipalities, 26% from other municipalities of Tuscany Region, 4% from other Italian regions (Emilia-Romagna, Lazio, Apulia), and 1% from other European countries (France). Consequently, the sample of visitors is mostly represented by members of local community (residents in Florence and Sesto Fiorentino municipalities).

The results of pairwise comparison show that the most appreciated image of Monte Morello forest is the image 3 "ST scenario" (priority score of 0.5034), followed by the image 2 "TB scenario" (0.2873), and in the last place the image 1 "BU scenario" (0.2093). In other words, results show that respondents prefer managed forests (image 2 and image 3), while unmanaged forests (baseline scenario) were evaluated negatively from the aesthetic point of view (Table 4).

The priority score of each image—representative of different forest restoration scenarios—was used as a proxy of

Table 2 Volume of growing stock and deadwood collected in the three forest restoration scenarios in Monte Morello forest

	BU scenario	TB scenario	ST scenario
Volume of growing stock (m^3 ha^{-1})	0.0	134.7	202.0
Volume of deadwood (snags and logs) (m^3 ha^{-1})	0.0	9.5	18.2
Volume harvested for surface unit (m^3 ha^{-1})	0.0	144.2	220.2
Annual income for surface unit (€ $year^{-1}$ ha^{-1})	0.0	337.8	515.8

Table 3 Changes in C-stock (tCO_2 ha^{-1}) and in C-sequestration (tCO_2 ha^{-1} $year^{-1}$) in Monte Morello forest in the three forest restoration scenarios

	BU scenario	TB scenario	ST scenario
Changes in C-stock (tCO_2 ha^{-1}) of which (tCO_2 ha^{-1} $year^{-1}$):	0.0	−144.9	−219.6
Above-ground/Below-ground biomass	0.0	−139.2	−208.8
Deadwood	0.0	−5.7	−10.8
Annual volume increment (m^3 ha^{-1} $year^{-1}$)	12.2	26.0	17.3
C-sequestration in above/below ground biomass (tCO_2 ha^{-1} $year^{-1}$)	17.7	37.8	25.2
C-sequestration in soil (tCO_2 ha^{-1} $year^{-1}$): of which (tCO_2 ha^{-1} $year^{-1}$):	−19.6	11.6	17.7
Sequestration	1.3	33.3	36.9
Emissions (taken with negative sign)	−20.9	−21.7	−19.2
C-sequestration: soil + biomass (tCO_2 ha^{-1} $year^{-1}$)	−1.89	49.4	42.9
Changes in C-sequestration (tCO_2 ha^{-1} $year^{-1}$) compared with the baseline scenario (Δ)	-	51.3	44.8
Time for the C-stock recovering (year)		3	5
Potential annual economic benefits from the sale of CCs (€ ha^{-1} $year^{-1}$)	-	487	425
Potential annual economic benefits from the sale of CCs in 15-year rotation period (€ ha^{-1})	-	8422	7350
Global economic benefits from the sale of CCs on the whole Monte Morello (€ $year^{-1}$)	-	504,365	440,204

visitor attendance to estimate the change in the number of visitors after the thinning from below and selective thinning. The hypothesis is that the attendance of a site is directly related to the preferences assigned for that site. Currently, the annual number of visitors (BU scenario) is equal to 18,475 visitors $year^{-1}$. Therefore, in the TB scenario, an increase of visitors of 7.8% (19,916 visitors) is assumed, while in the ST scenario, an increase of 29.4% (23,908 visitors) is assumed.

The results of the negative binomial (NB) regression model show that the most important variables to describe the number of trips in Monte Morello forest were the reasons for visiting the site. In particular, sports activities and non-wood forest products (NWFP) are motivations that influence the increase in the number of trips, while picnicking and relaxing in the nature are inversely related to the number of annual trips. Based on these results, it is presumable that visitors consider the destination as a suitable site for more active recreational activities (e.g., sports activities and NWFP collection) rather than for picnicking and relaxing in the nature. Regarding the socio-demographic characteristics of the respondents, results show that the gender has no influence on the number of trips, while the age of the respondents shows a positive and statistically significant effect on the response variable, indicating that elderly carry out a higher number of trips per year compared with young people.

The estimated CS is 10.04 € per visit that it is in line with similar studies focused on recreational forest areas (Grilli et al. 2014; Ezebilo 2016). Taking into account the estimated consumer surplus, the current economic importance of recreational benefits in Monte Morello forest is 179.2 € ha^{-1} $year^{-1}$ (BU scenario), while—in accordance with the visitors' preferences—in future years, the potential economic benefits related to the recreational opportunities could increase to 193.2 € ha^{-1} $year^{-1}$ in the TB scenario and to 231.9 € ha^{-1} $year^{-1}$ in the ST scenario (Table 4).

3.4 Preferences for forest restoration scenarios

The results about the importance of the ESs provided by Monte Morello forest show that the recreational opportunities (mean = 4.74, SD = 0.53) were considered the most important ecosystem service by respondents, followed by

Table 4 Changes in the recreational opportunities in Monte Morello forest in the three forest restoration scenarios

Scenario	BU	TB	ST
Priority score (AHP)	0.2093	0.2873	0.5034
Consistency index (CI)	0.000416	0.000416	0.000416
Consistency ratio (CR)	0.000793	0.000793	0.000793
Annual number of visitors	18,475	19,916	23,908
Recreational economic benefits (€ ha^{-1} $year^{-1}$)	179.2	193.2	231.9
Recreational economic benefits in 15-year rotation period (€ ha^{-1})	3,099	3,341	4,010

Table 5 Input matrix for MCDA (standardization with maximum method)

Scenario	I_1 [€ year^{-1} ha^{-1}]	I_{2a} [tCO_2 year^{-1} ha^{-1}]	I_{2b} [tCO_2 ha^{-1}]	I_3 [€ year^{-1} ha^{-1}]
Input matrix				
BU scenario	179.2	−1.89	0	0
TB scenario	193.2	49.4	144.9	337.8
ST scenario	231.9	42.88	219.6	515.8
Standardize matrix				
BU scenario	0.77	−0.04	1.00	0
TB scenario	0.83	1.00	0.34	0.65
ST scenario	1.00	0.87	0	1.00

the climate change mitigation (mean = 4.62, SD = 0.68). Conversely, the wood production was considered a marginal ecosystem service by respondents (mean = 2.69, SD = 1.25). Therefore, for the respondents, the order of importance of the three ESs provided by Monte Morello forest is recreational opportunities > climate change mitigation > wood production. This order of importance was also confirmed by other groups of stakeholders (representatives of public administrations, environmental non-governmental organizations, and private actors of forest-wood chain) as emphasized by Napoliello et al. (2018) in a qualitative research conducted with the stakeholders of the Monte Morello forest.

Finally, a MCDA was performed to identify the best forest restoration action regarding the three ESs considered in the present study. The input standardized matrix was built starting from the values of the indicators I_1, I_2, and I_3. In the input matrix, the indicators I_1, I_{2a}, and I_3 are considered as benefits, while the indicator I_{2b} is considered as a cost (Table 5).

The weigh vector has been defined following the above preferences declared by the respondents during the questionnaire survey. The most important ecosystem service is the recreational opportunities (ES1) provided by forest (mean = 4.74), immediately followed by the climate change mitigation (ES2, mean = 4.62), while the wood production (ES3) is considered the least important ecosystem service (mean = 2.69). The normalized weighted vector directly assigned is $I_1 = 0.393$, $I_2 = 0.383$ (I_{2a} and I_{2b} weight equally 0.5 and 0.5), and $I_3 = 0.223$.

The results show that the optimum forest restoration solution is the selective thinning followed by the thinning from below (Fig. 4). Overall, the I_1 (recreational opportunities) gives a strong contribution to the total score in all three scenarios. The I_1 value is slightly higher in the TB and ST scenario compared with the BU scenario; conversely, I_{2a} is remarkable in the post-harvesting scenarios, and absent in the BU scenario. The contribution of indicator I_{2b} (C-stock lost due to the thinning actions) is important only in the BU scenario. Finally, the contribution of I_3, which takes into account the wood harvested valorization, contributes to the final score in TB scenario and ST scenario.

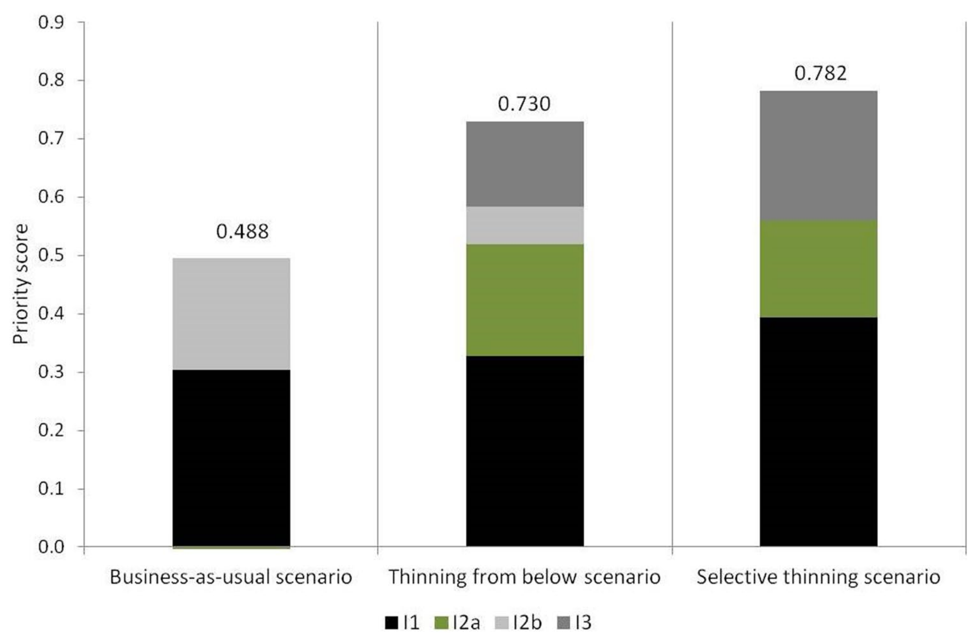

Fig. 4 Result of multiple-criteria decision analysis (MCDA) comparing the three forest management scenarios

4 Discussion

The results of the present study show that both types of thinning have a positive effect on the three ESs considered (wood production, climate change mitigation, recreational activities) increasing the benefits both at local and global level. However, the selective thinning provides the best performance. Regarding recreational opportunities, only applying the selective thinning is possible to increase the number of visitors (+29%) due to the higher accessibility of the forest after the interventions and to the increased recreational attractiveness. Regarding C-sequestration, the better performance is shown by the TB scenario (49.4 against 44.4 tCO_2 $year^{-1}$ ha^{-1}) in absolute term. Nonetheless, in relative terms (C-sequestration/biomass released after the thinning), the two scenarios have the same performances (about 12%). To confirm this trade-off between the C-sequestration and the thinning system, the measurements on biomass and soil C-sequestration capacity should be repeated after 5 years from the thinning actions (2 years is a very short period considering the forest temporal dynamics). The income in the ST scenario is 55% greater than in the TB scenario. Therefore, it is possible to assert that the ST scenario is the optimum solution for ES3-wood production. The ES2 considers both the C-stock lost due to the harvesting action and the carbon stored due to the trees and soil sequestration capacity. The results show that, even if the loss of C-stock is greater in the ST scenario, the C-sequestration increase is comparable with the TB scenario. Overall, the results of MCDA underline that in a degraded forest, the improvement of ES supply could be reached by means of silvicultural treatments. The BU scenario is the worst solution. On the contrary, the selective thinning seems to be the most rational and sustainable forest restoration option, because with comparable costs for the forest activity, it makes possible to obtain better profits from wood valorization, improvement in recreational attractiveness, and comparable C-sequestration capacity. In other words, with the application of the thinning from below, the earnings from wood valorization and the C-sequestration are not enough high to lead to noticeable advantages compared with the BU scenario. In summary, silvicultural treatments (selective thinning or thinning from below) have positive effects on the provision of the three ESs in the degraded forest; trade-offs between ESs are rather limited and the main positive effects are obtained in the first years after thinning. The most positive effect of selective thinning on ESs compared with thinning from below is presumably related to both the greatest basal area removed (30–40% with the selective thinning vs. 15–20% with the thinning from below) and the characteristics of trees harvested (both large and small trees with the selective thinning vs. small and leaned trees with the thinning from below).

The AHP method used in the present study to analyze the effects of silvicultural treatments on trade-offs between forest ESs highlighted some important methodological considerations. In particular, the AHP method allows the interdependence of evaluation criteria including both quantitative and qualitative data. Besides, we can confirm that the AHP method provides simple results for complex problems facilitating the decision-making process in accordance with the preferences of forest users. However, the application of the AHP method in the present research was characterized by some limitations. First of all, only three forest ESs were taken in consideration and assessed. Probably, a greater number of ESs would have allowed an in-depth trade-off analysis. Secondly, the weight of the indicators was assigned by visitors and not by all groups of stakeholders operating in the forest area. In this sense, it can be assumed that if all the stakeholders had been involved, the order of priority of the ESs would have been different. However, the weights assigned by our sample of respondents can be considered an expression of the opinion of the local community whereas 68% of visitors are also residents of Florence and Sesto Fiorentino municipalities. Thirdly, in this study, the ESs flows were assessed considering the data collected 2 years after the silvicultural treatments, while if the data had been collected after 5 or 10 years, the results would have been different. Despite these limitations, the results of this study confirm the positive feedback obtained by other authors who have applied the AHP method in forest planning. Nordström et al. (2009) and Maroto et al. (2012) aggregated stakeholders' preferences about strategies and objectives using AHP method in two forest plans in Sweden and Spain. Both of these authors concluded that AHP is a powerful and useful method to integrate stakeholder preferences into sustainable forest management. Wolfslehner et al. (2005) used and compared AHP and Analytic Network Process (ANP) methods to evaluate four different strategic management options with a set of 6 criteria and 43 indicators related to sustainable forest management. Those authors emphasized that AHP is a broad method for setting priorities in participatory forest planning based on the stakeholders' preferences. Recently, Nilsson et al. (2016) used the AHP method to set weights for objectives in long-term forest management planning based on stakeholder preferences. Segura et al. (2018) used AHP and PROMETHEE to support decision makers in drafting a collaborative management of ESs in Natural Parks.

In the international literature, many authors have assessed the effects of forest management practices on ESs considering trade-offs and synergies between them. Briner et al. (2013) evaluated trade-off between ESs (protection against gravitational hazards, biodiversity, C-sequestration, food provision) in a mountain forest in the south of Switzerland

(Saas Valley) managed with the aim to increase recreational attractiveness and habitats for plants and wildlife. Then, Pardos et al. (2016) assessed the impact of management practices on the provision of four ESs (timber production, protection against gravitational hazards, carbon sequestration, and biodiversity) in Valsaín forest in Spain. The authors highlighted that multi-species management can better realize the full potential of economically, ecologically, and culturally valuable ES (Pardos et al. 2016). Lafond et al. (2017) assessed trade-offs and synergies between three ESs (timber production, biodiversity conservation, and protection against natural hazards) in uneven-aged mountain forests in Western Alps. The study showed that the optimal forest restoration scenario to enhance synergies between production and protection is a low intensity thinning (Lafond et al. 2017). Likewise, Cameron (2002) demonstrated the positive effect of selective thinning on stands' stability in a Sitka spruce stands in Scotland, while Häyhä et al. (2015) highlighted in Fiemme and Fassa Valleys in Italian Alps the effects of the application of close-to-nature forest management on several ESs (timber and bioenergy production, mushrooms, berries, fresh water for provisioning services, C-sequestration and hydrogeological protection for regulating services, and recreational activities for cultural services). Recently, Marchi et al. (2018) have estimated the effects of two silvicultural treatments (thinning from below and selective thinning) on the biophysical provision of five ESs (wood production, mechanical stability of the forest system, C-sequestration, tree species diversity, floristic diversity) in two artificial black pine forests in Central Italy. The authors emphasized that the selective thinning can enhance most ESs compared with the thinning from below. The results provided by those authors are perfectly in line with findings of the present study.

The results of this study, supported by literature, emphasize that forest management practices are crucial in the early stages of artificial conifer stands to guarantee the ecosystem functionality and the forest capacity to provide ESs. In this context, thinning is a good practice to stimulate annual increment volume and improve the stem quality of the candidate trees. Besides, thinning can have a positive impact on C-sequestration and at the same time on wood production. In addition, thinning improves forest accessibility—removing standing dead trees and lying deadwood—and recreational opportunity for visitors.

5 Conclusion

This study has pointed out that a rational and efficient forest management practice is a "win-to-win" approach for the sustainable management of degraded forests. The selective thinning can enhance the production of wood biomass generating simultaneously positive impacts on other ESs, in this case recreational activities and climate change mitigation. The wood product valorization has been marginally considered in the present case study due to the low quality of raw materials obtained from a degraded black pine forest. However, if a part of the harvested wood is allocated for wood packaging or poles higher, ES values are expected both in terms of carbon stocked and of income from timber sales.

From the methodological point of view, the main advantage of the proposed method is the objective comparison of different forest management alternatives. This enables to choose the alternative that allows greater enhancement of ES. Conversely, the main disadvantage is taking in consideration only three ESs because of the limited available information. However, it is important to remember that MCDA must be considered a tool of support in decision-making processes but not a decision maker itself; consequently, outputs and results must be deeply analyzed and discussed before taking them for granted.

Future findings of this study will consist in increasing the number of ESs assessed and evaluated—also including the supporting services (i.e., habitat and biodiversity)—and the indicators involved in the MCDA. In addition, it would be advisable to test the effects of other silvicultural treatments aimed at forest restoration of degraded forests. A larger number of ESs and forest restoration scenarios considered in the MCDA can improve the quality of information provided to support the forest planning decision-making process.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The authors declare that they obtained the approval of the project LIFE "Recovery of degraded coniferous Forests for environmental sustainability Restoration and climate change Mitigation" (LIFE14/CCM/IT/905) ethics committee for conducting the present study based on interviews/survey. The authors declare that they obtained the informed consent from human participants involved in this study.

References

Baral H, Guariguata MR, Keenan RJ (2016) A proposed framework for assessing ecosystem goods and services from planted forests. Ecosyst Serv 22:260–268. https://doi.org/10.1016/j.ecoser.2016.10.002

Becagli C, Puletti N, Chiavetta U, Cantiani P, Salvati L, Fabbio G (2013) Early impact of alternative thinning approaches on structure diversity and complexity at stand level in two beech forests in Italy. Ann Silv Res 37:55–63. https://doi.org/10.12899/ASR-802

Blattert C, Lemm R, Thees O, Lexer MJ, Hanewinkel M (2017) Management of ecosystem services in mountain forests: review of indicators and value functions for model based multi-criteria decision analysis. Ecol Indic 79:391–409. https://doi.org/10.1016/j.ecolind.2017.04.025

Borges JG, Marques S, Garcia-Gonzalo J, Rahman AU, Bushenkov V, Sottomayor M, Carvalho PO, Nordström EM (2017) A multiple criteria approach for negotiating ecosystem services supply targets and forest owners' programs. For Sci 63:49–61. https://doi.org/10.5849/FS-2016-035

Boscolo M, Vincent JR (2003) Nonconvexities in the production of timber, biodiversity and carbon sequestration. J Environ Econ Manag 46:251–268. https://doi.org/10.1016/S0095-0696(02)00034-7

Briner S, Huber R, Bebi R, Elkin C, Schmatz DR, Grêt-Regamey A (2013) Trade-offs between ecosystem services in a mountain region. Ecol Soc 18:35. https://doi.org/10.5751/ES-05576-180335

Cameron AD (2002) Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. Forestry 75:25–35. https://doi.org/10.1093/forestry/75.1.25

Chazdon RL, Laestadius L (2016) Forest and landscape restoration: toward a shared vision and vocabulary. Am J Bot 103:1–3. https://doi.org/10.3732/ajb.1600294

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260. https://doi.org/10.1016/S0921-8009(98)00020-2

Daily GC (1997) Nature's Services. Island Press, Washington, DC

De Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41:393–408. https://doi.org/10.1016/S0921-8009(02)00089-7

De Meo I, Angelli EA, Graziani A, Kitikidou K, Lagomarsino A, Milios E, Radoglou K, Paletto A (2017) Deadwood volume assessment in Calabrian pine (Pinus brutia Ten.) peri-urban forests: Comparison between two sampling methods. J Sustain Forest 36: 666–686. https://doi.org/10.1080/10549811.2017.1345685

De Meo I, Lagomarsino A, Agnelli AE, Paletto A (2018) Direct and Indirect Assessment of Carbon Stock in Deadwood: Comparison in Calabrian Pine (*Pinus brutia* Ten. subsp. *brutia*) Forests in Italy. Forest Science (in press). https://doi.org/10.1093/forsci/fxy051

Deal RL, Cochran B, LaRocco G (2012) Bundling of ecosystem services to increase forestland value and enhance sustainable forest management. For Pol Econ 17:69–76. https://doi.org/10.1016/j.forpol.2011.12.007

Duncker PS, Barreiro SM, Hengeveld M, Lind T, Mason WL, Ambrozy S, Spiecker H (2012) Classification of forest management approaches: a new conceptual framework and its applicability to European forestry. Ecol Soc 17:51. https://doi.org/10.5751/ES-05262-170451

Duncker PS, Raulung-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn HP, Smith M, Eckmüllner O, Spiecker H (2012) How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. Ecol Soc 17:50. https://doi.org/10.5751/ES-05066-170450

EC (European Commission) (2011) Our Life Insurance, Our Natural Capital: an EU Biodiversity Strategy to 2020. Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions, COM/2011/0244 Final.

Eyvindson K, Hujala T, Kurttila M, Kangas A (2015) Interactive preference elicitation incorporating a priori and a posteriori methods. Ann Oper Res 232:99–113

Ezebilo EE (2016) Economic value of a non-market ecosystem service: an application of the travel cost method to nature recreation in Sweden. Int J Biodivers Sci Ecosyst Serv Manag 12:314–327

Garcia-Gonzalo J, Bushenkov V, McDill ME, Borges JG (2015) A decision support system for assessing trade-offs between ecosystem management goals: an application in Portugal forests. Forests 6:65–87

Grilli G, De Meo I, Garegnani G, Paletto A (2017) A multi-criteria framework to assess the sustainability of renewable energy development in the Alps. J Environ Plann Man 60:1276–1295. https://doi.org/10.1080/09640568.2016.1216398

Grilli G, Nikodinoska N, Paletto A, De Meo I (2015) Stakeholders' preferences and economic value of forest ecosystem services: an example in the Italian Alps. Baltic Forestry 21:298–307

Grilli G, Paletto A, De Meo I (2014) Economic valuation of forest recreation in an Alpine Valley. Baltic Forestry 20:167–175

Haines Young R, Potschin M (2017) Common International Classification of Ecosystem Services (CICES) V5.1. Guidance on the Application of the Revised Structure. Fabis Consulting, Nottingham.

Hamrick K, Gallant M (2018) Unlocking potential, state of the voluntary carbon markets - Forest Trends' Ecosystem Marketplace, Washington, DC.

Hanley N, Barbier E (2009) Pricing nature: cost-benefit analysis and environmental policy. Edward Elgar Publishing, Cheltenham

Häyhä T, Franzese PP (2014) Ecosystem services assessment: a review under an ecological-economic and systems perspective. Ecol Model 289:124–132. https://doi.org/10.1016/j.ecolmodel.2014.07.002

Häyhä T, Franzese PP, Paletto A, Fath BD (2015) Assessing, valuing, and mapping ecosystem services in Alpine forests. Ecosyst Serv 14:12–23. https://doi.org/10.1016/j.ecoser.2015.03.001

La Notte A, D'Amato D, Mäkinen H, Paracchini ML, Liquete C, Egoh B, Geneletti D, Crossman ND (2017) Ecosystem services classification: a systems ecology perspective of the cascade framework. Ecol Indic 74:392–402. https://doi.org/10.1016/j.ecolind.2016.11.030

Lafond V, Cordonnier T, Mao Z, Courbaud B (2017) Trade-offs and synergies between ecosystem services in uneven-aged mountain forests: evidences using Pareto fronts. Eur J For Res 136:997–1012. https://doi.org/10.1007/s10342-016-1022-3

Langemeyer J, Gómez-Baggethun E, Haase D, Scheuer S, Elmqvist T (2016) Bridging the gap between ecosystem service assessments and land-use planning through multi-criteria decision analysis (MCDA). Environ Sci Policy 62:45–56. https://doi.org/10.1016/j.envsci.2016.02.013

Langner A, Irauschek F, Perez S, Pardos M, Zlatanov T, Öhman K, Nordström EM, Lexer MJ (2017) Value-based ecosystem service trade-offs in multi-objective management in European mountain forests. Ecosyst Serv 26:245–257. https://doi.org/10.1016/j.ecoser.2017.03.001

Marchi M, Paletto A, Cantiani P, Bianchetto E, De Meo I (2018) Comparing Thinning System Effects on Ecosystem Services Provision in Artificial Black Pine (*Pinus nigra* J. F. Arnold) Forests. Forests 9: 188. https://doi.org/10.3390/f9040188

Maroto C, Segura M, Ginestar C, Uriol J, Segura B (2012) Aggregation of stakeholder preferences in Sustainable Forest Management using AHP. In: Proceedings of the 1st International Conference on Operations Research and Enterprise Systems (ICORES-2012): 100–107.

Martínez-Espiñeira R, Loomis JB, Amoako-Tuffour J, Hilbe JM (2008) Comparing recreation benefits from on-site versus household surveys in count data travel cost demand models with overdispersion. Tourism Econ 14:567–576. https://doi.org/10.5367/000000008785633532

Mazza G, Agnelli AE, Cantiani P, Chiavetta U, Doukalianou F, Kitikidou K, Milios E, Orfanoudakis M, Radoglou K, Lagomarsino A (2019) Short-term effects of thinning on soil CO_2, N_2O and CH_4 fluxes in Mediterranean forest ecosystems. Sci Total Environ 651:713–724. https://doi.org/10.1016/j.scitotenv.2018.09.241

Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington DC, USA

Myšiak J (2006) Consistency of the results of different MCA methods: a critical review. Environ Plann C: Politics and Space 24:257–277. https://doi.org/10.1068/c04103s

Næsset E (1999) Relationship between relative wood density of *Picea abies* logs and simple classification systems of decayed coarse woody debris. Can J Forest Res 14:454–461. https://doi.org/10.1080/02827589950154159

Napoliello L, Paletto A, De Meo I (2018) Ecosystem services provided by Monte Morello forest: stakeholders' knowledge and opinions. Gazzetta Ambiente 2:63–84

Naveh Z (2005) Epilogue: toward a transdisciplinary science of ecological and cultural landscape restoration. Restor Ecol 13:228–234. https://doi.org/10.1111/j.1526-100X.2005.00028.x

Nilsson H, Nordström EM, Öhman K (2016) Decision support for participatory forest planning using AHP and TOPSIS. Forests 7:100. https://doi.org/10.3390/f7050100

Nocentini S (1995) The renaturalization of forest plantations. An experimental trial with Pinus nigra and P. nigra var. laricio on Monte Morello near Florence. L'Italia Forestale e Montana 50:425–435

Nordström EM, Romero V, Eriksson LO, Öhman K (2009) Aggregation of preferences in participatory forest planning with multiple criteria: an application to the urban forest in Lycksele, Sweden. Can J For Res 39:1979–1992. https://doi.org/10.1139/X09-107

Paletto A, Guerrini S, De Meo I (2017) Exploring visitors' perceptions of silvicultural treatments to increase the destination attractiveness of peri-urban forests: a case study in Tuscany Region (Italy). Urban For Urban Gree 27:314–323. https://doi.org/10.1016/j.ufug.2017.06.020

Paletto A, Tosi V (2010) Deadwood density variation with decay class in seven tree species of the Italian Alps. Scand J Forest Res 25:164–173. https://doi.org/10.1080/02827581003730773

Palomo I, Felipe-Lucia MR, Bennett EM, Martín-López B, Pascual U (2016) Disentangling the pathways and effects of ecosystem service co-production. Adv Ecol Res 54:245–283. https://doi.org/10.1016/bs.aecr.2015.09.003

Pardos M, Pérez S, Calama R, Alonso R, Lexer MJ (2016) Ecosystem service provision, management systems and climate change in Valsaín forest, central Spain. Reg Environ Change 17. doi: https://doi.org/10.1007/s10113-016-0985-4

Pohekar SD, Ramachandran M (2004) Application of multi-criteria decision making to sustainable energy planning—a review. Renew and Sustain Energy Reviews 8:365–381. https://doi.org/10.1016/j.rser.2003.12.007

Potschin M, Haines-Young R, Fish R, Turner R (eds) (2016) Routledge Handbook of Ecosystem Services. Routledge.

Ram KS, Seidl AF, Moraes AS (2002) Value of recreational fishing in the Brazilian Pantanal: a travel cost analysis using count data models. Ecol Econ 42:289–299. https://doi.org/10.1016/S0921-8009(02)00106-4

Rodríguez García L, Curetti G, Garegnani G, Grilli G, Pastorella F, Paletto A (2016) La valoración de los servicios ecosistémicos en los ecosistemas forestales: un caso de estudio en Los Alpes Italianos. Bosque 37:41–52. https://doi.org/10.4067/S0717-92002016000100005

Ruddell S, Sampson R, Smith M, Giffen J, Hagan J, Sosland D, Godbee J, Heissenbuttel J, Lovett S, HelmsJ PW, Simpson R (2007) The role of sustainably managed forests in climate change mitigation. J Forest 105:314–319. https://doi.org/10.1093/jof/105.6.314

Saarikoski H, Barton DN, Mustajoki J, Keune H, Gomez-Baggethun E, Langemeyer J (2016) Multi-criteria decision analysis (MCDA) in ecosystem service valuation. In: Potschin, M. and K. Jax (eds): OpenNESS Ecosystem Services, Reference Book. EC FP7 Grant Agreement no. 308428.

Saaty TL (1987) The analytic hierarchy process—what it is and how it is used. Math Modell 3–5:161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty TL, Alexander JM (1989) Conflict Resolution – The Analytic Hierarchy Process. Praeger, New York

Santos-Martín F, García Lorente M, Quintas-Soriano C, Zorrilla-Miras P, Martín-López B, Loureiro M, Benayas J, Montes M (2016) Spanish National Ecosystem Assessment: Sovio-economic valuation of ecosystem services in Spain. Synthesis of the key findings. Biodiversity Foundation of the Spanish Ministry of Agriculture, Food and Environment, Madrid.

Segura M, Maroto C, Belton V, Ginestar C, Marqués I (2018) Collaborative Management of Ecosystem Services in Natural Parks Based on AHP and PROMETHEE. In: Huber S, Geiger MJ, Teixeira de Almeida A (eds.), Multiple Criteria Decision Making and Aiding, Springer Nature Switzerland AG: 31–255.

Tabacchi G, Di Cosmo L, Gasparini P (2011) Aboveground tree volume and phytomass prediction equations for forest species in Italy. Eur J For Res 130:911–934. https://doi.org/10.1007/s10342-011-0481-9

TEEB (2010) A synthesis of the approach, conclusions and recommendations of TEEB. Mainstreaming the Economics of Nature. UNEP, Geneva, The Economics of Ecosystems and Biodiversity

Tóth SF, McDill ME (2009) Finding efficient harvest schedules under three conflicting objectives. For Sci 55:117–131. https://doi.org/10.1093/forestscience/55.2.117

Vacchiano G, Berretti R, Romano R, Motta R (2018) Voluntary carbon credits from improved forest management: policy guidelines and case study. iForest 11: 1–10. https://doi.org/10.3832/ifor2431-010

Valasiuk S, Czajkowski M, Giergiczny M, Zylicz T, Veisten K, Landa Mata I, Halse AH, Elbakidze M, Angelstam P (2018) Is forest landscape restoration socially desirable? A discrete choice experiment applied to the Scandianvian transboundary Fulufjället National Park. Restor Ecol 26:370–380. https://doi.org/10.1111/rec.12563

Vihervaara P, Rönkä M, Walls M (2010) Trends in ecosystem service research: early steps and current drivers. Ambio 39:314–324. https://doi.org/10.1007/s13280-010-0048-x

Wolfslehner B, Vacik H, Lexer MJ (2005) Application of the analytic network process in multi-criteria analysis of sustainable forest management. For Ecol Manage 207:157–170

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