Sustainable Forest Strategies as Natural Climate Solutions in Degraded Coniferous Forests

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ABSTRACT

The present research implemented two improved forest management practices in a study area in Central Italy (Monte Morello Forest) to analyze their effects on C-sequestration and C-stock in all C pools (above-ground and below-ground biomass, deadwood, litter, and soil). It also estimated silvicultural treatment effects on two additional ecosystem services — wood production and recreational activity. A thinning from below and a selective thinning were applied in a degraded coniferous forest to increase the C-sequestration in the medium-long term. The results showed that after the two thinnings, above-ground biomass and deadwood C-stock decreased (–145 and –220 t CO_2 ha^{-1} after thinning from below and selective thinning, respectively). However, these silvicultural interventions led to an increase in C-sequestration, recovering the lost C-stock in a period of between four and nine years and generating a positive flow in the medium-long term. Moreover, both thinnings positively affected wood production and the aesthetic-visual perception of the forest for visitors.

TANULMÁNY INFÓ

Kulcsszavak:
Szénkészlet
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Javított erdőgazdálkodási gyakorlatok
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KIVONAT

Fenntartható erdőstratégiák, mint természetes éghajlati megoldások degradált tűlevelű erdőkben. A jelen kutatás két különböző módszerrel menedzselt közép-olaszországi (Monte Morello) erdőt vizsgált. Elemeztük az erdőművelés és erdőgazdálkodási módszerek hatását a szénmegkötésre, a szénkészletre valamint a teljes széntartalékra (föld feletti és föld alatti biomassza, holtfa, avar és talaj). Ezen túlmenően a tanulmány a fatermelésre és a rekreációs tevékenységre gyakorolt hatásokat is vizsgálta és összehasonlította. Egy leromlott állapotú tűlevelű erdőben alulról történő ritkítást és szelektív ritkítást alkalmaztunk a szénkötöttség középtávú növelése érdekében. Az eredmények azt mutatták, hogy a két különböző ritkítás után a föld feletti biomassza és a holtfa szénkészlete csökkent (-145 és -220 t CO_2 ha^{-1} az alulról történő ritkítás és a szelektív ritkítás után). Ezek az erdőművelési beavatkozások azonban a szénkötöttség növekedéséhez vezettek, négy és kilenc év közötti időszakban visszanyerték az elveszett szénkészletet, és középtávon pozitív áramlást eredményeztek. Ezenkívül mindkét ritkítás pozitívan befolyásolta a fatermelést és az erdő esztétikai-vizuális megítélését a látogatók számára.

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1 INTRODUCTION

Forests act as a net sink for carbon dioxide (CO_2), contributing to climate change mitigation by removing atmospheric CO_2 and storing it in five carbon pools (i.e., above-ground and below-ground biomass, soil, deadwood, litter) (Somogyi, 2008; Kotroczó et al., 2012). As confirmed by inventory measurements in managed and unmanaged forests in temperate and tropical regions, forests can offset 2 % to 30 % of expected emissions during this century (Pan et al., 2011). Moreover, forests comprise a vital carbon (C) reservoir since they store about twice the amount of C in the atmosphere. As estimated by Grassi et al. (2022), the mean net global sink was $-1.6\ Gt\ CO_2\ yr^{-1}$ over the period 2000–2020, largely determined by a sink on forest land ($-6.4\ Gt\ CO_2\ yr^{-1}$), followed by source from deforestation ($+4.4\ Gt\ CO_2\ yr^{-1}$). The capacity of ecosystems to store C depends on the balance between net primary productivity (NPP) and heterotrophic respiration. Whether a particular ecosystem functions as a sink or greenhouse gas (GHG) emissions source may change over time, depending on its vulnerability to climate change and other stressors and disturbances. Therefore, monitoring and estimating the biomass and soil C stocks of forests is vital to support the development and verification of GHG inventories in the "Land Use, Land Use Change, and Forestry" (LULUCF) sector (Somogyi et al., 2008).

Absent or inappropriate management can result in forest degradation, implying a decrease in canopy cover and natural regeneration (Kruk and Kornatowska, 2014), which, in turn, affects the annual increment of C-sequestration, reducing the potential of these forests to act as sinks or transforming them into a GHG source (Herold et al., 2011). CO_2 emissions from deforestation and forest degradation have been estimated to account for about 12–20 % of global anthropogenic CO_2 emissions (IPCC, 2007). Deforestation and forest degradation are major contributors to global GHG emissions, but if these processes are controlled, forests can significantly contribute to climate change mitigation. Forest-based strategies offer a cost-effective means to mitigate climate change; therefore, appropriate forest management can help reduce CO_2 emissions from deforestation and forest degradation and increase C removals (Balderas Torres et al., 2013).

In this conceptual framework, Natural Climate Solutions (NCS) comprise a range of strategies involving conservation, restoration, and effective land management practices, primarily aimed at alleviating GHG emissions from terrestrial ecosystems while optimizing their capacity for C sequestration (Griscom et al., 2017). This portfolio of twenty land stewardship options has been introduced as a cost-effective tool that increases C storage in natural and planted forests, grasslands, agricultural lands, and wetlands (Fargione et al., 2018) while also sustaining biodiversity and other ecosystem services (Kaarakka et al., 2021).

Among the NCS practices, forest pathways for NCS — in particular reforestation, avoided forest conversion, and improved forest management (IFM) — have the potential to offset approximately 30 % of GHG emissions and contribute as much as 50 % of the total C-sequestration possible through NCSs globally (Griscom et al., 2017; Fargione et al., 2018). These NCS options offer the best climate mitigation potentials. They also extend the highest positive impacts on provisioning and regulating, and on cultural ecosystem services (Paletto et al., 2021).

IFM offers cost-effective mitigation opportunities, many of which could be quickly realized without land use changes, providing a salient approach to increasing C-sequestration in forested systems (Fargione et al., 2018). Early definitions of IFM comprised only extended rotations and did not consider other IFM strategies that included silvicultural systems such as selection and retention harvesting. Offering a broad and comprehensive overview, Kaarakka et al. (2021) evidenced various definitions of IFM deriving from state and government agency protocols, non-governmental organizations associated with the forest sector, and published literature. According to Kaarakka et al. (2021), IFM includes a variety of silvicultural management practices that incorporate above-ground and below-ground biomass C components and soil C stock. Thinnings in planted and natural forests play a crucial role in increasing growth (i.e., volume increment) and improving crown development and stand stability within these silvicultural management practices. Therefore, thinning interventions can directly and positively affect C-sequestration.

Starting from these considerations, the LIFE14 CCM/IT/905 project "Recovery of degraded coniferous Forests for environmental sustainability Restoration and climate change Mitigation" (FoResMit) has implemented innovative silvicultural practices in degraded coniferous forests to evaluate the impact of IFM interventions on climate change. In particular, different silvicultural practices have been applied in the Monte Morello Forest (Tuscany Region, Central Italy) to increase the C-sequestration in the medium to long term and simultaneously improve the provision of other ecosystem services (e.g., wood production and recreational activity). The following questions address the research objective:

- Q1. What impact do thinning interventions (selective thinning and thinning from below) have on the C-stock of an unmanaged coniferous planted forest?
- Q2. What impact do thinning interventions (selective thinning and thinning from below) have on the C-sequestration of a coniferous planted forest in the medium and long term?
- Q3. What impact do thinning interventions (selective thinning and thinning from below) have on other ecosystem services?

2 MATERIALS AND METHODS

2.1 Study area

Monte Morello Forest (43°51′20″N; 11°14′23″E) is near the urban area of Florence (Tuscany Region), at an altitude of approximately 600 m a.s.l. (*Figure 1*).

The primary stone is calcareous flysch (turbidites) constituted by alternating limestone, marly limestone ("alberese"), marl, claystone, and, subordinately, sandstone. Therefore, soils are mainly calcareous, presenting a loam or clay loam texture, rich in carbonates, with pH ranging between 7.5 and 8.2 (Lagomarsino et al., 2021).

A Mediterranean climate with dry summers characterizes the area, with July and August as the driest months. The average annual rainfall is 876 mm (period 1890–2018), concentrated from autumn to early spring, and the average annual temperature is 13.3 °C.

Monte Morello has been reforested on degraded soils affected by overgrazing. The reforestation activities aimed to provide hydrogeological stability and facilitate the natural succession toward mixed forests with a large component of broadleaved species (Cantiani and Chiavetta 2015; De Meo et al. 2019).

No silvicultural treatments have been applied since the reforestation activities performed between 1909 and 1980, and the stands have been largely abandoned (De Meo et al., 2017). These stands — characterized by a dominant layer of *Pinus nigra* and *Pinus brutia* with minor presence of *Cupressus sempervirens* and *Quercus cerris* — currently exhibit visible degradation symptoms with many dead and damaged trees. *Cupressus arizonica*, with regeneration of Mediterranean shade-tolerant broadleaf species such as *Fraxinus ornus* and *Acer campetris*, occupy the understory layer (Mazza et al., 2019).

The mean tree density in Monte Morello Forest is 980 tree ha^{-1}. The mean basal area is 62.9 m^2 ha^{-1}, and the mean height is 17.1 m (Mazza et al., 2019). De Meo et al. (2017) estimated an average deadwood volume of 75.08 m^3 ha^{-1}. Divided by component, this equals 59.91 m^3 ha^{-1} in lying deadwood, 13.92 m^3 ha^{-1} in standing dead trees, and 1.25 m^3 ha^{-1} in stumps.

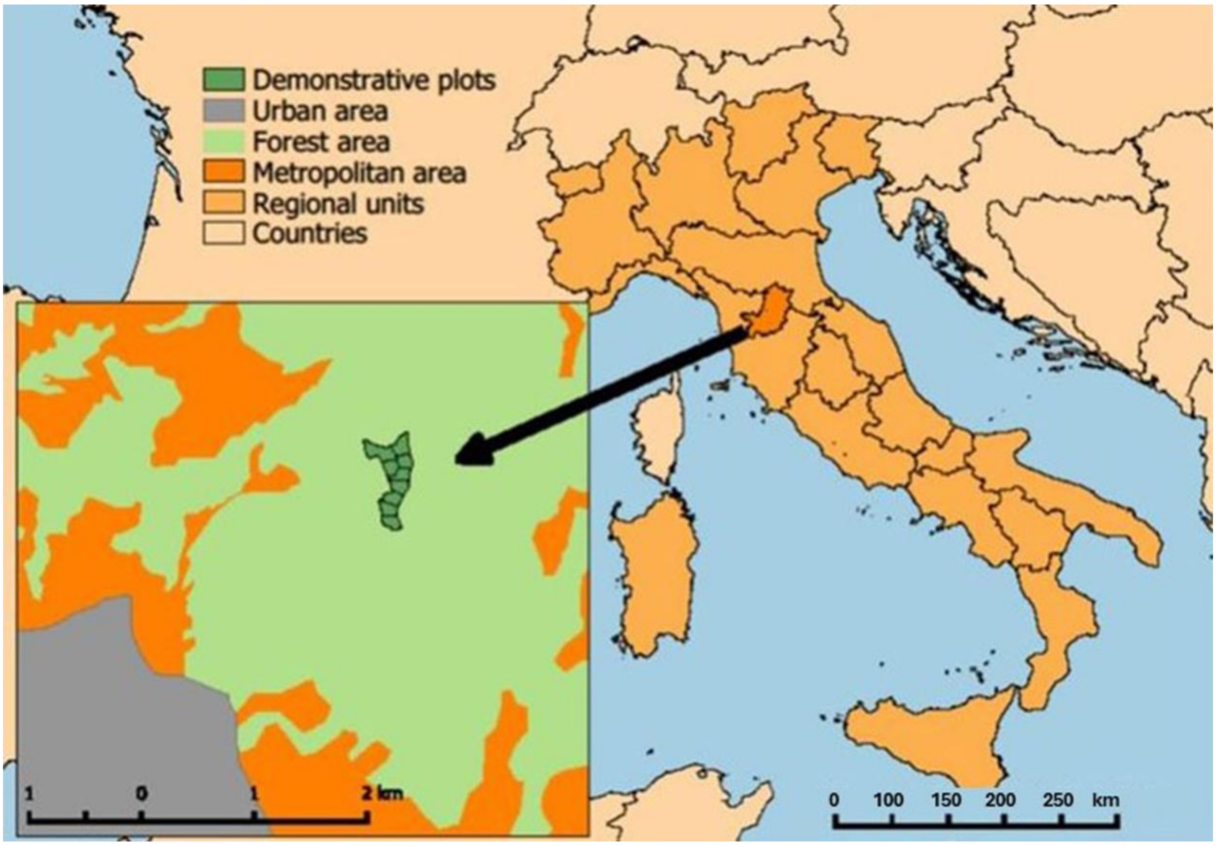

Figure 1. Location of study area (Monte Morello Forest) in Italy

2.2 Experimental design and field measurements

The IFM practices implemented to increase the C stocked in Monte Morello were thinning from below and selective thinning. The C-stock changes these two thinnings caused were estimated from five carbon pools: above-ground and below-ground biomass, deadwood, soil, and litter. The effects of the two silvicultural interventions were compared with each other and with control plots (without interventions).

The data used to assess the C stocked were collected in the field before thinning in the winter of 2016 and two years later in 2018. Thinning implementation followed a randomized design with three replicates for each silvicultural option (thinning from below, selective thinning, without interventions). 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; Paletto et al., 2021). The 18 sampling plots were circular, with a fixed area of 531 m^2 (13 m of radius).

The main dendrometric data — height and diameter at breast height (dbh) for all standing living trees with a dbh greater than 5 cm, number of stems, and canopy cover overstorey — were collected in each sampling plot. The standing living (stem) volume was estimated using the model elaborated by the second Italian National Forest Inventory (NFI) for black pine species. In this model, the diameter at breast height (dbh) and the total tree height (h) have been adopted as independent variables for the prediction equations (Tabacchi et al., 2011).

All three deadwood, all three components with diameters greater than 5 cm were measured in the sampling plot: lying deadwood (sound and rotting pieces of wood located on the ground), standing dead trees with a height greater than 1.3 m, and stumps with a height of less than 1.3

m. The deadwood volume was estimated per the protocol proposed by De Meo et al. (2017). Species and decay classes were also recorded for each deadwood element using a five-class classification system (Casagli et al., 2022) to improve the C-stock estimate.

Litterfall was collected seasonally using 72 traps. The main litter components (conifers vs. broadleaves: pine needles, deciduous leaves, twigs and branches with diameters less than 5 cm, reproductive structures, and bark) were separated. Forest floor litter was collected once a year (2015, 2016, 2017, and 2018) and separated into three representative fractions: L – fresh or almost undecomposed litter; F – medium to strongly fragmented material with many mycelia and thin roots; H – completely decomposed amorphous material.

Soil was collected once a year (2015, 2016, 2017, and 2018) from the same position as forest floor litter at depths of 0–10 and 10–30 cm within each plot. Soil samples were homogenized at 0.5 mm, and C content was measured using a CN elemental analyzer (Flash 2000, Thermo Fisher sci.). Undisturbed soil samples were collected for soil bulk density (BD) measurement to calculate soil organic C-stock for each depth.

2.3 Improved forest management (IFM) practices

The IFM practices were applied on a pilot area of 10.09 ha in Monte Morello forest, while 6.35 ha were used as control plots. In particular, the three silvicultural options can be summarized as follows:

- Selective thinning applied on a surface of 4.74 ha. In this thinning, the choice of the trees to be cut is based on a positive selection, and around 100 trees per hectare are selected from among the better-formed and mechanically stable subjects. All crown-volume competitors are harvested to increase the growth of selected trees (30–40 % of the basal area is removed). Standing dead trees and lying deadwood slightly decomposed are also removed.
- Thinning from below applied on a surface of 5.35 ha. In this thinning, the choice of the trees to be cut is based on a negative selection, and only dominated, small, or standing dead trees are harvested during in-field operations (thinned from below 15-20 % of basal area). Logs are not removed during the harvesting operations (Pieratti et al., 2019). Thinning from below is the most common silvicultural treatment applied in Central Italy in both natural forests and plantations, developed according to regional forest acts (Marchi et al., 2018).
- Baseline/Control option to monitor the forest on a surface of 6.35 ha. In this case, no silvicultural treatments are implemented, and deadwood is not removed from the forest. The forest is temporarily left to its natural evolution.

The three silvicultural options were analyzed and compared considering a rotation period of 15 years (the period between two thinning). The 15-year rotation period is hypothetical and 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 estimates (Paletto et al., 2021).

2.4 Climate change mitigation assessment

The impact of silvicultural options on climate change mitigation was quantified as difference in C-stock and C-sequestration after the two IFM practices considering all five carbon pools. The data collected in the control plots (without interventions) defined the baseline.

The changes of C-stock in above-ground and below-ground biomass due to the two thinnings have been calculated following the equations proposed by Vacchiano et al. (2018) (eq.1):

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

Where:

$C_{stock\text{-}biomass}$:	tons of CO_2 per hectare lost due to the thinning actions (t CO_2 ha^{-1})
k :	conversion factor from C to CO_2
$V_{i,IFM}$:	volume post thinning (m^3 ha^{-1})
$V_{i,baseline}$:	volume in the control plots without IFM actions (m^3 ha^{-1})
BEF:	species-specific biomass expansion factor (1.33 for black pine)
WBD:	species-specific wood basal density (0.47 for black pine)
R:	species-specific root/shoot ratio (0.36 for black pine)
b:	carbon lost from emissions due to unplanned natural disturbances
i:	reference thinning method (i= thinning from below or selective thinning.

Regarding the deadwood (lying deadwood and/or standing dead trees) removed during the silvicultural treatments, the change in deadwood C-stock has been calculated as follows (eq.2):

$$C_{stock-deadwood} = k \cdot \sum_n \left[\left(D_{i,IFM} - D_{i,baseline}\right) \cdot WBD\right] \quad \text{(eq.2)}$$

Where:

$C_{stock\text{-}deadwood}$:	tons of CO_2 per hectare lost due to the deadwood harvesting (t CO_2 ha^{-1});
k:	conversion factor from C to CO_2
$D_{i,IFM}$:	deadwood volume post thinning (m^3 ha^{-1})
$D_{i,baseline}$:	deadwood volume in the control plots without IFM actions (m^3 ha^{-1})
WBD:	wood basal density of each decay class (kg m^{-3})
n:	number of decay classes (5).

The Wilcoxon signed-rank test determined whether the changes in C-stock after the two silvicultural treatments were statistically significant. A non-parametric rather than parametric test was adopted for two reasons: data does not follow a normal distribution (Anderson-Darling test: A^2=1.035, p=0.008), and the sample size is small (18 sampling plots in total).

The effect of silvicultural treatments on C-sequestration in woody biomass was calculated using the annual increment of volume measured in the study areas before and after thinning: 12.16 m^3 ha^{-1} yr^{-1} in the control plots, 25.96 m^3 ha^{-1} yr^{-1} after the thinning from below, and 17.29 m^3 ha^{-1} yr^{-1} after the selective thinning. The formula used to estimate CO_2 yearly sequestered is the following (eq.3):

$$C_{seq-biomass} = (BEF\ + R) \cdot I \cdot WBD \cdot k \quad \text{(eq.3)}$$

Where:

$C_{seq\text{-}biomass}$:	tons of CO_2 sequestered per cubic meters of biomass yearly [tCO_2 m^{-3} yr^{-1}];

BEF:	biomass expansion factor (1.33 for black pine);
WBD:	wood basal density (470 kg m^{-3} for black pine);
R:	root to shoot ratio (0.36 for black pine);
k:	wood carbon content (50 %) multiplied for 3.67 kg CO_2 kg^{-1} (conversion factor from C to CO_2).

Finally, the change in C-sequestration before and after the thinning interventions were calculated with eq. 4 and 5:

$$\Delta_{C_t} = C_t - C_b \quad \text{(eq.4)}$$

$$\Delta_{C_s} = C_s - C_b \quad \text{(eq.5)}$$

Where:

C_b:	tons of CO_2 sequestered by the annual wood increment in the control plots without IFM actions
C_t:	tons of CO_2 sequestered by the annual wood increment after thinning from below
C_s:	tons of CO_2 sequestered by the annual wood increment after selective thinning.

The C-sequestration in soil was calculated as the difference between C accumulation in the soil organic and mineral layers after thinning and the quantity of CO_2 equivalents lost as emissions of CO_2 equivalents (CO_{2eq}). The formula used to estimate the C-sequestration in soil is the following (eq.6):

$$C_{seq-soil} = k \cdot \left(C_{soil\ post} - C_{soil\ pre}\right) - CO_{2eq}\ \text{emitted} \quad \text{(eq.6)}$$

Where:

$C_{seq\text{-}soil}$:	amount of CO_2 accumulated in the soil net of GHG emissions (t CO_2 ha^{-1} yr^{-1})
k:	conversion factor from C to CO_2
$C_{soil\ post}$:	C stock in the first 30 cm 2 years after thinning (t ha^{-1})
$C_{soil\ pre}$:	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*CH_4 + 298*N_2O (t CO_2 ha^{-1} yr^{-1}).

2.5 Other ecosystem services assessment

The impacts of silvicultural treatments were estimated on two additional ecosystem services to climate change mitigation: wood production for the provisioning services category and recreational activity for the cultural services category.

Wood production was assessed considering the current local market prices and wood volumes harvested during the silvicultural treatments in each scenario. The economic value of wood production was evaluated through the direct calculation of profit from the annual income derived from the sale of wood assortments (€ ha^{-1} yr^{-1}) considering the local price and a rotation period of 15 years (eq.7):

$$R = \frac{Vt_0}{\frac{(1+i)\cdot[1-(1+i)^{-t}]}{i}} \qquad \text{(eq.7)}$$

Where:

R:	annual income derived from the sale of wood assortments at the time t_0 (€ ha^{-1} yr^{-1})
V_{t0}:	total current value derived from the sale of wood assortments (€ ha^{-1})
i:	average inflation rate in Italy for the last five years
t:	rotation period (15 years).

The impact of thinning on recreational activities was assessed through a semi-structured questionnaire to a sample of visitors to the Monte Morello Forest. The questionnaire focused on visitors' preferences towards visual-aesthetic impacts of the two silvicultural treatments (thinning from below and selective thinning) and the estimation of consumer surplus (CS) through the Travel Cost Method (TCM).

The respondents assigned their visual-aesthetic preferences for the three forest management scenarios (baseline/control, thinning from below, and selective thinning scenarios) by comparing pairs of images of Monte Morello Forest representing the three scenarios (pairwise comparison). In addition, the questionnaire collected all key data of the TCM, including visitor residence, number of site visits in the past year, the length of the trip, the amount of time spent at the site (hours), and travel expenses (e.g., accommodation, meals, and transportation).

During the data processing, the image preferred by the visitors was identified by calculating the priority value of each image/scenario using the Analytic Hierarchy Process (AHP) approach (Saaty, 1987). The image/scenario preferred by the visitors was identified with the calculation of the priority value of each image using the eigenvalue method. The distribution of visitors' visual-aesthetic preferences for the three images was used to estimate the potential number of visitors in the three forest scenarios and the changes from the baseline/control scenario. Besides, the recreational value was indirectly calculated using the TCM and considering individual total cost expenditures for the trip to Monte Morello Forest. The TCM assumes that visitors are travel cost-sensitive, meaning that the expected number of trips to a specific site is lower when the cost to reach the destination increases. Finally, the typical welfare measure estimable from a TCM was calculated. This is CS, a proxy for the benefit people derive from visiting. CS is calculated as the negative inverse of the travel cost coefficient.

3 RESULTS

3.1 Climate change mitigation assessment

The results show that above-ground biomass and deadwood C-stock decreased by 145 t CO_2 ha^{-1} after the thinning from below (96 % of changes were in the above-ground biomass and 4 % in deadwood), while C-stock decreased by 220 t CO_2 ha^{-1} after the selective thinning (95 % of changes were in above-ground biomass and 5 % in deadwood). Consequently, both thinnings reduced C-stock in these two carbon pools in the short term, as shown in *Figure 2*. Conversely, thinning did not directly affect the below-ground biomass C-stock because roots were not removed during the silvicultural interventions.

However, the Wilcoxon signed-rank test results (α=0.01) show that the differences in C-stock for both silvicultural treatments between before and after thinning are not statistically significant: thinning from below and selective thinning (p=0.031 for both, respectively).

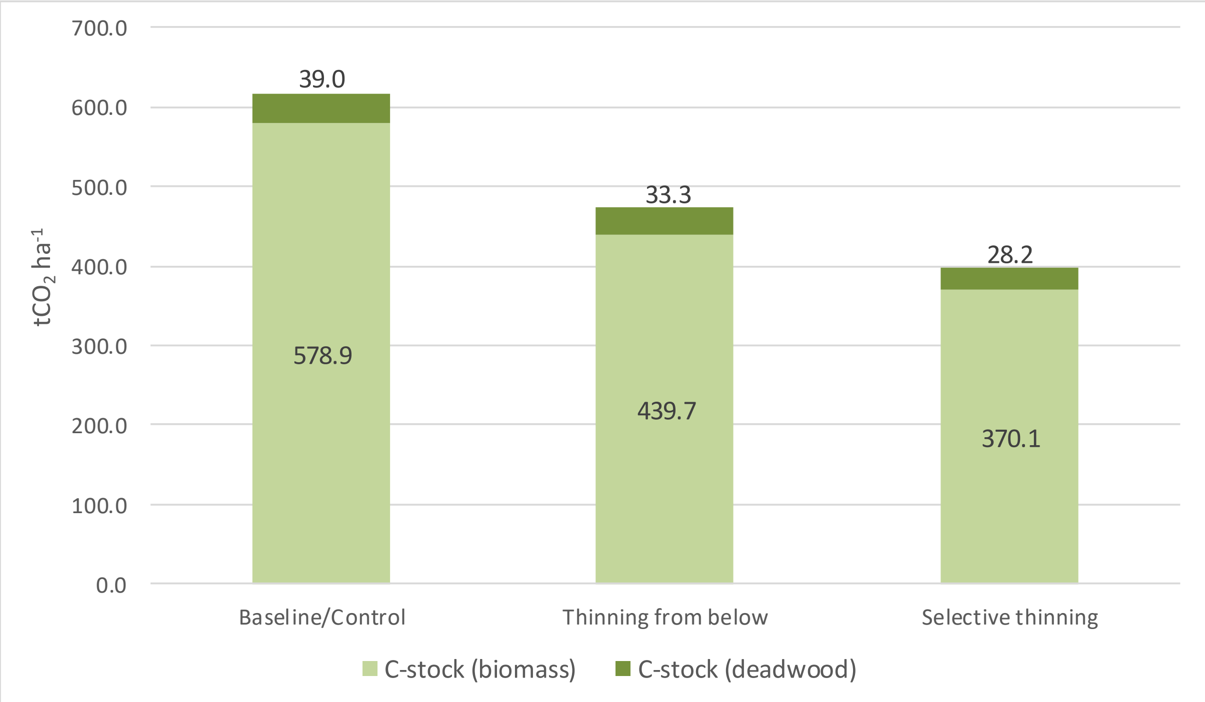

Figure 2. Change in C-stock in biomass and deadwood after thinning from below and selective thinning compared to the baseline

Regarding the C fluxes, the results show that the C-sequestration in the control plots (without IFM interventions) was 17.71 t CO_2 ha^{-1} yr^{-1}, while after the implementation of silvicultural treatments, there was a marked increase (*Figure 3*). In the plots managed with thinning from below, the C-sequestration was estimated at 37.80 t CO_2 ha^{-1} yr^{-1} (Δ_{Ct} = 20.09 t CO_2 ha^{-1} yr^{-1}), while in the plots managed with selective thinning, the C-sequestration was equal to 25.18 t CO_2 ha^{-1} yr^{-1} (Δ_{Cs} = 7.47 t CO_2 ha^{-1} yr^{-1}). These results indicate that it takes four years to restore the C lost in the above-ground biomass and deadwood with thinning from below and nine years with selective thinning. However, C-stock lost by the forest ecosystem is closely related to the lifespan of the forest products obtained (from a minimum time for woodchips/fuelwood to a maximum for timber for building).

Table 1 shows the effect of the two thinning treatments on soil and litter C-stock in the four years of the project's monitoring. The results indicate that the effect of thinning on soil C-stock became evident two years after treatments (*Table 1*), with an increase of 29 % and 33 % in thinning from below and selective thinning, respectively. Overall, 32.0 and 35.6 t CO_2 ha^{-1} yr^{-1} were sequestered into the soil up to 30 cm depth with thinning from below and selective thinning, respectively.

Concerning litter, the results show that coniferous litterfall fraction decreased after selective thinning compared to the control plots, while deciduous litterfall fraction increased. Thinning increased litter biomass in all horizons immediately after the intervention, whereas two years after thinning, a reduction of litter was observed, which was more evident in selective thinning (*Table 1*).

Table 1. Changes in C-stock (MgC ha^{-1}) in soil and litter after thinning from below and selective thinning in the study area

Year	2015	2016	2017	2018
		Soil		
Control	99	148	119	100
Thinning from below	102	133	105	129
Selective thinning	104	161	131	134
		Litter		
Control	9.0	9.2	11.8	9.1
Thinning from below	8.1	14.7	12.0	10.3
Selective thinning	9.8	11.8	12.1	7.3

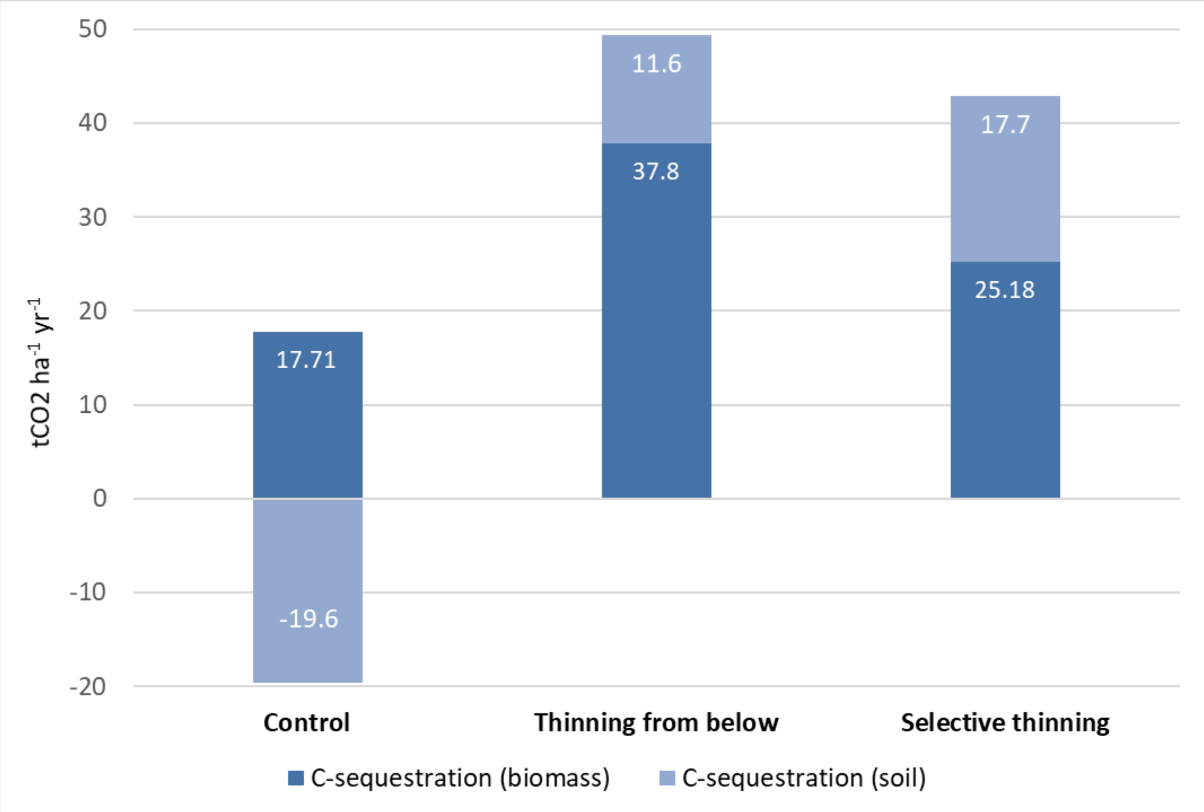

Figure 3. Change in C-sequestration in biomass and soil after thinning from below and selective thinning

3.2 Other ecosystem services assessment

Regarding wood production, the results show that following the silvicultural treatments, 24 % of the growing stock was harvested in the forest area managed through thinning from below (134.7 m^3 ha^{-1}), and 36 % of the growing stock in the forest area managed with the selective thinning (202.0 m^3 ha^{-1}). In addition, in the selective thinning, logs, and snags (deadwood) of the first two decay classes were harvested to produce woodchips (18.2 m^3 ha^{-1}). With thinning from below, only snags of the first two decay classes were harvested (9.5 m^3 ha^{-1}).

All wood volume harvested (144.2 m^3 ha^{-1} with the traditional thinning, 220.2 m^3 ha^{-1} with the selective thinning) was chipped due to the low quality of wood and delivered to a combined heat and power (CHP) plant 12 km away from the Monte Morello Forest. Based on the current local prices, the average annual income is estimated at 337.8 € yr^{-1} ha^{-1} after the thinning from below and at 515.8 € yr^{-1} ha^{-1} after the selective thinning. Conversely, in the baseline/control scenario, the income is zero because active management is not implemented.

Concerning recreational activity, 201 visitors of the Monte Morello Forest filled out the questionnaire at the end of the survey administration period. The results of pairwise comparison reveal Image 3, "Selective thinning scenario" (priority score of 0.5034) as the most appreciated image of Monte Morello Forest, followed by Image 2, "Thinning from below scenario" (0.2873), and Image 1, "Baseline scenario" (0.2093). In other words, respondents prefer managed forests (Image 2 and Image 3), while visitors negatively evaluated unmanaged forests (baseline/control scenario – Image 1) from a visual-aesthetic point of view (*Table 2*). The priority score of each image has been used as an indirect measure of visitor attendance to estimate the potential change in the number of visitors after the silvicultural treatments in each scenario. The hypothesis is that site attendance is directly related to the preferences assigned for that site. Currently, the annual number of visitors to Monte Morello Forest (baseline/control scenario) is 18,475. Therefore, the thinning from below scenario assumes a +7.8 % visitor increase (19,916 visitors), while selective thinning assumes a +29.4 % increase (23,908 visitors).

The estimated Consumer Surplus (CS) is 10.04 € per visit with a consequent total social surplus in terms of recreational benefits in the site equal to 179.2 € ha^{-1} yr^{-1} (baseline/control scenario). In the future, the potential economic benefits related to recreational activities could increase to 193.2 € ha^{-1} yr^{-1} in the thinning from below scenario and to 231.9 € ha^{-1} yr^{-1} in the selective thinning scenario in accordance with the visitors' preferences from a visual-aesthetic point of view (*Table 2*).

Table 2. Changes in the recreational activities in Monte Morello Forest in the three forest management scenarios

Scenario	Baseline/Control	Thinning from below	Selective thinning
Priority score (AHP)	0.2093	0.2873	0.5034
Annual number of visitors	18,475	19,916	23,908
Recreational economic benefits (€ ha^{-1} yr^{-1})	179.2	193.2	231.9

4 DISCUSSION

The European Union (EU) has recently identified Nature-based solutions (NbS) as key climate change adaptation and disaster risk reduction tools (EEA, 2021). Within this "umbrella" concept, the NCS includes all actions aimed at storing carbon by reducing CO_2 related to land use and changes in land use, capturing and temporarily storing additional CO_2 from the atmosphere, and improving the resilience of natural ecosystems. Improved management of natural forests and plantations (IFM) are the two actions on the forest resource that can increase C-sequestration in the medium-long term and simultaneously improve the provisioning and regulating ecosystem services provided (Paletto, 2019). The present study confirmed these theoretical principles by implementing two IFM practices (thinning from below and selective thinning) in a degraded coniferous forest in Central Italy. Implementing IFM practices led to an initial loss of C-stock (–145 and –220 t CO_2 ha^{-1} after thinning from below and selective thinning, respectively) since all harvested above-ground and deadwood volume went to woodchip production. As some authors highlight, the lifespan of woodchips is approximately six months with a short-term remission of CO_2 into the atmosphere if compared to other wood products such as poles, packaging, and timber for buildings (Karjalainen et al., 1999;

Deniz and Paletto, 2022). Despite this weakness of the destination of wood products in the case study, the results show a positive increase in C-sequestration following both thinning: 37.8 and 11.6 t CO_2 ha^{-1} yr^{-1} in biomass and soil after thinning from below, respectively; 25.18 and 17.7 t CO_2 ha^{-1} yr^{-1} in biomass and soil after selective thinning, respectively. When comparing these data with the control plots (without interventions), it is crucial to emphasize that the positive effects of silvicultural treatments can recover the above-ground and deadwood C-stock lost in a few years and generate a positive flow in the medium-long term. In response to our research questions, the results of this study conducted within the LIFE FoResMit project showed a negative effect of thinning on C-stock in the short term, offset by a very positive effect on C-sequestration in the medium to long term.

In addition, our results showed that the aforementioned silvicultural interventions positively impact climate change mitigation and other ecosystem services, such as provisioning and cultural services. Regarding provisioning services, thinning produces raw materials (mainly woodchips, wood for packaging, and poles) destined for the wood market. In particular, the results of the present study estimated an average annual income of 337.8 € yr^{-1} ha^{-1} after the thinning from below and of 515.8 € yr^{-1} ha^{-1} after the selective thinning over the 15-year rotation period. Regarding cultural services, thinning in degraded coniferous forests can improve landscape aesthetics and the consequent recreational attractiveness of the site (Paletto et al., 2017). The results of this study showed that thinning from below could positively impact site attractiveness, leading to a +7.9 % increase in the number of visitors, while the impact of selective thinning could lead to an estimated +29.4 % visitor increase. As other studies have emphasized, thinning interventions can also increase the mechanical stability of the stand (regulating services), reducing slenderness (height/diameter) ratio and improving the vertical and horizontal stand structure and tree species composition (Marchi et al., 2018). These last two aspects are related to the natural diversity of forest ecosystems and, consequently, supporting services. However, although synergistic with wood production and recreational opportunities, thinning to improve C-sequestration can hinder some aspects of forest biodiversity. As some authors have emphasized, the biodiversity of ecological communities in forests is crucial (direct and indirect impacts) for long-term carbon storage (Díaz et al., 2009; Burton et al., 2013). Therefore, thinning can have synergistic effects with stand structure and tree species composition diversity (Marchi et al., 2018), but potential trade-offs with ecological communities.

For practical applicability, the obtained results on a limited portion of the Monte Morello forest (10.09 ha) were used to predict the future impacts of active management on the entire forest (1,035 ha). In particular, the results showed that selective thinning can impact C-sequestration, wood production, and recreational activity more positively than thinning from below. Therefore, implementing selective thinning in the Monte Morello Forest and all unmanaged coniferous planted forests in Central Italy is more appropriate for climate change mitigation.

5 CONCLUSIONS

This study has pointed out that a rational and efficient forest management practice based on two IFM practices helps increase C-sequestration. In addition, the project results showed that the two methods positively impact the different categories of ecosystem services. From a political point of view, selective thinnings in unmanaged coniferous planted forests in Italy could contribute to achieving the Paris Agreement objectives set during the UN Climate Change Conference (COP21) in 2015. Additionally, active management of Italian unmanaged planted forests is of fundamental importance to achieving a zero-emission circular economy by 2050 per the National Forestry Strategy (2022). As a lesson learned, choosing an optimal IFM method (e.g., thinning from below, selective thinning, or other silvicultural interventions) for a forest area must be based on the objectives and ecosystem services to be valorized (e.g., climate change mitigation through CO_2 storage). For this objective, the results of the present study allow us to consider the trade-offs and synergies between ecosystem services during NCS implementation.

Future findings of this study could involve testing other IFM approaches, like different silvicultural interventions, that can enhance forest C storage and increase the C-sequestration in the medium-long term. These kinds of best management practices and silvicultural systems offer guidance for practitioners and researchers in Italy, but the methodological approach can be replicated in different contexts all over Europe and beyond.

In addition, testing the effects of other silvicultural treatments to increase the climate mitigation potential of forests can improve the quality of information provided to support the forest planning decision-making process.

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REFERENCES

Balderas Torres, A., Ontiveros Enríquez, R., Skutsch, M., Lovett, J.C., 2013. Potential for Climate Change Mitigation in Degraded Forests: A Study from La Primavera, México. Forests 4, 1032–1054. https://doi.org/10.3390/f4041032

Burton, J.I., Ares, A., Olson, D.H., Puettmann, K.J. 2013. Management trade-off between aboveground carbon storage and understory plant species richness in temperate forests. Ecological Applications 23, 1297–1310. https://doi.org/10.1890/12-1472.1

Cantiani, P., Chiavetta, U., 2015. Estimating the mechanical stability of Pinus nigra Arn. Using an alternative approach across several plantations in central Italy. iForest 8, 846–852. https://doi.org/10.3832/ifor1300-007

Casagli, A., De Meo, I., Alfano, A., Becagli, C., Orlandini, A., Paletto, A., 2022. Variation of deadwood density by decay class in Douglas fir (Pseudotsuga menziesii (Mirbel) Franco) stands in Italy. Forest Systems 31(2), eSC04. https://doi.org/10.5424/fs/2022312-19186

De Meo, I., Agnelli, A.E., Graziani, A., Kitikidou, K., Lagomarsino, A., Milios, E.,... Paletto, A., 2017. Deadwood volume assessment in Calabrian pine (Pinus brutia Ten.) peri-urban forests: Comparison between two sampling methods. Journal of Sustainable Forestry 36(7), 666–686. https://doi.org/10.1080/10549811.2017.1345685

De Meo, I, Lagomarsino, A., Agnelli, A.E., Paletto, A. 2019. Direct and indirect assessment of carbon stock in deadwood: Comparison in Calabrian Pine (Pinus brutia Ten. subsp. brutia) forests in Italy. Forest Science 65(4), 460–468. https://doi.org/10.1093/forsci/fxy051

Deniz, T., Paletto, A., 2022. A forest-based circular bioeconomy for sustainable development: a case study of Konya Province, Turkey. International Forestry Review 24(4), 1–17. https://doi.org/10.1505/146554822836282527

Díaz, S., Hector, A., Wardle, D.A., 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current Opinion in Environmental Sustainability 1, 55–60. https://doi.org/10.1016/j.cosust.2009.08.001

EEA (2021), Nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction. EEA Report No 1/2021, European Environmental Agency, Copenhagen.

Fargione, J.E., Bassett, S., Boucher, T., Bridgham, S.D., Conant, R.T., Cook-Patton, S.C., Ellis, P.W., Falcucci, A., Fourqurean, J.W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M.D., Kroeger, K. D., Kroeger, T., Lark, T.J., Leavitt, S.M., Lomax, G., McDonald, R.I., ... – Griscom, B.W., 2018. Natural climate solutions for the United States. Science Advances, 4. https://doi.org/10.1126/sciadv.aat1869

Grassi, G., Conchedda, G., Federici, S., Viñas, R.A., Korosuo, A., Melo, J., Rossi, S., Sandker, M., Somogyi, Z., Vizzarri, M., Tubiello, F.N., 2022. Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. Earth System Science Data 14, 4643–4666. https://doi.org/10.5194/essd-14-4643-2022-supplement

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Fargione, J., 2017. Natural climate solutions. Proceedings of the National Academy of Sciences 114(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Herold, M., Román-Cuesta, R.M., Heymell, V., Hirata, Y., Van Laake, P, Asner, G.P., Souza, C., Avitabile, V., MacDicken K., 2011. A review of methods to measure and monitor historical carbon emissions from forest degradation. Unasylva 238, 16–24.

IPCC (2007), IPCC fourth assessment report, working group III. Chapter 9, Forestry. Available online at: www.ipcc.ch

Kaarakka, L. – Cornett, M. – Domke, G. – Ontl, T. – Dee, L. E. (2021): Improved forest management as a natural climate solution: A review. Ecological Solutions and Evidence 2(3), e12090. http://doi.org/10.1002/2688-8319.12090

Karjalainen, T., Pussinen, A., Kellomäki, S., Mäkipää, R., 1999. Scenarios for the carbon balance of Finnish forests and wood products. Environmental Science & Policy 2, 165–175. https://doi.org/10.1016/S1462-9011(98)00047-1

Kotroczó Z., Veres, Z., Fekete, I., Papp, M., Tóth, J.A., 2012. Effects of Climate Change on Litter Production in a Quercetum petraeae-cerris Forest in Hungary. Acta Silvatica & Lignaria Hungarica 8, 31–38.

Kruk, H., Kornatowska, B., 2014. Sustainable forest management in Poland – theory and practice. Folia Forestalia Polonica 56, 45–55. https://doi.org/10.2478/ffp-2014-0005

Lagomarsino, A., De Meo, I., Agnelli, A.E., Paletto, A., Mazza, G., Bianchetto, E., Pastorelli, R., 2021. Decomposition of black pine (Pinus nigra JF Arnold) deadwood and its impact on forest soil components. Science of the Total Environment 754, 142039. https://doi.org/10.1016/j.scitotenv.2020.142039

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 JF Arnold) forests. Forests 9(4), 188. https://doi.org/10.3390/f9040188

Mazza, G., Agnelli, A.E., Cantiani, P., Chiavetta, U., Doukalianou, F., Kitikidou, K., Lagomarsino, A., 2019. Short-term effects of thinning on soil CO2, N2O and CH4 fluxes in Mediterranean forest ecosystems. Science of the Total Environment 651, 713–724. https://doi.org/10.1016/j.scitotenv.2018.09.241

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 Forestry & Urban Greening 27, 314–323. https://doi.org/10.1126/science.1201609.2017.06.020

Paletto, A., Pieratti, E., De Meo, I., Agnelli, A.E., Cantiani, P., Chiavetta, U., Lagomarsino, A, 2021. A multi-criteria analysis of forest restoration strategies to improve the ecosystem services supply: an application in Central Italy. Annals of Forest Science 78(1), 1–16. https://doi.org/10.1007/s13595-020-01020-5

Paletto, A., 2019. Così si vince la battaglia del clima. World Energy 45, 24-27.

Pan, Y.D., Birdsey, R.A., Fang, J.Y., Houghton, R., Kauppi, P.E., Kurz, W.A., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333(6045), 988–993. https://doi.org/10.1126/science.1201609

Pieratti, E., Paletto, A., De Meo, I., Fagarazzi, C., Migliorin, M.G.R., 2019. Assessing the forest-wood chain at local level: A Multi-Criteria Decision Analysis (MCDA) based on the circular bioeconomy principles. Annals of Forest Science 62(2), 123–138. https://doi.org/10.15287/afr.2018.1238

Saaty, R.W., 1987. The Analytic Hierarchy Process—what it is and how it is used. Mathematical Modelling 3-5, 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Somogyi, Z., Teobaldelli, M., Federici, S., Matteucci, G., Pagliari, V., Grassi, G., Seufert, G., 2008. Allometric biomass and carbon factors database. iForest 1, 107–111. https://doi.org/10.3832/ifor0463-0010107

Somogyi, Z., 2008. Recent Trends of Tree Growth in Relation to Climate Change in Hungary. Acta Silvatica & Lignaria Hungarica 4, 17–27. https://doi.org/10.37045/aslh-2008-0002

Tabacchi, G., Di Cosmo, L., Gasparini, P., 2011. Aboveground tree volume and phytomass prediction equations for forest species in Italy. European Journal of Forest Research 130, 911–934. https://doi.org/10.1007/s10342-011-0481-9

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