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Comparing Thinning System Effects on Ecosystem Services Provision in Artificial Black Pine (*Pinus nigra* J. F. Arnold) Forests

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Abstract: Provision of forest ecosystem services is influenced by site and stand characteristics as well as forest management practices. In order to evaluate the influence of forest management on ecosystem services provision, two artificial black pine forests located in Central Italy were studied where two different thinning approaches (traditional and selective) were applied under the SelPiBio LIFE project. Four main ecosystem services were selected and assessed: timber and bioenergy production, carbon sequestration, forest stand stability-protection, and biodiversity conservation. Even if not supported by statistical evidence, results highlighted an interesting trend just 2 years after treatment. The selective thinning was able to enhance the majority of ecosystem services compared to the traditional one. A higher growth rate of selected crop trees was measured (i.e., carbon sequestration). The slenderness ratio was sensibly reduced (i.e., mechanical stability) with a positive implication on soil retention and the prevention of landslides. Moreover, valuable and interesting commercial assortments have been proven to be retrieved from the stands with the selective approach. Larger and also better formed trees were harvested, given the impact of selective thinning on the co-dominant class. The Shannon index increased only with the selective thinning intervention. In conclusion, the provided results and methods are encouraging and might represent the basis for novel and longer monitoring efforts.

Keywords: selective thinning; thinning from below; forest management practices; planted forests; forest multifunctionality; Mediterranean area

1. Introduction

According to the Millennium Ecosystem Assessment (MEA) and the definition given in 2005, an "ecosystem service" (ES) can be defined as the benefits provided by ecosystems that contribute to making human life both possible and worth living [1,2]. ES can be classified into four categories, namely, (i) provisioning services; (ii) regulating services; (iii) supporting services; and (iv) cultural services. With special regard to forests, provisioning services include wood and non-wood forest products; regulating services include carbon sequestration, water regulation, natural hazard protection; supporting services include plant production, biodiversity and nutrient cycling; and cultural services include recreational opportunities, historical and spiritual values [3–5].

Since the ES concept has been developed, both the scientific community and forest managers started to investigate the relationship between forest management practices and provision of ESs [6–8].

Currently, one of the most important research challenges is how to manage forests for timber and bioenergy production while maintaining and/or improving other ESs such as habitat and biodiversity conservation, natural hazard protection, carbon sequestration, water regulation, and recreation [9]. Forest management trajectories and strategies can generate ES trade-offs, particularly if interactions among ESs are not well known [10,11]. Trade-offs can occur when—due to a forest management choice—the provision of one ES is reduced as consequence of the increased use of another one [12]. On the contrary, in some cases the relationship between various forest ESs might be synergistic and complementary [13].

Forest management choices that can affect the provision of ESs include the silvicultural system (i.e., forest structure: high forest or coppice, even or uneven-aged), rotation period and thinning regime. In particular, silvicultural treatments affect the level of biodiversity, the water cycle components, but also recreational services, influencing forest species composition, horizontal and vertical stand structure, stand density and age [14]. Furthermore, silvicultural treatments can modify the natural cycle of elements. For instance, the mineralization of carbon and nutrients (cycles of the elements) can be highly influenced by the amount and the spatial distribution of solar radiation that hits the ground [15]. The result is higher micro-climatic variability, reflected by a higher level of soil biodiversity (e.g., fungi and bacteria) especially at the understory level. Moreover, recent studies have evaluated the utility of forest management as a tool to mitigate the effects of climate change on ESs as well as to maintain high growth rates (i.e., carbon sequestration) in living trees [8,16–18]. In this view, the relationship between forest management and ES provision represents a focal point for future development of many forested zones and a new challenge to cope with a changing environment [19,20]. Maintaining and balancing the ESs supplied by forests require thorough assessment and evaluation at different spatial and temporal scales [21]. In the international literature, two main approaches are generally used to assess ESs from the biophysical point of view: the first one is based on a qualitative assessment of ESs, using experts' opinion and stakeholders' evaluation [22]. The second one focuses on the quantitative assessment of ESs through the measurement of field-based biophysical outcomes [23].

During the last decades and especially after the First and Second World War, many afforestation programmes were planned in most of the European countries. Such activities were seen as an important strategy for people's safety and wellbeing [24–26]. Artificial stands were established with pioneer conifers (e.g., *Pinus nigra* spp., *Pinus pinaster* Aiton, *Pinus halepensis* Mill.) not only in degraded or abandoned lands by farmers but also in mountain zones at high elevation and coastal areas. The purposes ranged from soil protection to recreation and from dune protection to scenic beauty. According to the second Italian National Forest Inventory (2005), black pine (*Pinus nigra* J.F. Arnold spp.) stands cover an area of 236,467 ha, corresponding to 2.5% of the total national forest area. Generally, such artificial stands are characterized by a low biodiversity level, due to their reduced species composition and spatial structure (i.e., structural homogeneity). Actually, these stands represent the most simplified forest systems in Italy, mostly occurring in pure stands of even-aged forests (50 years old on average), established during the 19th and early 20th century, on bare or overexploited soils for protective purposes, following a rigid planting scheme [26]. The squared design was the most applied for planting, with 2500 4-year-old seedlings per hectare (2 × 2 m) and canopy closure occurring at an early age, forecasting a first pre-commercial thinning at age 15, followed by additional thinning every 15 years [27,28]. This treatment was rarely applied, as well as other scheduled interventions. Despite the low value of timber production, a new interest in artificial ecosystems is currently rising in the whole Europe, mainly thanks to their valuable ecological importance, and provision of ESs such as carbon sequestration and hydrological safeguarding [26,29,30]. Managing such stands may represent a challenging opportunity for forest managers, aiming to guide natural evolution to more complex and stable systems (e.g., climax specific composition) and testing innovative management practices [20]. On the basis of the positive results obtained by thinning from below of medium-heavy intensity [15,31–33], selective thinning has been discovered as an interesting opportunity even in artificial forest stands. In fact, thinning from below of heavy intensity is able to influence the structure of the forest even in the dominant layer, usually the focus of selective thinning. When applied to artificial black pine stands, the species reacted positively, even to late-thinning, and both timber harvesting and ES provisions were improved [34,35]. Selective thinning, widely used in many forest systems (i.e., beech forests, mixed forests) [36] has been rarely applied in artificial pine forests. Conversely, thinning from below (i.e., removing the smaller, weaker and poorer quality trees to concentrate growth on the better trees remaining and according to a specific dbh or basal area threshold) still remains the most applied treatment. Its impact on the stands' structures has been demonstrated to be very low, especially concerning the carbon cycle, soil biodiversity and improvement of ecological dynamics (i.e., natural mortality). In addition, economic sustainability is rarely achieved [6,8,35]. In selective thinning, the choice of the trees to be cut is based on a positive selection of candidate trees (i.e., crop tree). In other words, candidate trees are first selected and then valorized by removing their direct competitors at crown level. The average number of candidate trees per hectare must be balanced according to species and rotation age (i.e., maximum potential crown width), selected among the most vigorous and stable ones. With selective thinning, 30–40% of basal area is removed and all crown competitors trees are harvested, including standing dead trees and lying deadwood slightly decomposed [37,38].

Starting from these considerations, the aim of this study is to evaluate the effects of two different forest management practices (selective thinning and traditional thinning) on three categories of ESs (provisioning services, regulating services and supporting services) analysing trade-offs and synergies that are generated. The effects of forest management practices on ESs are analysed through a combined approach of quantitative and qualitative biophysical assessment of ESs [39]. The study is conducted in two case studies in Central Italy (Amiata and Pratomagno) characterized by different site and stand features.

2. Materials and Methods

2.1. Study Area

2.1.1. Pratomagno Study Area

The first study area is named "Pratomagno" (Figure 1) and is located in the north-west of the Arezzo province in Tuscany region (43°39′ N 11°39′ E). The Pratomagno study area covers around 3000 ha and the main tree species are European beech (*Fagus sylvatica* L.) and Turkey oak (*Quercus cerris* L.), while black pine stands cover a surface of about 800 ha. The latter is the result of a reforestation programme, which began in 1954 and ended in the late 1980's. Among the numerous black pine subspecies, the main used in the early years of reforestation in Italy was laricio pine (*Pinus nigra* ssp. *laricio*). However, Austrian pine (*Pinus nigra* ssp. *nigra*) was commonly used but preferred in areas with low fertility (especially pasture ridge). The study area of Pratomagno has an average elevation of 1150 m a.s.l., a prevailing south-west aspect and average slope of 40%. From the lithological point of view, Pratomagno is characterized by quartz-feldspar sandstones alternated by siltstones and argillites. The argillites and siltstones provide a very thin layer ranging from a few up to 15 cm, while the thickness of the sandstone layers is more considerable, exceeding half a meter; this implies the emersion of large banks of thick sandstone whose heads are well visible.

The average annual temperature is 10.5 °C (maximum of 19 °C in July and minimum of 1.5 °C in January), while the average rainfall is 997 mm with a maximum peak in autumn and minimum precipitation in June.

2.1.2. Amiata Study Area

The second study area is Amiata (Figure 1), located in the Castiglione d'Orcia municipality (42°53′ N 11°37′ E, Siena province in Tuscany region). Similar to the previous area, artificial pine forests are the result of 50 years of reforestation programs and currently cover an area of 115 ha. Concerning the forest area (approximately 1930 ha), the main tree species are Austrian pine and Turkey oak, followed by Downey oak (*Quercus pubescens* L.), hedge maple (*Acer campestre* L.), and silver fir (*Abies alba* Mill.).

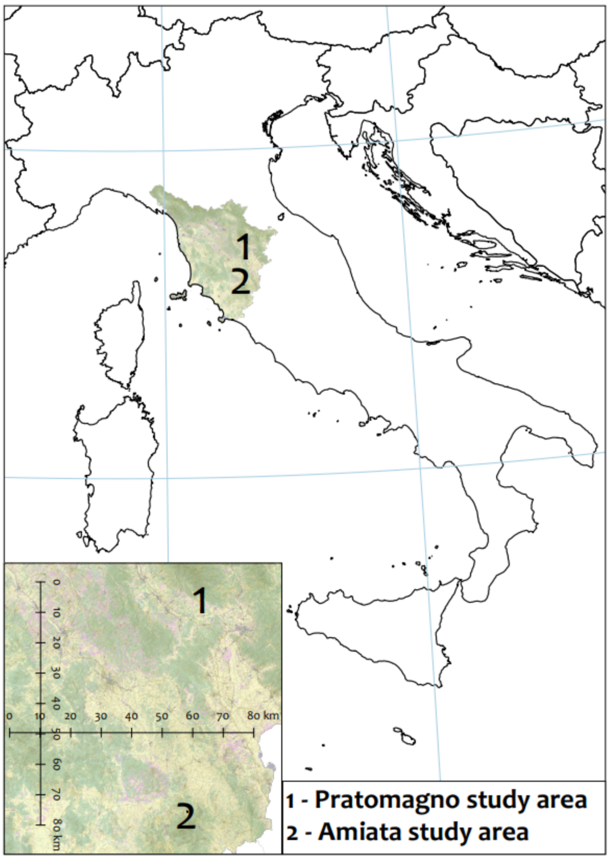

Figure 1. Geographic position of the two study areas.

From the lithological point of view, the Amiata study area is characterized by fissile clays, silty clays, marly clays with sporadic inclusions of limestone, basic limestone. This lithotype forms morphologies consisting of long, wavy sides with slope mainly moderate to strong, subject to erosion by channelled water and mass movement.

The average annual temperature is 12.5 °C and the average rainfall is 687 mm. July is the driest month with 28 mm, while January receives the max rain-snowfall (average of 88 mm). July is the hottest month with an average temperature of 21.7 °C, while January has an average temperature of 4.5 °C, the lowest in the year.

2.2. Field Measurements

The data were collected in 36 circular fixed area sampling plots (15-m radius), half of which were located in each study area. In particular, in each study area, 18 sampling plots randomly located in 6 forest monitoring sectors of 1 ha in size (3 plots in each forest monitoring sector) were identified. A monitoring sector is a thinning replicate whose treatment was randomly assigned. With this experimental design, each plot corresponded to a sub-replicate.

In each sampling plot, the main dendrometric data—i.e., tree height and diameter at breast height (dbh) for all standing living trees, number of stems, canopy cover (percentage of ground covered by crown projection dissolving intersections between polygons), height and diameter at breast height (dbh) for all standing dead trees—were collected before and two years after the silvicultural treatments. All data were stored in an open access and freely available dataset in ESRI shapefile format before the application of the silvicultural treatment [37]. In addition, in-field operational stages were supervised: all the activities of forest enterprises assigned for timber harvesting were controlled to prevent discrepancies between stored information and applied silvicultural treatment.

Subsequently, in each study area, 3 forest monitoring sectors were managed by selective thinning (3 ha in total, 9 plots per study area) and 3 forest monitoring sectors were managed by traditional thinning (3 ha in total, 9 plots per study area). The selective and traditional thinnings were conducted between spring and summer 2015 in both study areas (Figure 2). In the selective thinning, 100 trees per hectare were selected from among the better formed and mechanically-stable trees. During cutting, all crown competitors of target trees were harvested to increase their growth (positive selection). All standing dead trees and lying deadwood slightly decomposed were also removed (1st and 2nd decay classes). In the traditional thinning, only dominated, small or standing dead trees were harvested (negative selection) during in-field operations. This was done up to 40% of total trees per hectare. In this thinning, lying deadwood is not removed from the forest. The traditional thinning represents the most common silvicultural treatment applied in Central Italy in both artificial and natural stands, developed according with regional forest laws.

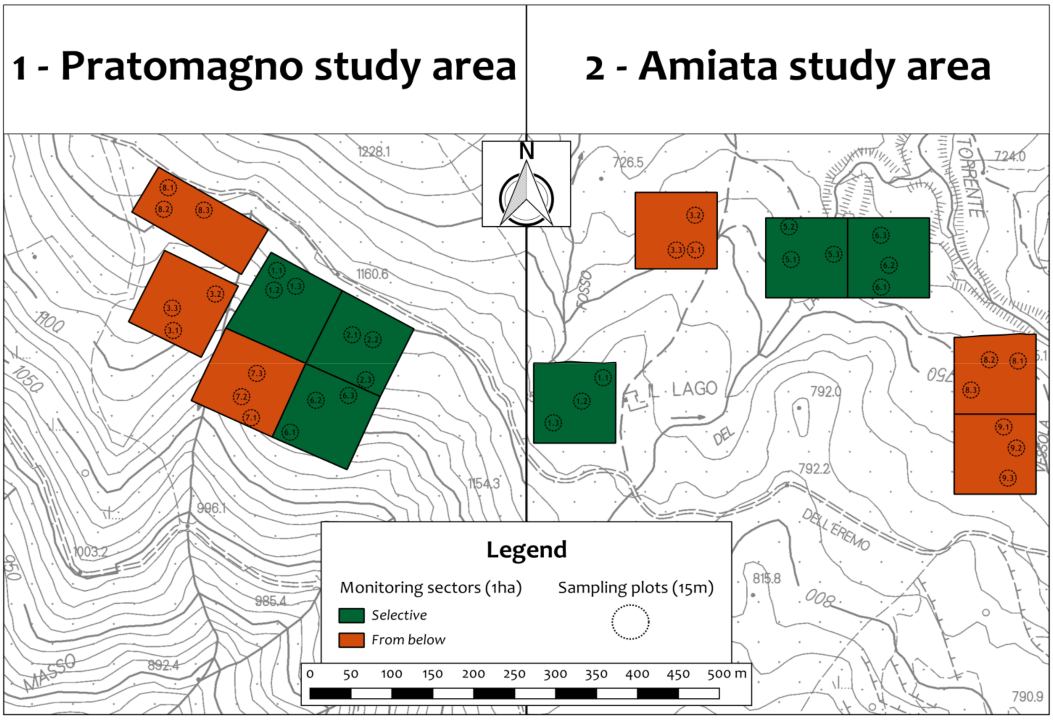

Figure 2. Spatial distribution of monitoring sectors and sampling plots in both of the study areas. The different thinning systems applied are marked with different colours.

2.3. Assessment of Ecosystem Services

The ecosystem services were evaluated using the data collected in the field and the information provided by local forest enterprises. The biophysical assessment of ESs after the silvicultural treatments was done using a combined approach of quantitative and qualitative information.

In order to evaluate the effects of thinning on ES provision, three categories of ESs were assessed: provisioning services (wood assortments), regulating services (mechanical stability of the forest system, carbon sequestration), and supporting services (tree species diversity, floristic diversity).

At the end of the ES assessment, a matrix of the effects of silvicultural treatments on ESs in the two study areas was produced in order to compare traditional thinning and selective thinning in black pine forests.

2.3.1. Provisioning Services

The volume of trees harvested was quantified using the most updated volume tables for black pine, considering the harvesting rate applied with the traditional and selective thinning. Total harvested timber has been estimated using data measured in the field and volume tables provided by the second Italian National Forest inventory [40], using Equation (1):

$$V = b_1 + b_2 \times d^2 \times h + b_3 \times d \tag{1}$$

where the total Volume (V) of the stem and large branches is provided in cubic decimeters, the diameter at breast height (d) and total tree height (h) are expressed in centimeters and meters respectively, and b_1, b_2 and b_3 are species-specific coefficients.

Moreover, the proportions of different wood assortments (e.g., roundwood, poles and woodchips) were estimated by means of a local assortment table [41]. Finally, a check between the potential wood assortments and those effectively sold by the forest enterprise was done.

2.3.2. Regulating Services

Two regulating services were assessed in the present study: mechanical stability of the forest system and carbon sequestration.

2.4. Mechanical Stability of the Forest System

The slenderness ratio (height/diameter) is widely acknowledged as the main indicator of single-tree mechanical stability, especially in artificial stands and for conifers, where the dense planting scheme often influences trees growth [26,42]. Even if this indicator has been rarely used at stand-level, being the "average" stability a concept quite far away from a simple arithmetic mean of single-tree values, it can be considered a fair proxy of the protective capacity (i.e., hydrogeological and natural hazard protection) of forest stand [18,26,43]. However, variations in H/D ratios are largely a result of spacing and, consequently, of stand density resulting from silvicultural treatments. Actually, recent studies [44] show that a high H/D can indicate that a tree has grown in a dense stand under the influence of close mutual support; besides, trees with a high value can be more vulnerable because their stems have not been able to develop to conditions of high mechanical perturbation. In addition, the H/D is directly related to the ability of the forest stand to protect from landslides and snow damage [45].

In the present study, an average H/D value for the dominant trees only (i.e., the trees we would select as candidates to be the final goal of our treatment) and around 100 trees ha^{-1} has been used as a proxy to evaluate the ability of the system to maintain the protective function and the general (mechanical) stability. This was done to avoid biases in H/D values due to the treatment. Indeed, the two thinning systems are well-known to change the average H/D ratio differently for the whole stand and due to the different diameter classes, which are going to be cut. By doing so, just the H/D values of released trees whose growth we would like to maximise and on which we are going to concentrate the carbon stocking were considered. The H/D ratios were calculated before and after the traditional thinning and selective thinning application in each plot and then averaged. For each plot, 7 well shaped and dominant trees (i.e., 7 × 3 × 3 = 63 trees per treatment in each study area) were marked and measured before and two years after treatment.

2.5. Carbon Sequestration

The method used to estimate the annual carbon sequestration is based on the IPCC "Good Practice Guidance for Land use, land-use Change and Forestry" [46]. The annual forest capacity to transform atmospheric carbon into biomass was estimated considering two carbon pools (above-ground biomass and below-ground biomass); while the other three carbon pools (litter, soil, and deadwood) were not considered as the changes in the annual increment of carbon stock are negligible. In accordance with the approach proposed by [38,47], the biophysical assessment of carbon sequestration (C) in above-ground and below-ground biomass of the two study areas was estimated using the annual increment of tree volume (m^3 $ha^{-1} \cdot yr^{-1}$) measured after the two silvicultural treatments.

The carbon sequestration was estimated using as variables the annual increment of volume before thinning (I_b), the annual increment of volume after the traditional thinning (I_t) and the annual increment of volume after the selective thinning (I_s). Annual increments of volume were estimated by taking random wood samples with a Pressler borer from trees distributed across all diameter classes in the forest monitoring sectors and estimated at plot level. The other parameters considered in the estimation of C sequestration in above-ground and below-ground biomass were wood basal density, biomass expansion factor, and root/shoot ratio of black pine [38,47].

The changes in carbon sequestration before and after the two types of thinning were calculated using the following equations (Equations (2) and (3)):

$$\Delta_{ct} = C_t - C_b \tag{2}$$

$$\Delta_{ct} = C_S - C_b \tag{3}$$

where C_b is the annual carbon sequestration before thinning (tC $ha^{-1} \cdot yr^{-1}$), C_t is the annual carbon sequestration after the traditional thinning (tC $ha^{-1} \cdot yr^{-1}$), C_s is the annual carbon sequestration after the selective thinning (tC $ha^{-1} \cdot yr^{-1}$), Δ_{ct} is the change in carbon sequestration in the traditional thinning scenario, Δ_{cs} is the change in carbon sequestration in the selective thinning scenario.

2.6. Supporting Services

Two supporting services were assessed in the present study: tree species diversity and floristic diversity.

2.6.1. Tree Species Diversity

The field measurements were also used to evaluate the species diversity. The overall diversity level of tree species in the two studied areas was evaluated by means of the Shannon diversity index (H') (Equation (4)):

$$H' = -\Sigma pi \times log_z(pi) \tag{4}$$

where pi represents the relative frequency of the species (i.e., the relative abundance in each sampling plot). This index was calculated to assess the alpha diversity (α-diversity) of each sampling plot and treatment, intended as the mean species diversity in sites or habitats at a local scale (Whittaker 1972). Firstly, a before-treatment value was calculated for the 18 sampling plots. Then, this parameter was measured again after the thinning interventions.

2.6.2. Floristic Diversity

The floristic diversity was evaluated in accordance with the Braun-Blanquet phytosociological method based on the estimation of plant cover and number of individual plants [48,49]. The floristic sampling was carried out every year during spring and summer, when vegetation is flowering and species identification is easier. Within each sampling plot, vegetation species were identified and their abundance-dominance was assessed in a sub-sampling plot of 10-m radius using the Braun-Blanquet scale amended by from 1 to 5 (class 1 = cover 1–5%, class 2 = cover 6–25%, class 3 = cover 26–50%, class 4 = cover 51–75%, class 5 = cover 76–100%). The symbol "+" was given to species with cover <1%, and "r" was used for rare species. The floristic list of the species was then compiled and a value of ground coverage was assigned to each species through a visual estimation. Data analysis was conducted after transformation of the abundance-dominance list obtained with the Braun Blanquet method in specific frequencies to calculate percentage contribution, according to the Van der Maarel scale [48]. Then, similar to tree species diversity, the floristic diversity was evaluated using the Shannon index and the α-diversity of each sampling plot was calculated before and after the thinning interventions.

2.7. Statistical Analysis

All the studied biological processes were tested for statistical significance. Given the different nature of collected data, two different statistical analyses were run. Firstly, the total volume of timber harvested was analyzed by means of a classic parametric ANOVA between treatments. Then, differences in radial increment (RI), H/D ratio, tree species diversity (tH') and floristic diversity (fH') were evaluated by means of Linear Mixed-models, given the intrinsic autocorrelation between measurements (longitudinal study). While site and treatment sector were used as replicates, the two thinning systems (treatment) and sampling year were the fixed effects, with the sampling plots as sub-samples. Only the zone (i.e., Amiata and Pratomagno) was set as a random effect. Actually, we were not interested in evaluating the effect of the treatment at each site but to test whether the treatment was somehow significant for artificial black pine stands. Linear mixed models were run using the *lme4* package [50] available in the R statistical environment [51].

3. Results

3.1. Provisioning Services

The results show that the harvested rate in the Amiata study area was 18.5% of total standing volume after the traditional thinning and 30.1% after the selective thinning, while the harvested rate in the Pratomagno study area was 19.4% of total standing volume after the traditional thinning and 29.6% after the selective thinning. Consequently, in both study areas, the harvested volume was higher with the selective thinning than with the traditional thinning. Such differences were also statistically significant (p-value < 0.05) both globally (selective versus traditional) and even within the same study area (i.e., analyzing the two study areas separately).

In the Amiata study area, 100% of wood products was provided as woodchips, while in Pratomagno, roundwood and pole production contributed for 70% of the total value of provisioning services in traditional thinning and 78% in selective thinning (Table 1). Results show that only in the Pratomagno study area were real and potential production of assortments similar, while in Amiata the opportunity for timber production has not been taken into account by local forest enterprises.

Table 1. Provisioning services before and after thinning in the two study areas. The potential percentage of wood assortment is reported in parentheses.

			Wood Assortments	
	Volume before Thinning (m^3 ha^{-1})	**Harvested Volume (m^3 ha^{-1})**	**Timber (Roundwood & Poles)**	**Woodchips**
		Amiata study area		
Traditional thinning	362.9	67.3	0% (68%)	100% (32%)
Selective thinning	456.6	137.4	0% (74%)	100% (26%)
		Pratomagno study area		
Traditional thinning	721.1	139.6	70% (75%)	30% (25%)
Selective thinning	586.6	173.9	78% (79%)	22% (21%)

3.2. Regulating Services

3.2.1. Mechanical Stability of the Forest System

The mixed model showed that differences in H/D between the two thinning treatments were not statistically different after two years. The H/D ratio slightly decreased for both types of interventions.

In this sense the detected annual variation was higher after the selective thinning, suggesting this treatment has a higher capacity to increase the mechanical stability of the stand compared to the traditional thinning. After the selective thinning, the annual variation was −1.3% in the Amiata study area and −1.0% in the Pratomagno study area, while after the traditional thinning, the annual variation was −1.0% in Amiata and −0.89% in Pratomagno (Table 2).

Table 2. H/D ratios before and after thinning in the two study areas.

	H/D Ratio (before Thinning)	H/D Ratio (Two Years after Thinning)	Annual Variation (%)
	Amiata study area		
Traditional thinning	63.15	61.93	−0.979
Selective thinning	66.32	64.62	−1.284
	Pratomagno study area		
Traditional thinning	61.05	59.96	−0.889
Selective thinning	52.81	51.74	−1.012

3.2.2. Carbon Sequestration

The mixed model did not show statistically significant differences in the annual increment of volume and carbon sequestration between the two treatments after the thinning interventions. Results showed that in the Pratomagno study area, after the thinning, the annual increment of volume was 1.52 m^3 ha^{-1}·yr^{-1} and 0.71 m^3 ha^{-1}·yr^{-1} for the selectively and traditionally thinned plots, respectively. In the Amiata study area, the values were 1.11 m^3 ha^{-1}·yr^{-1} and 1.55 m^3 ha^{-1}·yr^{-1} (Table 3). The change in carbon sequestration after the traditional thinning was 0.27 tCO_{2eq} ha^{-1}·yr^{-1} in Amiata and 0.12 tCO_{2eq} ha^{-1}·yr^{-1} in Pratomagno, while the change in carbon sequestration after the selective thinning was 0.47 tCO_{2eq} ha^{-1}·yr^{-1} in Amiata and 0.37 tCO_{2eq} ha^{-1}·yr^{-1} in Pratomagno. Even if not supported by statistical evidence, in both study areas, the radial growth of crop trees that were selectively thinned and their annual carbon sequestration were stimulated more than under traditional thinning.

Table 3. Change in carbon sequestration (Δ) after thinning in the two study areas.

Silvicultural Treatments	Annual Increment (m^3 ha^{-1}·yr^{-1})		C (tCO_{2eq} ha^{-1}·yr^{-1})		Δ (tCO_{2eq} ha^{-1}·yr^{-1})
	Before	After	Before	After	
			Amiata study area		
Traditional thinning	1.37	1.55	1.14	1.61	0.2682
Selective thinning	0.78	1.11	1.99	2.26	0.4693
			Pratomagno study area		
Traditional thinning	0.63	0.71	0.92	1.04	0.1195
Selective thinning	1.27	1.52	1.85	2.22	0.3746

3.3. Supporting Services

3.3.1. Tree Species Diversity

The results of the Shannon index for tree species are reported in Table 4. The mixed model was not statistically significant (only a significant intercept term was found). *Pinus nigra* ssp. *laricio* was largely detected as the most abundant species in the Amiata study area, with a homogeneous distribution across both the forest monitoring sectors (91% each) with just a few hardwood species (*Quercus cerris* L. and *Quercus pubescens* Willd., 1805) covering less than 4% each. Concerning the Pratomagno study area, *Pinus nigra* ssp. *laricio* is still the most important species, but with different percentages between forest monitoring sectors. Actually, while a value similar to Pratomagno was recorded for the selective treatment (92%), a lower percentage (73%) was found in the zones under traditional thinning, with a relevant presence of *Abies alba* Mill. (25%). This is the main reason for a quite different starting *H′* value detected in the Pratomagno study area (Table 4). The main variation is observed in the Amiata study area where both thinning operations increased the species diversity. Indeed, the *H′* variation recorded in both cases is +0.11. On the contrary, a different situation is observed in the Pratomagno study area. While the selective thinning seems to increase the overall species diversity (+0.07), a lower *H′* value is observed in the zones where the traditional thinning is applied (−0.02).

Table 4. Tree species' Shannon index (*tH′*) before and after thinning in the two study areas.

Silvicultural Treatments	*tH′* before Thinning	*tH′* after Thinning	Variation
	Amiata study area		
Traditional thinning	0.53	0.64	+0.11
Selective thinning	0.50	0.61	+0.11
	Pratomagno study area		
Traditional thinning	0.91	0.89	−0.02
Selective thinning	0.40	0.47	+0.07

3.3.2. Floristic Diversity

As far as the Shannon index is concerned, the mixed model showed that differences between selective and traditional treatments two years after the thinning were not statistically significant. The measurements highlight an increase in the Shannon index after the thinning in both study areas (Table 5). The increase is higher in the sampling plots under selective thinning (variation +0.2 in Amiata study area and +0.3 in Pratomagno). The floristic composition is characterized by the dominance of the endemic species *Brachypodium rupestre* (Host) Roem. & Schult.; its presence has not been influenced by the thinning intervention. Conversely, the occurrence of heliophilous species belonging to the *Leguminosae* family is increased by the thinning due to the higher penetration of light to the soil surface. In the Pratomagno study area, the species are those typical of a pine stand herbaceous layer, while in the Amiata study area, there is a relevant presence of species typical of open grass-land-habitats. The increase in the mean number of species is higher for sampling plots under selective thinning and more evident in Amiata study area, where the number of species show an increase of 38, while in the Pratomagno study area, the increase is 7 species after the selective thinning.

Table 5. Change in the floristic Shannon index (*fH′*) and species richness after thinning in the two study areas.

Silvicultural Treatments	N° Species before Thinning	N° Species after Thinning	Variation	*fH′* before Thinning	*fH′* after Thinning	Variation
			Amiata study area			
Traditional thinning	78	92	+14	3.1	3.2	+0.1
Selective thinning	54	92	+38	2.9	3.1	+0.2
			Pratomagno study area			
Traditional thinning	38	42	+4	2.1	2.2	+0.1
Selective thinning	38	45	+7	2.2	2.5	+0.3

At the end of the assessment of three categories of ESs, a matrix was prepared in order to compare the results for the study area and thinning intervention (Table 6). The matrix shows that in both study areas, the selective thinning increased the ES provisions: wood provision, mechanical stability of the forest system, carbon sequestration, tree species biodiversity and floristic biodiversity.

Table 6. Comparison among ecosystem services in the two study areas.

	Provisioning	Regulating		Supporting	
	Harvested Volume (m^3 ha^{-1})	Mechanical Stability of the Forest System (Annual Variation H/D Ratio)	Δ Carbon Sequestration (tCO_{2eq} $ha^{-1} \cdot yr^{-1}$)	Floristic Biodiversity	Tree Species Biodiversity
				Variation *fH′*	Variation *tH′*
			Amiata study area		
Traditional thinning	67.3	−0.969	0.2682	+0.1	+0.11
Selective thinning	137.4	−1.284	0.4693	+0.2	+0.11
			Pratomagno study area		
Traditional thinning	139.6	−0.889	0.1195	+0.1	−0.02
Selective thinning	173.9	−1.012	0.3746	+0.3	+0.07

4. Discussion

Thinning is a strategy for forest managers to modify forest structure and composition according to forest management goals, regulating inter- and intra-specific competition to concentrate biomass allocation on a few target trees [16,17]. In Italy, thinning from below is generally recognized as the most important early-stage operation carried out between canopy closure and the final harvest and is also suggested as the unique approach for artificial stand management [26,35]. Despite that, even if our results were not able to demonstrate the lower performance of thinning from below in ES delivery in artificial black pine stands (none of the analyzed ESs were supported by statistical evidence), the detected trends possibly suggest an interesting starting point just 2 years after treatment. Therefore, even if no conclusive evidence of increased ES provisioning generated by selective thinning is found, early trends suggest that selective thinning treatment may show differences in ES provisioning over longer monitoring periods [9,13,39]. Moreover, even if energy wood harvesting has often been evaluated as one of the main products of artificial softwood stands [30], and especially those located in the Italian central Apennines [26], roundwood and many other ESs might be successfully obtained from such stands if managed properly. It is well known that the diameter growth of forest species is directly connected to early thinning, especially in conifer stands [18,28]. Moreover, the use of an early implementation of selective thinning has also been advised as one of the main tools for stand stability and high quality wood production [27].

Concerning wood products and despite the main protective goal of such stands, our results confirmed that different thinning interventions could influence the provisioning services in terms of wood assortment production. Concerning wood production, the selective thinning yielded a higher harvesting rate and a higher percentage of roundwood compared with woodchips. The results are comparable to those in a black pine peri-urban forest in Central Italy where the harvesting rate is higher with selective thinning [38]. Even if the Italian market is mainly directed toward bioenergy production, more valuable wood assortments (i.e., roundwood or poles) can be obtained and sold on the market. The results are in accordance with the review by Cameron [27], demonstrating that selective thinning is an investment from an economic point of view because it improves future timber quality and economic value. Moreover, as highlighted by Macdonald and Hubert [52] in Sitka spruce (*Picea sitchensis* (Bong.) Carrière) stands in the United Kingdom, selective thinning improves straightness and branching characteristics and is the recommended thinning intervention for sawlog production. Actually, once the potential assortments of a harvesting activity are evaluated, knowledge of the market and skills of local enterprises represent the main gap to be filled by public research. Indeed, with almost the same stand type and structure, the two forest enterprises (one per study area) worked with a completely different harvesting scheme and profit. In particular, the main variables that influenced the allocation of wood assortments on the market are the prices of different wood products on the local market, the quality of wood, and the local communities' customs and dynamics. In such a framework, the ability of forest enterprises to place their products on the market is the main driver [53].

When regulating services are concerned, it is recognized that the mechanical stability of trees is a fundamental issue in public safety and erosion control. In this view, even if not supported by statistical evidence, our results suggested that black pine is a very plastic and reactive species, even when a late selective thinning is applied (>40 years old). Selective thinning is also very suitable for improving stand structure and stability, more than traditional thinning. A positive reaction was observed on all candidate trees (i.e., a decreasing H/D ratio and higher current radial increment). The H/D ratio of taller trees (i.e., candidate trees) was reduced (i.e., more stable trees) just 2 years after the treatment and in line with previous studies in similar zones [35]. Consequently, positive implications on soil retention and the prevention of landslides might be attributed to the selective thinning, thanks to higher ground coverage and survival of healthy and well-formed trees [54] The positive effect of selective thinning on stands' stability due to the reduction of the H/D ratio of higher trees is also reported by Cameron [27] for Sitka spruce stands in Scotland. In this sense, del Río et al. [55] highlighted the importance of the kind and intensity of thinning for stand stability. In particular, for Scots pine (*Pinus sylvestris* L.) stands, the long-term positive effect of thinning from above on stand stability was found compared to thinning from below.

These positive results found for selective thinning seem to be interesting, even concerning the higher growth rate trends measured on selected trees and mainly concentrated on diameter increment, which also includes higher carbon sequestration. Even if not significant, our carbon sequestration results are not different from those derived for other forest systems. For instance, in a long-term Mediterranean thinning experiment, Ruiz-Peinado et al. [56] reported mean values that ranged from 128 Mg C ha^{-1} to 193 Mg C ha^{-1} at the age of 52 years depending on the thinning treatment, with the greatest value in unthinned plots. Del Río et al. [55] highlight how in Mediterranean pine forests carbon sequestration changes over time, and with different forest management strategies: carbon sequestration rates are influenced by the rotation length, thinning intensity, stand composition, with different results amongst species. However, for Mediterranean maritime pine, heavy thinning increased carbon sequestration when carbon fixed in removed wood was also considered. In general, our results are in accordance with literature showing that the total carbon sequestration potential usually increases with thinning [56,57].

When considering supporting services, the Shannon index expressing tree species diversity tended to increase in both study areas with both tested treatments and mainly with the selective thinning intervention. This aspect is in line with expected results, with selective thinning being much more plastic than traditional thinning and able to preserve all small broadleaves species which must be removed with thinning from below. However, *tH'* increment values are also highly correlated to before-treatment vertical and horizontal stand structures, and while a homogeneous starting point (0.5) was found in the Amiata study area, quite a different situation was found in the Pratomagno area with 0.9 and 0.4 *tH'* starting values. Such differences are also connected to the genesis of the stands: rural mid-elevation areas in Amiata with broadleaves trees often occur in plots; high elevation and steep zones in Pratomagno with species admixture occur only in some areas. Actually, starting differences were mainly due to silver fir or European beech trees, planted in mixture with black pine in more fertile zones only. However, in the end, the results demonstrated that the two systems are almost interchangeable in Amiata, where trees biodiversity is balanced; instead in Pratomagno, in an environment with low species richness, thinning from below is not able to improve tree species diversity. This fact is probably due to the rigid thinning scheme to be applied, which cut trees according to their dbh, removing all dominant trees despite their taxonomy.

Concerning the understory level, floristic diversity—expressed by the Shannon index—increased with both thinning systems and more so with the selective than with the traditional one. Without statistical significance, such results must be considered as a trend to be confirmed with additional data in the next few years. The results showed that the number of species (particularly light-demanding ones) increased with thinning intervention. The effect was higher in plots under the selective regime with "new" species coming from the surroundings of the plots we studied. Consequently, our results can be interpreted as an activation of available seeds in the soil. In other words, the activation of existing potential. The results of the present study are comparable with other studies investigating the effects of silvicultural systems on understory plant diversity, including species composition, structural attributes and functional organization. Studies demonstrated that, in general, the species pool was higher for selectively cut areas, and a high proportion of light reaching the forest floor induced the spread of light-demanding species and the detriment of true forest species [15,58].

The matrix synthesizing the effects of silvicultural treatments on ESs shows that in both study areas the selective thinning suggested a promising effect on all ESs investigated (apart from tree species biodiversity in Amiata). It is a fact that the thinning regime influences competition relationships among plants, changing the overall ecosystem complexity. Thus, it is important to support experiments on different thinning regimes where the objective is to improve the forest multi-functionality (biodiversity, wood production, soil protection) [17]. Even if our results report data only for two years after treatments, the trends described might justify further monitoring activities.

5. Conclusions

Artificial pine forests in Italy are an extremely simplified system, poorly managed and characterized by a low biodiversity level. Their original function was to improve soil nutrients and to catalyze ecological succession on bare and overexploited soils and to prepare soil for more demanding species. This shift from an artificial conifer stand to a mixed forest type through natural regeneration, attributed to autochthonous species, was and currently represents the final goal. However, while in a former concept the substitution was planned to be realized by means of clear-cutting of pines and artificial plantation of autochthonous trees, current evidence demonstrates that a gradual substitution can be encouraged by thinning [20], also improving ESs delivered by such stands. In such a framework, the selective thinning can be successfully implemented even in older structures for a gradual enhancement of species composition and natural regeneration where crop trees can represent those to be favored in order to improve their seed dispersal capacity.

From the methodological point of view, the method used to assess and compare the effects of thinning on ES is simple and easy to apply. The small time period between the treatment and post-harvesting surveys probably represents the major issue in our experimental design. However, funding time is always rigid in European Union (EU) projects and this may be the cause for a lack of statistical significance. The results are encouraging and can represent the basis for novel survey campaigns or longer projects. In future, the possibility to derive single-tree statistics, e.g., with dendrometers and terrestrial laser scanning techniques, could represent an interesting approach.

The matrix on the effects of silvicultural treatments on ESs provides useful information to decision makers to choose the most appropriate forest management strategy based on the forest stand. Conversely, the applied method provides a partial analysis of the effects of silvicultural treatments on ESs because only one sub-set of all ES forests was assessed. Therefore, future findings of this study will consist of assessing the effects of different thinning regimes on a larger number of ESs, including cultural services (e.g., recreational activities).

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