

New silvicultural approaches for multipurpose management in beech forests

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Abstract Traditional thinning and stand silviculture had positive effects on tree stability, stand efficiency and tree growth if compared to the lack of management. Nevertheless, the tree oriented silviculture has proven to be a type of management best meets the multifunctionality purposes required by forests today. In Italy beech high forests are generally managed with traditional thinning from below ascribable to stand silviculture; in the last decades tree oriented silviculture, an innovative management system is spreading in Europe. The aim of the study is to compare two thinning types applied in two localities of central Italy, in beech stands deriving from shelterwood system, aged 45-50 years: stand silviculture (SS), tree-silviculture (TS) and control (C). All trees were periodically measured in order to assess growth, mortality and production from 2008 onwards. Crop trees DBH, selected for each silvicultural approach, was annually measured while, an evaluation of the stem quality, crown development and stability were carried out between the 1st and last thinnings. Differences in vertical and horizontal diversity stand structures were assessed. Results pointed out similar growth rate at stand level; while a superior growth in diameter, in dimension of the crown and stability of the crop trees were observed in TS. The TS has proven to be the management option that best meets the multifunctionality required by forests today.

Keywords: beech, thinning, crop trees, silviculture, traditional silviculture, tree-oriented silviculture.

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Introduction

Nowadays in Italy and in other European Countries some silvicultural systems oriented to irregular structures - such as Continuous Cover Forestry or Close-to-nature silviculture (Hahn & Fanta 2001, Mason et al. 2003, Von Teuffel & Heim 2004, Brang et al. 2014) - are gaining in relevance, ensuring multifunctionality and guaranteeing forest-based goods and services.

These silvicultural approaches can provide higher ecosystem services compared to traditional ones based on “thinning from below” (higher aesthetical value, higher soil protection, larger assortment right from first thinning) and can contribute to increasing resilience levels and therefore combating climate change (Löf et al. 2015). The conversion from regular high forest to irregular high forest has to start in the pole stage or young high forest stage, applying frequent and moderate thinnings, able to focus the increment in a restricted number of crop trees. During an intervention the silviculturalist has to manage the quality of the stand, preserving and improving the growth of the crop trees, harvesting wolf and malformed trees, maintaining biodiversity and, at the same time, managing the understory layer and regeneration (Armand 2002).

A new silvicultural approach based on the selection of a small number of crop trees (tree-oriented management system or tree-oriented silviculture) has been developed in recent decades in central Europe. This approach, developed in the 1st half of the 20th century, originated from the early selection of final crop trees (Michealis 1907, Ducellier 1930, Möller 1931), where the production of valuable timber - high quality and large-sized - is concentrated. This silvicultural approach has been further developed by other authors (De Saint-Vaulry 1969, Bastien 1997, Bastien & Wilhelm 2000, Wilhelm 2003, Wilhelm & Rieger 2017).

It differs from classical selective thinning, where a large number of candidates are chosen and favored in the young stand (pole stage) during the first thinning. In the following

thinning the selection of the best candidates will be repeated until deciding on a final small number (Schädelin 1942, Schütz 1990, Boncina et al. 2007, Piussi & Alberti 2015). In tree-oriented silviculture, since the first thinning, only a small number of crop trees (similar to the final density expected at the end of the rotation period) are selected.

This silvicultural system has been applied so far mainly to oak and beech high forests in central Europe and North America, in order to produce valuable timber of merchantable size in a shorter time at lower costs (Jobling & Pearce 1977, Perkey et al. 1994, Perin & Claessens 2009, De Potter et al. 2012), or to preserve and increase the presence of minor tree species both in mixed high forests and coppice stands (Spiecker 2006, Brunet et al. 2010, Sansone et al. 2012, Pelleri et al. 2013, Manetti et al. 2016, Manetti et al. 2020).

In this context, tree-oriented silviculture can be suitably applied both to manage, in a uniform way, even-aged beech forests, with a short regeneration period, or to manage irregular beech forests, diversifying in time the final cut of the crop trees, applying a long regeneration period.

In Italy this approach has been applied in Trentino and Piedmont in beech coppice stands converted into high forests (Wolynski et al. 2006, Wolynski 2002a, 2002b, Mairota et al. 2016, Negro et al. 2014).

Beech (*Fagus sylvatica* L.) represents one of the most important species in Italy, covering an area of 1,035,103 hectares. This tree species is characteristic in the mountain forests of the Alps and Apennines, and reaches the forest limit in most of the Apennine Mountain range. In Tuscany, according to the National Inventory of Forests and Forest Carbon Sinks (Tabacchi et al. 2007), there are 72,262 hectares of beech forests. These forests are managed as coppice (52%), mainly coppice with a standard system, high forests (16%) and coppice converted into high forests (16%). Despite their mainly protective and tourist functions, beech forests

also have played an important productive role, principally in firewood production. Coppicing for charcoal supply in local markets has been the major factor affecting forest structure (Cullotta et al. 2016, Coppini & Hermanin 2007, Ciancio et al. 2006, Meyer et al. 2003). With falling demand for charcoal, most of the beech coppices were no longer managed, and many are currently being converted to high forests. Valuable timber production can be obtained only in some high forests and in coppices converted into high forests.

Generally, beech high forests are managed with a uniform shelterwood system and long rotation period (90-100 years), a regeneration period of about 20-30 years and the application of thinning from below starting at the age of 20-30 years (Nocentini 2009, Mariotti et al. 2017).

This study reports the results of the comparison between two different silvicultural management systems applied in beech forests: traditional silviculture and tree-oriented silviculture.

The goal of this study is to evaluate whether tree-oriented silviculture is able to produce more valuable and larger-sized assortments in comparison to traditional stand silviculture, and whether it favors the creation of multifunctional and irregular beech stands.

Materials and Methods

Study areas

The research was carried out in two important forest districts of Tuscany (Central Italy): Monte Amiata (Grosseto) and Abetone (Pistoia), areas covered by beech high forests managed in the past by intensive silviculture and by coppices converted into high forests.

Monte Amiata is an important area, near the Mediterranean Sea, characterized by a relevant presence of chestnut (*Castanea sativa* L.) and beech forests for wood production. The Amiata study area (coordinates 42,903064 N and 11,624496 E) is located at a height of

1,300 to 1,420 m a.s.l. on a trachyte bedrock. The most common soil is Andic Dystrudepts coarse loamy, siliceous, mesic (unit GUA1 – <http://sit.lamma.rete.toscana.it/websuoli/>), deep, soft, not gravelly, not calcareous, acidic, well drained. The climate is mountain-Mediterranean, with an annual rainfall of 1,547 mm mainly in the autumn and winter months, and a mean annual temperature of 10°C. In this area two pure young high forest stands, 700 m from each other, originating from a shelterwood system, were selected: the *Marsiliana* stand (AM1), 45 years old, not thinned; the *Pozzo Stella* stand (AM2), 50 years old, characterized by a previous light thinning from below.

The Abetone district is a typical Apennine mountain area characterized by pure or mixed beech and silver fir (*Abies alba* Mill.) forests. The study area is located 1,200-1,270 m a.s.l. near the small village of *Cecchetto* (AB) on a sandstone bedrock. The most common soil is Humic Dystrudepts coarse loamy, mixed, mesic (unit MRS1 - <http://sit.lamma.rete.toscana.it/websuoli/>) quite deep, non-gravel or gravelly, sandy loam, not calcareous, acidic, well drained. The climate is typical of the Apennine mountain, with an annual rainfall of 2,447 mm concentrated in the autumn and winter months, with a mean annual temperature of 6.6°C. In this area, originating from a shelterwood system, one pure high forest stand, 50 years old (coordinates: 44,124382 N and 10,702399 E), was selected.

Experimental silvicultural treatments

Two silvicultural approaches were tested in the study areas. Traditional silviculture, characterized by low thinning of medium intensity, and tree-oriented silviculture, which some authors break down into five main points (Bastien & Wilhelm 2000, Bastien et al. 2005, Wilhelm & Rieger 2017, Kerr & Haufe 2011):

- in the first phase of stand development (pruning or qualifying phase) trees are selected by natural processes (breakdown

into social classes and natural pruning);

- at the end of the qualifying phase, a small number (50-150 crop trees per hectare) of dominant, well-shaped, vigorous and healthy crop trees, evenly distributed, are selected;
- a crown thinning around crop trees is carried out to eliminate direct competitors and free up their crown, while the dominated layer is preserved to protect the soil and reduce the sprouting of new epicormic branches from the stem of crop trees;
- thinning is repeated every 4-8 years to stimulate crown-free growth and maintain a high and constant DBH increment until the merchantable market size (DBH 60 cm according to local market conditions) is achieved;
- thinning intensity is generally lower in terms of the number of felled trees (N%), but is similar in terms of basal area (BA%) compared with traditional thinning from below. The thinning cycle is more frequent, but decreased progressively with age.

Experimental trials

In our research, eight experimental plots were established in both areas: 5 plots in Amiata, in 2008, and 3 in Abetone, in 2011. In these plots the following silvicultural approaches were tested and compared:

- tree-oriented silviculture for around 100 crop trees (TS);

- traditional stand silviculture (SS);
- Control plot, unmanaged (C).

In the TS experimental plot about 100 dominant crop trees were selected, and crown thinning was carried out to make their crowns completely isolated and free from the competition of surrounding trees. Tree competitors around crop trees were removed, and a buffer space of 2-3 m (crown release - détourage) was created to allow the free development of the crown. The remaining stand was preserved, and just a few trees were felled to allow logging operations. Crop trees were selected according to tree vigor, stem features, crown shape, lack of disease symptoms and spatial distribution. In the SS plot traditional thinning from below was carried out, removing mainly dominated and intermediate trees (Table 1).

In the control plot (C) no silvicultural intervention was carried out.

Data collection, monitoring and analysis

Stand level

In all experimental plots, periodic inventories were carried out, in correspondence of the thinning (2008, 2011 and 2018 in Amiata; 2011 and 2016 in Abetone), using a 5 cm DBH threshold. Specific composition, diameter at breast height (DBH), social rank and a sample of 70 tree height (H) per plot were measured. For each plot, the following stand parameters were calculated before (BT) and after thinning (AT):

Table 1 Main site characteristic and silvicultural treatment applied in the selected plots.

Plot	Silvicultural treatment	Surface (m ²)	Age of 1 st thinning (years)	Aspect	Slope (%)	Altitude (m a.s.l.)	1 st inventory (years)	N of thinning
AM1	TS	2000	45	NE	14	1415	2008	3
AM1	SS	2000	45	NE	14	1415	2008	2
AM2	TS	4900	50	NW	20	1315	2008	3
AM2	SS	4900	50	NW	20	1310	2008	2
AM2	C	1400	50	NW	20	1320	2008	--
AB	TS	2800	48	NE	39	1240	2011	2
AB	SS	2800	48	N	38	1230	2011	1
AB	C	1200	48	NE	20	1250	2011	--

site quality (through the dominant height), stand density (number of trees), productivity (basal area and volume), species composition (number of species, Shannon index – Shannon 1948), importance value for the dominant component (average of relative stem density and relative basal area of trees in the dominant layer - Chapman et al. 2006).

Differences among tree distributions per diameter classes in each protocol (AM1 and AM2 in Amiata and AB in Abetone) were verified using the Kruskal-Wallis test, a non-parametric method for testing whether two or more independent samples of equal or different sample sizes originated from the same population.

Thinning type was assessed as a function of removal intensity (percentage of removed stems N%, percentage of removed basal area BA%, percentage of removed volume V%) and the ratio of removal intensity to BA% and to N% (TT ratio - Kerr & Haufe 2011). This index defines the type of thinning accounting whereby values higher than 1.1 highlight thinning where dominant trees are being removed (selective thinning, thinning from above, crown thinning), while values lower than 0.9 define thinning where dominated trees are being removed.

Differences among silvicultural options and areas were assessed at stand level by comparing the differences in basal area (BA), volume (V) and their increment through inventories using Gurnaud's control method (in Mariotti et al. 2017):

$$I = \frac{V2 - V1 + Vh}{t2 - t1}$$

where V1 and V2 are the volumes at survey 1 and 2 respectively, and Vh is the harvested wood during the period t2-t1, calculating the corresponding growth rate (Gr % year⁻¹) according to the following equation:

$$Gr = \frac{I}{V1}$$

Differences in forest structure at stand level were analyzed by transects, located inside the plots, of 600 m² (20 x 30 m) using a structural

index both at horizontal and vertical level. Forest structure is both a product and driver of ecosystem processes and biological diversity. It is a result of management, disturbances and dynamics, but also has an important ecological role in ecosystem functioning, forest diversity and environmental value (Pommerenning 2006, Pretzsch 2009). Two indexes of structural diversity were selected to analyze and compare the effects of silviculture on stand structure. This investigation was carried out in the plots previously unmanaged (3 in Abetone AB and 2 in Amiata AM1), not considering the 3 plots previously thinned in Monte Amiata.

Among the vertical diversity indexes, we used the Vertical Evenness (VE, Neumann and Starlinger 2001) index, calculated by splitting tree population into three height layers (0-1/3, 1/3-2/3, 2/3-1 of dominant height), and counting in the formula the number of trees within each layer:

$$VE = \sum s_i \cdot p_i \cdot \frac{\ln(p_i)}{\ln(s_i)}$$

where s = number of height classes, $p_i = n_i / N$ with n_i the number of trees in each height class and N the total number of trees. The index is a descriptor of tree layering, and it can range from 0 (one-layered stand) to 1 (multi-layered stand).

Among the horizontal diversity indexes, we used the Cox index (CI), quantifying clumping by the ratio between variance and the number of trees in equal sized sub-plots (Neumann and Starlinger, 2001). A variance to mean ratio of 1 indicates a random distribution, values less than 1 even distribution and values greater than 1 an increasingly clustered distribution. To understand whether different social classes exhibit different behaviors, the Cox index was also calculated considering only dominant trees.

Tree level

During the inventories carried out before and after thinnings (3 in Amiata 2008, 2011,

2018 and 2 in Abetone 2011, 2016), additional periodic measurements were made on the crop trees of TS in order to allow a comparison of different silvicultural options. An equivalent number of crop trees were also selected in SS and C plots. For each crop tree, several additional parameters were recorded: diameter (DBH), total height (H), crown insertion (Hins), crown dimension (Dcr) and stem quality according to the 4 classes used for valuable broadleaved tree species (according to CEN standard, Nosenzo et al. 2012). Crop trees' DBH was measured annually at the end of the growing season.

In order to evaluate the impact of different silvicultural approaches on stem stability, the H/D and Dcr/H ratios of the crop trees were used as monitoring parameters, calculated at the beginning and at the end of the monitoring period.

In addition, the damage to crop trees caused by thinning or logging operations were recorded.

Differences among thinning options were assessed at crop tree level by comparing the DBH current annual increment (CAI), periodical DBH increment (PI), crown dimension (Dcr) by the analysis of variance (ANOVA), and the post-hoc HSD Tukey test, after verifying the normality distribution of the data (Kolmogorov-Smirnov and Lilliefors tests). Differences in stem quality class

distribution were also evaluated using the χ^2 Tukey test. All the analyses were performed using the software Statistica 7.1 (StatSoft USA).

Results

Stand characteristics before thinning

Before thinning, the Kruskal-Wallis test showed that no significant differences in the DBH distribution were recorded among the plots in each sites ($p = 0.63$ in AB, $p = 0.75$ in AM1, $p = 0.79$ in AM2).

The two sites at Monte Amiata (AM1 and AM2) showed differences in stand density and productivity due to past treatments (Table 2). In AM1 the absence of management has resulted in a very large number of trees (more than 4,000 trees ha⁻¹ in AM1 and less than half that number in AM2), and higher values for basal area and volume. At the same time, the impact of thinning carried out in AM2, before the commencement of research activity, is evident in the higher values of DBH and dominant diameter and in the importance value recorded for dominant component (0.51-0.58 in AM2 and 0.39-0.42 in AM1). Tree biodiversity is very low at both sites, only one other tree species (*Prunus avium* L.) was recorded in one plot.

At the Abetone site, plots were more homogeneous (Table 3), beech was the

Table 2 Beech stands in Amiata and Abetone. Mensurational parameters, tree diversity and beech importance values in the study areas before thinning occurrence: (TS) tree oriented silviculture, (SS) stand silviculture, (C) control.

Plot		AM1	AM1	AM2	AM2	AM2	AB	AB	AB
		TS	SS	TS	SS	C	TS	SS	C
Year of 1 st thinning	--	2008	2008	2008	2008	2008	2011	2011	2011
Number of trees	n ha ⁻¹	4200	4095	1469	1069	1679	2493	2421	2500
Dominant height	m	20.7	20.1	21.6	22.3	21.4	21.4	22.3	19.1
DBH _g	cm	11.6	11.2	16.6	20.3	16.0	11.8	12.8	11.7
DBH _D	cm	22.2	24.1	27.3	30.6	25.9	27.4	26.9	24.7
Basal area	m ² ha ⁻¹	44.32	41.66	31.78	34.52	33.68	27.18	31.29	26.65
Volume	m ³ ha ⁻¹	419.5	391.8	340.6	386.1	355.9	262.3	337.7	253.6
Tree diversity	Shannon index	0.00	0.00	0.00	0.02	0.00	0.08	0.27	0.30
Number of species	n	1	1	1	2	1	4	6	3
Importance value	Dominant trees %	0.42	0.39	0.51	0.52	0.58	0.30	0.27	0.40

Table 3 Beech stands in Amiata and Abetone. Mensurational parameters, tree diversity and importance value of the dominant trees in the study areas, at the last inventory, after silvicultural management: (TS) tree oriented silviculture, (SS) stand silviculture, (C) control.

Plot		AM1	AM1	AM2	AM2	AM2	AB	AB	AB
		TS	SS	TS	SS	C	TS	SS	C
Age	years	55	55	58	58	58	53	53	53
Number of trees	n ha ⁻¹	2605	975	755	414	1671	2225	1061	2767
Dominant height	m	23.4	22.9	25.1	25.4	24.2	24.0	24.1	21.0
DBH _g	cm	12.3	18.6	19.7	27.7	17.8	10.8	18.1	12.3
DBH _b	cm	27.2	26.2	33.9	34.4	30.0	28.5	29.1	27.5
Basal area	m ² ha ⁻¹	30.81	26.38	23.00	24.91	41.76	20.22	27.21	32.84
Volume	m ³ ha ⁻¹	298.2	274.5	283.3	325.4	487.7	216.9	328.1	320.5
Tree diversity	Shannon index	0.00	0.00	0.00	0.03	0.00	0.06	0.38	0.26
Number of species	n	1	1	1	2	1	4	6	3
Importance value	Dominant trees %	0.33	0.71	0.55	0.92	0.55	0.20	0.39	0.39

dominant species, but was associated with a larger number of other sporadic trees, such as silver fir (*Abies alba* Mill), golden rain (*Laburnum anagyroides* Medik.), sycamore (*Acer pseudoplatanus* L.), rowan (*Sorbus aucuparia* L.), larch (*Larix decidua* Mill.). The importance values for dominant trees were similar to those recorded at the AM1 site (0.27-0.41).

Thinning management

At all sites thinning carried out for the two silvicultural options (TS and SS) differed in terms of frequency, intensity and social rank of the harvested trees (Figure 1).

In TS silvicultural treatment thinning was more frequent, with a lower intensity and a higher amount of removed dominant trees compared with SS treatment. Crown thinning (TS options) carried out around the crop trees to keep the crown of selected trees free to grow, was repeated after 3 and 7 years in Amiata and after 5 years in Abetone. The first thinning phase reduced stem density by 19% in Monte Amiata and 14% in Abetone AB TS. The second thinning was less intensive at the Abetone site (11% of stem density) and AM1 site (13%), but higher in AM2 (26%). Finally, the third thinning phase carried out at Amiata showed a lower intensity of removed stems (11% in AM1 and 12% in AM2). In SS treatment only one thinning intervention was carried out at Abetone, whilst at Monte Amiata

a thinning was repeated after 10 years.

Thinning caused a significant reduction in stem density in all plots: 55%, 30% and 58% respectively in AM1, AM2 and AB during the first thinning; 38% and 43% in AM1 and AM2 in the second thinning.

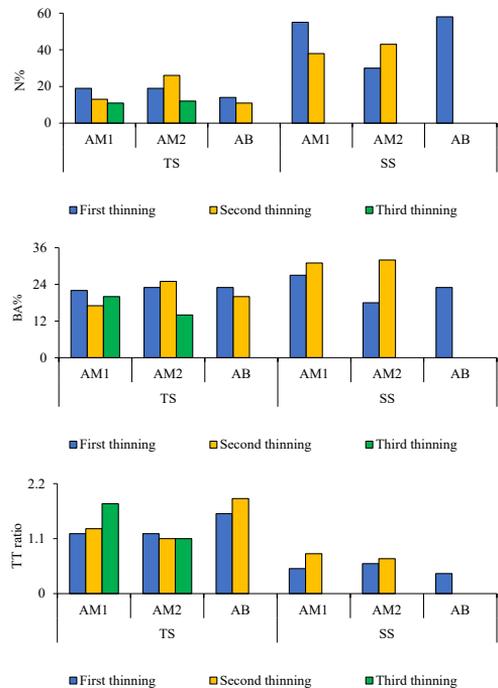


Figure 1 Thinning intensity (N% and BA%) and thinning type (TT ratio) in the different treatments (TS, SS) in Amiata (AM1 and AM2) and Abetone (AB) plots.

Considering the basal area parameter, the two silvicultural approaches proved to be similar in terms of BA% reduction. At Monte Amiata, the TS option reduced BA by 17-22% in AM1 and 14-25% in AM2, while the SS option reduced BA by 27-31% in AM1 and 18-32% in AM2. At Abetone thinning intensity reduced BA by 20-23 % for TS and by 23% for SS.

Differences in thinning were also well described by the TT ratio. Values higher than 1.1 were always obtained for the TS silvicultural option, while values ≤ 0.8 were obtained for SS options in both areas (Figure 1).

Stand characteristics after silvicultural management

At the Monte Amiata site, after 10 years of silvicultural management (three thinnings in TS and two thinnings in SS), the Kruskal-Wallis test showed significant differences in both sites ($p = 0.04$ in AM1 and $p = 0.01$ in AM2). Significant differences were recorded between the two thinning methods (TS and SS) at both sites; at the AM2 site the C plot was different to SS treatment, but not to TS treatment.

At the Abetone site the length of monitoring was only 5 years, with two thinnings (for TS) and one thinning (for SS) carried out. The Kruskal-Wallis test, for all diameter classes, showed no significant differences ($p = 0.92$) among the three methods. On the other hand, frequency distributions for the smaller diameter classes (up to 12 cm) showed significant differences ($p < 0.01$), between SS and the other methods.

The number of trees (Table 3) recorded in the last inventory had fallen in all thinned plots as a function of past management (one thinning from below was carried out in AM2 before the commencement of monitoring), number of thinnings (2-3 at Amiata and 1-2 at Abetone) and thinning type (TS or SS).

Tree density varied from 2,605 (TS) to 975 (SS) trees per hectare in AM1, from 1,671 (C) to 755 (TS) and 414 (SS) trees per hectare in

AM2, from 2,767 (C), to 2,225 (TS), to 1,061 (SS) trees per hectare in AB.

The basal area values were more homogeneous and lower in thinned plots ($26.4\text{--}30.8\text{ m}^2\text{ ha}^{-1}$ in AM1, $23.0\text{--}24.9\text{ m}^2\text{ ha}^{-1}$ in AM2, $20.2\text{--}27.2\text{ m}^2\text{ ha}^{-1}$ in AB) than in the control plot ($41.8\text{ m}^2\text{ ha}^{-1}$ in AM2 and $32.8\text{ m}^2\text{ ha}^{-1}$ in AB). The mean diameter values were higher for the SS approach (18.6 cm in AM1, 27.7 cm in AM2 and 18.1 cm in AB) compared to the TS option (12.3 cm in AM1, 19.7 cm in AM2 and 10.8 cm in AB), although no differences were recorded for the dominant diameter. The diversity indices did not change after thinning, while the importance value for dominant trees was influenced by the type of thinning: in SS the dominant component was higher, and increased in relation to the first inventory; in TS the values were lower than for the previous inventory; in the control plot the index did not show significant changes.

Growth at stand level

The total annual volume increment between different inventories (Gr%) and corresponding growth rate (I) showed up similar values between the different silvicultural options, but was slightly higher for the TS approach (Table 4). At the Amiata site total annual volume increments, calculated from the 1st to the 3rd inventories (2008-2018), reached higher values in AM2 (from 13.2 to $14.5\text{ m}^3\text{ ha}^{-1}\text{ yr}^{-1}$) than AM1 (from 9.3 to $11.8\text{ m}^3\text{ ha}^{-1}\text{ yr}^{-1}$). The corresponding growth rate Gr varied from 2.4% in AM1 SS to 4.3% in AM2 TS. At Abetone the total annual increment, calculated from the 1st to the 2nd inventories (2006-2016), reached values from 10.6 (SS) to 14.6 (TS) $\text{m}^3\text{ ha}^{-1}\text{ yr}^{-1}$, with a corresponding growth rate going from 3.1% to 5.6%.

Stand structures

Structural diversity indices (Figure 2) showed multi-layered stands and a clustered distribution of trees in both areas. At Abetone higher vertical index values were recorded for the control plot

Table 4 Harvested volume (V), total annual increment calculated by Gurnaud control method (I) and corresponding growth rates (Gr) before thinning (BT) and after thinning (AT).

Plot / treatment	Harvested volume				V2-last IV, AT	Total Vh	I m ³ ha ⁻¹ yr ⁻¹	Gr %
	V1-1 st IV, BT	1 st Th	2 nd Th	3 rd Th				
AM1 TS	419.5	91.7	63.5	84.2	298.2	239.4	11.8	2.8
AM1 SS	391.8	93.6	--	117.0	274.5	210.6	9.3	2.4
AM2 TS	340.6	78.8	78.3	45.3	283.3	202.4	14.5	4.3
AM2 SS	386.1	63.0	--	139.9	325.4	202.9	14.2	3.7
AM2 C	355.9	--	--	--	487.7	--	13.2	3.7
AB TS	262.3	62.6	55.7	--	216.9	118.3	14.6	5.6
AB SS	337.7	62.5	--	--	328.1	62.5	10.6	3.1
AB C	253.6	--	--	--	320.5	--	13.4	5.3

Note: Iv: inventory; Th: thinning; Vh: harvested volume.

(0.94), and lower (0.89) for the SS approach. At Amiata the vertical structure was also more articulated in different layers in the plot thinned using the tree-oriented silviculture (0.72) compared with traditional thinning (0.69).

Cox index values were higher than 1 in all areas (cluster distribution), except for Monte Amiata, managed according to the traditional silviculture system, showing an even distribution (SS = 0.33). The analysis of dominant layer horizontal diversity showed a more even tree distribution in all plots. A clustered distribution was preserved only for TS at Amiata (1.45).

Growth at crop tree level

Amiata

The effects of different thinning options caused significant differences on crop trees in terms of DBH, periodical increment of diameter and crown diameter (Figure 3 and Figure 5). In particular, in 2019 in AM1 crop trees reached a mean DBH of 26.4 cm and 21.8 cm respectively for TS and SS while, in AM2, crop tree DBH in thinned plots reached 32.8 cm and 32.1 cm, for TS and SS respectively. These values were significantly higher compared with 26.1 cm measured in the C plot in 2019 (Figure 3a). The effect of thinning on diameter growth is more evident analyzing the periodical increment (PI) calculated for the period 2008-2019 in Amiata. The PI of the crop trees for TS are significant superior (6.3 and 7.8 cm rispecciveli for AM1 and AM2) to the other silvicultural options in

all the two protocols (Figure 5). The effect of different thinning options is even more evident analyzing the crown diameter in 2019 at the end of the monitoring period: in AM1 the Dcr of the crop trees reached 5.6 m in TS and 4.1 m in SS, while in AM2 the Dcr reached 7.4 m, 5.7 m and 4.7 m respectively for TS, SS and C (Figure 3c).

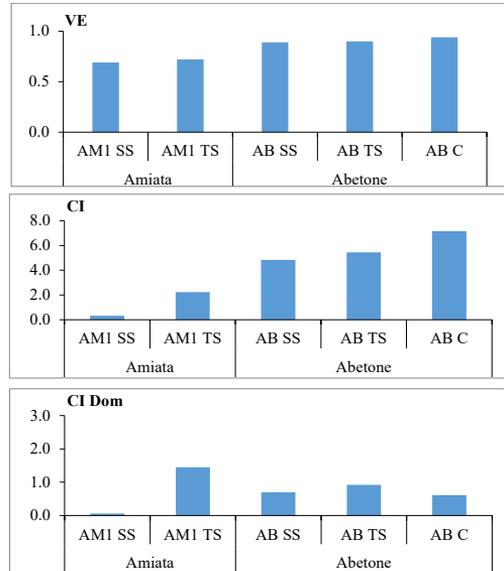


Figure 2 Indexes of structure diversity (VE = vertical index, CI = Cox index of horizontal structure, CI Dom = Cox index of horizontal structure of the dominant layer) in the different thesis (SS, TS, C) in Monte Amiata and Abetone plots, at the last inventory, after the silvicultural treatment.

No significant differences were observed for height values in AM1, while in AM2 differences seen during the first inventory were maintained in the last inventory (Figure 3b). The monitoring of CAI of diameter showed a significant growth increment for the TS treatment (Figure 3d). In particular, DBH CAI trends showed a superior reaction of the crop trees under the TS option compared to the traditional SS, but larger inter-annual variations. The crop trees selected in the AM1 area had a lower growth rate in 2008 compared to those selected in AM2, and showed a slower reaction to different thinning methods.

Abetone

At the Abetone site the effects of thinning options are less evident and not significant than at Amiata. In 2019, the mean DBH value of crop trees in TS was greater (28.7 cm) than in SS (27.1 cm) and control plots (24.9 cm) but not significant (Figure 4a). In Abetone the superior diameter growth in TS is more evident and significant considering the periodical increment (PI) calculated for the period 2011-2016 (Figure 5). After 5 years, PI of the crop trees reached 5.1 cm in TS, while values of 3.1 and 3.6 cm were found respectively for

SS and C. There were significant differences only for height values (Figure 4b) both in 2011 and 2019. In particular, the height of AB SS and AB TS reached 24.3 and 23.6 compared to 21.8 measured for AB C at the end of 2019. Significant differences were found in Dcr: the crown diameter reached 6.6 m for the TS option but only 5.7 and 4.4 m for the SS and C options in 2019 (Figure 4c). Also, at the Abetone site the analysis of DBH CAI trends showed a superior reaction of crop trees under the TS options compared to traditional SS (Figure 4d).

Tree stability, stem quality and damage

Interesting differences were found in the H/DBH ratio. Before thinning (2008 in AM1 and AM2 and 2011 in AB), there were no significant differences among the plots of all three experimental sites. At the end of the monitoring period (2019), there was a reduction in the H/DBH ratio in all the plots under tree-oriented silviculture, as well as an increase in tree stability. On the other hand, in the plots under traditional stand silviculture the H/DBH ratio slightly rose (in AM2 and AB) or remained stable (in AM1), while in the control plots there was a general increase in this ratio

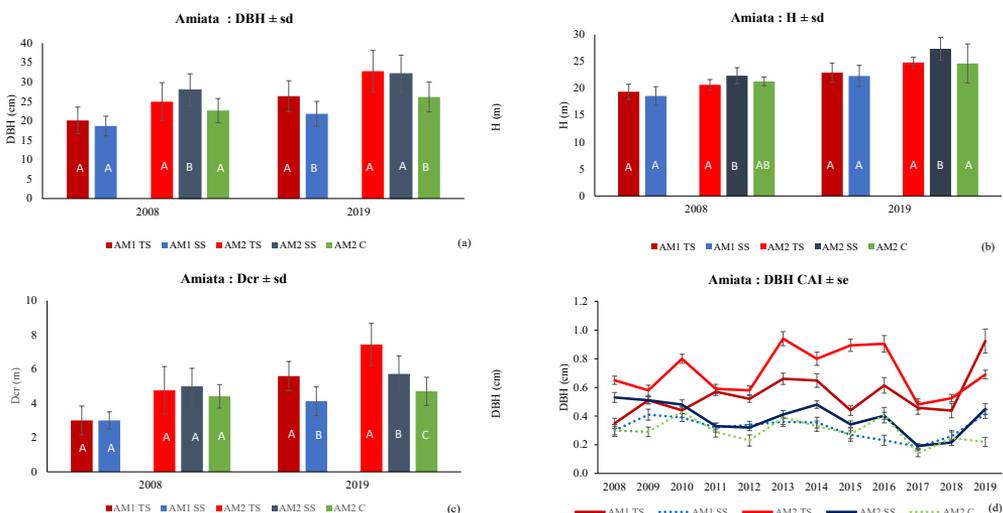


Figure 3 Main characteristics of the crop trees per silvicultural options in the two area of Monte Amiata. Letters indicate the differences among thesis (HSD test).

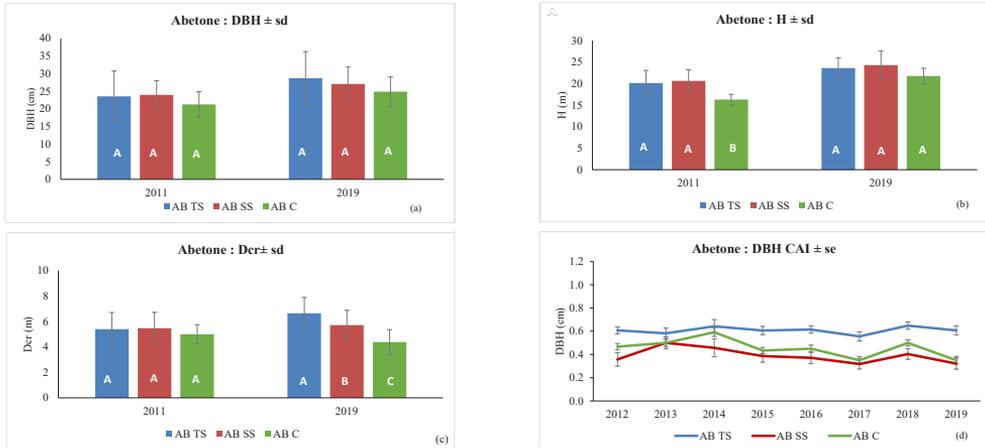


Figure 4 Principal characteristics of the crop trees per silvicultural options in the two area of the Abetone. Letter indicate differences among thesis (HSD test).

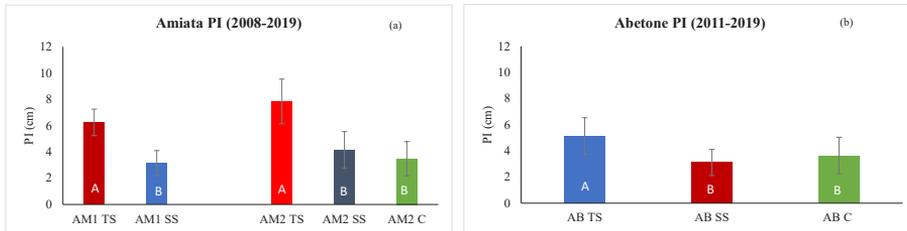


Figure 5 Periodical increments (PI) in the plots of Monte Amiata (AM; 2008-2019) and Abetone (AB; 2011-2019).

(Table 5). The HSD test showed significant differences among treatments in AM1 and in AM2, while no differences were observed in AB.

Growth conditions were also analyzed using another synthetic index (Dcr/H), correlating crown diameter to tree height. In the first inventory, this ratio was similar for each experimental protocol (AM1, AM2 and AB), and no differences were observed among silvicultural treatments. In 2019 significant differences were observed between the TS plots and the other two approaches (SS and C). A clear rise in this ratio, as well as an increase in stability and crown development, was observed in crop trees under tree-oriented options. This ratio varied slightly for the SS option, while there was a progressive fall in the Dcr/H ratio for the crop trees of the control plots.

Stem quality classes of crop trees were evaluated at the beginning of research activity

(2008 in AM1 and AM2 and 2011 on AB) and in 2019. Stem quality distributions, dividing the stem quality classes of crop trees into two categories (A+B suitable for industrial transformation veneering and saw timber and B+C suitable only for firewood and biomass production), are shown in Table 6.

At the beginning of the trial, the Tukey χ^2 test showed significant differences only in AM1, where the quality of TS was better compared to the SS option. In the other two trials (AM2 and AB), no differences were noted in stem quality distribution. In 2019 significant differences in stem quality distribution was noted only in AB. Generally, for the TS options, the stem quality of crop trees was higher compared with stem quality observed in crop trees selected in the stand silviculture and control plots, but these differences were not evident with the Tukey χ^2 test.

Table 5 Indexes of tree stability.

Plot / treatment	2008 / 2011				2019			
	H/DBH	HSD	Dcr/H	HSD	H/DBH	HSD	Dcr/H	HSD
AM1 TS	100±14	A	0.16±0.05	A	88±11	A	0.24±0.04	A
AM1 SS	102±11	A	0.16±0.04	A	102±13	B	0.19±0.04	B
AM2 TS	88±15	A	0.23±0.06	A	79±12	A	0.29±0.04	A
AM2 SS	83±10	AB	0.22±0.04	A	87±11	B	0.21±0.04	B
AM2 C	97±14	B	0.21±0.04	A	98±7	C	0.19±0.03	B
AB TS	89±16	A	0.27±0.06	A	85±14	A	0.28±0.05	B
AB SS	87±10	A	0.27±0.06	A	91±14	A	0.24±0.05	A
AB C	78±10	A	0.31±0.04	A	87±12	A	0.20±0.04	A

Note: H/DBH and Dcr/H (where H = total height, DBH = diameter at breast height, Dcr = crown diameter) calculated for the crop trees in both areas and silvicultural approach. Mean values, standard deviation and significance HSD test are reported at the beginning and the end of monitoring period.

Table 6 Stem quality classes distribution per plot at the beginning and the end of monitoring period.

Plot / treatment	2008 / 2011				2019			
	A+B	C+D	Total	A+B %	A+B	C+D	Total	A+B %
AM1 TS	13	7	20	65	17	4	21	81
AM1 SS	7	15	22	32	15	7	22	68
Total	20	22	42	48	32	11	43	74
		χ^2	4.624	p<0.05		χ^2	0.920	n.s.
AM2 TS	19	30	49	39	29	17	46	63
AM2 SS	22	26	48	46	24	24	48	50
AM2 C	8	7	15	53	7	7	14	50
Total	49	63	112	44	60	48	108	56
		χ^2	1.137	n.s.		χ^2	1.820	n.s.
AB TS	24	3	27	89	25	2	27	93
AB SS	23	5	28	82	17	11	28	61
AB C	7	5	12	58	7	5	12	58
Total	54	13	67	81	49	18	67	73
		χ^2	5.033	n.s.		χ^2	8.739	p<0.05

Note: The Tukey χ^2 test was applied grouping the stem classes in two categories: A+B (industrial transformation) and C+D (firewood and biomass production).

The analysis of damage occurring to crop trees during thinning operations (felling and logging), showed that damage was mainly localized for the TS approach (10-15% of crop trees), in particular on the stem of the tree. On the other hand, damage was absent (in AM1 and AB) or limited (4% in AM2) for the SS approach.

Discussion

The main effects of silviculture intervention were to modify stand structure, reduce stem density and competition processes. The effects depended on thinning type, length and number of treatments. In our experiments two different silvicultural approaches were tested:

- The stand silviculture (SS), easy to apply and tending to generate monolayer, pure

and even-aged stands. The main effects were the simplification of stand structure, the widespread presence of trees in the dominant layer and the progressive death of light-demanding minority tree species.

- The tree-oriented silviculture (TS), more difficult to apply, mainly in the pool stage, due to the selection of crop trees and logging difficulties for first thinnings. This approach helps to maintain a multi-layered stand structure, and to preserve the presence of minority tree species. The TS approach makes it possible to adapt treatment to the biological needs of different tree species, and favors the conservation of light-demanding species, such as wild cherry and rowan (Pelleri et al. 2013, Schütz et al. 2016).

Thinning intensity was not particularly different for the two approaches: for TS the basal area removed was 5-6 m² ha⁻¹ (20-23 %) in Abetone, and 4-10 m² ha⁻¹ (17-25%) in Amiata. For SS 7 m² ha⁻¹ (23 %) in Abetone, and 6-12 m² ha⁻¹ (18-32%) in Amiata were removed. Nevertheless, tree-oriented silviculture guaranteed larger-sized timber assortments of, better quality and easier market placement, as already found for chestnut coppices (Manetti et al. 2016) and black Pine stands (Marchi et al. 2018) under different thinning methods.

Quantities are rather low, but the presence of a good network of forest tracks makes such intervention economically sustainable (Pelleri et al. 2013). Slightly higher values were obtained in other experimental trials in Italy for chestnut coppices (Manetti et al. 2016) where, during the 1st and the 2nd thinnings, BA removed reached 8-10 m² ha⁻¹ in Amiata and 4-13 m² ha⁻¹ in the Colline Metallifere. Similar intensities were obtained for beech stands in Italy, with 26-32% of BA removed (Mariotti et al. 2017) and in Slovenia, with 18-27% and 16-22% of BA removed under different selective thinning regimes (Boncina et al. 2007). Similar BA removal (5-10 m² ha⁻¹) was observed in regular beech high forest stands in France managed under a TS approach (Bastien et al. 2005).

At stand level, the application of TS caused, according to the Gurnaund method, higher total volume increments compared with traditional SS both at the Abetone and Amiata plots. These values are higher than the indexes obtained by Mariotti et al. (2017) in beech stands converted to high forest, managed with two different thinning methods (selective and low). At Amiata total volume increments (I) from 9.3 to 14.5 m³ ha⁻¹ yr⁻¹ were observed, while at Abetone values from 10.6 to 14.6 m³ ha⁻¹ yr⁻¹ with growth rates (G%) from 2.4 to 4.3% in Amiata and from 3.1 to 5.6% in Abetone were recorded. These higher volume increments derived from higher soil fertility and from higher volumes at the time of the first

inventory. It is important to point out that when applying the TS option most of the volume increment is concentrated in a small number of crop trees, causing a higher increment in volume and value of the assortment produced by these trees, whereas for the other option (SS), the total increment is spread among all the stands, and mainly among dominant trees. The different length of treatment, and above all the number of thinning interventions, resulted in important structural differences following the application of the two approaches. At the Amiata site, after 11 years and 2-3 thinnings, the TS approach produced a higher stand density and therefore lower DBH values; a more articulated vertical structure and consequently lesser importance of the dominant component; a higher growth rate of crop trees due to the isolation of the crowns. At the Abetone site, the trend was similar, but a shorter monitoring period (5 years) and fewer thinnings (1-2), did not make it possible to see more significant differences among the approaches.

Spatial distribution was also influenced by the monitoring period and number of thinnings. At the Amiata site trees were evenly distributed for the SS approach and clumping distributed for TS. On the other hand, at the Abetone site, all plots had a clumping distribution. The differences between approaches emerged when the social layers were analyzed separately. Trees in the dominant layer showed a regular or random distribution for all plots, except for TS in Amiata.

Other authors too found a clear difference between the spatial distribution of overstorey and understorey both in old-growth Norway Spruce, Douglas-fir and beech forests (Svensson and Jeglum 2001, Franklin et al. 2002, Boncina et al. 2007, Becagli et al. 2016). Generally, trees in the understorey were clumped because they can develop mainly in the spaces between overstorey trees, and groups of small diameter shade-tolerant trees can grow under an overstorey of large well-spaced trees.

Similar to the control plots, the TS approach maintains a high stem density and complex stand structure, but a lower competition level and higher growth rate, as revealed by other authors regarding beech forests (Boncina et al. 2007). On the other hand, the SS approach differentiates plots in terms of both structure and stand growth. This simplification is easier to manage but less functional from an ecological point of view.

Growth analysis at crop tree level pointed out a higher growth in DBH and crown dimension of the crop trees selected in the TS plots, while the progressive reduction in height growth of the crop trees was due to the lower competition levels and to the effects of crown isolation. These parameters have influenced the individual stability of crop trees, as shown by the stability index. This index went down over time in the crop trees selected in the TS plots, while an increase was observed in the crop trees selected in the SS plots. Similar results were observed in beech forests managed with selective thinning compared with forests managed with thinning from below (Mariotti et al. 2017) and in black Pine artificial forests (Marchi et al. 2018).

The higher crown development and lower height growth also caused an increase in the Dcr/H ratio in the crop trees under the TS option, showing a reduction in competition levels tested by this simple index in oak stands (Lemaire 2010).

The DBH current increments for crop trees underlined significant differences between the TS option and the other two approaches (SS and C). Current increment values were always greater in the plot managed under TS, while the other two approaches showed comparable and lower DBH current increments.

The application of TS helped to keep the crown of the crop trees isolated and free to grow over time without the competition of the surrounding trees. In our case, this made it possible to obtain a higher growth of the crown diameter, about 24 cm yr⁻¹ at Amiata and 18

cm yr⁻¹ at Abetone, a value three times higher than the growth obtained under SS. Higher crown increments of the crop trees, from 36 to 50 cm yr⁻¹, were obtained in younger beech stands (12-14 m of dominant height) managed under TS and subjected to different intensities of crown release (De Potter et al. 2012).

Overall, the application of TS enhances best trees, in terms of vigor and stem quality, stimulating their diameter growth and development of the crown. These factors help to improve crop tree stability by reducing the slenderness ratio and blocking the insertion of the crown, preventing its progressive rising due to the strong competition of surrounding trees. In this way, much of the growth of the stand is concentrated on a limited number of dominant trees, the best being able to provide the most valuable assortments as per market demand. With this silvicultural approach, a broad and valuable assortment will be obtained in a shorter time compared with the traditional SS, with undoubted advantages from an economic and environmental point of view.

Conclusion

Compared with non-management, both applied silvicultural methods had positive effects on tree stability, stand efficiency and tree growth. These benefits can help to counteract the negative effects of climate change - such as wind storms, fire and pathogen attack - and increase the environmental and landscape value of stands in areas having a high tourist vocation, such as those we have analyzed. Nevertheless, tree-oriented silviculture has proven to be the management type that best meets the multifunctionality requirements of the nowadays forests. Tree-oriented silviculture indeed is able to combine the productive function with the protection and preservation aspects, granting not only economic but also ecological, environmental and landscape benefits. These functions can be further enhanced when the regeneration phase is long term, and when management

helps to preserve stands having an irregular structure. On the other hand, while traditional stand silviculture has some environmental advantages, economic aspects are given the absolute priority.

The main strengths of tree-oriented silviculture as seen in our research are:

- producing high-value assortments with a longer Life Cycle Assessment;
- developing economic aspects, especially a higher quality of assortments obtained with intermediate thinning; enhancing the sporadic tree species of particular ecological, environmental and economic interest;
- preserving articulated, complex and differentiated stand structures, even in small areas;
- increasing and preserving biodiversity, even despite the small number of minority tree species;
- increasing the mechanical stability of trees;
- allowing higher carbon sequestration by concentrating most of the volume in a few large trees; overcoming the idea of rotation periods and introducing the concept of a longer regeneration period.

The main weaknesses can be highlighted as follows:

- a need for more knowledge, care and complexity in forest planning; training of technical and operating personnel;
- care needed during felling and logging operations, since damage caused to a single crop tree can thwart the management's efforts;
- type and size of the forest property: this innovative system may not be understood by small private owners, who make up the majority of owners;
- trends of wood markets and local supply chains.

In traditional stand silviculture, the main strengths are:

- an increase in the quantity of the final

product, with a standard quality;

- simple management, both in the planning phase and for felling operations;
- adaptability to the needs of private property.

The main weaknesses revealed by our study are:

- a low degree of structural complexity;
- scarce attention paid to sporadic tree species.

In conclusion, only a knowledge of the main strengths and weaknesses of the two silvicultural approaches can help to choose the management type that best suits the economic, social and environmental characteristics of a specific territory.

In our study, a definitive evaluation of the two silvicultural approaches can only be obtained at the end of the rotation period, by evaluating production aspects, other ecosystem services and difficulties during the regeneration phase.

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Declaration on conflicts of interest

The authors declare that they have no conflict of interest.

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