

Article

Structural Traits of Old-Growth Beech Forests in the Central Apennines (Italy)

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Abstract

Old-growth forests are recognized as key reference systems for biodiversity conservation and sustainable forest management, yet they remain rare and highly fragmented ecosystems across Europe. In this study, we developed and applied a quantitative, measurement-based framework to assess candidate old-growth beech stands by comparing their structural attributes with reference old-growth forests and with a broader set of beech forests from the National Forest Inventory (NFI). Specifically, we compared the structural attributes of two candidate old-growth (COG) beech stands to assess their degree of naturalness and their similarity to three reference old-growth (ROG) beech forests in the central Apennines. The approach integrated field-based structural measurements, deadwood quantification, dendrochronological assessment of dominant trees and diachronic aerial imagery evaluation, comparing COG stands with both ROG and other beech forests from the NFI database. The two COG stands differ clearly from common beech forests, exhibiting lower stem density, larger size variability, higher occurrence of large trees and of standing wood biomass. Stem diameter distributions followed a reverse J-shaped pattern, typical of uneven-aged and scarcely managed forests. Some very old trees were also found, especially at one of the two COG sites. These characteristics are largely comparable to the ROG beech forests, except for deadwood volumes, lower at the two COG forests. In addition, historical aerial imagery and tree-ring analysis suggested that these forests are intermediate stages along an old-growth gradient. Our findings demonstrate that a prolonged forest management abandonment of over 70 years can induce the development of old-growth attributes in Mediterranean mountain beech forests, even in stands previously coppiced or pastured for a long time. This study provides a replicable measurement-based approach for identifying and validating candidate old-growth forests, under current Italian regulations and contributes to conservation targets consistent with the EU Biodiversity Strategy for 2030.

Keywords: ancient forest; *Fagus sylvatica*; forest structure; forest abandonment



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1. Introduction

Old-growth forests are ecosystems of relevant ecological, scientific and conservation value, due to their complex stand structures and high biodiversity [1,2]. Old-growth forests are not necessarily primary forests unmodified by human actions, but they developed with little anthropogenic past disturbances and include all the silvigenetic phases, from natural regeneration to senescence and deadwood decay [3]. Key features are the occurrence of large and old trees, abundant deadwood, multi-layered canopies, and a spatially

heterogeneous structure driven by natural gap-disturbance regimes [4,5]. The structural complexity of old-growth forests supports a wide range of organisms and ecosystem functions. Numerous studies have highlighted their role in maintaining vascular plant diversity, cryptogams such as bryophytes and lichens, saproxylic fungi and invertebrates and vertebrate wildlife [6–8]. In addition to biodiversity conservation, old-growth forests contribute to key ecosystem services, like carbon sequestration, regulation of hydrological processes, climate buffering, and landscape stability. For these reasons, they are increasingly considered reference systems for assessing forest naturalness and for guiding sustainable forest management practices [9,10].

In Europe, millennia of forest exploitation have caused an extensive reduction and fragmentation of old-growth forests, that today represent only a small share of the entire forest cover area and are mainly limited to isolated patches [11,12]. There is a growing international interest in identifying forest stands that, although not strictly primary, have developed structural and functional attributes of old-growth forests because of a long-term abandonment of management. Such stands are core areas for ecological networks at the regional and national scales. In Italy, primary forests no longer exist; nonetheless, both in the Alps and Apennines, several stands—or their portions—display structural features associated with old-growthness [7,13–15]. These stands have been increasingly investigated not only within the framework of forest naturalness assessment and conservation, but also as reference ecosystems for conservation-oriented forest planning and management. Several national and European guidelines were used to establish the National Network of Italian Old-Growth Forests, based on standard criteria and requirements [16,17]. According to recent data, in Italy these forests are mainly located in the central and southern Apennines, where European beech (*Fagus sylvatica* L.) is the dominant mountain tree species [15]. Nonetheless, the newly created national network will provide a more precise overview of spatial distribution, surface area, and characteristics of these forests.

Apennine beech forests have been subjected for centuries to intensive management, primarily as coppice with standards systems for firewood and especially charcoal production [18]. Following the socio-economic transformation that occurred in the mid-20th century, many beech coppices were abandoned, and they either evolved toward lapsed coppices or converted to even-aged high forests, frequently with highly simple composition and structure [19,20]. After the long-term extensive exploitation of Italian forests, anthropogenic pressure decreased in the 1950s, and in some less exploited stands this favored the development of more complex structures featuring ecological processes typical of ancient forests [13,21,22].

In this study, we identified two new candidate old-growth beech stands in the central Apennines of the Marche region, Italy, showing limited evidence of past forest management. Our aim was to assess whether these candidate stands exhibit structural attributes consistent with recognized old-growth forests and are clearly distinguishable from managed or less structurally complex beech forests commonly found in the regional forest landscape. We hypothesized that, if these stands are indeed approaching old-growth conditions, their structural characteristics should more closely resemble those of reference old-growth forests than those of typical regional beech forests, which demonstrates that—even within a complex human-modified forest mosaic—patches exhibiting old-growth characteristics can persist or develop. To test this hypothesis, we compared the structural characteristics of the two candidate stands with those of three reference old-growth forests from another region of the central Apennines, as well as with a broader set of beech forests from the Italian National Forest Inventory. This study contributes to improving the scientific basis for forest naturalness assessment, conservation planning, and the development of sustainable forest management objectives.

2. Materials and Methods

2.1. Study Areas

Two candidate old-growth (COG) stands were identified in the Marche region, after a selection process conducted with the collaboration of the Carabinieri Command of the Forest, Environmental and Agri-food Units and the regional forest service (Table 1). The two stands were recently proposed for inclusion in the Italian Network of Old-Growth Forests, which grants protected status to stands meeting the following criteria: (i) the presence of native species consistent with the biogeographical context; (ii) characteristic biodiversity resulting from the absence of disturbance for at least 60 years; (iii) the presence of successional stages associated with natural regeneration and senescence; (iv) surface area ≥ 10 hectares [16].

Table 1. Main characteristics of the candidate old-growth (COG) and of the reference old-growth (ROG) forests. The number of sampled plots is reported in the last column.

Group	Code	Site Name	Elevation [m a.s.l.]	Slope [°]	Aspect	Plots [n]
COG	TEC	Tecchie	800	18	NE	6
	SPG	Spina di Gualdo	1600	26	NW	5
ROG	VCE	Val Cervara	1400	15	NW	5
	FON	Fonte Novello	1300	8	NE	4
	ASC	Aschiero	1600	10	NW	5

The first stand, the Tecchie forest (TEC), is in the municipality of Cantiano and located within the Bosco di Tecchie Regional Nature Reserve on the Serre del Burano mountain range, within the northern sector of the Marche region. The highest elevation is 1020 m a.s.l. between the montane and the sub-montane zones, where beech is mixed with *Quercus cerris* L. and other sporadic broadleaved species over marl-sandstone substrate. The second stand, the Spina di Gualdo forest (SPG), is in the municipality of Castelsantangelo sul Nera, within the Sibillini Mountains National Park, in the southern sector of the Marche region. The forest is situated along the main Apennine ridge, in the upper montane zone (1600 m a.s.l.), where beech forests are mainly pure over limestone substrates. Although both candidate stands occur within protected areas, this status does not automatically imply strict protection from human use or forest management, nor recognition as old-growth forest. Therefore, both sites required a stand-specific assessment against the national old-growth criteria.

As reference sites we used three well-known old-growth beech forests (ROG) in the central Apennines: the Val Cervara, the Fonte Novello and the Aschiero forests [4,7,23]. The first one is in the northwestern sector of the Abruzzo, Lazio and Molise National Park at 1200–1850 m a.s.l. The other two forests are situated on the northern slopes of the Gran Sasso massif, within the Gran Sasso-Monti della Laga National Park at 1200–1600 m a.s.l. The Val Cervara forest (VCE) is a well-known site in Central Italy [13] with features comparable to other European old-growth beech forests [9,24,25]. The stem diameter structure, the occurrence of some very old beech trees (>500 years), the frequent canopy gaps filled by beech natural regeneration and the specific vascular plants diversity are clear indices of old-growthness [4,7]. The Fonte Novello (FON) forest remained unmanaged for many decades, due to ancient disputes among neighboring villages [26–29]. Its structural complexity is typical of late-successional stages, with large trees, regeneration gaps and a high share of large sized deadwood [23]. Aschiero (ASC) is a small (10 ha) high forest patch, within a larger beech coppice matrix, that probably remained almost untouched after a rockfall

dated to the Little Ice Age [4,23] that left diffuse rock outcrops favoring the occurrence of very ancient trees, abundant deadwood and locally well-developed natural regeneration.

2.2. Data Collection

During spring–summer 2025, we sampled 25 field plots, 11 in the two COG forests and 14 plots in the three ROG forests (Figure 1). In addition, we used structural data of 21 common beech stands (beech density $\geq 35\%$) from the National Forests Inventory (NFI) data set (www.inventarioforestale.org, last access on 1 September 2025). These 21 plots are mainly located on the Sibillini mountains (Marche), a relevant Apennine chain where several peaks above 2000 m asl where beech forests are dominant.

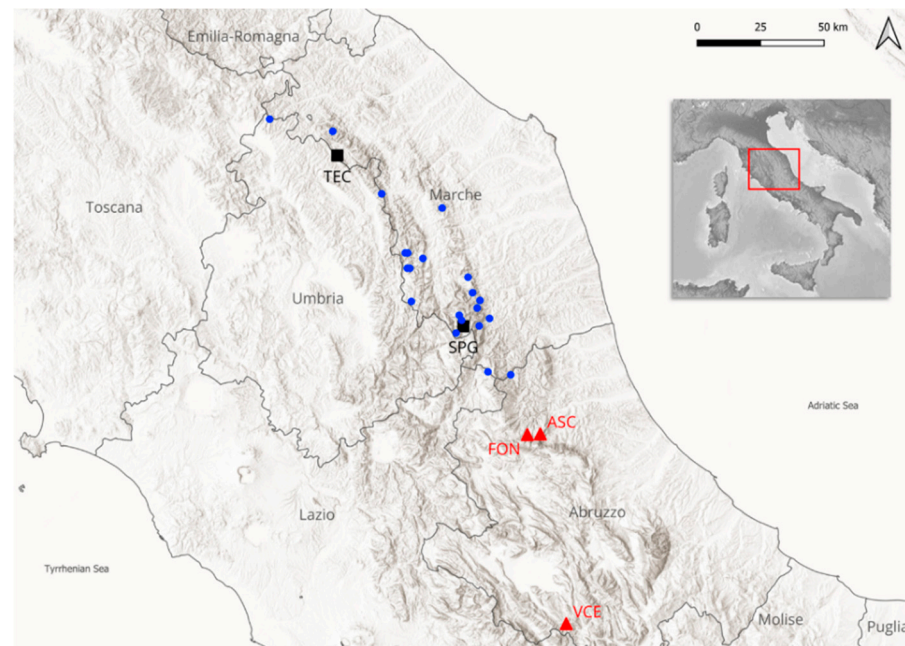


Figure 1. Location of the study sites in the central Apennines. Black squares are the two candidate old-growth (COG) forests of Tecchie (TEC) and Spina di Gualdo (SPG). Blue dots indicate the National Forest Inventory (NFI) plots selected in the Marche region, and red triangles indicate the three reference old-growth (ROG) forests in the Abruzzo region: Fonte Novello (FON), Aschiero (ASC) and Val Cervara (VCE).

In the field, we applied the “National Inventory of Forests and Forest Carbon pools” protocol [30] that involves the use of circular plots (radius = 13 m), and the measurement of the DBH (stem diameter at breast height, 1.3 m) and the tree height of all standing living and dead stems with DBH ≥ 5 cm. We also measured the DBH and top height of snags (standing dead trees > 1.3 m tall, DBH ≥ 5 cm), stumps (height < 1.3 m, DBH ≥ 5 cm) and coarse wood debris (CWD; diameter ≥ 5 cm at both ends, length ≥ 1 m). When possible, we also identified the CWD tree species. For all the 46 plots we computed the following variables to characterize the living tree stand structure: share of beech trees (Beech %), stem density per hectare (Stem density), mean of DBH (DBH mean), density (trees/ha) of stems with DBH ≥ 50 cm (DBH50), DBH standard deviation (DBH std), mean of tree height (H mean), tree height standard deviation (H std) and standing wood volume per hectare (VOL), estimated with national allometric equations [31]. For both the COG and ROG forests, we estimated deadwood volume (snags, stumps, CWD), using standard procedures proposed by the National Forest Inventory [30]. Finally, in each COG plot, with a Pressler increment borer, we extracted one core at breast height (1.3 m) from one dominant tree.

2.3. Data Analysis

We applied a Principal Component Analysis (PCA) to the living trees' structural variables of all the 46 study plots, using the `prcomp` function of the 'stats' package in R (v. 4.5.2). The analysis converted correlated and high-dimensional data into orthogonal and uncorrelated principal components, allowing the exploration of possible gradients in stand complexity. The same variables were also compared among groups (COG, ROG and NFI). The assumptions required for one-way ANOVA were assessed separately for each response variable. Variance homogeneity was tested using Levene's test implemented in the 'car' package, while residual normality was assessed using the Shapiro–Wilk test. Homogeneity of variances was not met for Beech, DBH50 and Stem density, while residual normality was not met for Beech, H std and VOL. Accordingly, standard one-way ANOVA followed by Tukey's HSD was retained only for variables satisfying both assumptions, whereas Welch's ANOVA followed by Games–Howell post hoc comparisons, or Kruskal–Wallis followed by Dunn's post hoc test, were used when assumptions were violated; Games–Howell and Dunn's tests were performed using the 'rstatix' package (Version 0.7.2).

We visually assessed the DBH distribution and calculated quantitative descriptors of DBH structure for each COG and ROG site. The de Liocourt q coefficient [32] was estimated from the slope of the linear relationship between $\log_{10}$ -transformed stem density and DBH class, using 5 cm DBH classes. Values of q greater than 1 indicate a progressive decline in stem density across increasing DBH classes. We also calculated weighted skewness, using DBH-class midpoints weighted by stem density per hectare, to quantify the asymmetry of the diameter distribution.

Deadwood volume differences among COG and ROG sites were tested separately for total deadwood volume and for each component: coarse woody debris, snags and stumps. Residual normality and homogeneity of variances were checked using the Shapiro–Wilk and Levene's tests, respectively. Depending on assumption fulfillment, site differences were assessed using classical one-way ANOVA, Welch's one-way ANOVA with Games–Howell post hoc comparisons, or the non-parametric Kruskal–Wallis test with Dunn's post hoc test. Statistical analyses and graphical outputs were performed in R using the 'tidyverse', 'car', 'rstatix' and 'ggpubr' packages (Version 0.6.3).

The collected cores were prepared according to standard procedures for dendrochronological analysis [33]. For each core of the two COGs, we measured ring widths using a LINTAB semi-automatic system (Rinntech, Heidelberg, Germany) and we estimated the pith offset from high-resolution scans (2400 DPI) using the embedded application of the CooRecorder software v. 7.7 [34]. With this procedure, we computed the minimum tree age of all sampled trees. We then crossdated the individual tree-ring series with validated central Apennine beech chronologies [35] and we used COFECHA (v. 6.06P) for the statistical quality control [36]. We converted the ring-width series to basal area increments (BAI) using the `bai.out` function in the 'dplR' package [37] in the R environment [38]. We compared the mean BAI site chronologies to assess growth differences and detect shifts related to stand development and senescence. We restricted the BAI analysis to the 1950–2024 time interval to ensure an overall adequate sample depth and include post-juvenile forest dynamics. Annual differences in BAI between the two sites (1950–2024) were calculated and assessed using a paired Wilcoxon signed-rank test to evaluate whether the median difference deviates from zero.

Lastly, we also used historical aerial imagery as ancillary visual information to simply provide qualitative context on past forest cover and visible management legacies at the two COG sites. We visually inspected aerial photographs from 1954, obtained from the Italian Military Geographical Institute (IGMI), together with regional orthophotos and recent satellite imagery from two subsequent reference periods, 1978/1988 and 2024. The

comparison was merely a visual assessment of major changes in forest cover, canopy closure, open areas, and visible signs of past management or land use. No quantitative landscape metrics were derived from these images.

3. Results

The overall comparison of the 46 plots revealed a wide structural variability of beech forests across the central Apennines (Table 2). The stem density of all living trees ($\text{DBH} \geq 5 \text{ cm}$) ranged from 94 to 2053 trees per hectare. For both COG and ROG plots, mean DBH was always $\geq 22 \text{ cm}$, and large trees (DBH_{50}) were more abundant in COG (84.8–101.7 trees/ha) than in ROG plots (64–84.8 N/ha). Among NFI plots, only 28.6% hosted trees with $\text{DBH} \geq 50 \text{ cm}$ and in only one of these plots the value exceeded 64 per hectare. DBH and height standard deviations at OGF and COG plots were much higher (DBH std: 19.8–23.6 cm; H std: 12.1–19.5 m) than in NFI plots (DBH std: 2.5–14.4 cm; H std: 1–4.5 m). Wood volume of living trees (VOL) varied greatly from less than $20 \text{ m}^3/\text{ha}$, in recently harvested coppices, to over $1000 \text{ m}^3/\text{ha}$ in senescent forests.

The PCA displays two distinct groups separated mainly along Dim1, which explained 58.5% of the total variance and represented a structural complexity gradient rather than a direct measure of old-growthness (Figure 2). The left group (blue) included most NFI plots, mainly associated with high stem density and dense coppice structures with relatively low standing volume. The right group clustered mostly ROG (red) and COG (black) plots, where FON1, FON2 and TEC5 stood out for their large and tall trees. This separation was consistent with the comparisons in Figure 3, where ROG and COG plots generally have lower stem density, higher standing volume, larger mean DBH and height, and greater diameter and height variability than NFI plots. The relatively high DBH and tree height standard deviations across the COG and ROG forest plots indicated relevant size heterogeneity, consistent with structurally complex and scarcely managed stands. The density of large trees ($\text{DBH} \geq 50 \text{ cm}$) in the COG forests ($>50 \text{ trees ha}^{-1}$) was comparable with that in the ROG forests (Figure 3). Overall, these results indicated that the COG and ROG plots share several structural discriminant attributes from most NFI plots, although variation within the ROG–COG group suggests different degrees of structural development.

The DBH frequency distributions generally showed an uneven-aged pattern (Figure 4). However, very large trees ($\text{DBH} > 80 \text{ cm}$) were also recorded, confirming the occurrence of exceptionally large individuals within these stands. When log10-transformation was applied to stem density values, the TEC, SPG and ASC showed the clearest variants of the rotated J-shaped distribution commonly associated with old-growth forests in temperate regions. All sites showed a negative relationship between log10-transformed stem density and DBH class (de Liocourt q coefficients greater than 1) and positive weighted skewness values, indicating a predominance of small-diameter trees and a progressive decrease in stem density toward larger DBH classes (Table 3).

As for deadwood volume, especially snags, we found much higher values in ROG forests, particularly at VCE, compared to COGs (Table 4). Besides the numerical variation, no significant differences in deadwood volume were detected among sites for any of the analyzed components. For STUMPS, the typical one-way ANOVA showed no significant site effect. For TOTAL and CWD, residuals did not significantly deviate from normality, but Levene's test indicated heterogeneity of variances; therefore, Welch's one-way ANOVA followed by Games–Howell post hoc comparisons was used. The results confirmed the absence of significant differences among sites for CWD and Games–Howell comparisons and did not identify significant pairwise differences. For SNAGS, both normality and homogeneity of variances were violated; therefore, a Kruskal–Wallis test was used, but and showed no significant differences among sites.

Table 2. Main structural variables of each plot. The first three columns respectively indicate the data source, the site and plot identifiers: NFI are data from the National Forest Inventory database; COG and ROG are respectively the ad hoc sampled data from two candidate old-growth forests and the three reference old-growth forests. Stem density is the number of trees/ha; Beech is the percentage of beech stems over the total number; DBH mean and DBH std are the average and relative standard deviation of tree diameters at breast height; DBH50, number of trees/ha with DBH ≥ 50 cm; H mean and H std, mean and standard deviation of tree heights; VOL, volume of living trees. The mean value is reported in bold formatting.

Group	Site ID	Plot ID	Stem Density [Trees/ha]	Beech [%]	DBH Mean [cm]	DBH Std [cm]	DBH50 [Trees/ha]	H Mean [cm]	H Std [cm]	VOL [m ³ /ha]
NFI	132285		1111	49	20.4	10.8	20.6	13.4	4.4	391.3
	133366		1676	99	17.6	6.9	0	12.9	2.3	342.5
	139762		640	38	12.4	2.9	0	8.0	1.3	42.0
	141102		942	72	25.8	14.0	75.3	15.1	3.7	567.2
	145844		1450	38	11.8	3.9	0	10.6	1.8	136.8
	145845		1074	49	14.6	5.6	0	10.1	1.6	116.9
	146387		94	80	19.8	4.3	0	12.3	1.0	18.7
	147457		1883	79	12.0	2.7	0	9.0	1.7	153.7
	147458		377	35	12.7	8.3	0	8.8	3.4	55.3
	148296		1300	90	12.8	2.5	0	7.1	1.7	65.8
	149943		565	97	27.5	14.4	37.7	14.7	3.6	364.3
	150776		848	91	16.7	7.5	0	9.1	2.2	112.7
	151026		1676	51	13.1	3.4	0	8.6	1.4	114.5
	151590		1507	100	17.6	10.1	56.5	15.0	3.6	463.2
	152362		414	100	15.5	13.6	37.7	6.4	1.6	64.5
	152630		433	70	22.5	9.1	0	15.4	2.4	166.2
	152874		1488	91	15.0	5.7	0	11.5	2.5	209.7
	153393		1281	66	19.5	9.4	18.8	14.6	3.0	386.5
	154162		659	97	11.0	3.1	0	6.6	1.3	34.3
	158221		678	56	16.6	7.4	0	14.2	4.1	146.8
	158477		735	69	18.9	12.0	0	15.1	4.5	284.4
COG	TEC	TEC1	396	86	25.9	22.4	56.5	17.4	10.1	512.3
		TEC2	396	100	24.9	22.7	56.5	15.9	11.1	482.2
		TEC3	603	78	21.6	21.7	131.8	14.9	9.1	572.2
		TEC4	659	97	19.5	18.7	75.3	14.4	9.4	490.4
		TEC5	113	100	77.3	20.9	94.2	35.4	5.0	1038.2
		TEC6	509	100	22.7	21.3	94.2	14.8	9.9	507.2
			446	93	24.8	23.6	84.8	16.1	10.4	600.4
	SPG	SPG1	452	100	27.5	26.8	113.0	13.0	9.4	570.2
		SPG2	527	100	25.2	24.8	131.8	11.1	5.7	454.8
		SPG3	829	100	19.6	18.0	94.2	10.8	4.7	390.6
		SPG4	320	100	40.9	34.5	113.0	17.1	7.4	766.9
		SPG5	2053	100	18.0	17.2	56.5	13.3	6.4	1066.4
			836	100	22.0	22.0	101.7	12.8	6.7	649.8
	ASC	ASC1	509	74	23.4	21.7	37.7	14.8	7.5	438.9
		ASC2	678	100	16.1	23.8	75.3	8.7	3.9	352.5
		ASC3	433	96	20.3	16.7	37.7	12.5	6.8	202.1
		ASC4	188	100	42.8	32.1	75.3	13.8	7.5	400.6
		ASC5	509	100	26.3	28.0	94.2	13.1	8.8	692.1
			463	94	22.9	24.6	64.0	12.1	7.1	417.3
	FON	FON1	151	100	55.5	39.0	75.3	23.0	7.3	759.9
		FON2	546	100	42.8	13.8	150.7	28.6	3.5	1311.4
		FON3	584	97	25.4	16.6	37.7	18.6	4.6	498.4
		FON4	678	100	22.1	21.7	75.3	12.1	5.3	523.6
			490	99	31.4	22.8	84.8	19.5	8.1	773.3
	VCE	VCE1	697	100	21.2	17.0	18.8	13.7	9.4	466.5
		VCE2	584	97	22.1	19.8	37.7	14.0	9.2	488.7
		VCE3	678	100	20.8	19.2	113.0	11.9	7.7	439.1
		VCE4	810	100	22.1	19.5	94.2	15.3	7.4	669.2
		VCE5	716	100	25.3	23.6	113.0	15.9	8.0	873.4
			697	99	22.3	19.8	75.3	14.2	8.3	587.4

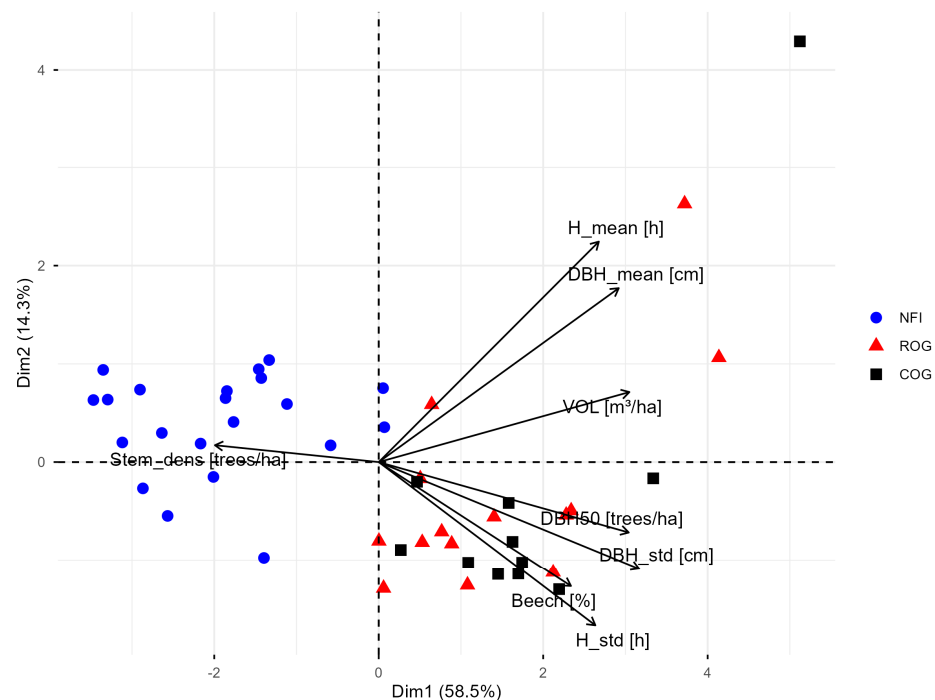


Figure 2. Biplot of the PCA with structure variables of beech forest plots. NFI plots in blue, ROG in red, and COG in black. Arrows represent the structural variables: their direction indicates the gradient of increasing values, and their length the strength of their correlation with the displayed PCA axes. Stem_dens is density of trees/ha; Beech, percentage of beech over the total number of trees; DBH_mean and DBH_std, average and standard deviation of diameters at breast height; DBH50, number of trees/ha with DBH ≥ 50 cm; H_mean and H_std, mean and standard deviation of tree heights; VOL, volume of living trees.

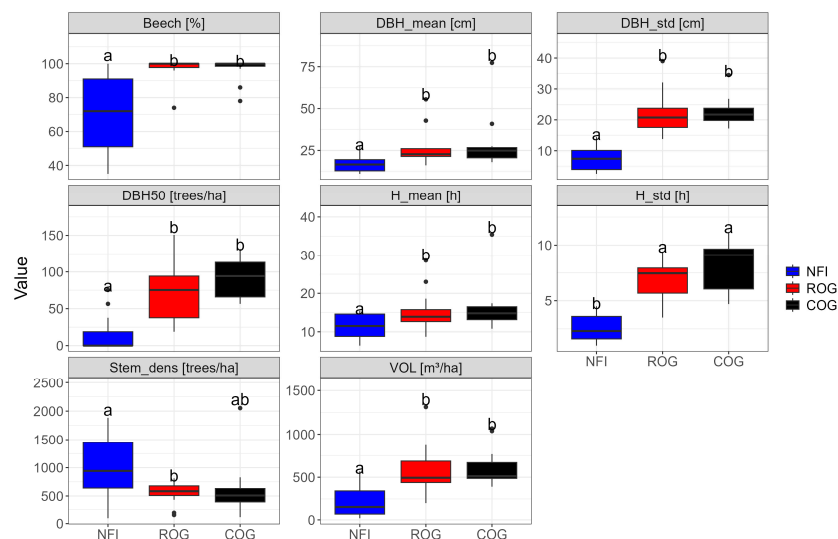


Figure 3. Comparison of structure variables of the three groups of forest plots: NFI plots in blue, ROG in red and COG in black boxes. Stem_dens is the density of trees/ha; Beech, percentage of beech over the total number of trees; DBH_mean and DBH_std, average and standard deviation of diameters at breast height; DBH50, number of trees/ha with DBH ≥ 50 cm; H_mean and H_std, mean and standard deviation of tree heights; VOL, volume of living trees. Different letters indicate significant differences among groups based on the appropriate post hoc test selected after testing normality of residuals and homogeneity of variances for each variable, as described in the Section 2.3.

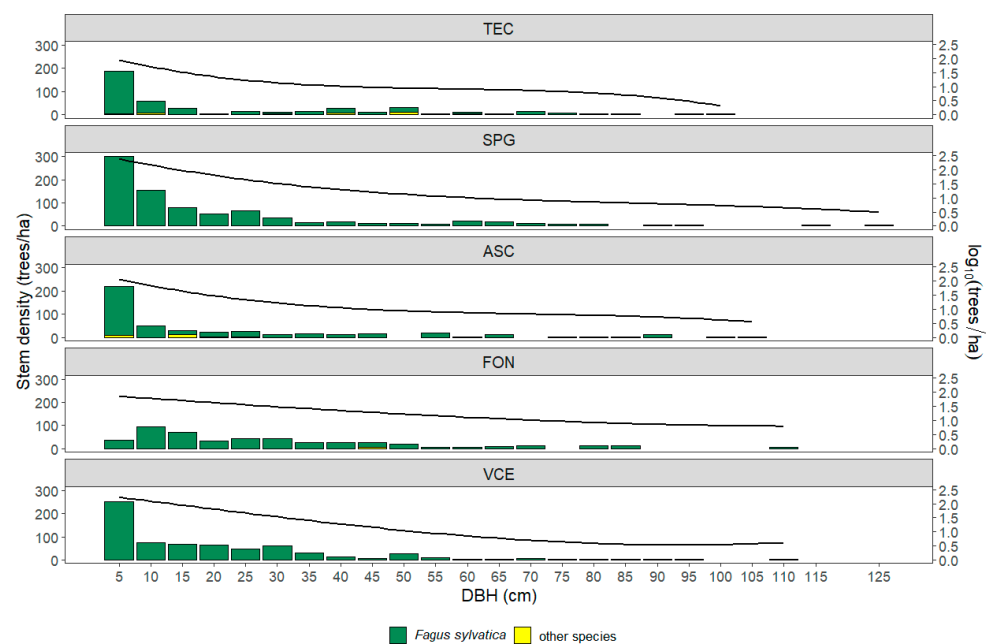


Figure 4. Tree diameter (DBH) distributions expressed as stem density (N/ha) in the COG (TEC and SPG) and ROG (ASC, FON and VCE) forests. *Fagus sylvatica* is shown in green and other species in yellow. The fitted curve (units on the right axis) represents a third-order polynomial model of $\log_{10}$ -transformed stem density.

Table 3. Quantitative descriptors of DBH-class distributions for each study site. Slope and R^2 refer to the $\log_{10}$ -transformed stem density–DBH-class relationship. All p -values < 0.05. The de Liocourt q coefficient and weighted skewness describe the decline and asymmetry of the diameter distribution, respectively.

Group	Site	Slope	R^2	de Liocourt q Coefficient	Weighted Skewness
COG	TEC	−0.013	0.52	1.159	1.208
	SPG	−0.015	0.81	1.182	2.039
ROG	VCE	−0.013	0.70	1.156	1.703
	ASC	−0.011	0.65	1.136	1.249
	FON	−0.018	0.84	1.227	1.841

Table 4. Mean values of deadwood attributes at COG and ROG forests.

Group	Site	SNAGS [m ³ /ha]	CWD [m ³ /ha]	STUMPS [m ³ /ha]	VOL Deadwood [m ³ /ha]	VOL Dead/Living [%]
COG	TEC	0.9	9.6	2.5	13.1	2.2
	SPG	6.4	12.6	3.6	22.6	3.5
ROG	VCE	10.9	12.8	3.0	26.8	4.6
	ASC	29.3	36.2	0.3	65.8	15.8
	FON	1.7	45.4	18.4	65.5	8.5

The visual inspection of the historical and current aerial images provided qualitative support for interpreting the changes occurred in forest cover and stand structure at the two COG sites over 70 years (1954–1978/1988–2024) (Figure 5). In the SPG, as in many high-elevation Apennine beech forests, in the 1954 imagery the canopy texture appears much less dense than today. The former isolated beech patches are currently embedded

within a younger forest matrix, likely resulting from the progressive reduction in pastoral use and following canopy closure due to tree crown enlargement and infilling of natural regeneration. In the TEC, the legacy of former pastoral use is less evident, as the canopy cover of dominant beech and Turkey oak (*Quercus cerris* L.) trees remained visually more stable over time, while adjacent open areas progressively developed into secondary forests. In both the SPG and TEC, field observations within canopy gaps proved the entrance of dense clusters of seedlings and saplings (Figure 6).

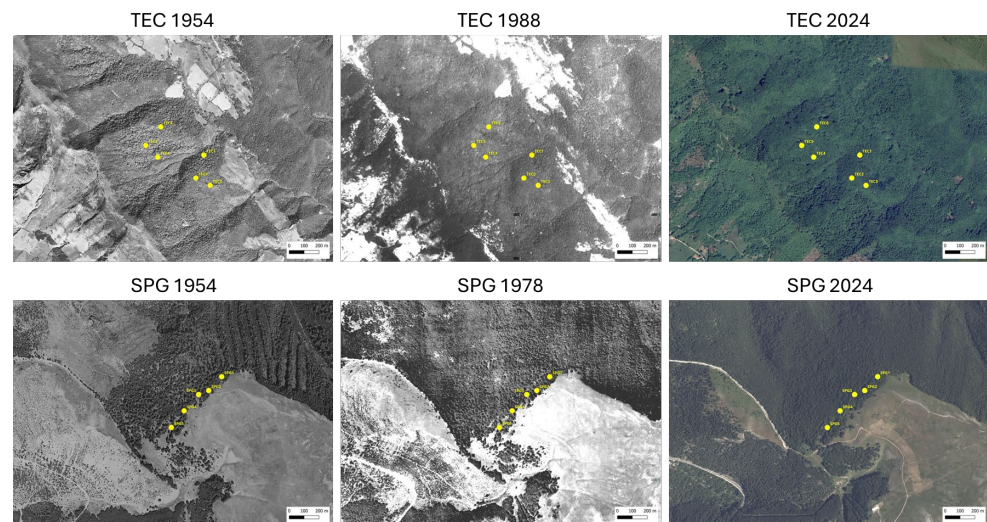


Figure 5. Forest cover changes over time from aerial (1954 and 1978–1988) and satellite (2024) imagery at the two COGs: Tecchie (TEC) and Spina di Gualdo (SPG). Yellow dots are sample plots.



Figure 6. Stand structures and natural regeneration in canopy gaps at TEC (above) and SPG (below) forests.

Cambial age is consistently higher at SPG, where all the sampled trees are older than those at TEC. The oldest tree at SPG counted 334 measured tree-rings, but we estimated 402 years due to the 45.7 mm distance to the missing pith. Also, other trees in this forest are older than 300 years. Conversely, at TEC the maximum estimated age of the oldest tree sampled was 128 years (Table 5). Other dominant trees are slightly older than one century. Mean ring width is therefore three times higher at TEC. Consequently, also for the common interval 1950–2024, pairwise annual basal area increments are significantly higher at TEC than at SPG (Figure 7). In particular, TEC and SPG respectively have interquartile ranges of

37.8–51.8 and 22.8–31.3 cm² tree^{−1} year^{−1}. From 2005 onward, growth at TEC declined to values similar to those at SPG.

Table 5. Main tree-ring series statistics of beech at the two COGs.

Site	Number of Trees	Series Interval (Years)	Mean Series Length (Years)	Max Estimated Age (Years)	Total Interseries Correlation	Interseries Correlation 1950–2023	Mean Ring Width ± SD (mm)
TEC	6	1897–2024	97	128	0.482	0.422	3.25 ± 2.1
SPG	5	1669–2024	281	402	0.361	0.522	1.14 ± 0.64

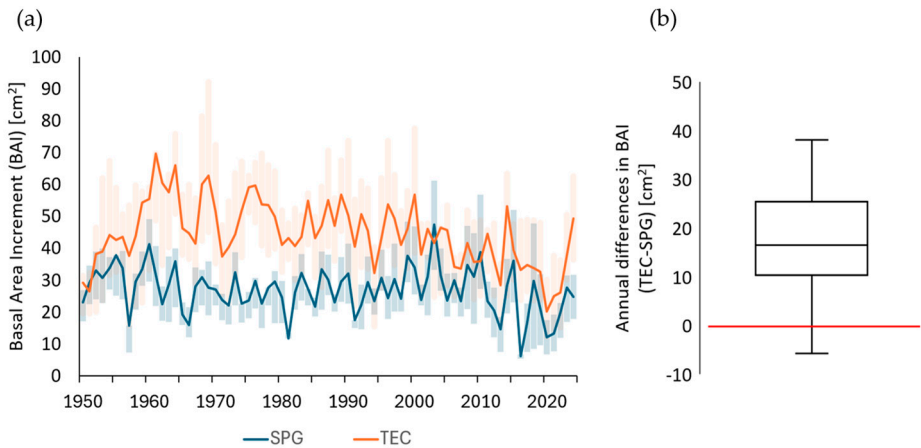


Figure 7. (a) Mean basal area increments (BAI) of the sampled trees at the two COG forests for the interval 1950–2023. Before 1950, trees at TEC were too young to provide a robust mean curve. The bars show the annual interquartile range among the sampled trees (5 at SPG and 6 at TEC). (b) Boxplot showing the distribution of annual BAI differences between TEC and SPG (central line represents the median). Differences are significantly different from zero (Wilcoxon signed-rank test, $p < 0.001$).

4. Discussion

The results highlighted a consistent gradient of structural diversity across the central Apennine beech forests: from simpler NFI to more complex COG and ROG forests. In particular, the TEC and SPG exhibit lower stem density, higher densities of large trees and higher standing volumes. The greater structural variability of COG and ROG stands involves more stratified canopy layers and therefore a higher potential for habitat diversity found in over-mature forests [38]. The observed gradient is consistent with studies from temperate and boreal forests worldwide, which identify structural heterogeneity as one of the principal attributes of old-growth conditions. In particular, i tree size variability and the presence of large trees frequently represent the main indices of old-growth structure because they integrate the cumulative effects of long-term natural disturbances, gap dynamics and the coexistence of multiple developmental stages within the same stand [39–42].

NFI stands are more homogeneous with higher stem density and lower DBH, tree height and standing volume variability. This pattern reflects the legacy of former land and forest use in the central Apennines. Here, beech forests were shaped for centuries by extensive coppicing to meet local communities’ needs and, more recently, by the abandonment of coppicing and the conversion to regular even-aged high forests, which maintain relatively simple stand structures for several decades. At even earlier times, beech forests were more expanded than today, but at higher elevations they were cleared for pasture and at lower elevations; the species was inhibited by overly short coppice rotation cycles [20,43]. Within this context, it is not easy nowadays to find residual forests with higher levels of naturalness. Nonetheless, the structural traits observed in the COG stands were largely

comparable to those of the ROG, considered as reference old-growth forests in the central Apennines. The tree frequency distribution is always a key parameter of forest structure and in fact both COGs, as well as two of the ROG forests (VCE and ASC), display a clear uneven-aged pattern (Figure 4). The log10 transformed frequency records produced negative exponential curves, which in the case of the SPG and TEC displayed two inflection points [44]—one associated with competition-driven mortality in younger trees and the other with senescence-related mortality in larger individuals, whose fall generates canopy gaps that favor natural regeneration. Several authors considered this particular structure common in old-growth forests of temperate regions [45–48]. Reverse J-shaped diameter distributions and high variability in tree dimension have been reported in old-growth forests across Europe, North America and East Asia, where they are generally interpreted as evidence of continuous regeneration, long-term absence of stand-replacing disturbances and the coexistence of multiple successional stages [49–52].

Despite these similarities, there are some relevant differences between COG and ROG forests, particularly in terms of deadwood. In ROG sites, especially in the VCE and ASC, deadwood volume is much higher than in COG stands. Although the TEC and SPG exhibit key attributes of structural complexity, they may not yet represent fully developed old-growth forests [53]. In the TEC, deadwood occurrence and “old-growth” features appear to be more influenced by site fertility and fast stand dynamics than by stand age and senescence. Silvigenetic processes seem accelerated and productivity is higher, with dominant tree height reaching the unusual value of 40 m, a condition that may increase susceptibility to mechanical instability and treefall.

One of the requirements for including a stand within the national old-growth forest network is an absence of at least 60 years of anthropogenic disturbances, namely pasture and wood harvesting. Historical aerial imagery proved to be very useful to verify such conditions. In the 1950s, the two COG beech forests both had a suitable forest canopy cover. The subsequent abandonment of agro-silvo-pastoral practices in the surrounding areas induced forest infilling and recolonization. These have been common processes in the Apennines over the last 70 years [20,54].

Dendrochronological analysis proved the different cambial ages and radial growth dynamics of the two COGs. The SPG hosts older trees, even exceeding 350 years that are the legacy of the “wood pastures” scattered trees [20,55,56]. These are historical semi-natural ecosystems combining pastures with sparse, often pollarded trees. In the Mediterranean mountain areas, nowadays these systems are marginal and threatened by the abandonment of traditional management [57]. In the TEC, canopy cover has remained more homogeneous through time because of faster tree growth, with trees reaching more than 1 m in DBH and 40 m in height in little more than a century (maximum age recorded = 128 years). This is a sub-montane beech forest, at a lower altitude and with fertile marl-sandstone substrates and good soil water availability that—particularly for beech [58,59]—are promoting growth rates and accelerating forest dynamic processes.

In general, the structural metrics of the oldest patches in the SPG and TEC fall within the ranges reported for European old-growth or primary beech forests. In particular, basal area ($63.5 \text{ m}^2 \text{ ha}^{-1}$ and $41 \text{ m}^2 \text{ ha}^{-1}$ respectively at the SPG and TEC) and the density of large trees ($\text{DBH} \geq 50 \text{ cm}$: 102 and 85 trees ha^{-1} , respectively) are comparable to values for old-growth *Abieti-Fagetum* stands in southeastern Europe, such as Perućica and Biogradska Gora in Montenegro ($60 \text{ m}^2 \text{ ha}^{-1}$; 87 trees ha^{-1}) and Lom and Janj in Bosnia-Herzegovina ($56 \text{ m}^2 \text{ ha}^{-1}$; 93.5 trees ha^{-1}) [5]. The fact that structural heterogeneity and large-tree abundance explain most of the variability among stands in our study is fitting with several continent scale assessments of old-growthness, which identify tree-size variability, the

density of large trees and deadwood accumulation as the most robust indicators of forest naturalness across a wide range of forest ecosystems [40–42,60].

However, considering the density of very large trees (DBH > 80 cm) the two COG forests (12.6 trees ha^{−1} in the TEC and 22.6 trees ha^{−1} in the SPG) featured lower values than the ones from southeastern European primary stands (~31 trees ha^{−1}) [5,60]. Moreover, the limited occurrence of senescent individuals and the relatively small size of canopy gaps indicate a limited expression of late-successional disturbance regimes [61]. Accordingly, the TEC and SPG could be better classified as secondary old-growth stands [54,62] or, following Buchwald's framework [3], as long-untouched forests (stage 5). This interpretation is consistent with studies showing that the development of fully expressed old-growth attributes may require many decades or even centuries following the cessation of management, while the long-term action of small- and intermediate-scale natural disturbances contributes to the development and maintenance of old-growth conditions by promoting structural heterogeneity and multiple developmental stages within forest stands [51,63–65]. Therefore, the detection and the strict conservation of these forests are essential to promoting the achievement of old-growth conditions especially in areas that have formerly undergone intensive agro-silvo-pastoral use. Overall, our results suggest that even small residual patches of structurally complex beech forests can still be found within managed forests of the central Apennines and may represent important hot spots within old-growth forest networks [47].

From a management perspective, priority should be given to the strict protection of these structurally complex islands. Closer-to-nature silvicultural practices could be applied, where necessary, only in the surrounding areas to establish protective buffer margins and accelerate the development of old-growth attributes and enhance stand resilience. In this context, closer-to-nature silviculture refers to management approaches that emulate natural forest dynamics through the retention of habitat trees and deadwood, the promotion of natural regeneration, maintenance of mixed and structurally heterogeneous stands, and the application of light and recurrent interventions rather than intensive harvesting [66–68]. In addition, connecting these high-natural areas through wildlife corridors and stepping-stones would help increase biodiversity [69]. Such strategies are particularly relevant for small forest patches such as the SPG (11 ha), where natural disturbance regimes operating within a limited area are unlikely to maintain the full spectrum of successional stages typical of large old-growth forests [61]. In general, the identification and protection of even small forest patches exhibiting advanced structural complexity may represent an efficient strategy for increasing the representativeness of old-growth forests in human-modified landscapes, particularly in Mediterranean regions, where millennia of management have drastically reduced the extent of primary and old-growth forests. Forest management plans should explicitly identify senescent patches within the larger forest matrix and exclude direct human disturbances in these areas to promote rewilding processes and the restoration of carbon-rich and highly biodiverse Mediterranean forests [70].

5. Conclusions

Our results provide a quantitative structural assessment of two candidate old-growth beech stands in the Marche region and show that both sites have several attributes commonly associated with old-growth conditions, including high structural heterogeneity, large trees, uneven diameter distributions and evidence of long-term canopy continuity. Overall, the structural attributes documented in both sites are consistent with the structural criteria defined by current national guidelines and support their recognition as structurally complex stands worthy of protection. However, the two COG forests found do not represent the most advanced stages of old-growth development. Their occurrence was favored by man-

agement abandonment within areas where human pressure significantly decreased over the last 70 years. Therefore, our findings suggest that some old-growth-related structural attributes may already appear or become more evident a few decades after management abandonment, especially where biological legacies such as large and old trees are already occurring. In the central Apennines, where forests have been largely shaped by centuries of coppicing and even-aged management, these stands represent rare and local examples of increasing structural complexity and naturalness. Their detection, assessment, and conservation contribute to enhancing forest heterogeneity and ecological functionality at the landscape scale. Detection and conservation of these stands should be a priority of regional forest policy and planning, and may also help enhance strict conservation, low-impact management, or closer-to-nature silviculture in surrounding stands to favor the development of old-growth attributes and the improvement of landscape connectivity.

Future studies should assess the current biodiversity value of these evolving old-growth stands more directly, particularly by integrating structural assessments with ecological indicators. In this context, the assessment and monitoring of structural attributes should be integrated with biodiversity evaluations, for instance through the inventory of tree-related microhabitats (TreMs), which are widely recognized as effective and reliable proxies of structural complexity, naturalness, ecological continuity and forest biodiversity potential [71–73].

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