

Variability in Silver Fir Growth in the Tuscan Apennine Alps in the 20th Century

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Abstract— Climate variables have shown that monthly mean temperature (MT) and monthly rainfall (MR) are non-stationary in the Tuscan Apennine Alps during the 20th century; similarity between trends in monthly climate variables varies irregularly through time at the seasonal and monthly scales, and site. High variability and anomalies in silver fir (*Abies alba* Mill.) growth have been observed in various regions of Europe and Italy. This scenario has suggested to investigate if tree-ring chronologies in silver fir vary among sites during the 20th century in the Tuscan Apennine Alps, if there are differences in tree-ring growth at upper and lower elevation within silver fir forests, and if there are anomalous or unexpected growth patterns in tree-ring chronologies of silver fir. Results shows that similarity in Residual Tree-rings series (RTRs) varies highly, frequently, and irregularly during the 20th century among sites and, to a lesser extent, within silver fir forest sites in the Tuscan Apennine Alps. Unexpected patterns of growth occur in silver fir in the last decades of the 20th century; and similarity between RTRs of the silver fir study stands tends to reduce with increasing distance among sites. Results recommend monitoring and extend this and similar investigations in the view of the climate change scenarios recently provided by research where the impacts on the viability and possibly shift of silver fir populations – and other species - in their southern European range rise serious concerns.

Keywords— silver fir, tree-rings, dendrochronology, forest management, climate change.

I. INTRODUCTION

Analysis of trends in climate variables in the Tuscan Apennine Alps have shown that monthly mean temperature (MT) and monthly rainfall (MR) are non-stationary during the 20th century. In particular, similarity between trends in monthly climate variables varies irregularly through time at the seasonal and monthly scales, and site (Brunetti et al, 2006; D'Aprile et al., 2010; D'Aprile et al., 2011). In this contest, it can be pointed out that variations in trends and/or in values of climate

variables that may occur at different elevation within forests would not be detected by meteorological stations although different growth response can take place in stands at the upper and lower margins of forests.

High variability and anomalies in silver fir (*Abies alba* Mill.) growth have been observed in various regions of Europe and Italy. Actually, changes in the climate-growth relationships have been verified during the 20th century in Europe (Pretzsch et al., 2014; Linder et Calama, 2013; Bertini et al, 2011). For example, silver fir forests show a strong decrease in radial growth from the late 1950s to the 1970s in Slovenia (Torelli et al., 1999) and from the 1970s to the 1990s in Poland (Podlaski, 2002). Moreover, non-stationary responses of tree-ring chronologies to climate have been identified in the European Alps (Leonelli et al., 2011), and anomalous growth trends in silver fir have been identified since the 1960s in the Lower Bavarian region of Germany (Wilson et Elling, 2004) and in the Central Apennine Alps of Italy (Gallucci et Urbinati, 2009). And, changes in tree-growth response to climate changes are expected to occur in the 21st century (Walther et al, 2005; Battipaglia et al., 2009). Thus, influence of MT and MR on silver fir growth was expected to occur in the Tuscan range of silver fir, which is mainly located in the Apennine Alps; non-stationary similarity in trends of monthly climate variables could have different influence on tree-ring growth among silver fir stands in the study area.

This scenario would suggest three main questions:

- do tree-ring chronologies in silver fir vary among sites during the 20th century in the Tuscan Apennine Alps?
- are there differences in tree-ring growth at upper and lower elevation within forests?
- are there anomalous or unexpected growth patterns in tree-ring chronologies of silver fir in the study area in the 20th century?

In this study, I describe the tree-ring chronologies sampled at all sites in the study area and verify the presence of trends, test the level of association in tree-ring

chronologies within and between forest sites, and analyse whether the association between tree-ring chronologies during the 20th century among the study stands are stationary.

II. THE STUDY AREA

2.1 The meteorological stations

The climate pattern in the Tuscan Apennine Alps is classified as a Mediterranean montane with relatively mild summer, and rainfall tends to provide moisture

enough to not cause drought. Winter is cold and frequently snowy; the permanence of snow varies from weeks to months. The meteorological stations that are located at the silver fir forests of Abetone, Camaldoli, La Verna, and Vallombrosa in the Tuscan Apennine Alps are shown in Fig. 1.1; distances between the meteorological stations and their elevation, and periods of climate data available are shown in Table 1.1. The site names are abbreviated respectively as ABE, CAM, LAV, and VAL.

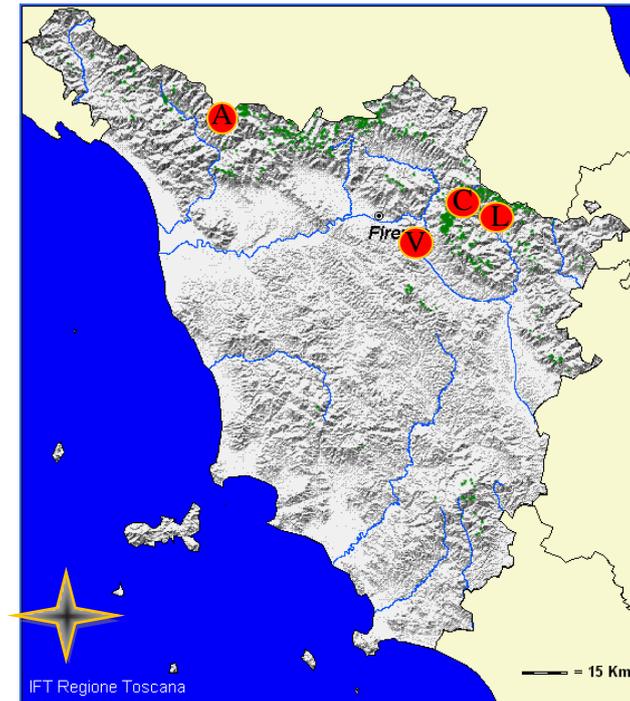


Fig.1.1: Location of the meteorological stations on tops of the Tuscan Apennine Alps. A is Abetone, C is Camaldoli, L is La Verna, and V is Vallombrosa.

Table.1.1: UTM coordinates, elevation, distance, and periods of climate data available of the meteorological stations in the Tuscan Apennine Alps. The climate data series cover different time periods. Notation ⁽¹⁾ is for CREA- Research centre for Forestry and Wood, notation ⁽²⁾ is for the 'Annals' (ex-Hydrography Office of Pisa, Ministero dei Lavori Pubblici, Italy)

Meteo Station	Coordinates UTM	Elevation of meteo station (m. asl)	Distance between meteo stations (km)			Periods of data available	
			LAV	CAM	VAL	Temperature	Precipitation
ABE	4889150.00N 633615.00E	1340	112.3	100.1	84.6	1934-1996	1931-2000
LAV	4843695.00N 736295.00E	1120		13.2	30.4	1956-1990	1924-2006
CAM	4853040.00N 727035.00E	1111			22.3	1885-1993 ⁽¹⁾ 1925-1996 ⁽²⁾	1885-1993 ⁽¹⁾ 1931-1996 ⁽²⁾
VAL	4845450.00N 706000.00E	955				1872-1989 ⁽¹⁾ 1933-2006 ⁽²⁾	1872-1989 ⁽¹⁾ 1932-2006 ⁽²⁾

2.2 The silver fir stands

Silver fir in the Apennine Alps is at its southern range limit, where most of the silver fir forests are restricted to

the tops of the mountains. In these sites, silver fir forests are likely to provide a particularly sensitive record of climate variation. Within the region, only a few silver fir

forests have a relatively long history of continuous management and regeneration, where a suitable number of stands with old firs can be found and where management and climate data have been regularly recorded and collected. Based on the distribution and availability of meteorological stations and suitable silver fir forests, I identified four main study sites: ABE (north-western Tuscany), CAM and LAV (south-eastern Tuscany), and VAL (central-south-eastern Tuscany) (Fig. 1.1). Their respective climate patterns are similar among sites, although the values of climate variables vary with site.

The meteorological stations are located within the borders of each forest, and therefore the distances between meteorological stations correspond to the distances between sites (Table 1.1).

Among the suitable silver fir forests in the Apennine Alps, there is variation in site quality, species composition, stand age and structure, and management history. In addition to meteorological data, I used the following criteria to select stands at the study sites:

- a) primarily silver fir;
- b) stand surface >2 ha;
- c) age >100 years;

Table.1.2: Upper and lower elevation and relative gradient of elevation within forest site, prevailing aspect, mean slope, topography, and age of the study stands in the study area. The age refers to the year 2007.

Forest stand	Elevation of stand (m asl)	Elevation gradient (m)	Aspect	Mean slope	Topography	Age (years)
ABE-Upper	1445	165	SE	32%	Ridge	>180
ABE-Lower	1280		SE	17%	Along ridge	116
LAV-Upper	1204	46	SES	50%	Close to peak	>150
LAV-Lower	1158		SES	40%	Along slope	>150
CAM-Upper	1130	70	S	20%	Along ridge	109
CAM-Lower	1060		S	58%	Along slope	106
VAL-Upper	1113	210	N	40%	Along ridge	117
VAL-Lower	903		N	30%	Ridge	105

2.2.2 Tree sampling

Within each stand 14 trees were selected by applying these criteria:

- a) social position (dominant and co-dominant trees were selected; suppressed trees were excluded) (Pinto et al, 2008);
- b) stem condition (trees with external evidence of damage were excluded); and
- c) crown shape and development (strongly asymmetric trees were excluded).

In each tree, two tree core samples perpendicular to the main slope were extracted with a tree corer ~1.3 m above the ground; stem diameters perpendicular to the slope were measured; and crown class and position were taken along the transect elevation gradient.

- d) similar silviculture and management within each forest;
- e) availability of stand management records;
- f) within each forest, similarity in site characteristics (i.e., exposure, drainage, geology) within the bound of highest potential elevation gradient;
- g) between forests, highest potential elevation and latitudinal gradients.

2.2.1 Elevation of the forest stands

The elevation of the selected forests shows an average span of 385m (Table 1.2), with a difference of 542m between the upper stand at ABE (ABE-Upper) and the lower stand at VAL (Table 1.2); the elevation gradient between study stands within forest differs among forests. CAM and LAV are relatively close (about 13 km) and the meteorological stations have similar elevation (Table 1.1) but they differ in site characteristics, topography, geology, composition, and silviculture, and especially in the elevation gradient of the study stands between the two forests, whereas the difference between the lower at CAM (CAM-Lower) and the upper at LAV (LAV-Upper) is 144m.

III. METHODS

I used matrix correlation (MC) to test the average level of association in residual tree-ring chronologies (RTRs) within and between forest sites, and agglomerative hierarchical clustering (AHC) to verify how RTRs tend to group among sites (Piovesan et al., 2005; Leal et al., 2008; Oberhuber et al., 2007). MC and AHC show the level of similarity within forest sites and among sites and its variability with distance among sites. However, these statistics do not show if similarity between tree-ring growth series is stationary during the 20th century within and/or among forests sites.

The presence of periods or cycles 3.9, 5.0, 6.0, 8.3 and 13.3 years has previously been observed in silver fir tree-ring growth in Italy (Schirone, 1992). So, I verified if any cycle in RTRs is present at the study sites also. The

presence of cycles in RTRs could be used to verify whether any period in RTRs relates to periods in MT and/or MR in order to provide a lag for moving averages. In fact, moving averages are frequently used in the analysis of climate-tree-ring growth relationships. Thus, I used spectral (Fourier) analysis to investigate the presence of peak periods common to all the RTRs chronologies. I tested the variability in similarity of RTRs during the 20th century within and among the study stands by applying the Pearson's correlation to moving averages between paired series of RTRs, where the time lags shown by spectral analysis were implemented.

3.1 Tree-ring sample preparation for dating

I prepared 224 core samples extracted from the eight-silver fir stands at four study sites to observe variation in growth ring widths and wood anatomical features and ensure accurate dating for climate analysis by using standard dendrochronological techniques (Stokes and Smiley, 1996; Fritts, 1976; Cook and Kairiukstis, 1990). Cores were mounted and glued onto grooved boards and sanded to a mirror finish using progressively finer grade sandpaper (120, 280, 400, 600, 800 grit) to produce flat surfaces where the ring boundaries are clearly defined under magnification. Then, I scanned the cores with a high-resolution digital scanner at 1600-2400 dpi; ring width was measured to 0.01mm precision.

3.2 Cross-dating of tree-ring chronologies

Cross-dating is key to the development of robust chronologies for climate analyses. In this research, I cross-dated the tree-ring series by using a digital image analysis system (WinDENDRO, Regent Instruments Inc., Canada). Then, I analyzed statistically the visual cross-dating by using COFECHA (Holmes, 1983) under the protocols described by Grissino-Mayer (2001). Core samples that could not be reliably cross-dated were excluded from further analyses.

3.3 The statistics in cross dating

Various statistics were calculated to describe each chronology of the silver fir stands sampled:

- mean sensitivity (MS), a measure of the mean relative change between adjacent ring widths calculated over the whole tree-ring series (Fritts, 1976);
- tree-ring standard deviation (SD): MS and SD assess the high-frequency variation of the series;
- first-order serial autocorrelation (AC) detects the persistence retained before and after the standardization;
- mean correlation between trees (Rbar);

- common variance among the individual tree-ring series explained by the "Expressed Population Signal" (EPS) (Wigley et al., 1984).

The quality of cross-dating was assessed with the EPS and the running Rbar. When some tree-ring chronologies did not cross-date well in the same individual or between trees, I excluded it from further analyses to select the best subset of tree-ring series in each silver fir stand in the study area. To do this, I compared each individual tree-ring series with the mean correlation of all the tree-ring series of the respective stand and removed those chronologies that would reduce the higher correlation of the master series and lower the EPS chronology.

3.4 Standardization of tree-ring chronologies

Growth trends partially depend on the biological development of the tree and their screening may enhance the variability in tree-ring growth related to the influence of climate factors (Fritts, 1976). For example, sharp changes in tree growth could be due to cultural interventions such as thinning, local disturbances caused by wind storms, heavy snow, or insect attack. Among the numerous factors likely to influence ring width, age has the primary role (Fritts, 1976). This precludes the direct comparison of trees and stands of varied ages and the identification of the influence of the other factors. The commonest way to circumvent this difficulty is to transform each measured ring width into a growth index which is most frequently expressed in percent, the ratio of each actual width versus a reference values previously established for the corresponding current ring age (cambial age). To reduce the effects of similar disturbing factors, standardization of tree-ring chronologies aims to highlight the variability in tree-ring growth due to climate variability by building curves that are meaningful to dendrochronological analysis.

I used the computer program ARSTAN (Cook and Holmes, 1984) to standardize the tree-ring series by applying a multi-step approach that accounts for both the age-related growth trend and other factors such as past disturbances to further reduce the influence of non-climatic factors. All tree-ring series were initially transformed to series of dimensionless indices with a mean of one and stabilized variances using an adaptive power transformation (Cook and Kairiukstis, 1990; Druckenbrod and Shugart, 2004). This enabled the tree-ring series to meet the assumptions of normality and equal variance required for subsequent regression analyses with the climate variables (Cook and Holmes, 1984). Then, first-detrending was applied to all the sets of tree-ring chronologies by using Hugerhoff polynomial curves to standardize each individual tree-ring series with a 50-year spline. A 50-year spline curve was adopted to amplify the climate signal (high frequency) by removing the effects of

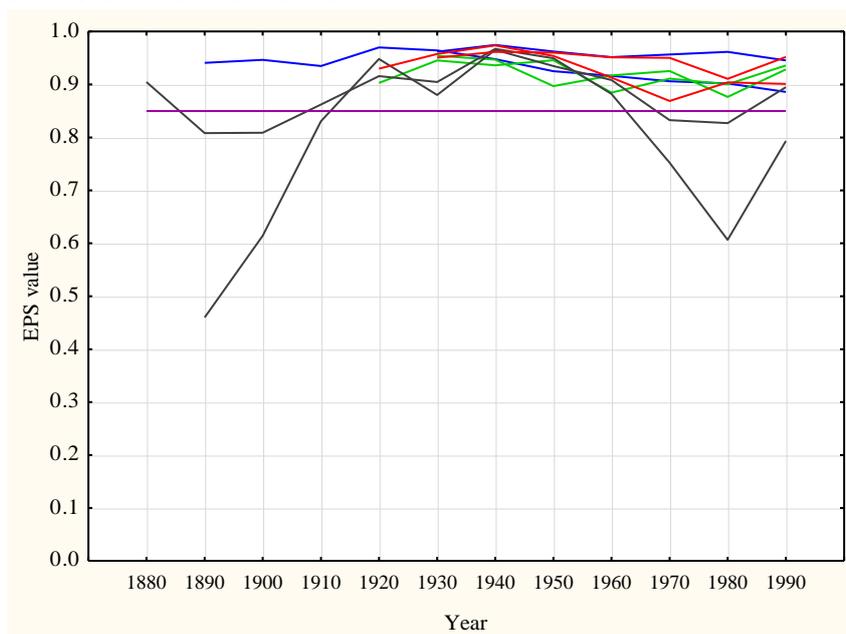
non-climate factors (low frequency) (Fritts, 1976; Cook and Peters, 1997, Chhin and Wang, 2005). Each series was modelled through a self-regression process where the order was selected on the basis of the minimum AIC (*Akaike Information Criterion*). So, the variance due to width measures distant from mean values was stabilised. Because a smoothing spline is a moving average of localized regressions, the choice of window size is important - a long window gives a stiff spline that removes low frequency variation, while a short window gives a flexible spline that may remove low and high frequency variation (Cook and Holmes, R. L., 1984). Therefore, I repeated this procedure by using a 20-year smoothing spline, but results did not substantially differ. Non-climatic factors that influence tree growth may result in autocorrelated growth trends in the series, where trees show a lagged growth response to growing conditions in previous years. Since environmental conditions in year t may influence growth in years $t + 1$, $t + 2$, to $t + n$ (i.e., autocorrelation) and correlation analysis with climate variables assumes that all observations are independent, an autoregressive modelling procedure was used to remove autocorrelation from individual tree-ring series and identify patterns of autocorrelation common to the

sample population. To account for autocorrelations, the detrended tree-ring series were pre-whitened using autoregressive modeling (AR). Autocorrelations were determined for each series and then removed. Then, all series were compared to identify any common autocorrelation components, which were then added back into the detrended series. To do this, all of these series were detrended and corrected for autocorrelated growth trends; I used a bi-weight robust mean to combine them into a final autoregressively standardized (ARSTAN) chronology. In this research, I used the residual chronologies to assess the variability between tree-ring chronologies and site related factors.

IV. RESULTS

4.1 Expressed Population Signal (EPS)

Both the EPS and Rbar were calculated by 50-year lags and 20-year lags with overlaps of 25 years and 10 years, respectively. Figure 1.2 shows EPS and Rbar of the tree-ring chronologies from each silver fir stand at the study area and their years of occurrence. In all cases, the EPS value is greater than the threshold value of 0.8 during the 20th century.



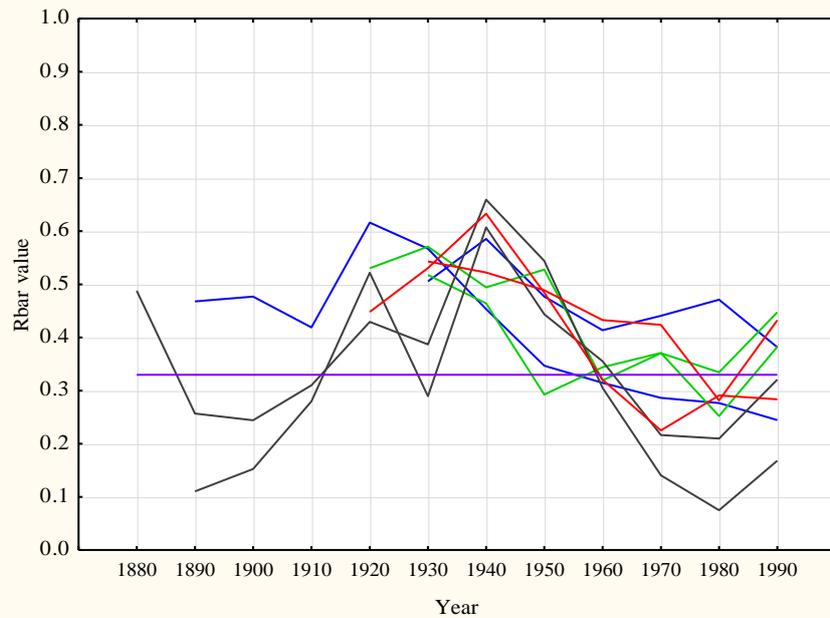


Fig.1.2: EPS (above) and detrended Rbar (below) in all the silver fir stands selected at the study site are calculated with 20-year lags and overlaps of 10 years. The magenta horizontal lines are respectively EPS equal 0.85 in the EPS graph (above) and mean interseries correlation equal 0.33 at the significance level 99% in the Rbar graph (below). Upper and lower ABE is blue, upper and lower CAM is green, upper and lower LAV is black and upper and lower VAL is red.

4.2 Master series of tree-ring chronologies of the silver fir stands in the Tuscan Apennine Alps

Descriptive statistics of tree-ring series for all the silver fir stands in the study area are shown in Table 1.3.

In this analysis, a cubic smoothing spline with 50% wavelength cut-off for filtering 32 years was used; segments examined are 50 years lagged successively by 25 years. Autoregressive modelling as applied and residuals were used in master dating series and testing. Absent rings were omitted from master series and segment correlations.

Normally, a coefficient of mean series intercorrelation >0.33 is conventionally used to accept a master series of tree-ring chronologies (Holmes, 1983; Grissino-Mayer, 2001). However, I increased this critical value to >0.50 to improve the quality of the master series from the silver fir stands in the study area. Results show (Table 7.1) that this coefficient is normally >0.6 in all the stands in the study area except LAV-Lower (0.575).

Therefore, the quality of cross-dating and the subsequent representativeness of tree-ring growth appear high at the study sites selected in the Tuscan Apennine Alps.

Table.1.3: Characteristics of the mean tree-ring chronologies of the silver fir stands in the study area. N is 'number of ring-width series', MRW is 'mean ring width', RW is 'ring width', 'standard deviation' is SD, 'first-order autocorrelation' is AC, 'mean sensitivity' is MS.

Stand	N	Mean series length	Mean series intercorrelation	MRW	Max RW	SD	AC	MS
ABE-Upper	2892	117	0.668	1.60	7.39	1.012	0.893	0.225
ABE-Lower	2517	107	0.699	2.18	6.32	0.898	0.821	0.171
CAM-Upper	1997	82	0.651	2.53	16.39	1.403	0.785	0.260
CAM-Lower	1490	61	0.665	2.56	7.71	1.273	0.784	0.245
LAV-Upper	2019	83	0.617	2.18	8.87	1.199	0.834	0.265
LAV-Lower	2175	89	0.575	2.58	11.43	1.465	0.822	0.268
VAL-Upper	2139	88	0.680	2.36	8.25	1.017	0.723	0.237
VAL-Lower	2149	89	0.619	2.04	7.48	0.846	0.769	0.205

4.2.1 Abetone: Silver fir stands ABE-Upper and ABE-Lower

Stand ABE-Upper (m1445 asl) is the upper site at Abetone and the higher in elevation among the silver fir

stands in this study. ABE-Lower (m1280 asl) is the lower stand at Abetone but is at a higher elevation than all the other stands except ABE-Upper (Table 1.4).

Table.1.4: Characteristics of master series of tree-ring chronologies in the stands ABE-Upper and ABE-Lower.

Silver fir stand	ABE-Upper	ABE-Lower
Number of dated series	24	28
Master series	1864–2007, 144yrs	1901–2007, 107 yrs
Total rings in all series	2892	2517
Total dated rings checked	2891	2508
Mean length of series	120.5	89.9
Portion with two or more series	1865/2007, 143yrs	1910/2007, 98yrs

4.2.2 Camaldoli: Silver fir stands CAM-Upper and CAM-Lower

At Camaldoli, stand CAM-Upper (m1130asl) is the upper and CAM-Lower (m 1060 asl) is the lower one. Both these stands (Table 1.5) are at lower elevation than the

stands at La Verna. This reduction in the number of tree-ring series was caused by decayed rings in intermediate traits of the core samples that made crossdating ineffective. Missing rings were not found in CAM-Upper and CAM-Lower.

Table.1.5: Characteristics of master series of tree-ring chronologies in the upper and lower stands at CAM.

Silver fir stand	CAM-Upper	CAM-Lower
Number of dated series	21	18
Master series	1901-2007, 107 years	1909-2007, 99 years
Total rings in all series	1997	1490
Total dated rings checked	1994	1490
Mean length of series	95.1	82.8
Portion with two or more series	1904–2007, 104 years	1909–2007, 99 years

4.2.3 La Verna: Silver fir stands LAV-Upper and LAV-Lower

The tree-ring chronologies from La Verna are (Table 3.4) the longest after ABE-Upper (Table 1.6). Silver fir at LAV appears much older than 150 years; however, longer chronologies could not be extracted because of the

internal decay that affects many trees from the inner trunk outward. Decayed wood caused also some cores to be discarded as unsuitable for crossdating and some cores to not crossdate at an acceptable quality level for this analysis

Table.1.6: Characteristics of master series of tree-ring chronologies in the stands LAV-Upper and LAV-Lower.

Silver fir stand	LAV-Upper	LAV-Lower
Number of dated series	18	19
Master series	1864-2007, 144 yrs	1859-2007, 149 yrs
Total rings in all series	2019	2175
Total dated rings checked	2016	2171
Mean length of series	112.2	114.5
Portion with two or more series	1867–2007, 141 yrs	1863–2007, 145 yrs

4.2.4 Vallombrosa: Silver fir stands VAL-Upper and VAL-Lower

The lower stand at Vallombrosa shows longer continuous time span and mean length of tree ring chronologies than the upper stand (Table 1.7).

Table.1.7: Characteristics of master series of tree-ring chronologies in the stands VAL521 (upper) and VAL460 (lower).

Silver fir stand	VAL-Upper	VAL-Lower
Number of dated series	26	23
Master series	1909–2007, 99 yrs	1895–2007, 113 yrs
Total rings in all series	2139	2149
Total dated rings checked	2138	2146
Mean length of series	82.3	93.4
Portion with two or more series	1910–2007, 98 yrs	1898–2007, 110 yrs

4.3 Trends in master tree-ring chronologies at all study sites

The raw ring-width chronologies, standardized chronologies, residual chronologies, and autoregressively standardized chronologies of silver fir from the sites in the Tuscan Apennine Alps during the 20th century show the patterns of growth (Figures 1.3–1.6).

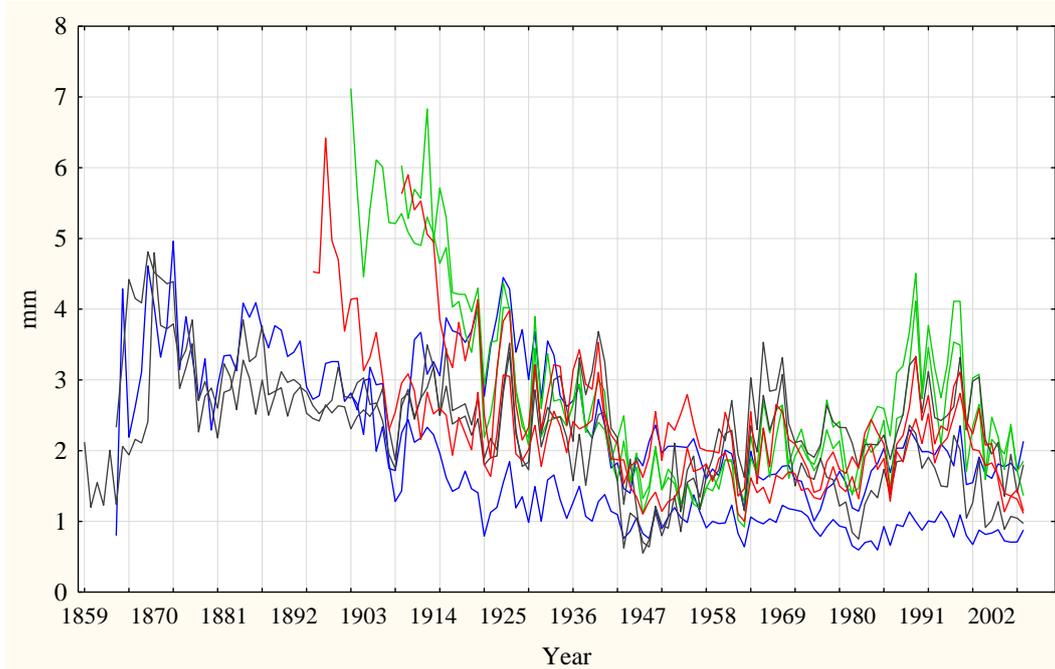


Fig.1.3: Raw tree-ring width chronologies from the late 1850s to the year 2007 in all the silver fir stands in the study area. Upper and lower ABE is blue, upper and lower CAM is green, upper and lower LAV is black and upper and lower VAL is red.

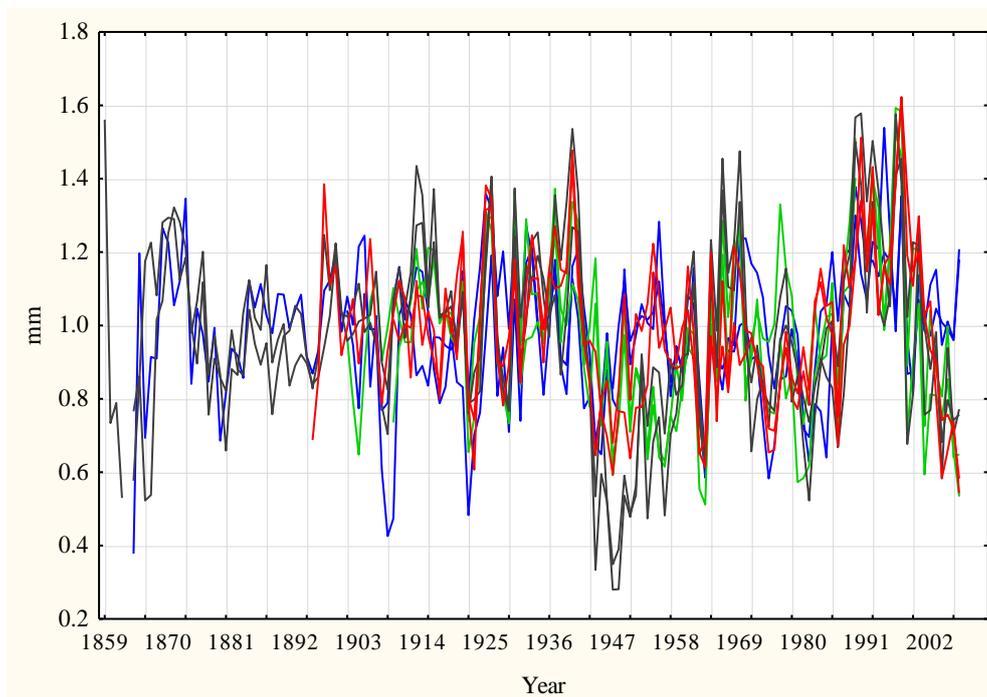


Fig.1.4: Standardized tree-ring width chronologies from the late 1850s to the year 2007 in all the silver fir stands at the study area. Upper and lower ABE is blue, upper and lower CAM is green, upper and lower LAV is black and upper and lower VAL is red.

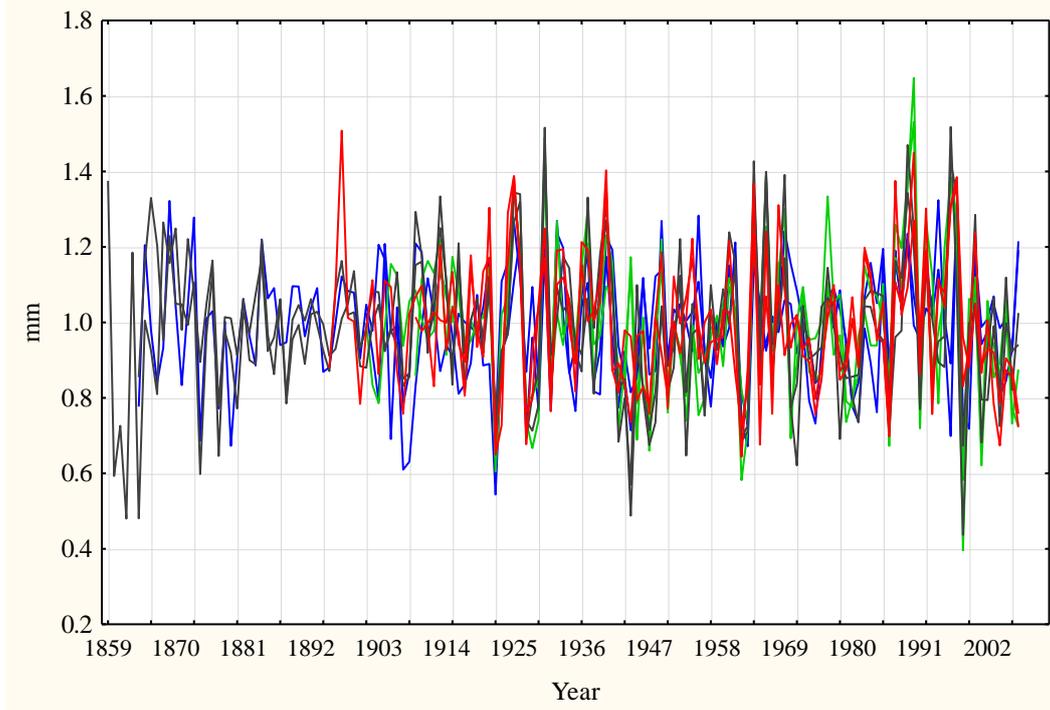


Fig.1.5: Residual tree-ring width chronologies from the late 1850s to the year 2007 in all the silver fir stands at the study area. Upper and lower ABE is blue, upper and lower CAM is green, upper and lower LAV is black and upper and lower VAL is red.

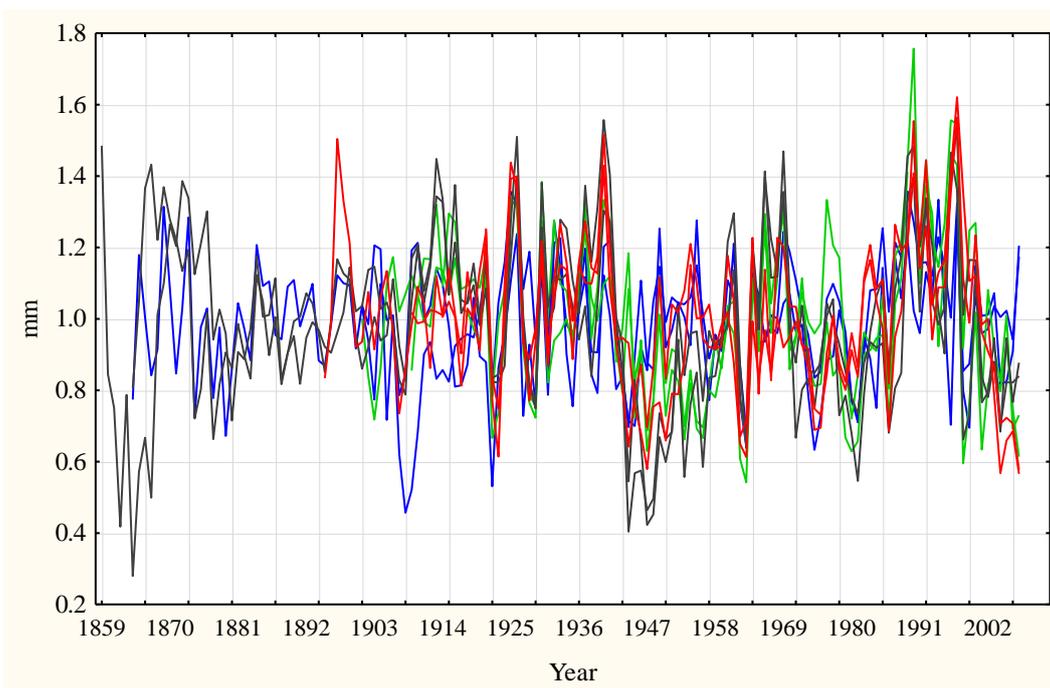


Fig.1.6: ARSTAN tree-ring width chronologies from the late 1850s to the year 2007 in all the silver fir stands at the study area. Upper and lower ABE is blue, upper and lower CAM is green, upper and lower LAV is black and upper and lower VAL is red.

The growth curves that underlie the raw ring width chronologies show that a negative exponential curve is appropriate for standardisation in all the silver fir stands sampled in this study; this growth pattern is typical of pure, even-aged conifer stands (Speer, 2010; Bernetti, 1998; Fritts, 1976). The curves show a markedly different

slope until the 1930's, which is more pronounced in the younger stands (CAM and VAL) with respect to the older ones (ABE and VAL). The silver fir stands at LAV, especially LAV-Lower, could not show the first years - or decades - of growth because of the decay in the inner trunk. Although silver fir at LAV is currently managed as

an uneven-aged stand mixed with broad-leaved tree species (e.g., *Fagus sylvatica* L.); historical records suggest that these forests were probably even-aged during the previous centuries.

4.4 Periods in residual tree-ring chronologies in the Tuscan Apennine Alps

The presence of cycles or periodicity in the RTRs was tested by spectral (Fourier) analysis. Results show periods that occur more frequently in all the silver fir stands. Principal periods are 3.00, 3.96, 4.95, 5.82, 7.07, 12.38-14.14 (average 13.26), 19.80, 24.75, and 33.0 years of length (Table 1.8). They appear to differ little from those found in silver fir radial growth in southern Italy (province of Isernia) by Schirone et al. (1992) where cycles 3.93, 5.00, 6.00, 8.28, and 13.33 years were detected; the 8.28-years and 3.93-years periods would show higher frequency. It can be noted that the 13.3-years period in southern Italy is the average between the 12.4-years and 14.1-years period in the Tuscan sites, and the 8.28-years period observed in southern Italy occurs also in the study area (8.25-years).

I noted that:

- the periods 14.1, 49.5, and 99.0 years are multiples of the period 7.1 years, which is a

common sub-dividend among the various periods; and, the periods 49.5 years and 99.0 years are nothing but multiples of the period 24.75 years (Table 1.8);

- the periods 7.07-years and 33.0-years, which are detected in the RTRs in the study area, differ little from submultiples of the Atlantic Multidecadal Oscillation (AMO), which has a cycle of 70 years;
- the 11.0-year period (Table 1.8) corresponds to the Hale hemi-cycle (solar sunspots);
- the 18-19 years period has length similar to the North Atlantic Oscillation (18 years) or the lunar node cycle; and
- the periods 9.00 years (secondary peak) and 19.8 years are also present in the RTRs during the study period observed.

Although these potential coincidences – or similarities – do not prove the existence of a direct influence of solar-terrestrial physical factors on silver fir growth in the study area, still spectral (Fourier) analysis of RTRs would suggest the presence of regular cycles or periods where length is a multiple of approximately 7-years periods.

Table.1.8: Periods (years) that occur most frequently in the RTRs as shown by spectral (Fourier) analysis. Peak periods are shown by yellow cells; secondary peaks are shown by grey cells.

ABE Upper	ABE Low	CAM Upper	CAM Low	LAV Upper	LAV Low	VAL Upper	VAL Low
99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0
49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5
33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
24.8	24.8	24.8	24.8	24.8	24.8	24.8	24.8
19.80	19.8	19.8	19.8	19.8	19.8	19.8	19.8
16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4
11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9
9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
7.1	7.1	7.1	7.07	7.1	7.1	7.1	7.1
6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30
4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96
3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54
3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19
3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.83
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68
2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02

4.5 Association between tree-ring chronologies within and among sites in the Tuscan Apennine Alps

4.5.1 Matrix correlation tests of tree-ring chronologies from the study sites

Matrix correlation tests provide a first insight into the overall level of association between tree-ring series within

and among forest sites (Table 1.9). However, this statistic does not show if similarity is stationary over time in tree-ring series between upper or lower stands either within forests and among sites.

Table.1.9: Pearson's r matrix correlation of RTRs among the silver fir stands in the study area. The period 1909-2007 is common to all the tree-ring chronologies. All the correlations are significant at p-value <0.0001 and significance level alpha 0.05.

	ABE Upper	ABE Lower	CAM Upper	CAM Lower	LAV Upper	LAV Lower	VAL Upper	VAL Lower
ABE-Upper	1.00	0.67	0.43	0.39	0.47	0.48	0.44	0.39
ABE-Lower	0.67	1.00	0.52	0.57	0.52	0.45	0.55	0.49
CAM-Upper	0.43	0.52	1.00	0.86	0.73	0.72	0.69	0.60
CAM-Lower	0.39	0.57	0.86	1.00	0.72	0.73	0.71	0.64
LAV-Upper	0.47	0.52	0.73	0.72	1.00	0.86	0.65	0.56
LAV-Lower	0.48	0.45	0.72	0.73	0.86	1.00	0.64	0.57
VAL-Upper	0.44	0.55	0.69	0.71	0.65	0.64	1.00	0.82
VAL-Lower	0.39	0.49	0.60	0.64	0.56	0.57	0.82	1.00

Results show that the association between RTRs from upper and lower silver fir stands at the same site is always higher than among sites (Table 1.9). Within the study sites, the Pearson's r coefficient is >0.83 at CAM, LAV, and VAL except at ABE where r is 0.67. Instead, the level of association among the study sites appears to weaken with increasing distance; in fact, r is >0.57 and <0.73 at CAM, LAV, and VAL and <0.57 at ABE.

4.5.2 Agglomerative hierarchical clustering of tree-ring chronologies in the study sites

Agglomerative hierarchical clustering (AHC) was used to show how RTRs tend to group among the silver fir stands in the study area (Fig. 1.7). Results show higher association between tree-ring growth within sites and decreasing association among sites with increasing distance. To verify if different kinds of clustering were shown by different methodological approaches to AHC, the AHC tests were performed by both the Pearson- r and Euclidean distance measures. The linkage rules 'single linkage', 'complete linkage', and 'unweighted pair-group average' were applied. Results differ very little from those shown in Figure 1.7.

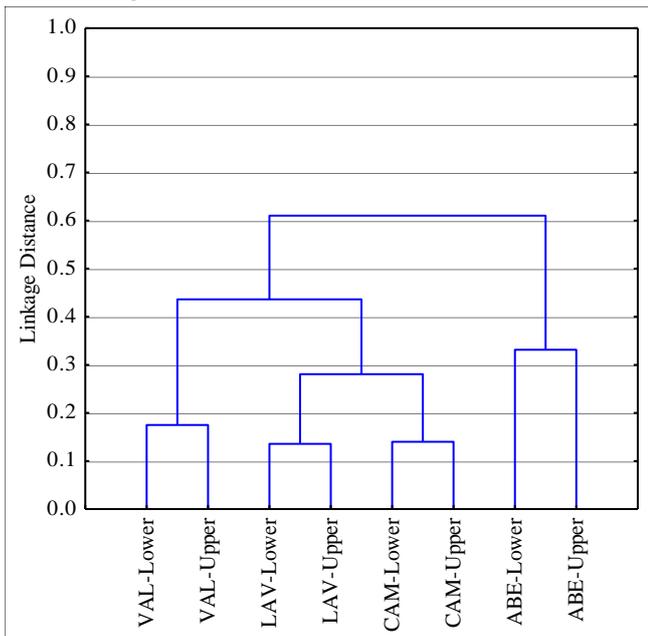


Fig.1.7: Agglomerative hierarchical clustering of RTRs in the period 1909-2007 from the silver fir study stands in

the study area. The test is based on the Pearson's r coefficient, method "complete linkage".

4.5.3 Moving averages of Pearson's correlation coefficients

The presence of a sub-period about 7 years in the RTRs would suggest using it as a time-lag (temporal window) in the Pearson's r correlations of 7-years moving averages of paired RTRs. Results show that similarity in RTRs during the 20th century in the study area (Figures 3.7, 3.8, and 3.9) is more non-stationary among sites than within forest sites. Figure 1.8 shows that r between upper and lower silver fir stands within sites is normally >0.60 and <0.98 but it drops frequently to <0.60 at ABE and VAL, and at LAV in the 1970s. In particular, similarity between RTRs strongly reduces at VAL in the mid-1940s and in the late 1950s. Before the 1920s, similarity in RTRs between upper and lower stands within sites is null or very weak and correlation coefficients show even negative values at all sites. At LAV, similarity appears very strong although this may be due to little difference in elevation between the upper and lower stands, where low similarity at CAM and VAL before the 1920s might be related to the young age of silver fir. At ABE also the lower stand is younger than the upper stand.

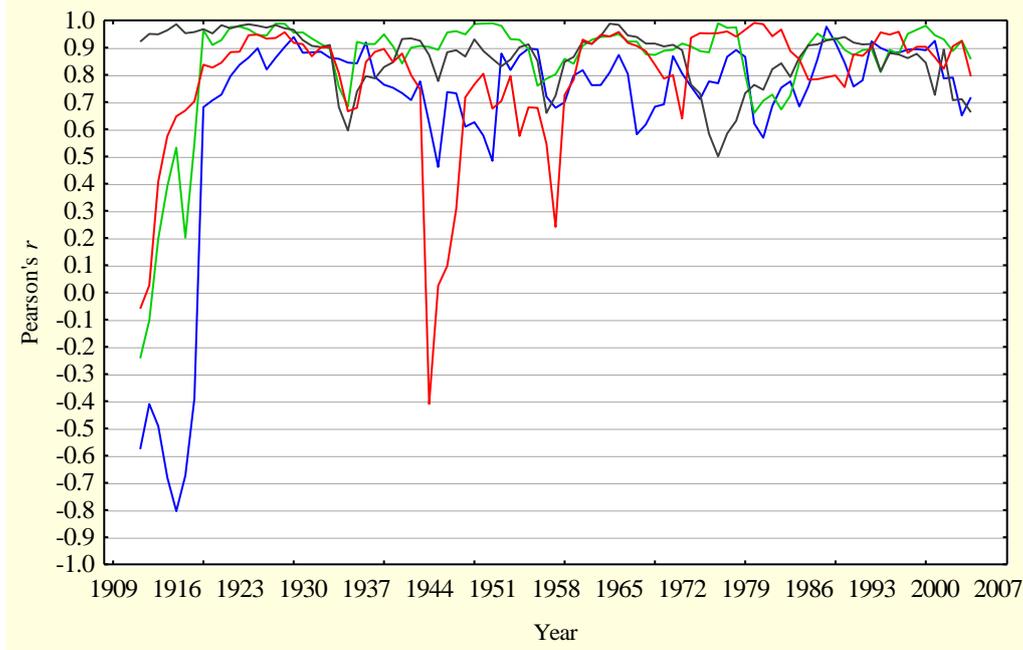


Fig.1.8: Variability in the correlation of 7-year moving averages of RTRs between upper and lower study stands within silver fir forests in the study area; period 1909-2007. Blue is ABE, green is CAM, dark grey is LAV, and red is VAL.

Variability in similarity of trends of RTRs between sites is more pronounced and irregular than within sites (Figures 1.8-1.10). The correlation coefficient frequently turns from highly positive values to negative values – and vice versa - even in short time and irregularly among sites. Moreover, fast changes in similarity among sites may not include some of them. In other words, the correlations between paired RTRs may differ in sign even in the same period among sites. For example, the level of correlation is high ($0.62 < r < 0.84$) between the upper stands at ABE-VAL, ABE-LAV, and LAV-VAL in the 1940s, and even negative ($0.20 < r < -0.58$) at CAM-LAV, CAM-VAL, and ABE-CAM in the same period.

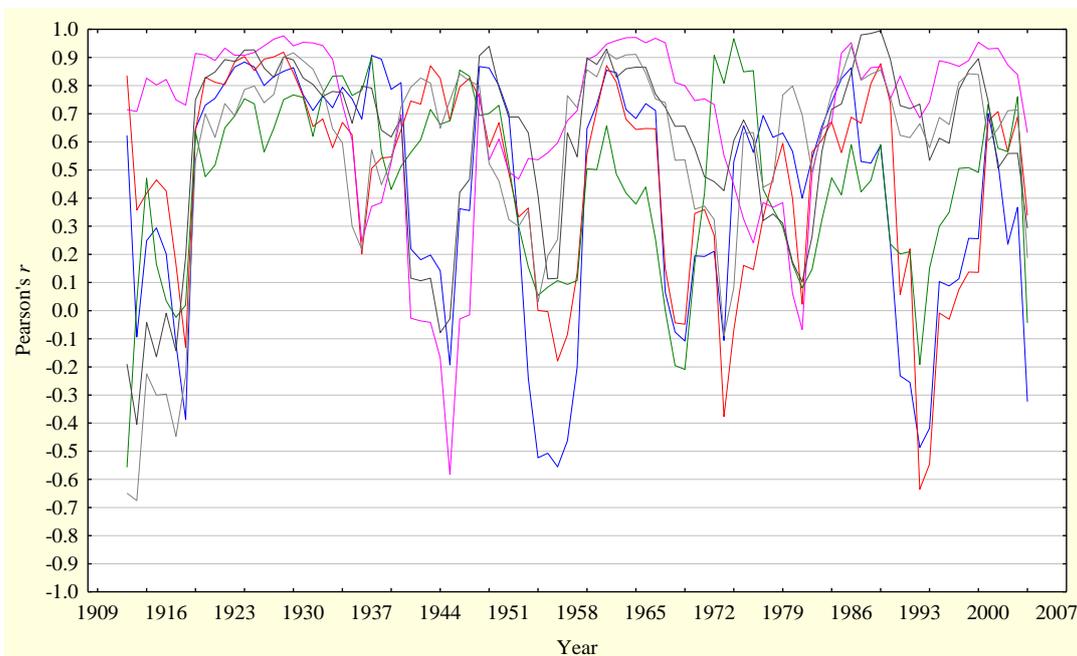


Fig.1.9: Variability in the correlation (Pearson's r) of 7-year moving averages between RTRs among the upper study stands of silver fir forests in the study area; period 1909-2007. ABE-CAM is blue, ABE-LAV is red, ABE-VAL is green, CAM-LAV is magenta, CAM-VAL is dark grey, and LAV-VAL is light grey.

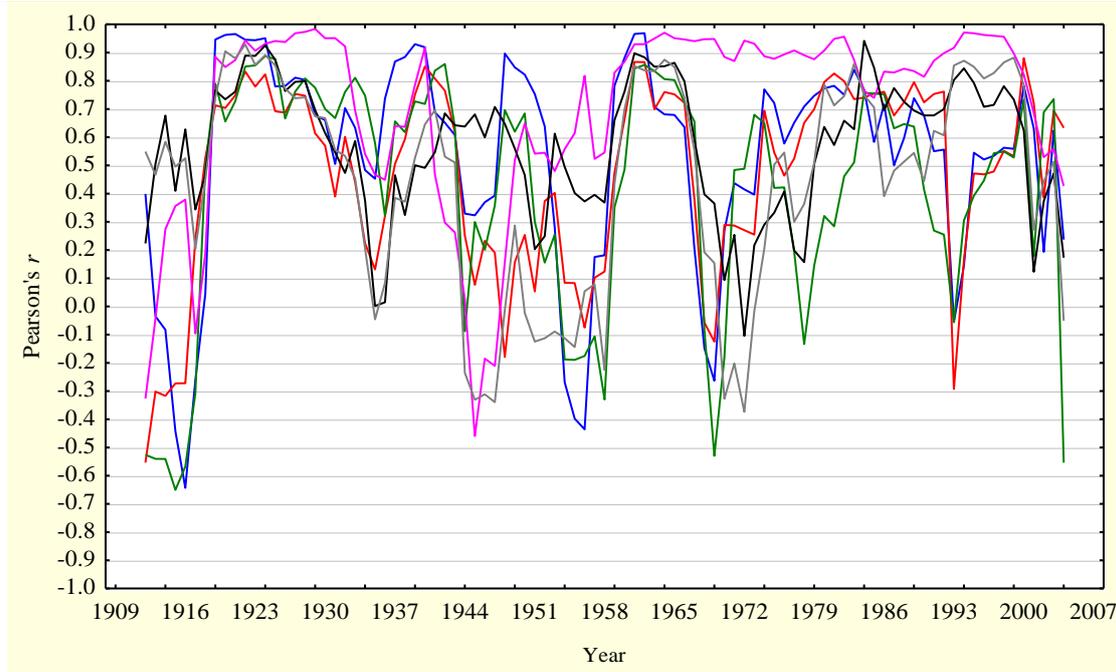


Fig.1.10: Variability in the correlation (Pearson's r) of 7-year moving averages between RTRs among the lower study stands of silver fir forests in the study area; period 1909-2007. ABE-CAM is blue, ABE-LAV is red, ABE-VAL is green, CAM-LAV is magenta, CAM-VAL is dark grey, and LAV-VAL is light grey.

V. SUMMARY OF RESULTS

The tree-ring series sampled from the silver fir stands in the study area show:

- non-stationary similarity in RTRs among sites and, at a lower extent, between upper and lower sites within silver fir forests during the 20th century; in particular:
 - similarity in RTRs between upper and lower study stands in each forest site is non-stationary. However, its variability seems to decrease from the 1980s onward (Fig. 1.8);
 - similarity in RTRs respectively between upper study stands and between lower study stands is highly variable (Fig. 1.9 and Fig. 1.10); it frequently changes from high similarity to dissimilarity during the 20th century. This would indicate that growth response of silver fir to environmental influence differs with site in the study area.
- non-stationarity is featured by strong changes in correlation values between paired series of RTRs; these changes occur irregularly during the 20th century;
- faster growth and positive trends RTRs seem to occur from the mid-1940s to the mid-late 1990s (Figures 1.3-1.6). This would suggest that climatic-environmental stimulation of growth increases after the mid-1940s;
- rapid and strong decrease of growth from the late 1990s to the mid-2000s. At ABE, the decrease

appears to stop in the early 2000s in both the upper and lower silver fir stands;

- in the RTRs, pronounced troughs are shown in the periods, between the mid-1940s and the mid-1950s, from the mid-1970s to the mid-1980s, and in the 2000s. The lower values are shown from the mid-1940s to the mid-1950s; a very fast reduction in growth is noted in the early 1940s (Figure 1.5);
- an unprecedented peak period during the 20th century occurs in the 1990s at all the study stands (Figures 1.3-1.6); the higher values occur in this decade except at ABE-Lower in the period 1925-1935 (Table 1.10).

Table.1.10: Peaks in mean ring width (MRW) of tree-ring chronologies of the silver fir study stands in the period 1990-2000 compared with the other higher peaks of the respective entire chronologies.

	Period	MRW
ABE-Upper	1865-1875	1.06
	1990-2000	1.16
ABE-Lower	1925-1935	1.14
	1990-2000	1.14
CAM-Upper	1925-1935	1.08
	1990-2000	1.24
CAM-Lower	1931-1941	1.08
	1989-1999	1.33
LAV-Upper	1961-1970	1.04
	1989-1999	1.23

LAV-Lower	1930-1940	1.20
	1989-1999	1.28
VAL-Upper	1930-1940	1.12
	1990-2000	1.26
VAL-Lower	1930-1940	1.13
	1990-2000	1.28

VI UNEXPECTED INCREASE OF TREE-RING GROWTH IN RECENT DECADES IN THE TUSCAN APENNINE ALPS

The tree-ring chronologies show that the influence of climate on radial growth during the 1990s is unprecedented during the 20th century in the study area (Figures 1.3-1.6; Table 1.10); this occurs at all age, elevation, and site features of the silver fir study stands. In the Tuscan Apennine Alps, tree-ring growth in silver fir appears to increase from the late 1940s to the late 1990s while the average ring-width growth in the respective yield tables (Cantiani and Bernetti, 1963; Castellani et al., 1984) would decrease. In other words, the occurrence of a peak period of growth in the 1990s and a secondary peak in the 1960s appears to contrast with the expected growth curve of ring-width in pure, mono-aged silver fir stands, which is shown by ring-width curves that follow a negative exponential distribution (Boncina, 2011; Božič et al., 2006; Susmel, 1988; Fritts, 1976). This pattern of ring-width growth is considered typical of many conifer species, including the mono-aged silver fir stands both in the study area and in Italian sites other than the Tuscan Apennine Alps as shown by various yield tables.

VII DISCUSSION

Tree-ring growth is expected to be non-stationary over time (Fritts, 1976); how it varies among and within sites concerns dendrochronology. In the study area, similarity in RTRs varies highly and irregularly among sites during the 20th century and, at lower extent, within sites; peaks and troughs are more pronounced from the 1940s onward. Normally, changes in the shape of curve from raw ring width to RTRs are expected. At ABE, CAM, and VAL, RTRs appear to show that variability in trends becomes more pronounced after the late 1930s (Figure 1.5). The association of RTRs between upper and lower study stands is normally high except at ABE, where it is moderate. This would suggest that biological and/or non-climatic factors progressively reduce their influence on tree-ring growth until the 1920s-1930s. In particular, a pronounced depression in tree-ring growth occurs in all the study stands in the mid-1940s and an unprecedented high tree-ring growth is observed during the 1990s.

These results would indicate that the influence of climate on silver fir growth differs among sites in the medium-long term during the 20th century; short-term variability in

silver fir growth possibly due to local, short-term events and interventions (i.e., windstorms, snowfall, parasites, cuts) is minimal or at least secondary.

During the 20th century seven out of eight silver fir study stands of any age show higher RTR in the 1990s. This trend appears to contrast with the known curve of growth in pure, even-aged conifer stands where growth is expected to slowly decrease in silver fir stands >60-80 years of age. A similar increase in silver fir growth has also been detected in various regions of Europe in the last decades of the 20th century (Becker et al., 1995; Filipiak and Ufnalski, 2004; Elling et al., 2009; Toromani et al., 2011). Moreover, a change in trend of raw tree-ring chronologies occurs in the late 1930s–early 1940s in all the study stands, which is followed by more pronounced peaks and troughs.

The scenarios from the European to the Italian regional and local scales show that strong depression in silver fir radial growth occurs frequently (i.e., in the 1940s, in the 1960s-1970s, and in the 2000s) and alternates irregularly with positive trends in radial growth during the 20th century. For example, in the period 1975-1985 a severe crisis of silver fir occurs in Europe and Middle Italy. In southern Germany, silver fir growth shows a negative trend in mean radial growth between the 1880s and the mid-1970s, which turns into positive in the late 1970s–early 1980s (Elling et al., 2009). Moderate reductions in radial growth occur in the early 1920s, in the late 1930s, and in the mid-1950s. It can be noted that the intensity of these growth depressions decreases with time; however, they are smaller than the growth depression that occurs in the 1970s. From the late 1980s, silver fir growth begins to increase rapidly in many European regions; the decades are featured by rapid and continued increase of ring width. In the mid-1990s–early 2000s, tree-ring width shows levels unprecedented from the late 1880s in southern Germany (Elling et al., 2009).

In the study area, presence of severe damage such as ‘silver fir decline’ was observed from the early 1970s to the late 1980s (Gellini and Clauser, 1986; Gellini et al., 1988; Bussotti and Ferretti, 1998); that is when the main growth depression occurs during the 20th century in southern Germany. In the study area, silver fir radial growth is low in this period and in the 2000s; otherwise, high tree-ring growth occurs in the periods 1965-1975 and 1990s, which would possibly indicate more favourable climate conditions. At VAL, the decline and high mortality of silver fir in the periods 1920-1940, 1945-1955, and 1975-1985 have been attributed to averaged 5-years periods of low annual rainfall preceding the crises (Moriondo and Caterini, 1988). Actually, Figures 1.3 and 1.4 show a reduction in radial growth in the period 1945-1955 at ABE-Upper, ABE-Lower, and VAL-Upper, which is more severe at CAM-Upper, CAM-Lower, and VAL-

Lower, and especially at LAV-Upper and LAV-Lower, and in the 1970s-mid 1980s.

VIII. CONCLUSIONS

This research provides evidence that similarity in RTRs varies highly, frequently, and irregularly during the 20th century among sites and, at a lower extent, within silver fir forest sites in the Tuscan Apennine Alps; unexpected patterns of growth occur in silver fir in the last decades of the 20th century; and similarity between RTRs of the silver fir study stands tends to reduce with increasing distance among sites. According to the results of this study, climate conditions seem to have influenced positively silver fir growth from the late 1980s through the 1990s. Then, continued climate warming may have built climate conditions progressively less favourable or adverse to silver fir growth. For example, warmer climate conditions may have initially limited silver fir growth at lower sites and advantaged it at upper elevation before creating unfavourable conditions even at upper elevation. This scenario raises the question whether the climate/tree-ring growth relationships have changed during and after the 20th century in the Tuscan Apennine Alps and, more in general, in the southern range of silver fir. It is commonly known that relationships between seasonal and monthly climate variables and silver fir growth can change over time. At this stage, results strengthen the need of approaching silver fir management by involving climate variability as a main driver of growth where no general assumptions should be used to plan and manage silver fir forests. In particular, it is stressed that each silver fir forest needs to be analysed in view of the effects or impacts of climate change at the local level, even within forests in some cases. Although the influence of changing climate conditions is likely to be the main key to understand the effects on silver fir growth, it needs to be ascertained at what extent temperature and/or rainfall thresholds for growth are trespassed under new climate scenarios. For example, silver fir growth may:

- decrease rapidly if the effects are negative;
- grow faster and/or for a longer time if the effects are positive.

The evidence provided would recommend monitoring and extending both this and similar investigations in the view of the climate change scenarios recently provided by research (IPCC Sixth Assessment Report (AR6); <https://www.ipcc.ch/sr15/>; Giorgi and Lionello, 2008), where the impacts on the viability and possibly shift of silver fir populations – and other species – in their southern European range rise serious concerns.

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