

Growth trends and dynamics in sub-alpine forest stands in the Varaita Valley (Piedmont, Italy) and their relationships with human activities and global change

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Abstract. A study of the forest lines, tree lines and the structures of the sub-alpine forest was performed in Vallone Vallanta and in Alevé forest in the Varaita Valley (Cottian Alps, Piedmont, Italy). Forest- and tree lines were analysed over 1728 ha while forest structures were studied on six 3000-m² plots located at the tree line (2), at the forest line (2) and inside the sub-alpine forest (2). Dendro-ecological analysis of living plants and stumps showed that *Larix decidua* was more abundant in the past than today and that *Pinus cembra* has expanded, both upwards and within sub-alpine forests. Age structure analysis revealed that the current sub-alpine forest stands were established 200 - 220 yr ago, probably following a clearcut. At the forest lines the tree density decreases, and some trees are more than 500 yr old, whereas at the tree lines most of the trees (almost exclusively *Pinus cembra*) are younger than 100 yr. Growth dynamics were investigated both by observing Basal Area Increment (BAI) in the old and dominant trees, and by comparing the BAIs of classes of trees with a given cambial age range in different time periods. The results showed that the growth rates of mature *Pinus cembra* and *Larix decidua* had increased. These increments are more substantial for *Pinus* than for *Larix*. The growth rate of young trees (< 100 yr) of both species has decreased over recent decades. This could be due to competition caused by increased tree densities that have resulted from a decrease in grazing.

Keywords: Basal area increment; Cambial age; Dendro-ecology; Forest line; *Pinus cembra*; *Larix decidua*; Stand structure; Tree line.

Abbreviations: BAI = Basal area increment; BSC = Basal area increment chronology; EMR = estimated missing radius; IRC = Individual raw chronology; SLC = Site low frequency chronology; SRC = Site raw chronology.

Introduction

Sub-alpine forests are important indicators of environmental change. The altitudinal and latitudinal limits of trees are mainly determined by temperature – trees do not generally grow in places where the mean temperature of the warmest month is less than ca. 10 °C (Tranquillini 1979). However, in some regions precipitation is the most important factor determining the upper tree limit (Lloyd & Graumlich 1997). Understanding dynamics at the upper limits is a key element in the investigation of global changes (Luckman 1996).

Many dendro-ecological studies have documented altitudinal and latitudinal expansion of tree populations at tree line in North America (e.g. Szeicz & MacDonald 1995; Peterson 1998), Scandinavia (e.g. Kullman 1993), the European Alps (e.g. Nola 1994), Russia and Asia (e.g. MacDonald et al. 1998). A smaller number of studies, however, have shown tree limits to be relatively stable (Hättenschwiler & Körner 1995). Even if the recent rises observed in Europe and North America have not equalled those in the early mid-Holocene (Innes 1991), they are quite striking and are frequently attributed to climate change.

Dendro-ecological analyses also have generally found recent increases in tree growth rates. The first paper to document an increase in the growth rate of trees at the tree lines, and to attribute this increase to global change, especially to the increase in CO₂, was La Marche et al. (1984). Many other studies of this phenomenon have since been carried out in North America (e.g. Payette et al. 1985; Graumlich 1991), Europe (e.g. Nicolussi et al. 1995), Asia (e.g. Jacoby et al. 1996) and New Zealand (D'Arrigo et al. 1998). With few exceptions (e.g. Kienast & Luxmoore 1988; Lara & Villalba 1993), these studies have observed an increase in the growth rate of trees.

Studying the effects of global change, especially climate fluctuations, on growth dynamics at the upper tree line in the European Alps, can be complex because

human disturbances are more intense and frequent than in other mountain areas. Human activity at the forest- and tree lines in the Alps has occurred for thousands of years. Deforestation started between 6000 and 3000 BP in the French Alps (Carcaillet 1998), by 4700 BP in the central Swiss Alps (Tinner et al. 1986), and by 2000 BP in areas in the southwestern Alps (Edouard et al. 1991; Tessier et al. 1993). Subsequent human activity radically changed sub-alpine forests in various ways. Large areas of forest were destroyed, lowering the forest line to create pasture or as the result of logging. In addition, the composition was modified because certain species (for example, *Larix decidua* and *Picea abies*) were favoured and others were eliminated (for example, *Pinus cembra* and *Abies alba*). Forest structure was also changed by management practices including thinning. Finally, forests were disturbed by the collection of forest litter. It is thus extremely difficult to distinguish the influence of ecological factors and climate fluctuations from the effects of human activity

This study was conducted in the Upper Varaita Valley (Piedmont, Italy), in an area which has been relatively free of human activity in recent decades. We had the following aims:

1. To determine the present upper forest- and tree lines, and their recent dynamics.
2. To characterize forest structure and dynamics at three altitudes: in the sub-alpine belt, where the forest is fully developed; at the forest line and at the tree line.
3. To determine growth trends of the two dominant species in sub-alpine forests in the Val Varaita: *Pinus cembra* and *Larix decidua*.

Material and Methods

The study area

The study area covers 1728 ha, and is situated in the upper Val Varaita (44° 37' N; 7° 05' E) from 1900 to 2500 m a.s.l. It extends in part over the Vallone Vallanta and in part over the Alevé forest, the largest *Pinus cembra* forest in the Alps (more than 800 ha of pure pine forest), on the south face of Monviso (3841 m a.s.l.).

There are two main types of sub-alpine forest. The first type, the most widespread in the Vallone Vallanta, is the subassociation *Rhododendro-Vaccinietum cembretosum* (Bono & Barbero 1971), which is typically found in the mesophyllous *Pinus cembra* forests on the cooler aspects. It is characterized by *Rhododendron ferrugineum*, *Vaccinium myrtillus* and, to a lesser extent, *V. vitis-idaea*, *V. uliginosum*, *Lonicera coerulea*, *L. alpigena*, *L. nigra*, *Juniperus nana*, *Rosa pendulina*,

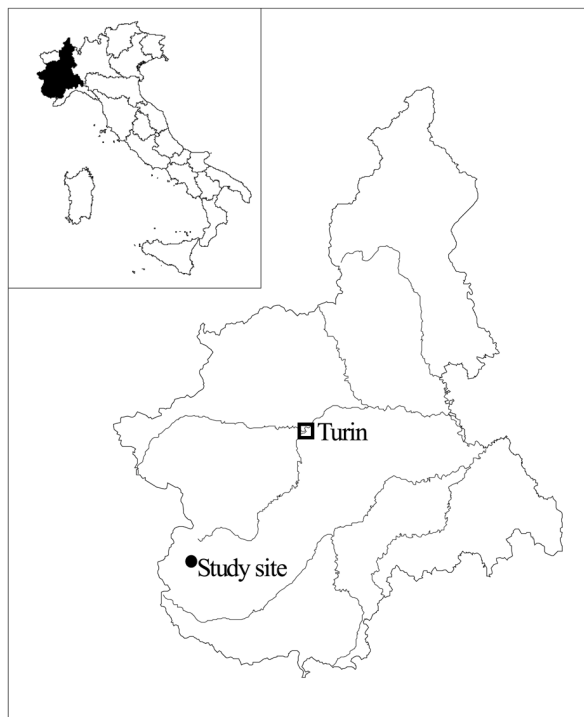


Fig. 1. Location of the study site (Piedmont, Italy).

Daphne mezereum, *Clematis alpina*, *Sedum anacampseros*, *Luzula sieberi*, *Festuca flavescens* and *Homogine alpina*. The second type, more common in the Alevé forest, is the subassociation *Junipero-Arctostaphyletum cembretosum* of the *Juniperion nanae* alliance (Bono & Barbero 1971), very different in terms of floristic composition and ecology from the *Pinus cembra* forests found in the rest of the Alps (Filipello et al. 1980). It is typically found on the south-facing exposures of the Upper Varaita Valley. It is characterized by *Juniperus nana*, *Arctostaphylos uva-ursi*, *Cotoneaster integerrimus*, *Avenella flexuosa*, *Vaccinium myrtillus*, *Minuartia laricifolia*, *Festuca flavescens*, *Galium obliquum* and *Brachypodium caespitosum*.

The Alevé forest lies predominantly on serpentine and metagabros rocks, whereas the Vallone Vallanta lies predominantly on carbonatic schists. The total rainfall is 854 mm/yr (Casteldelfino, 1296 m a.s.l.). The climate is sub-littoral alpine, with some continental characters.

Forest lines and tree lines

We used the following terminology (Piussi & Schneider 1985):

Forest line: the upper delimitation of the closed forest, forest being defined as having a cover of at least 30 % and a surface area of at least 500 m², the minimum conditions for the existence of a forest microclimate.

Tree line: the line connecting the outermost erect trees with a height of more than 2 m, growing at the highest altitudes. A tree is defined as a plant with a tree like structure (apical dominance and not multiple leaders) of a height of at least 2 m, even if it is not symmetrically shaped.

The establishment of these limits allowed three altitudinal sectors to be established:

1. *Forest area*: the area presently occupied by forest.
2. *Potential forest area*: the area lying between the forest line and the tree line. This area was further subdivided as follows:
 - 2A. *Viable potential forest area*: surface area where limiting physical and geographical features like rocky places and rock faces do not appear to impede the presence of 30 % tree cover;
 - 2B. *Unviable area*: limiting physical-geographical factors are such as to prevent tree cover reaching 30 %, although some trees and groups of trees are present.
3. *Area above the potential forest area*: it is assumed that the extreme climatic conditions at this altitude would prevent the formation of any substantial tree cover.

These limits were established by subdividing the entire study area into 11 sectors characterized by uniform exposures and slopes. The sectors were then observed from a distant point by binoculars, and provisional limits identified. These were then verified by checking directly in the field in each sector.

Stand structures

Once the limits were established, we selected two relatively uniform slopes, one having west-facing mixed *Larix decidua*-*Pinus cembra* forest (Vallanta = V) and the other south-facing *Pinus cembra* forest (Alevé = C). Three plots along an altitudinal gradient were selected on each slope: 200 m below the forest line (V1 and C1); at the forest line (V2 and C2) and at the tree line (V3 and C3). At each of these stands, a 30 m × 100 m (3000 m²) plots having the long side along the contour lines, was marked. In each plot the following information was recorded for trees with a diameter at breast height > 7.5 cm: identification; DBH, height and coordinates within the transect. Saplings (height > 10 cm and DBH < 7.5 cm) were counted throughout each plot, while seedlings (h < 10 cm) were counted in 16 sample areas of 1 m² randomly distributed over each plot. The coordinates were established by means of a Global Positioning System (GPS), and the plot borders were marked permanently.

Analysis of increment cores

The increment cores

In order to calculate age structure and to analyse growth trends, an increment core was taken at a height of 50 cm on the upslope side of each tree > 7.5 cm DBH (a total of 603 cores, referred to as C50). Additional cores (referred to as C130) were taken from 23 *Pinus cembra* and 19 *Larix decidua* at the forest line distributed over the whole study area, in order to build a reference chronology for each species. Two or three cores per tree were taken at breast height (the first one upslope and the other ones at 90°-120° from the first) and only the largest, apparently healthy and dominant trees were sampled. In the laboratory all the cores were fixed to wooden supports and smoothed with a razor blade or by sanding until optimal surface resolution allowed annual rings to be measured. Ring width was measured to within 0.01 mm. Data were collected and stored using the LINTAB device and the TSAP package (Rinn 1996).

Cross-dating and reference chronologies

Cross-dating, which ensures that the correct year is assigned to each annual ring, was initially accomplished on series derived from the C130 cores, both by visually checking the curves and by calculating the *t*-values relating to the coefficient of correlation (Baillie & Pilcher 1973) and *Gleichläufigkeit* or coefficient of agreement (Schweingruber 1988). Then the series resulting from the cores belonging to the same tree were averaged to create an individual raw chronology (IRC). A site raw chronology (SRC) for each species was obtained from the average of the IRCs.

As regards the C50 cores, cross-dating was accomplished by comparing each series with the SRC for the same species, both by visually checking the curves and by calculating *t*-values relating to coefficient of correlation and *Gleichläufigkeit*. A chronology of raw data was then created for each sampled tree (R50).

Tree-ring widths and basal area increments

In order to give a better estimate of net productivity of a tree, the simple tree ring widths were converted into basal area increments (BAI). This ought to eliminate the effect of reduction in ring widths due to the diameter increase of tree (and therefore a question of geometry) without eliminating the patterns of increase or decrease in ring width due to other causes (Tessier 1986; Briffa 1992; Visser 1995).

BAIs were calculated by means of the FISURF program from 3PBASE package (Guiot & Goeury 1996). Both the IRCs and the R50s were transformed into BAIs to give new series referred to as IBC and B50 respectively. The IBCs were then averaged to give new site

chronologies for *Larix decidua* and *Pinus cembra*: the site basal area increment chronology (SBC).

Growth trends in the dominant trees

To analyse the growth trends, a low pass filter (Fritts 1976) was applied to the SBCs for *Larix decidua* and *Pinus cembra* to highlight the low frequency signal, and the resulting series are referred to as SLCs (Site low frequency chronology). In order to avoid bias in the results no indexation process was applied to the data (Innes 1991).

Age structure

The C50 cores were used to construct age structure. Determination of the age of a tree at an annual level of resolution is very difficult, uncertain and time consuming. Such information is, however, essential to the reconstruction of stand history. There are two major limitations of using increment borers in age determination: the difficulty of intercepting the pith at the coring height and the differences in years between coring height and the total age (age at the root collar).

Estimating pith location and missing rings at the coring height.

The cores were classified into three groups: (1) cores including pith; (2) cores that fall short of the pith with strongly curved innermost rings, on which it was possible to estimate the position of the pith and hence the number of missing rings; (3) cores with apparently uncurved innermost rings. The age of the tree at sampling height was calculated for the cores in (1) and (2), but not for those in (3) because it was impossible to estimate the position of the pith and hence the number of missing rings, since the rate of growth of juveniles even within a restricted area is very variable at the sub-alpine level (Schütz 1969; Piussi 1976). For group (1), age was taken as the number of rings between the pith and the cambium; while for group (2) the number of rings was estimated. How to estimate the number of missing rings from incomplete cores has been the object of a number of studies, and a variety of methods exist (Norton et al. 1987; Norton & Ogden 1989; Villalba & Veblen 1997). In this study we adopted a graphical procedure for estimating pith location (starting from the innermost part of the core) and used a pith locator (Josza 1988). Once pith location had been estimated, the length of missing radius was estimated. The number of rings on the innermost part of the core was counted for a segment as long as the estimated missing radius (EMR). This number was added to the number of rings in the core, to obtain the estimated age of the tree at the coring height. Where the innermost rings showed evidence of abrupt growth change, especially of abrupt growth release

(Lorimer & Frelich 1989; Schweingruber et al. 1990), the estimated number of missing rings was derived only from the segment of core preceding the abrupt growth change and extended to the whole EMR using a simple proportion. This method assumes that the estimated missing rings form concentric circles.

Estimation of age at coring height

The estimation of the years the trees had taken to attain the coring height (50 cm) presents two difficulties: (1) it is almost impossible to find the exact position of the root collar of trees exposed to the snow as juveniles and of those which grow on microsites (stumps, dead wood and humps) where the lower stems are easily deformed under the weight of the tree (DesRochers & Gagnon 1997); (2) especially for species with initially slow growth, juveniles growth rates are very variable depending on microsite, competition and light conditions.

A previous study (Motta & Dotta 1994) conducted in the Alevé forest on 24 harvested *Pinus cembra* and on 12 *Larix decidua* saplings collected at altitudes from 1950 to 2200 m a.s.l., showed that the *Pinus cembra* took an average of 19.6 yr (range 8 - 36 yr) to reach a height of 50 cm and the *Larix decidua* took an average of 11.8 yr (range 6 - 22 yr). Even though we are aware of the limitations involved, these values (20 yr for *Pinus cembra* and 12 yr for *Larix decidua*) were added to the number of years counted or estimated at the sampling height. This procedure is based on the assumption that the harvested saplings grew at the same rate as the initial growth rate of the mature trees from which the partial cores were obtained (Veblen et al. 1992). The procedures used for age estimation can introduce errors into subsequent analysis. In order to account for these errors, age structure was constructed for 10-yr classes (Payette et al. 1990).

Growth trends within age stratified data

Radial growth was analysed within age classes to check whether there were any size differences between the BAIs related to rings produced by trees of the same cambial age in different periods (Becker 1987; Briffa 1992). In this approach BAI data are divided into age classes so that, only data derived from rings within a specific age range are averaged in succession. This gives tree-growth estimates within which the age of trees is held roughly constant through time (Briffa 1992). Data are averaged decade by decade, separately, for the two species. Four age classes were considered: 1-50, 51-100, 101-150 and 151-200. The R50 from plots C1 and V1 were used. Only series derived from complete cores and from cores where the innermost rings allowed the estimation of pith location and cambial age were included in the analysis.

Results

Forest lines and tree lines

The forest- and tree lines were among the highest in the Alps (Table 1). The 1728 ha study area was subdivided into four units:

- area covered by forest (542.6 ha, 31.4 % of the study area);
- meadows, pastures and *Alnus viridis* bushes below the forest line (252.2 ha, 14.6 %);
- area between forest line and tree line (475.2 ha, 27.5 %);
- area lying beyond the tree line (457.9 ha, 26,5 %).

The potential forest area, i.e. that lying between the forest line and the tree line, was then further subdivided into:

- viable potential forest area (177.7 ha, 10.3 % of the study area), and
- area where forest establishment is prevented by physical factors (295.5 ha, 17.2 %).

Plot data

Sub-alpine forest stands on the two slopes had similar structures even though species composition was different (Table 2). In plots C1 and V1 diameters distribution showed a few large trees and an exponential negative trend for the smaller classes (Fig. 2). There were a large number of stumps in both the plots, evidencing severe intensive logging in the past (Table 2). The advanced state of decay of most of the stumps indicated, however, that logging had ceased in recent decades and it is clear that the forest has since developed undisturbed by human practices.

The diameter distribution for plots C3 and V3, at the tree line, were also consistent with natural growth. The complete absence of stumps means that no trees have been logged in the recent decades, and suggest that no trees were present at the regeneration time. In contrast, the diameter distribution for plots C2 and V2, at the forest line, were more irregular, especially in plot C2, because

Table 1. Forest lines and tree lines.

	Mean ± SE (m a.s.l.)	Range (m a.s.l.)
Forest line	2339 ± 22	2180 - 2420
Tree line (<i>Pinus cembra</i>)	2484 ± 21	2350 - 2650
Tree line (<i>Larix decidua</i>)	2428 ± 16	2340 - 2520

of the lack of trees in the smaller classes (Fig. 2). The presence of decayed stumps indicated that logging had occurred, but had ceased a few decades ago (Table 2).

Of the 603 C50 cores, 532 (88.2 %) were used to count the tree rings (Fig. 3). Age structure analysis gave similar results for different populations at the same altitude. An apparent dramatic reduction in the number of trees younger than 70 yr old was found in all plots, probably due to the fact that most of the trees younger than 70 yr have a diameter < 7.5 cm and therefore were not recorded. The oldest trees in the sub-alpine plots C1 and V1, were 321 and 308 yr old, respectively. The age distribution in plot C1 was similar to that for diameter distribution with a scattered dispersion of the old trees and an exponential negative trend for the new cohorts. In plot V1, the 150-yr and 160-yr classes were the most frequent. Present populations appear to have established about 200 years ago in C1 and about 220 yr ago in plot V1. More recent establishment was observed in plots C3 and V3 (Fig. 3).

Apart from a few individuals, trees were less than 100 yr old. The oldest populations were observed at the forest line, in plots C2 and V2. The fact that there were few very ancient trees, however, indicates on the one hand that these areas have had continuous forest cover over the past few centuries, and on the other that they have been used as pasture because of the sparse density of the cover. This hypothesis is particularly plausible for the Vallone Vallanta area, where intensive grazing probably took place until the beginning of the 20th century.

Table 2. Main characteristics of the studied plots.

Plots	Altitude (m a.s.l.)	Trees total (no./ ha)	Trees <i>Pinus cembra</i> (no./ ha)	Trees <i>Larix decidua</i> (no./ ha)	Basal area total (m ² / ha)	Stumps total (no./ ha)	Stumps <i>Pinus cembra</i> (no./ ha)	Stumps <i>Larix decidua</i> (nr/ ha)
C1	2020	740	740	0	26.7	177	177	0
C2	2330	160	160	0	26.7	23	23	0
C3	2500	27	27	0	0.5	0	0	0
V1	2070	540	287	253	31.9	277	107	170
V2	2330	247	193	53	27.0	50	47	3
V3	2440	50	50	0	0.8	0	0	0

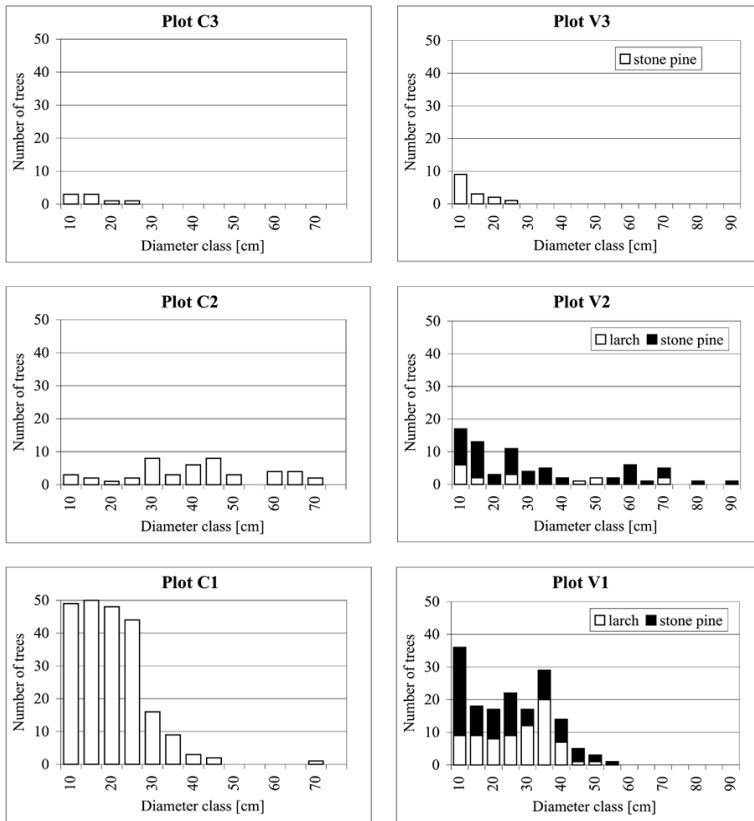


Fig. 2. Size class distributions for each species in the six plots.

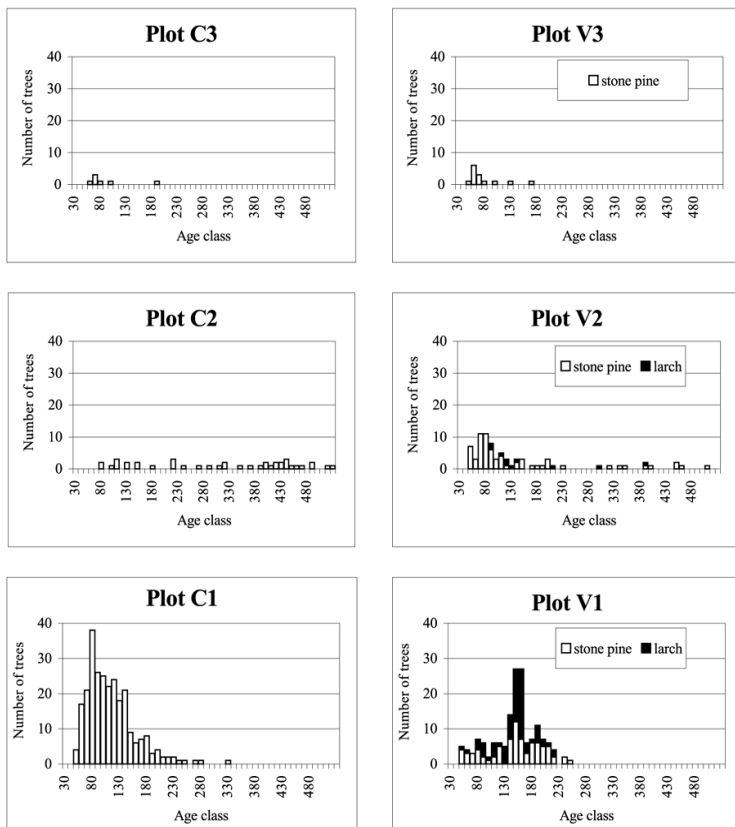


Fig. 3. Age class distributions for each species in the six plots.

Regeneration in plot V2 has been sporadic over the last 150 yr, and is more recent than that in sub-alpine plot V1. In contrast to the other plots, no period of particularly intense tree colonization was found for Plot C2 where the age structure did not fit the expected inverse J-shape trend. This may be because establishment in this plot was limited by topography, the rocky substrate and grazing (despite the fact that, according to written evidences from the municipality archive, livestock impact in this aspect was not as important as in the Vallanta Valley).

Regeneration was plentiful, however, on both the slopes and at all the altitudes examined (Table 3). Density of regeneration increased with elevation, the greatest density of regeneration and of seedlings found in plots C3 and V3. Most of the regeneration was of *Pinus cembra*. Only in plot V1 was there any *Larix decidua* regeneration, and it was still far less than that of *Pinus cembra* (Table 3).

The presence of both *Pinus cembra* and *Larix decidua* on the Vallone Vallanta slope allowed comparison of data from the two species on stumps, trees and regeneration. The results of this comparison (Fig. 4) show the gradual transformation of a previous stand dominated by *Larix decidua*, into a mixed *Larix decidua*-*Pinus cembra* stand and suggest a future transformation into an almost pure *Pinus cembra* stand.

Site chronologies

Table 4 shows the main features of the SRC chronologies for *Larix decidua* and *Pinus cembra*. A detailed description of the *Pinus cembra* can be found in Motta & Nola (1996) and of the *Larix decidua* in Nola (submitted). The mean site chronologies for both species were longer than five centuries. Average ring width was smaller in the *Larix decidua*, and had a lower standard error, lower auto-correlation and fairly high mean sensitivity, which was much greater than that observed for the *Pinus cembra*. Inter-series similarity within the chronologies, taken as the percentage of cases in which both the Student-*t* value and the *Gleichläufigkeit* were simultaneously significant at a probability level of over 95 %, was high for both species and reached almost 100 % for *Larix decidua*.

Growth trends in dominant trees

The low frequency chronologies (SLCs) obtained from the SBC chronologies for the two species (centred by subtraction of the mean) are shown in Fig. 5. The curves differed substantially between the two species. *Larix decidua* showed an alternation of periods in which the BAI was higher or lower than the mean value, without remarkable trends. BAI values were particularly low in the following periods: 1670-1700, 1810-1830,

Table 3. Occurrence (no./ha) of saplings (h > 10 cm and DBH < 7.5 cm) and seedlings (h < 10 cm) in the studied plots.

	Saplings total	Saplings <i>Pinus cembra</i>	Saplings <i>Larix decidua</i>	Seedlings <i>Pinus cembra</i>	Seedlings <i>Larix decidua</i>
Plot C1	867	867	0	9340	0
Plot C2	337	337	0	4910	0
Plot C3	2357	2354	3	1330	0
Plot V1	1600	1537	63	3375	1875
Plot V2	1803	1750	53	6350	0
Plot V3	2420	2373	47	11250	0

1865-1888 and 1960-1980. They peaked in the following periods: 1734-1809, 1940-1950 and 1982-1991. The *Pinus cembra* chronology, in contrast, was divided into two main periods: from 1593 to 1872, when growth was below average (even if values ascended slightly starting from 1730); and from 1873 to the present, when BAIs generally were above the mean and were increasing gradually, although with fluctuation.

Growth trends in age stratified data

The analysis of growth within cambial age classes was carried out on a total of 376 cores: 307 *Pinus cembra* cores (243 from plot C1 and 64 from V1) and on 69 *Larix decidua* cores (all from plot V1) (Fig. 6). The number of samples within the decades in each age class obviously varied widely, from a minimum of two for both species to a maximum of 106 for the *Pinus cembra* and 46 for the *Larix decidua*. The number of *Pinus cembra* cores was higher than that for *Larix decidua*, reflecting the abundance of the species in the study area. The points in the graph thus represent the mean of very different sample sizes, a fact that must be taken into account when interpreting the results. In contrast with the results obtained for the analysis of growth trends in

Table 4. Descriptive parameters of the mean site chronologies.

	<i>Pinus cembra</i>	<i>Larix decidua</i>
First year	1453	1426
Last year	1994	1997
No. of cores	42	40
No. of trees	23	19
Chronology length (yr):		
Min	160	120
Mean	329	393
Max	542	572
Mean ring width ± SE (mm)	0.82 ± 0.013	0.62 ± 0.011
Mean BAI value ± SE (mm ²)	757 ± 32.5	570 ± 23.8
Autocorrelation	0.89	0.82
Mean sensitivity	0.13	0.22
IS*	91	98

*IS = Interseries similarity: percentage of cases in which both the Student *t*-value and the agreement coefficient were contemporaneously significant at a probability level > 95 %.

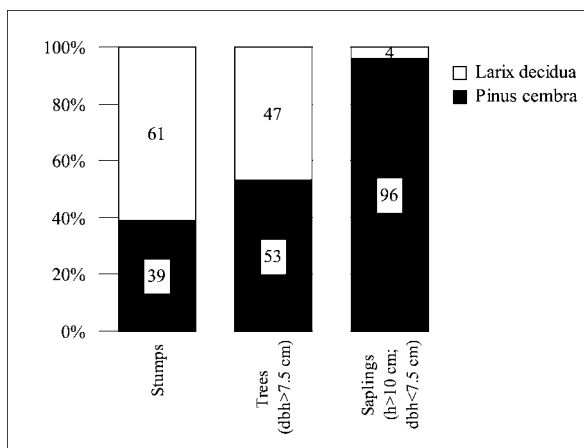


Fig. 4. Forest composition dynamics in plot V1 (stumps, trees and saplings).

dominant trees, the behaviour of the two species was found to be very similar. Both species showed a decline in growth over the last two centuries in the lowest cambial age class (1-50). In the next age class, although there was a slight downward trend, the data were widely dispersed around the trend line. In the other age classes (>100), the trend reversed, and growth increased within the period considered. The main difference between data for the two species, was that those for *Larix decidua* were far more widely dispersed around trend line than those for *Pinus cembra*. This may simply be due to the fact that there were more data for *Pinus cembra* than for *Larix decidua*.

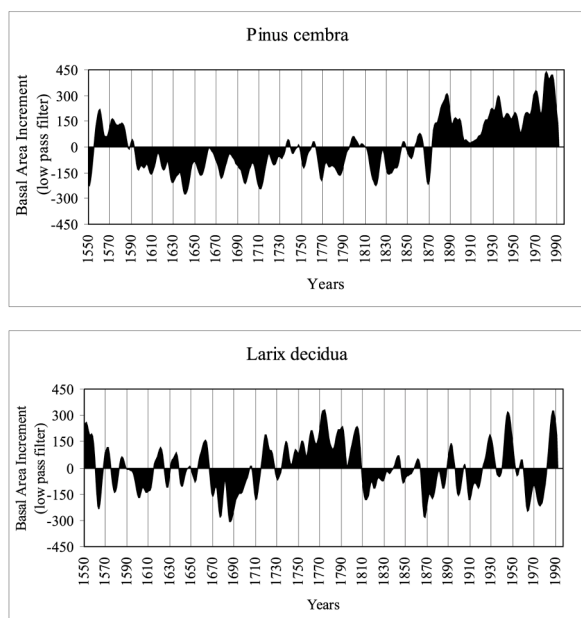


Fig. 5. Low frequency chronologies of basal area increments for each species: data are filtered by a low pass filter and plotted centered by subtraction of the mean.

Discussion

The forest- and tree lines in the studied area are amongst the highest in the Alps, and are expanding upwards. Most of the area being colonized by conifers today was formerly grazing land. It is thus difficult to tell to what extent the expansion observed is recolonization of deforested terrain or a response to climate changes.

The age structure data for plots C3 and V3, situated at the tree line showed that recolonization at the tree line began at the end of the last century. However, a lack of trees dating from a given period may be the result of a lack of establishment at that time, high mortality rates of trees that established at that time, or a combination of these factors (Johnson et al. 1994).

The living populations in C1 and V1 started establishing approximately 200-220 yr ago. The large number of decayed stumps in the two plots and some written historical documents suggest that the populations established following a clearcut that was probably carried out at the end of the 18th century. Following the Utrecht Treaty, the valley came under the reign of Savoias and for almost a century, from 1713 onwards, it saw several battles involving the Piedmont, French and Spanish armies. In this period thousands of soldiers crossed and were posted in the Varaita Valley. Local records report large scale deforestation during their long stay, carried out both to build forts and to supply fuel for heating and cooking. The age structure found for C1 showed that establishment and growth of the forest population took place largely undisturbed by men, while the more irregular age structure of V1 might reflect the use of the area for grazing.

The irregularity of the age structure of the tree populations in Plots C2 and V2, situated at the forest line, is probably also the result of past grazing. In contrast to areas at higher and lower altitudes, however, some tree cover has always been maintained. This is indicated by the advanced age of the oldest trees: 534 years old in C2 and 506 yr old in V2. In C2, the extensive rock cover probably limits the establishment of forest regeneration. There is some inertia in the response of conifer populations to environmental variations at this altitude (Slatyer & Noble 1992; Scuderi 1994; Hättenschwiler & Körner, 1995), but both *Pinus cembra* and *Larix decidua* are perfectly adapted to the sub-alpine environment, being long-lived species which can survive large climatic fluctuations such as those observed over the last few centuries. There was evidence of recently established natural regeneration in V2 but not in C2. This regeneration thus corresponds with the beginning of depopulation of the Piedmont mountains, which reached its maximum in the latter half of the

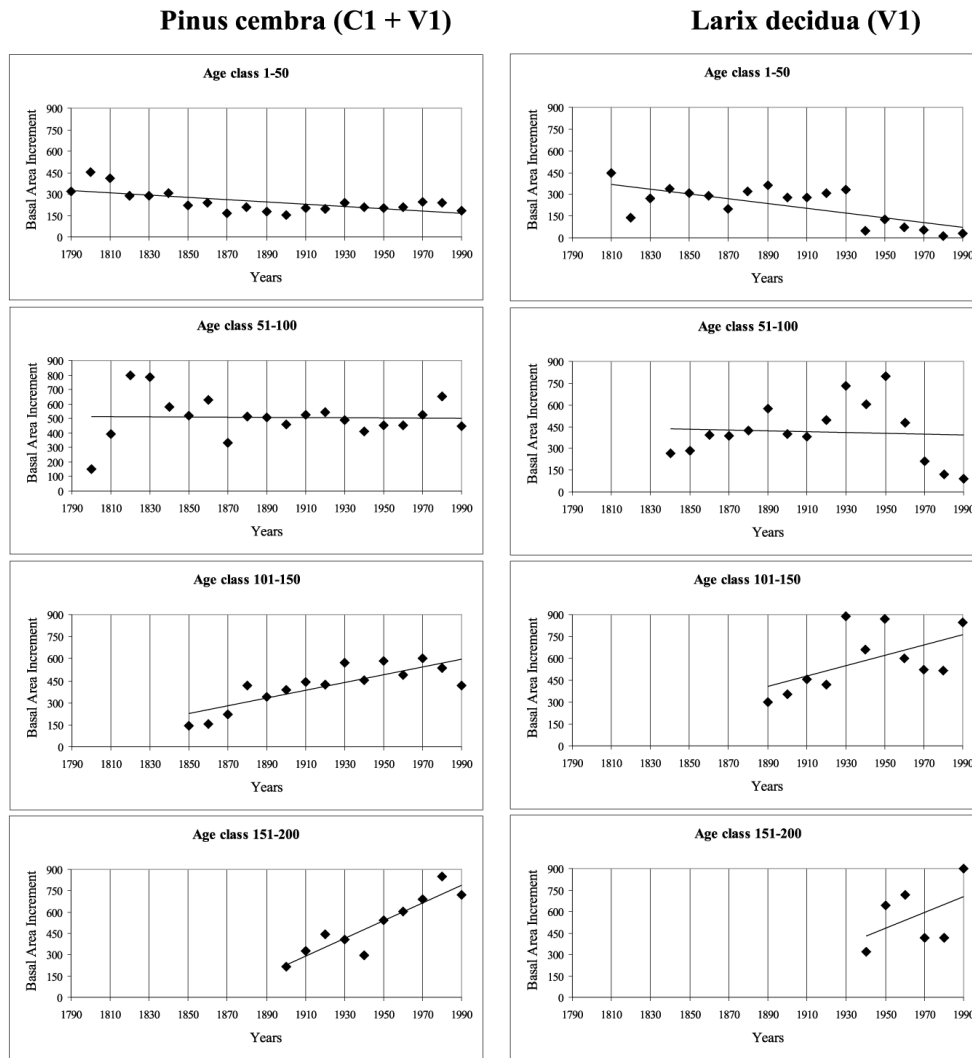


Fig. 6. Decadal averages of Basal area increment for different age classes of trees and for each species. Data are averaged decade by decade, separately, for the two species. Four age classes were considered: 1-50, 51-100, 101-150 and 151-200.

19th century. Although no data on domestic livestock management at the time are available, it is possible that the war led to a sharp decline in the civilian population of the area, and indirectly in grazing, as has happened over the last few decades as a result of economic changes (Cavallero et al. 1997).

Heavy grazing followed by periods of moderate grazing is often associated with the onset of tree regeneration invasion of many sites (Dunwiddie 1977; Vale 1981; Taylor 1990). According to Dunwiddie these changes in meadow conditions enhance tree invasion for 20 - 25 yr once intense grazing pressure is reduced. The simultaneous reduction of grazing pressure and increase in temperatures complicates the interpretation of the results.

In the case of the *Pinus cembra*, dispersal is accomplished by nutcrackers (*Nucifraga caryocatactes*), which allows establishment to take place even long after reduction or cessation of grazing (Mattes 1985). The action of the nutcracker also explains the increase in regeneration and seedlings with increasing altitude, since its preferred territory is at the forest and tree lines. The total absence of stumps in the study plots at the tree line also suggest the absence of tree populations at the time of establishment of the present stand.

Although decreased grazing was probably the main mechanism for the present tree dynamics at the forest- and tree lines, it does not explain the growth variations observed. Low frequency analysis of the BAIs of the dominant trees at the forest line detected a distinct

increasing trend in growth rates of *Pinus cembra* chronology over the last century. The fact that the same positive trend was not found for *Larix decidua*, whose BAIs oscillate substantially with periodic strong growth reductions, may be due to outbreaks of the larch bud moth (*Zeiraphera diniana* Gn.), whose effect is particularly intense at high altitude (Weber 1995). Other authors who have found differences in the growth trend of *Larix decidua* compared to other conifer species, have also attributed them to the action of the larch bud moth (Baltensweiler 1984; Rolland et al. 1998b). Climatic conditions on the south-facing slopes we investigated do indeed satisfy the critical temperature and insolation (Baltensweiler 1984) requirements on which the development of the larva depends. Furthermore, as Weber (1995) found that the outbreaks have reached the highest intensity during the last 160 years.

The age stratified data analysis showed, for both species, an increase in growth rate in age classes >100 years. Similar results have been obtained by other authors (Briffa 1992; Nicolussi 1995; Rolland et al. 1998a,b). In all these cases, growth rate increases had affected all age classes; in contrast we found a growth rate reduction in trees of age classes < 100 yr over the last few decades. This is possibly due to increased competition resulting from the increased density of regeneration; such high densities would not have been possible in the past, when the area was used intensively for grazing.

Interpretation of trends in tree-ring series is not easy or unequivocal. The major problem with the interpretation of tree-ring series trends is the method of indexation (Innes 1991), a problem examined in detail by Wigley et al. (1987) along with that of the recognition of long-term growth changes. We used BAIs, in an attempt to avoid any bias introduced by indexation. However, according to Briffa (1992) it is unclear to what extent an increase observed in BAI chronologies may be the result of systematic increases associated with tree ageing. Moreover BAI is only one, far from ideal, indication of net primary production, which takes no account of possible changes in total wood density which could compensate for volume changes.

Results from analysis of cambial age stratified data, although free from bias deriving from indexation, may also be influenced by the approximations required by the technique: it is necessary to estimate the age of the tree when the pith is not present in the core. Given the irregularity of the growth rate of juvenile trees and the great variety of factors that can affect it, age estimation can introduce errors that are difficult to predict or compensate. In addition, for the results obtained to be significant, all the age classes within the time period analysed must be well represented, so a large sample size is

required. In this study, the *Pinus cembra* cores satisfied both these conditions, while those for *Larix decidua* probably were not numerous enough because the species itself is scarce. Taken together, and allowing for the uncertainties, the results of both approaches argue in favour of a recent increase in growth rate, and our results are consistent with the results of several studies conducted with different techniques and in different areas. Our results support Briffa's (1992) conclusions that on this side of the Alps there is an increase in the rate of accumulation of woody biomass, which is of considerable importance, since it points to an increased rate of sequestering of CO₂ in the biosphere (Piuissi 2000).

With regard to the causes of these increases, some authors suggest climate change and other anthropogenic causes, such as changes in nutrient fluxes due to air pollution and/or the fertilization effect of increasing CO₂ (Brubaker 1986; Graumlich 1991; Briffa 1992; Graybill & Idso 1993). However, demonstrating the cause-effect relationship is difficult (Wigley et al. 1987). In addition, our chronologies start just at the beginning of the Little Ice Age, whose maximum was established in the period 1650-1850 by Grove (1988) on the basis of glaciological data. Thus, the growth rate increase starting around 1870 detected in the *Pinus cembra* chronology may be due to the termination of the unfavourable climatic conditions during the Little Ice Age, rather than to the beginning of favourable conditions. In contrast, the analysis of age stratified data showed an increase in the BAIs of trees older than 100 yr, which is gradual and continuous and which might be due to slow, ongoing environmental changes. A combination of different causes is also possible.

In conclusion, all the lines of evidence argue in favour of a widespread rise in forest- and tree lines and of a growth rate increase. However it is difficult to infer definitive cause/effect relationships from this site: the simultaneous occurrence of grazing reduction and the beginning of the climatic warming during the late 1800s complicates the interpretation of changes, particularly because grazing and climatic records are poor. The comparison of data from areas established as part of a wide-ranging monitoring network is an essential next step if we want to achieve a clearer idea of the forest dynamics acting at the sub-alpine level in the area studied, and in the Alps in general.

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