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Forest Ecology and Management 109 (1998) 103–118

Forest Ecology
and
Management

Potential sampling bias in long-term forest growth trends reconstructed from tree rings: A case study from the Italian Alps

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Accepted 16 December 1997

Abstract

Tree-ring studies of long-term growth trends have often produced controversial results. In such studies, the largest-diameter trees in a stand are usually sampled. We assessed the influence of stand dynamics on long-term growth trends by examining the past diameters of all the trees living in two uneven-aged subalpine Norway spruce (*Picea abies* (L.) Karst.) stands in the Italian eastern Alps, as reconstructed from ring widths. The trees were ordered according to diameter, and groups of 12 trees (the 12 largest, the 12 smallest, etc.) were formed. Different diameter groups have different increment curves. In both stands, the 12 largest trees in 1992 have not had consistently faster growth rates than smaller trees. This indicates that changes in diameter ranking order have occurred in the past and may be expected in the future. During stand development, changes occur in the relative position of individual trees, as ordered by diameter. The largest-diameter trees, at any time, may not always have been the largest trees and may not continue to be so. In a given year, the largest trees on average grow slower than other trees, which will become the largest in the future. The mean chronologies of the trees that were among the largest, prior to the harvest, and which presently (in 1992) are no longer in the top 12, and the mean chronologies of the trees that have moved up into the top 12 show very different growth trends. If analysed out of context, they would be interpreted differently, leading to different conclusions on long-term growth trends. When only the 12 largest-diameter trees are sampled, a bias may be present, as the trees may not have been open grown and free of competition in the past. Consequently, studies of long-term growth may be seriously affected by bias attributable to stand dynamics and sampling strategies. In future studies, the growth patterns of all diameter classes in a stand should be assessed, rather than restricting the sampling to the largest diameters. © 1998 Elsevier Science B.V.

Keywords: Dendrochronology; Long-term growth trends; Stand dynamics; Sampling bias; Subalpine Norway spruce; Alps

1. Introduction

Tree-ring width and stem radial increment have frequently been used as indicators of stress created by environmental changes. Dendroecological methods

have been used to reconstruct past climate, and, more recently, they have been used to identify and quantify anomalous growth trends. The majority of dendroclimatic studies have used a sample of dominant and co-dominant trees within the stand, to produce a long time series containing the maximum possible amount of climatic information. On the basis of the past growth of these trees, summer temperatures and

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precipitation regimes have been reconstructed for many regions. Similarly, a relatively small sample of dominant and co-dominant trees has been used to determine changes in growth patterns within specific stands. However, the interpretation of high- and low-frequency signals in long-term growth trends remains controversial.

Many growth analyses in managed forests have been concerned with the potential impact of air pollution on long-term growth patterns. Such studies may be particularly susceptible to sampling bias as a result of interactions between air pollution effects and stand dynamics. It is, therefore, useful to examine these studies of potential air pollution impacts in some detail. Classic studies around point sources of air pollution, such as smelters, have documented a clear effect of localized pollutants on tree-ring growth, often in the form of growth decreases (e.g. Vins, 1961; Pollanschütz, 1962; Vins and Mrkva, 1973; Kreutzer et al., 1983; McClenahan and Dochinger, 1985; Nöjd and Kauppi, 1995; Sander et al., 1995). Studies of the impact of air pollution at a regional scale have been more controversial, and there is considerable difficulty over the interpretation of the results (Innes and Cook, 1989; Weber and Grulke, 1995). However, evidence of the impacts of regional pollutants exists, such as the decreases in growth caused by ozone in the mountains around the Los Angeles basin in California (Peterson et al., 1987, 1991, 1993, 1995).

In the eastern USA, although tree-ring analyses undertaken as part of the investigation into reports of a regional decline of red spruce (*Picea rubens* Sarg.) indicate the existence of growth declines (Johnson and Siccama, 1983; McLaughlin et al., 1987; Cook, 1987; Conkey, 1988; Cook and Zedaker, 1992), they have been difficult to interpret. Stand dynamics seem to have strongly affected the results of many of these studies (Hornbeck et al., 1986; Federer and Hornbeck, 1987; LeBlanc, 1990). Van Deusen (1987, 1990) and Van Deusen et al. (1991) have argued that many observed growth declines in individual red spruces occurred in trees which show post-suppression releases. Cook (1990) demonstrated the dangers of using mean chronologies derived from large numbers of trees because of the effects of averaging separate populations. The role of simultaneous large-scale disturbances in the reported red

spruce growth decline has been thoroughly discussed, but remains uncertain (Reams and Van Deusen, 1993; Johnson et al., 1995; Reams and Van Deusen, 1995).

Similar debate has surrounded a purported decline in the growth of a number of pine species in the southern United States. Here, inventory results and dendroecological analyses suggest that there were reductions in the growth rates of several species in the 1970s and 1980s (e.g. Sheffield et al., 1985; Zahner et al., 1989; Van Deusen, 1992). Even the existence of a growth decline in the area is controversial (see, for example, Warren, 1990), and causal studies have, therefore, been difficult. Stand dynamics have been invoked as one of the mechanisms involved in the growth changes (Warren, 1990; Van Deusen, 1992), but nutritional problems (e.g. Binkley et al., 1989), pollution (e.g. Shafer et al., 1987) and climatic factors (e.g. Friend and Hafley, 1989) have also been discussed.

In Europe, some abrupt growth decreases were detected during the 1980s (e.g. Schweingruber et al., 1983; Kontic et al., 1986; Eckstein and Krause, 1989). In particular cases, it was possible to relate deteriorating crown condition to reductions in growth but, in others, no clear relationship existed (Innes, 1993). More recently, a long-term increase in radial growth has been documented by many authors (e.g. Innes, 1991; Becker et al., 1995; Neumann and Schadauer, 1995; Bräker, 1996; Lebourgeois and Becker, 1996; Spiecker et al., 1996). Various hypotheses have been proposed to explain the increase, including fertilization by carbon dioxide and/or nitrogen deposition, changing climatic conditions, and changing management practices. However, until the nature and distribution of the growth increase is better described, considerable difficulties exist over its interpretation.

The existence of changes in growth patterns in managed and unmanaged forests in Europe and North America suggests the need for more detailed analyses. However, such studies are complicated by the influence of stand dynamics on growth patterns. **The hypothesis examined here is that many dendroecological studies of long-term growth trends may have been affected by sampling bias attributable to the influence of stand dynamics (e.g. mortality, growth, competition) on particular trees. In particular, the restriction of the sampling to a few of the largest-**

diameter trees within a stand may have a marked influence on the ensuing results.

1.1. Standard sampling protocols

When assessing long-term growth trends, most investigators have sampled the largest-diameter trees in a stand. In even-aged stands, these are often the dominant and co-dominant trees. This strategy has arisen because of the wish to sample the oldest trees in a stand, which are often incorrectly assumed to be the largest. However, tree-ring patterns and the size of trees are strongly affected by forest management and natural disturbances, and the effects of restricting sampling to the largest trees has never been adequately documented.

Another reason for restricting sampling to the largest-diameter trees in a stand is to try to minimize the effects of stand-disturbance on tree-ring width–time series (Pilcher and Gray, 1982; Cook and Kairiukstis, 1990). Allometric relations suggest that the largest-diameter trees are also likely to be the tallest and, therefore, consisting of dominant and co-dominant trees. Such trees are generally believed to have been less affected by competition than other trees in the stand (Herman and DeMars, 1970; Abetz, 1985; Gerecke, 1988).

Most tree-ring studies attempt to collect cores from as homogeneous a population of trees as possible, so that effects due to non-climatic forcing factors, particularly endogenous disturbances, is minimized. Unfortunately, this is not always possible when the species being sampled grows in mixed-aged, unmanaged forests affected by gap-phase stand dynamics, or in managed stands. Sampling bias may be a major problem in such studies. Bias due to silvicultural treatments (Athari and Kramer, 1983; Abetz, 1985; Spelsberg, 1987; Badeau, 1995; Badeau et al., 1995) and to the mortality of a specific subset of the tree population (Lucier et al., 1989; Worbes et al., 1995) has been documented. In such cases, the trees involved in the analyses cannot be considered as representative of the original population within the stand, and may also be unrepresentative of the remaining population of trees.

Badeau (1995) and Badeau et al. (1995), studying the growth of high forests and coppice-with-standards stands of beech (*Fagus sylvatica*) in Lorraine (France),

argue that sampling the oldest trees alone in a stand restricts sampling to the weakest trees as the best trees have already been removed from the population as a result of selective thinning. The early growth of the oldest trees is therefore slow and past stand growth rates are underestimated. In contrast, Lucier et al. (1989), investigating red spruce in the northern Appalachians (USA), suggest that sampling the oldest trees in a stand results in only the best being sampled, because the weakest have been removed by selection, competition and timber cuts. The past stand growth rates are therefore overestimated. These conflicting conclusions, reflecting different environments and management approaches, indicate the importance of a detailed assessment of the available forest management information when assessing long-term growth trends.

Exceptions to restricting sampling to the largest-diameter trees in a stand include the studies of Eckstein et al. (1989) and Neumann (1993), who included analyses of the growth of suppressed and subdominant trees. However, Neumann (1993) adopted a forest yield approach, measuring the diameter of all trees in the stand. He restricted his tree-ring analyses to a sample of trees. Eckstein et al. (1989) found that all trees had systematic differences in their growth patterns, corresponding to their canopy class, regardless of which defoliation class they belonged to, and a pronounced association between general declining growth and increasing defoliation was detected only in the understorey and suppressed trees.

It is usually considered unlikely that the social status of subdominant trees could change to dominant or co-dominant trees through time. The pool of dominant trees will decrease with time as a result of tree mortality or increasing tree competition. This will reduce the social position of some trees, but not to such an extent that suppressed or subdominant trees become dominant. Therefore, a sample selected from the dominant trees in a stand is assumed to be a representative sample of the dominant trees in the past. This principle was formulated by Abetz (1985) for Norway spruce in even-aged stands in southwest Germany and has since been applied indiscriminately in virtually all the tree-ring studies which have been carried out to assess forest health condition in Europe, not only in even-aged but also in uneven-aged stands. A potential bias attributable to tree selection is prob-

ably more pronounced in uneven-aged than in even-aged stands. In uneven-aged stands, it is impossible to distinguish a dominant class of trees, and the largest-diameter trees have usually been sampled by dendrochronologists. In even-aged stands changes in the social status are believed to happen less frequently (Badeau et al., 1996) and thinning plays a major role in stand dynamics and strongly affects competition relationships among the trees in a stand. However, there are studies that show that trees in even-aged stands can also change their social position (e.g. Busse and Heske, 1930; Kramer and Kätsch, 1994). Thus, the common believe that dominant trees always stay dominant and that the currently dominant trees are representative of the dominant trees in the past may be false.

2. Materials and methods

In this study, the structure and the tree-ring growth dynamics of a Norway spruce (*Picea abies* (L.) Karst.) subalpine stand with a known silvicultural history was analysed.

2.1. Site description

Cross sections of Norway spruce were sampled in two areas of the Paneveggio Forest (Lat. 46°18', Long. 11°38') in Trentino, a region located in the eastern Alps (Dolomites, Italy). The areas lie adjacent to each other on the same slope and in the same forest compartment, have similar site characteristics, and differ only in elevation. The first plot (PAN1) is at an elevation ranging from 1700 to 1800 m a.s.l. and the second plot (PAN2) from 1800 to 1900 m a.s.l. The slope (gradient 30%) is exposed to the north. The soil is a typical spodosol, on a quartz-porphyrific bedrock. The forest (*Homogyno – Piceetum subalpinum myrtilletosum*) is dominated by Norway spruce (99%), with occasional European larch (*Larix decidua* Mill.) and Arolla pine (*Pinus cembra* L.). According to the forest management plan, the forest compartment containing both study areas has the following characteristics: 397 trees/ha, basal area ca. 50 m²/ha, average height 23 m, volume 513 m³/ha, and current annual increment 8.41 m³/ha. The stands are uneven-aged and consist of spatially fragmented cohorts (Cherubini

et al., 1996). *Calamagrostis villosa* (Chaix) J.F. Gmelin, *Vaccinium myrtillus* L. and *Sphagnum* sp. are abundant in the ground layer.

The mean annual temperature at the Passo Rolle weather station, 2002 m a.s.l. and 2.5 km from the site, is 2.4°C (1933–1978). The mean temperature in this region in the coldest month (January) is –5.1°C, and 10.4°C in the warmest month (July). At the meteorological station of Paneveggio, located at 1508 m a.s.l. and approximately 2 km from the site, the average total annual precipitation is 1207 mm (1922–1978), with a maximum in summer. The forest floor is covered with snow for about six months. Damage to the wood structure (radial cracks) of trees, probably caused by frost and/or frost drought, have been observed (Cherubini et al., 1997).

According to old management records for the forest, the compartment was harvested in the years 1870–1900, 1909–1913, 1919–1921, 1926–1933 and 1944–1946. Cutting operations were usually done during summer and autumn. Timber was extracted from the forest in winter, facilitated by frozen snow. Living trees were often damaged during this operation, as revealed by scarring. The synchronous occurrence of scars and growth releases enabled forest harvesting to be reconstructed for the years 1871 and 1912 at PAN1 and for the years 1871 and 1920 at PAN2 (Cherubini and Schweingruber, 1996). The harvesting in 1926–1933 or 1944–1946 was not associated with either scars or growth releases in the sample trees, suggesting that harvesting operations were restricted to parts of the compartment other than those used in this study.

2.2. Sampling methods

In June 1993, two plots (PAN1 and PAN2) approximately 0.4 ha in area were identified and all the living trees there labelled and mapped. For each standing tree, two perpendicular diameters at breast height (DBH), four crown projection radii (N, E, S, W), tree height, and two crown base heights, were measured to determine the vertical structure of the stand. The trees were then felled as part of a separate study of new silvicultural treatments for subalpine spruce stands by the 'Istituto di Selvicoltura, Università di Firenze'. Cross sections were taken at stump height ($n=73$ at PAN1, and $n=65$ at PAN2) and 4 m above the ground

($n=66$ at PAN1, and $n=65$ at PAN2). The 4 m cross sections reflect the common length for logs in the region, and enabled the normal logging of the timber. All the cross sections were seasoned in a fresh-air dry store, and sanded a few months later.

2.3. Dendrochronological analyses

Ring-width measurements were made to the nearest 0.01 mm on one radius (subjectively selected as the most regular) of each of the cross sections taken at 4 m height, using ANIOL-measurement equipment and the CATRAS-software package. The results were examined using the DENS-software package (Swiss Federal Institute for Forest, Snow and Landscape Research, WSL, Birmensdorf, Switzerland). The raw ring widths of the single curves of each dated tree were plotted. The single curves were checked visually and then synchronized by the *Gleichläufigkeit* (there is no English equivalent to this term), which is a measure of the year-to-year agreement between the interval trends of two chronologies based upon the sign of agreement (Kaennel and Schweingruber, 1995), and Student's *t*-test, which determines the degree of correlation between the curves.

The potential sampling bias arising from tree mortality could not be studied, as no data on past mortality were available for the stands. However, changes in social position were inferred by comparing tree diameter rankings over time. The past diameters of the trees at 4 m height were reconstructed from ring widths, and the trees ordered according to diameter in the years 1870, 1890, 1910, 1925, 1950 and 1992. The years 1870 and 1910 were analysed because they describe the diameter distribution before forest harvesting, and 1890 and 1925 were taken as post-cut years. The trees were divided into groups, with each group consisting of 12 trees, a common sample size in dendroecological studies. The first group was formed by the trees with the largest diameters in 1992, the second group by the trees having diameter from 13-to-24th largest, etc. A mean increment curve for each group of trees was then constructed.

As the cross sections taken at stump height were very irregular in shape, ring widths were not measured. Instead, the skeleton plot method was applied to gather information about the germination date and the juvenile growth of the trees. Three radii (the shortest,

the longest and one selected subjectively as the most regular) were analyzed. A skeleton plot was also performed for the 4 m cross sections, along the same measured radius. Skeleton plot analyses were carried out with the help of a stereomicroscope (Wild M3Z Leica), using the methods described by Stokes and Smiley (1968) and Schweingruber et al. (1990). During the skeleton plot analyses, the innermost rings (situated immediately next to the pith) and the presence of any abrupt growth changes were recorded. An abrupt growth change is defined as a sudden change (increase or decrease) in increment, at least 40% above or below the average increment over the previous four years. The difference between the age of the first abrupt growth release and the pith age on the stump cross section is termed the suppression time. The difference between the age of the innermost ring on the 4 m and on the stump cross sections enables retrospective studies of early height growth rates (e.g. Palik and Pregitzer, 1995). Master plots, which are averaged skeleton plots, for each tree and a master plot for the whole site were constructed.

3. Results and discussion

3.1. Size structure

The age of the innermost ring on the cross sections taken at stump height (Fig. 1) gives an approximate age of each tree in the plots. Both the plots are uneven-aged and appear to consist of different cohorts. The trees at PAN2 are, on average, older than at PAN1. The mean diameters at PAN2 are larger than at PAN1 (Fig. 2(A)). The trees at PAN2 are, on average, taller than at PAN1 (Fig. 2(B)). These figures, together with the lower mean height/diameter ratio (Fig. 2(C)) and the higher mean crown percentage at PAN2 (Fig. 2(D)), demonstrate the effects of the lower stand density at PAN2, and also suggest that PAN2 represents a more fully-developed stage than PAN1 in the stand development sequence.

3.2. Growth dynamics

The height growth in the juvenile period can be determined from the difference in pith age at 4 m height and the stump. At PAN1 ($n=66$), all trees took

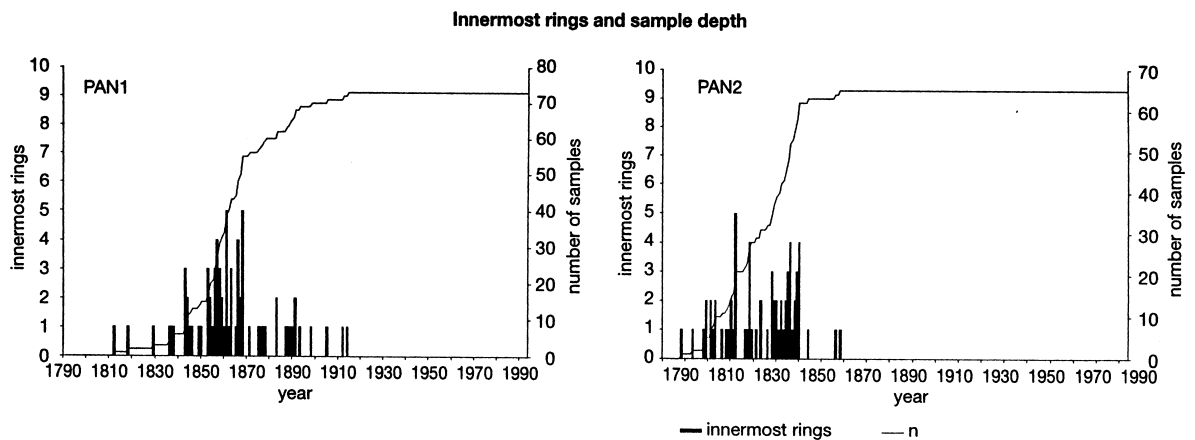


Fig. 1. Distribution of innermost rings on the cross sections taken at stump height and sample depth over time, at PAN1 and PAN2. The age of the innermost ring gives an approximate age of each tree in the plots. The plots are uneven-aged and the trees at PAN2 are on average older than at PAN1.

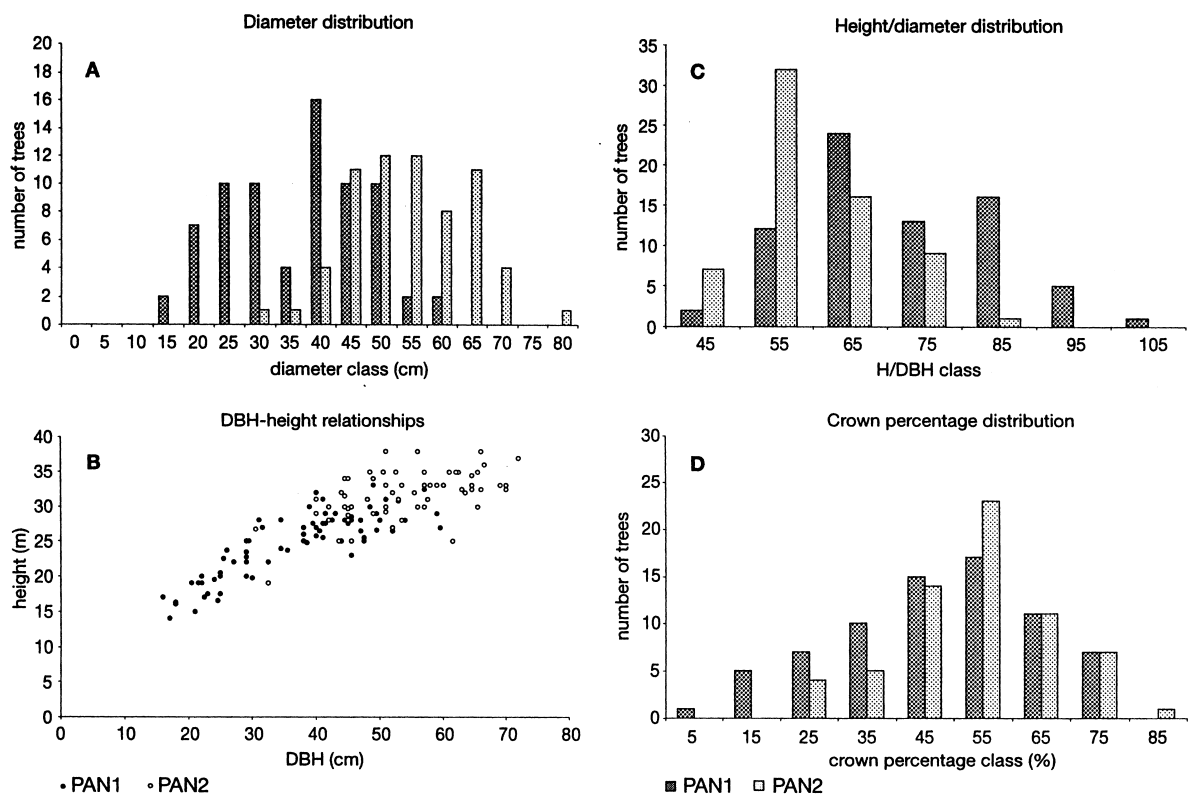


Fig. 2. (A) Frequency distribution of stem diameter at breast-height (DBH): the mean diameters at PAN2 are larger than at PAN1. (B) Relationships between diameter and height at PAN1 and PAN2: the trees at PAN2 are on average taller than at PAN1. (C) Distribution of the mean height/diameter ratio: the mean height/diameter ratio is lower at PAN2. (D) Distribution of mean crown percentage: the mean crown percentage is higher at PAN2.

at least 21 years to reach 4 m, 59% reached 4 m after 21–39 years, 30% after 40–59 years, and 11% after 60–71 years. The mean time taken to reach 4 m was 39 years, representing an average annual height increment of 10 cm. At PAN2 ($n=65$), 4% of the trees took less than 21 years to reach 4 m, 71% reached 4 m after 21–39 years, 25% after 40–59 years, and no tree took more than 60 years. The mean time necessary to reach 4 m was 34 years, i.e. 12 cm average annual height increment. The mean time taken to reach 4 m at PAN1 and at PAN2 was significantly different ($t>2,30$; $*P=0.02297$) in the two plots. Trees at PAN1 attained 4 m height slower than at PAN2, and it therefore seems likely that trees at PAN2 were freed from suppression earlier than at PAN1.

This hypothesis seems to be confirmed by the analysis of abrupt growth changes on the basal cross section. At PAN1 ($n=73$), 89% ($n=65$) of the trees had very small early growth rates, representing a period of suppression. At PAN2 ($n=65$), only 43% ($n=28$) of the trees showed such a suppression period. The mean suppression time, taking into account only those trees which show a period of suppression, is 32 years at PAN1 and 36 years at PAN2. Growth releases from suppression have enabled the times of forest harvesting at this site to be reconstructed (Cherubini and Schweingruber, 1996). The beginning of growth release after clearing varies from 1 to 5 years and the reaction time to the clearing event varies from tree to tree.

The presence of a period of suppression in many trees suggests that they were growing under the canopy. The seedlings and saplings were probably distributed sparsely on the forest floor, and the formation of a gap allowed their release from suppression. Trees suppressed for a long time were able to grow rapidly following release and had growth rates typical of saplings even though they were over 60 years old. There is a clear discrepancy between chronological and physiological age and very old trees may have smaller diameters than young trees.

The mean chronologies at PAN1 ($n=66$) and at PAN2 ($n=65$) were built by averaging all the living trees sampled in the plots (Fig. 3). The curves are characterized by an age trend and by abrupt growth releases dated ca. 1915 for PAN1 and few years later (ca. 1920) for PAN2. PAN2 had smaller ring widths than PAN1 from 1890 until 1950, with the exception

of a period of five years around 1925, presumably caused by the reaction to harvesting. Since 1950, the trees at PAN2, although older than at PAN1, have always had wider rings. Trees at PAN2 seem to have reacted more to the new conditions created by forest harvesting than those at PAN1. The greater reaction may be the result of more intense harvesting at PAN2, possibly associated with the greater age of the trees, but no evidence is available to confirm this hypothesis.

The increment of trees, grouped according to their diameter in 1992, is shown in Fig. 4. Different diameter groups have different increment curves. In both plots, the 12 largest-diameter trees in 1992 have not had consistently faster growth rates than smaller trees. At PAN1, the largest trees in 1992 have, in recent years, grown more slowly than smaller trees. This indicates that changes in diameter ranking order have occurred in the past and may be expected in the future.

A common method for assessing long-term growth trends is the analysis of past and present tree-ring growth (increment) within a stand. More recently, ring widths of the same cambial age have been compared (e.g. Becker, 1987; Bert and Becker, 1990; Nicolussi et al., 1995). These approaches, however, usually involve only 12 dominant and co-dominant trees. For PAN1 and PAN2, the effect of restricting the analysis to dominant trees was simulated by taking the 12 largest-diameter trees in 1992 and the 12 largest at other points in time. In Fig. 5, the mean increment of all groups is shown. Between forest harvesting (1912 at PAN1 and 1920 at PAN2) and 1992, the mean increment of the trees which were largest in 1992 was always greater than that of the trees which were largest in the past. This observation implies that, in a given year, the mean increment of the largest-diameter trees in a stand may be less than the mean increment of those trees that will be the largest in the future. Consequently, if only the 12 largest-diameter trees in 1992 are sampled, and their past and present increment is compared, results that are unrepresentative for the stand are obtained.

At PAN2, the trees that were the largest in diameter in 1870 reacted to the 1920 forest harvest more than the other trees and, in the recent past, they have grown faster than the trees that were the largest in diameter in 1890, 1910, 1925 and 1950. This is interesting in that it suggests that the extent of the reaction of individual trees to harvesting, at least at PAN2, is strongly

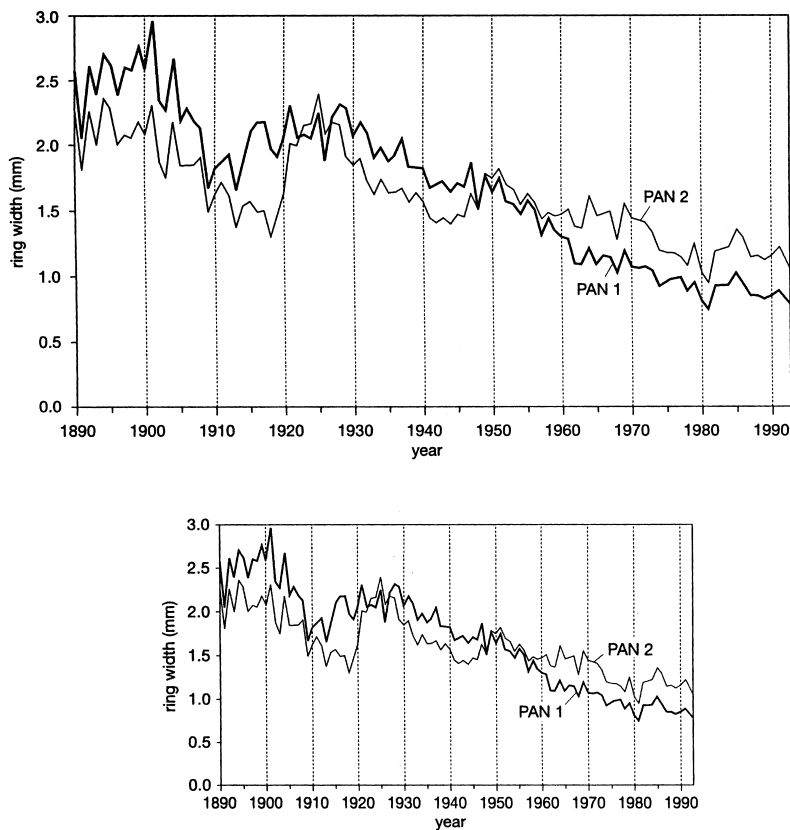


Fig. 3. Mean ring-width chronologies at PAN1 ($n=66$) and at PAN2 ($n=65$) on an arithmetical scale. They were built by averaging all the trees in the plots.

influenced by the size of the trees. Close examination of Fig. 5 indicates that these trees, although the largest in diameter in 1870, were growing more slowly than other trees at the site up to the time of the harvest. However, the growth of trees before harvesting is difficult to interpret because no information is available for those trees that were removed. The trees which were the largest in 1870 then reacted more strongly to the harvest than others, but still continued to have relatively slow growth. This changed between 1935 and 1940, with this group of trees showing increased growth relative to other tree groups. It is uncertain whether these represent random fluctuations or whether a process related to stand dynamics was operating. The cause for the recent increase in growth relative to the other trees is also uncertain.

Table 1 shows that of the 12 currently largest-diameter trees at PAN1 (Table 1(A)) and at PAN2

(Table 1(B)), only six were also ranked as the 12 largest-diameter trees in 1910 (at PAN1) or 1870 (PAN2). Of the 12 largest-diameter trees in 1992, six showed a substantial increase in tree-ring growth in recent years as compared to the average tree-ring growth in the stand and, therefore, increased their ranking order. In some cases, the greatest increase in ranking occurred between 1950 and 1992, in others it occurred earlier. Their diameters indicate that the social status of these trees has increased. This is contrary to the common assumption that the largest-diameter trees are little influenced by competition because their social status has remained constant over time.

A remarkable feature of the data shown in Table 1 is that at PAN1, nearly all the trees that dropped out of the group of the largest 12 trees after 1870/1910 or that entered the group of 12 largest trees in 1992 or earlier

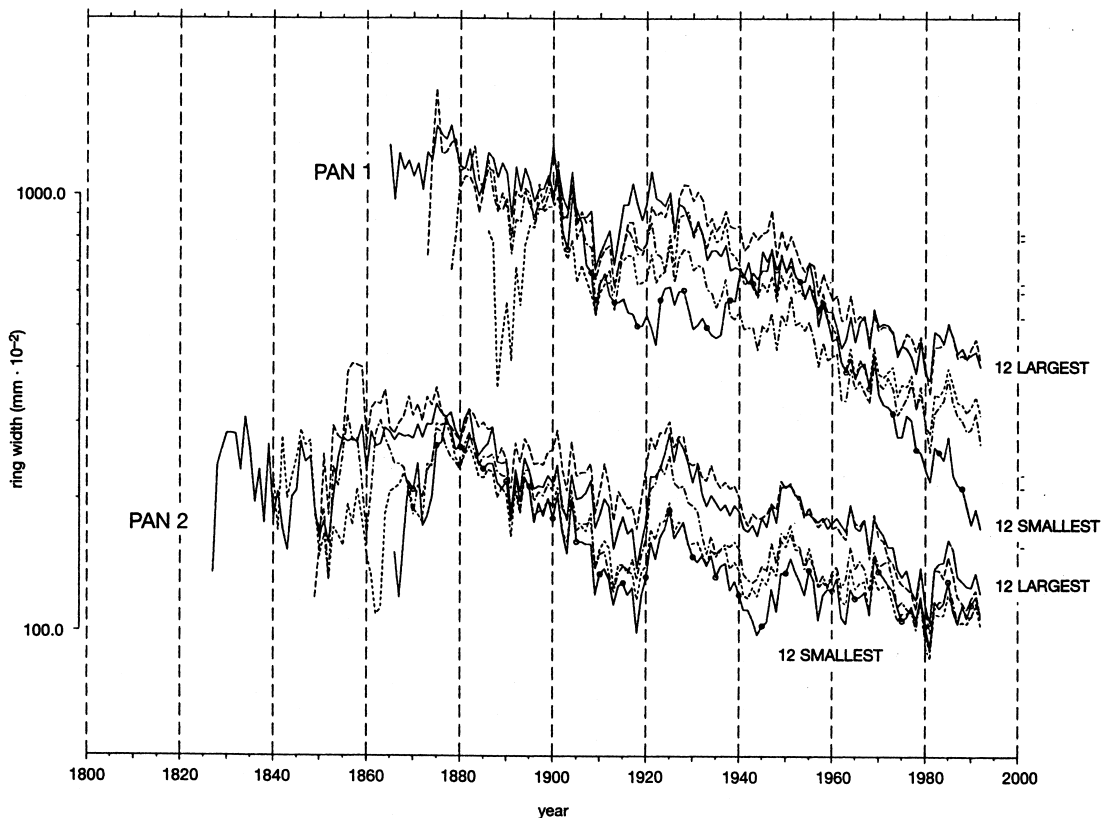


Fig. 4. Growth (increment) over time of trees grouped according to their diameter in 1992, at PAN1 and at PAN2. Each curve is the mean of 12 trees. Different diameter groups have different increment curves. In both plots, the 12 largest-diameter trees in 1992 have not had consistently faster growth rates than smaller trees.

(both marked in bold in the table) showed either a consistent decline or increase between the different time periods. During stand development, changes occur in the position of individual trees as ordered by diameter at 4 m height. The largest-diameter trees at any time may not always have been the largest trees and may not continue to be so. It seems likely that these changes occur independently from forest harvesting. The implication of these results is that, depending on which trees are chosen, very different growth trends may be derived.

The consequences of the above for growth studies within a stand is illustrated in Fig. 6. This compares the mean chronologies of the six trees that were among the largest diameters prior to the harvest, and which presently (in 1992) are no longer in the top 12, and the mean chronologies of the six trees that have moved up

into the top 12. The different groups show very different growth trends. If analysed out of context, they would be interpreted differently, leading to different conclusions on long-term growth trends. Given that 12 trees is a common size in dendroecological investigations, the risk of misinterpretation of the growth trends as a result of these stand effects is considerable.

4. Conclusions

At Paneveggio, tree-ring patterns are strongly influenced by past forest harvesting. This is a common finding in dendroecological studies. However, further analysis has revealed that different diameter groups have different tree-ring growth curves and that these

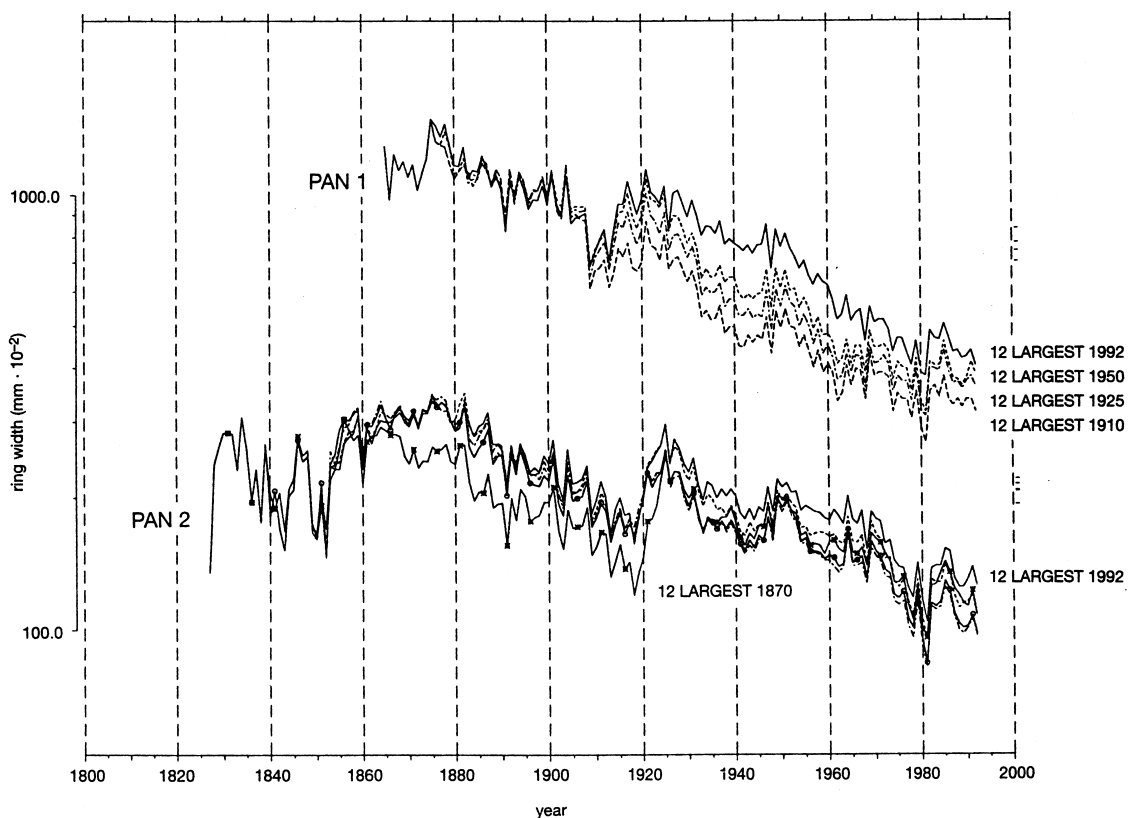


Fig. 5. Increment curves of the 12 largest-diameter trees in 1870, 1890, 1910, 1925, 1950 and 1992, at PAN1 and at PAN2.

vary unpredictably. Leaving mortality aside, during stand development, the relative diameters of individual trees change. The largest-diameter trees at any one time may not always have been the largest trees and may not continue to be so. Sampling only the 12 largest-diameter trees may create a bias in the results, as the trees might not have been open-grown and free of competition in the past. Moreover, at a particular time, the largest trees may be growing more slowly than smaller-diameter trees. Considering only the increment of the 12 largest-diameter trees in a given year, and comparing their past to present increment, therefore results in bias.

Site history is a major problem in regions where human activities have affected forest ecosystems for long periods of time. For example, the Norway spruce forests of the Alps have been managed for centuries and have been heavily affected by anthropogenic activities (e.g. silviculture, grazing, litter harvesting).

In such cases, great care needs to be taken to account for the effects of disturbances in the tree-ring chronologies prior to any attempt to analyze them in relation to forest decline or growth studies. Standardization techniques, commonly used in chronology construction to remove age-related sample bias, effectively minimize the effects of disturbances by removing the low-frequency variability attributable to stand dynamics, but they also remove other low-frequency signals, such as evidence of pollution and of long-term climate change (Briffa et al., 1996). We, therefore, suggest avoiding standardization techniques so as to emphasize long-term trends in tree-ring patterns. Disturbances (natural or anthropogenic) should be identified using the tree-ring patterns and written records (e.g. Delwaide and Fillion, 1988; Payette et al., 1990).

Most dendroecological studies of long-term growth trends in relation to forest decline have produced controversial results, probably because they were

Table 1

The trees were ordered according to their diameter for the years 1870, 1890, 1910, 1925, 1950 and 1992, for PAN1 (Table 1(A)) and PAN2 (Table 1(B)). For each year, the position of the tree No. (tree ID) within the diameter ranking order and its diameter (cm) are given. The ID (in bold) of trees that presently have the largest diameters but have changed their position over time are marked with a dotted line (tree No. 13, 89, 88, 105, 43 and 1 at PAN1 and No. 273, 226, 228, 252, 237 and 242 at PAN2). The ID (in bold) of trees that had the largest diameters in the past and now have smaller diameters are marked with a solid line (tree No. 111, 28, 5, 113, 31 and 114 at PAN1 and No. 209, 265, 213, 219, 208 and 210 at PAN2)

Ranking Order	1910	1925	1950	1992	
1	2	2	9	13	} sampled
2	9	9	2	91	
3	115	115	91	89	
4	3	3	18	9	
5	114	91	3	2	
6	7	111	115	3	
7	28	13	88	115	
8	91	28	88	88	
9	5	113	7	105	
10	113	7	96	43	
11	31	88	113	1	
12	114	5	28	7	
13	4	81	111	96	
14	18	96	92	97	
15	108	88	105	69	
16	35	114	5	114	
17	96	4	1	110	
18	88	92	31	113	
19	88	108	114	103	
20	92	8	98	28	
21	8	35	110	54	
22	17	17	8	92	
23	110	1	101	101	
24	1	98	108	108	
25	27	101	69	5	
26	19	110	4	21	
27	6	19	21	98	
28	98	21	35	8	
29	101	11	103	111	
30	11	6	97	19	
31	103	103	11	31	
32	29	105	17	11	
33	107	97	19	4	
34	21	27	22	22	
35	109	107	43	17	
36	16	109	6	35	
37	97	22	54	57	
38	26	16	109	38	
39	15	26	27	107	
40	18	29	107	109	
41	12	18	57	68	
42	105	69	18	6	
43	22	12	16	27	
44	69	15	68	39	
45	33	33	38	47	
46		68	26	18	
47		106	37	37	
48		39	12	29	
49		57	47	99	
50		43	39	26	
51			29	46	
52			15	16	
53			106	49	
54			46	45	
55			99	36	
56			79	79	
57			49	41	
58			33	106	
59			45	51	
60			56	12	
61			48	56	
62			52	52	
63			51	15	
64			41	80	
65			36	48	
66			80	33	

Table 1 (Continued)

Ranking Order	1870	1890	1910	1925	1950	1992	
1	275	275	275	275	275	275	sampled
2	203	202	202	202	202	202	
3	200	210	210	213	206	273	
4	211	203	242	242	278	206	
5	202	211	203	278	242	228	
6	265	242	206	203	203	228	
7	213	200	273	206	213	203	
8	219	210	211	211	211	252	
9	206	206	200	252	228	237	
10	268	273	252	271	241	211	
11	264	232	210	200	252	264	
12	210	271	271	244	264	242	
13	252	265	244	241	271	213	
14	278	228	241	219	228	241	
15	263	264	264	243	209	240	
16	214	214	261	264	216	234	
17	259	244	220	226	243	218	
18	258	208	243	246	244	261	
19	226	274	229	261	237	219	
20	274	259	274	229	218	271	
21	212	212	214	228	246	204	
22	242	229	246	237	240	246	
23	271	243	237	266	212	224	
24	233	210	212	212	234	259	
25	207	261	250	214	224	262	
26	269	255	285	274	229	209	
27	224	224	253	224	261	243	
28	251	234	266	259	259	244	
29	205	260	208	218	266	265	
30	262	205	259	255	245	272	
31	249	207	251	250	214	212	
32	234	258	260	234	208	210	
33	255	251	224	251	204	266	
34	244	250	272	272	207	229	
35	243	263	228	208	255	208	
36	229	233	267	245	262	245	
37	272	266	234	267	274	207	
38	260	272	207	268	265	260	
39	250	241	249	207	254	248	
40		262	218	260	210	250	
41		267	210	249	260	274	
42		215	215	254	248	254	
43		254	254	248	272	256	
44		249	233	240	267	214	
45		237	245	233	250	255	
46		246	205	215	251	233	
47		257	248	210	233	251	
48		269	258	262	256	263	
49		245	216	256	205	267	
50		248	263	216	263	217	
51		218	262	263	249	247	
52		247	256	205	247	231	
53		235	247	247	216	216	
54		216	257	258	215	232	
55		270	270	270	258	205	
56		256	269	217	217	235	
57		228	235	204	232	270	
58		217	240	236	270	258	
59		231	217	257	231	215	
60		236	236	269	269	227	
61		232	232	232	257	249	
62		223	231	235	236	257	
63		240	223	231	235	269	
64			204	223	223	236	
65				227	227	223	

affected by bias due to stand dynamics and to sampling strategies. Generally, only trees with the largest diameters have been sampled in such studies, and the trees were probably unrepresentative of the whole population. The literature reviewed in the introduction

indicates considerable variations in the interpretation of the growth results that have been obtained from tree-ring studies. The results presented here suggest that at least a part of this variation may be the result of difficulties created by the use of sampling designs

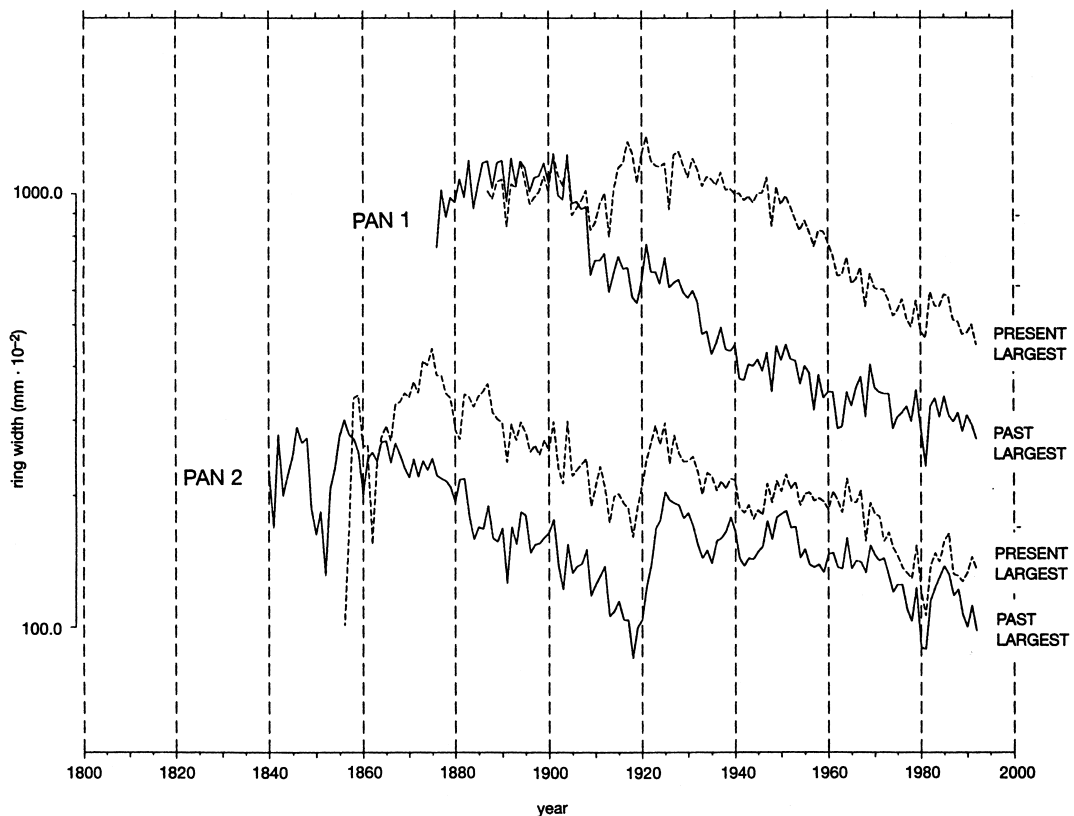


Fig. 6. Mean chronologies of those trees ($n=6$) that were among the largest-diameter trees in the past at PAN1 (1910) and at PAN2 (1870), and that are not presently (1992) among the 12 largest (—, labeled as PAST LARGEST in diameter), and of those ($n=6$) that are presently among the largest, but that were not the largest in the past (---, labeled as PRESENT LARGEST in diameter).

developed for little-disturbed, open-grown forests, rather than closed stands in managed forests. Consequently, future studies of growth trends in managed, closed forests should include a careful reconstruction of the individual histories of sample trees, and more than 12 trees should be included in the overall sample. The sample should not be restricted to the largest-diameter trees within the stand.

The effects of disturbances or forest management in tree-ring patterns should not be minimized through statistical manipulations. On the contrary, evidence of disturbances and other disruptions to normal tree growth patterns should be used to improve the knowledge of stand history, enabling a better interpretation of long-term trends. As a general rule, it is only possible to study stand dynamics and to avoid the misinterpretation of long-term growth patterns if tree-

ring patterns of different social classes of trees in the stand are analyzed.

Acknowledgements

The research was financially supported by the *Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)*, the *Istituto di Selvicoltura, Università di Firenze (Italy)* and the *Parco Naturale di Paneveggio e Pale di San Martino (Italy)*. The *Servizi Forestali Provincia di Trento (Italy)* provided technical support during the sampling. We thank Michael Rumpff for ring-width measurements, and Norbert Kräuchi, Giorgio Strumia and three anonymous referees for helpful discussions and comments on the manuscript.

References

- Abetz, P., 1985. Ein Vorschlag zur Durchführung von Wachstumsanalysen im Rahmen der Ursachenerforschung von Waldschäden in Südwestdeutschland. Allg. Forst-Jagdztg. 156, 177–187.
- Athari, S., Kramer, H., 1983. Zur Problematik der Erfassung von umweltbedingten Zuwachsverlusten in Fichtenbeständen. Forst-Holzwirt 38, 204–206.
- Badeau, V., 1995. Etude dendroécologique du hêtre (*Fagus sylvatica* L.) sur les plateaux calcaires de Lorraine. Ph.D. Dissertation, Université de Nancy, Nancy, pp. 238.
- Badeau, V., Becker, M., Bert D., Dupouey, J.-L., Lebourgeois, F., Picard, J.-F., 1996. Long-term growth trends of trees: Ten years of dendrochronological studies in France. In: Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P. (Eds.), Growth Trends in European Forests. European Forest Institute, Springer-Verlag, Berlin and Heidelberg, pp. 167–181.
- Badeau, V., Dupouey, J.-L., Becker, M., Picard, J.-F., 1995. Long-term growth trends of *Fagus sylvatica* L. in northeastern France. A comparison between high and low density stands. Acta Oecol. 16, 571–583.
- Becker, M., 1987. Bilan de santé actuel et rétrospectif du sapin dans les Vosges. Étude écologique et dendrochronologique. Ann. Sci. For. 44, 379–402.
- Becker, M., Bert, G.D., Landmann, G., Lévy, G., Rameau, J.C., Ulrich, E., 1995. Growth and decline symptoms of silver fir and Norway spruce in northeastern France: Relation to climate, nutrition and silviculture. In: Landmann, G., Bonneau, M. (Eds.), Forest Decline and Atmospheric Deposition Effects in the French Mountains. Springer-Verlag, Berlin, pp. 120–142.
- Bert, G.D., Becker, H.M., 1990. Vitalité actuelle et passée du sapin (*Abies alba* Mill) dans le Jura. Étude dendroécologique. Ann. Sci. For. 47, 395–412.
- Binkley, D., Driscoll, C.T., Allen, H.L., Schoeneberger, P., McAvoy, D., 1989. Acidic deposition and forest soils. Context and case studies in the southeastern United States. Springer-Verlag, New York, pp. 149.
- Bräker, O.U., 1996. Growth trends of Swiss forests: Tree-ring data. Case study Toppwald. In: Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P. (Eds.), Growth Trends in European Forests. European Forest Institute, Springer-Verlag, Berlin and Heidelberg, pp. 199–217.
- Briffa, K.R., Jones, P.D., Schweingruber, F.H., Karlén, W., Shiyatov, S.G., 1996. Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals. In: Jones, P.D., Bradley, R.S., Jouzel, J. (Eds.), Climatic Variations and Forcing Mechanisms of the Last 2000 Years. Springer-Verlag, Berlin and Heidelberg, pp. 9–41.
- Busse, J., Heske, F., 1930. Vom 'Umsetzen' unserer Waldbäume. Tharandter Forstliches Jahrbuch 81, 118–130.
- Cherubini, P., Schweingruber, F.H., 1996. Scars as evidence of past forest cuts in a subalpine spruce forest in the Alps. In: Dean, J.S., Meko, D.M., Swetnam, T.W. (Eds.), Tree rings, environment and humanity. Radiocarbon, University of Arizona, Tucson, pp. 371–378.
- Cherubini, P., Piussi, P., Schweingruber, F.H., 1996. Spatiotemporal growth dynamics and disturbances in a subalpine spruce forest in the Alps: A dendroecological reconstruction. Can. J. For. Res. 26, 991–1001.
- Cherubini, P., Schweingruber, F.H., Forster, T., 1997. Morphology and ecological significance of intra-annual radial cracks in living conifers. Trees 11, 216–222.
- Conkey, L.E., 1988. Decline in old-growth red spruce stands in western Maine: An analysis of wood density and climate. Can. J. For. Res. 18, 1063–1068.
- Cook, E.R., 1987. The use and limitations of dendrochronology in studying effects of air pollution on forests. In: Hutchinson, T.C., Meema, K.A. (Eds.), Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems. Springer-Verlag, New York, pp. 277–290.
- Cook, E.R., 1990. Bootstrap confidence intervals for red spruce ring-width chronologies and an assessment of age-related bias in recent growth trends. Can. J. For. Res. 20, 1326–1331.
- Cook, E.R., Kairiukstis, L.A., 1990. Methods of dendrochronology. Applications in the environmental sciences. International Institute for Applied Systems Analysis. Kluwer Academic Publishers, Dordrecht, p. 394.
- Cook, E.R., Zedaker, S.M., 1992. The dendroecology of red spruce decline. In: Eagar, C., Adams, M.B. (Eds.), Ecology and Decline of Red Spruce in the Eastern United States. Springer-Verlag, New York, pp. 192–231.
- Delwaide, A., Filion, L., 1988. Les coupes forestières dans les pessières à lichens: Effets sur la croissance et la régénération des conifères (Whapmagoostui Québec subarctique). Can. J. Bot. 66, 1013–1020.
- Eckstein, D., Krause, C., 1989. Dendroecological studies on spruce trees to monitor environmental changes around Hamburg. IAWA Bull. n.s. 10, 175–182.
- Eckstein, D., Krause, C., Bauch, J., 1989. Dendroecological investigation of spruce trees (*Picea abies* (L.) Karst.) of different damage and canopy classes. Holzforschung 43, 411–417.
- Federer, C.A., Hornbeck, J.W., 1987. Expected decrease in diameter growth of even-aged red spruce. Can. J. For. Res. 17, 266–269.
- Friend, A.L., Hafley, W.L., 1989. Climatic limitations to growth in loblolly and shortleaf pine (*Pinus taeda* and *P. echinata*): A dendroclimatological approach. For. Ecol. Manage. 26, 113–122.
- Gerecke, K.-L., 1988. Herleitung und Anwendung von 'Referenzbäumen' zur Beschreibung des Wachstumsgangs vorherrschender Tannen. Ph.D. Dissertation, Albert-Ludwigs-Universität, Freiburg im Breisgau, pp. 141.
- Herman, F.R., DeMars, D.J., 1970. Techniques and problems of stem analysis of old-growth conifers in the Oregon-Washington Cascade Range. In: Smith, J.H.G., Worrall, J. (Eds.), Tree-ring Analysis with Special Reference to Northwest America. University of British Columbia, Vancouver, pp. 74–77.
- Hornbeck, J.W., Smith, R.B., Federer, C.A., 1986. Growth decline in red spruce and balsam fir relative to natural processes. Water, Air and Soil Pollut. 31, 425–430.
- Innes, J.L., 1991. High-altitude and high-latitude tree growth in relation to past, present and future global changes. Holocene 1, 168–173.

- Innes, J.L., 1993. Forest health: Its assessment and status. CAB International, Wallingford, pp. 677.
- Innes, J.L., Cook, E.R., 1989. Tree-ring analysis as an aid to evaluating the effects of pollution on tree growth. *Can. J. For. Res.* 19, 1174–1189.
- Johnson, A.H., Siccama, T.G., 1983. Acid deposition and forest decline. *Environ. Sci. Technol.* 17, 294–305.
- Johnson, A.H., Cook, E.R., Siccama, T.G., Battles, J.J., McLaughlin, S.B., LeBlanc, D.C., Wargo, P.M., 1995. Comment: Synchronic large-scale disturbances and red spruce growth decline. *Can. J. For. Res.* 25, 851–858.
- Kaennel, M., Schweingruber, F.H., 1995. Multilingual glossary of dendrochronology. Terms and definitions in English, German, French, Spanish, Italian, Portuguese, and Russian. Swiss Federal Institute for Forest, Snow and Landscape Research, Haupt, Bern, p. 467.
- Kontic, R., Niederer, M., Nippel, C.-A., Winkler-Seifert, A., 1986. Jahrringanalysen an Nadelbäumen zur Darstellung und Interpretation von Waldschäden (Wallis Schweiz). *Eidgenöss. Anst. forstl. Vers.wes. Ber.* 283, 1–46.
- Kramer, H., Kätsch, C., 1994. Individuelles Wachstum von Waldbäumen in Abhängigkeit von natürlichen und anthropogenen Einflüssen. *Schriften aus der forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt* 117, 1–148.
- Kreutzer, K., Knorr, A., Brosinger, F., Kretschmar, P., 1983. Scots pine dying within the neighborhood of an industrial area. In: Ulrich, B., Pankrath, J. (Eds.), *Effects of air pollutants on forest ecosystems*. D. Reidel, Dordrecht, pp. 343–357.
- LeBlanc, D.C., 1990. Red spruce decline on Whiteface Mountain, New York. 1. Relationships with elevation, tree age, and competition. *Can. J. For. Res.* 20, 1408–1414.
- Lebourgeois, F., Becker, M., 1996. Dendroécologie du pin laricio de Corse dans l'ouest de la France. Évolution du potentiel de croissance au cours des dernières décennies. *Ann. Sci. For.* 53, 931–946.
- Lucier, A.A., Warnick, W.L., Hyink, D.M., 1989. Possible bias in tree-ring time series due to mortality. *J. For.* 87, 31–32.
- McClenahan, J.R., Dochinger, L.S., 1985. Tree ring response of white oak to climate and air pollution near the Ohio River Valley. *J. Environ. Qual.* 14, 274–280.
- McLaughlin, S.B., Downing, D.J., Blasing, T.J., Cook, E.R., Adams, H.S., 1987. An analysis of climate and competition as contributors to decline of red spruce in high elevation Appalachian forests of the Eastern United States. *Oecologia* 72, 487–501.
- Neumann, M., 1993. Zuwachsuntersuchungen an Fichte in verschiedenen Seehöhenstufen im österreichischen Zentralalpenbereich. *Forstwiss. Cent.bl.* 110, 221–274.
- Neumann, M., Schadauer, K., 1995. Die Entwicklung des Zuwachses in Österreich an Hand von Bohrkernanalysen. *Allg. Forst- Jagdztg.* 166, 230–234.
- Nicolussi, K., Bortenschlager, S., Körner, C., 1995. Increase in tree-ring width in subalpine *Pinus cembra* from the central Alps that may be CO₂-related. *Trees* 9, 181–189.
- Nöjd, P., Kauppi, P., 1995. Growth of Scots pine in a changing environment. In: Tikkanen, E., Niemelä, I. (Eds.), *Kola Peninsula pollutants and forest ecosystems in Lapland*. Final report of the Lapland forest damage project. The Finnish Forest Research Institute, pp. 62–64.
- Palik, B.J., Pregitzer, K.S., 1995. Variability in early height growth rate of forest trees: Implications for retrospective studies of stand dynamics. *Can. J. For. Res.* 25, 767–776.
- Payette, S., Filion, L., Delwaide, A., 1990. Disturbance regime of a cold temperate forest as deduced from tree-ring patterns: The Tantaré Ecological Reserve. Quebec. *Can. J. For. Res.* 20, 1228–1241.
- Peterson, D.L., Arbaugh, M.J., Robinson, L.J., 1991. Regional growth changes in ozone-stressed ponderosa pine (*Pinus ponderosa*) in the Sierra Nevada. California, USA. *Holocene* 1, 50–61.
- Peterson, D.L., Arbaugh, M.J., Robinson, L.J., 1993. Effects of ozone and climate on ponderosa pine (*Pinus ponderosa*) growth in the Colorado Rocky Mountains. *Can. J. For. Res.* 23, 1750–1759.
- Peterson, D.L., Arbaugh, M.J., Wakefield, V.A., Miller, P.R., 1987. Evidence of growth reduction in ozone-injured Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in Sequoia and Kings Canyon National Parks. *J. Air Pollut. Control Assoc.* 37, 906–912.
- Peterson, D.L., Silsbee, D.G., Poth, M., Arbaugh, M.J., Biles, F.E., 1995. Growth response of bigcone Douglas fir (*Pseudotsuga macrocarpa*) to long-term ozone exposure in southern California. *J. Air Waste Manage. Assoc.* 45, 36–45.
- Pilcher, J.R., Gray, B., 1982. The relationships between oak tree growth and climate in Britain. *J. Ecol.* 70, 297–304.
- Pollanschütz, J., 1962. Rauchschadensfeststellung unter besonderer Berücksichtigung von Bohrkernanalysen. *Allg. Forstztg.* 73, 1–4.
- Reams, G.A., Van Deusen, P.C., 1993. Synchronic large-scale disturbances and red spruce growth decline. *Can. J. For. Res.* 23, 1361–1374.
- Reams, G.A., Van Deusen, P.C., 1995. Reply: Synchronic large-scale disturbances and red spruce growth decline. *Can. J. For. Res.* 25, 859–869.
- Sander, C., Eckstein, D., Kyncl, J., Dobry, J., 1995. The growth of spruce (*Picea abies* (L.) Karst.) in the Krkonose-(Giant) Mountains as indicated by ring width and wood density. *Ann. Sci. For.* 52, 401–410.
- Schweingruber, F.H., Eckstein, D., Serre-Bachet, F., Bräker, O.U., 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* 8, 9–38.
- Schweingruber, F.H., Kontic, R., Winkler-Seifert, A., 1983. Eine jahrringanalytische Studie zum Nadelbaumsterben in der Schweiz. *Eidgenöss. Anst. forstl. Vers.wes. Ber.* 253, 1–29.
- Shafer, S.R., Heagle, A.S., Camberato, D.M., 1987. Effects of chronic doses of ozone on field-grown loblolly pine: Seedlings response in the first year. *J. Air Pollut. Control Assoc.* 37, 1179–1184.
- Sheffield, R.M., Cost, N.D., Bechtold, W.A., McClure, J.P., 1985. Pine growth reductions in the Southeast. *Resource Bull. SE-83*. USDA For. Serv., Southeast. For. Exp. Stn., Asheville, pp. 112.
- Spelsberg, G., 1987. Zum Problem der Beurteilung des Zuwachses in geschädigten Beständen. *Allg. Forst-Jagdztg.* 158, 205–211.

- Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P., 1996. Growth trends in European forests. European Forest Institute, Springer-Verlag, Berlin and Heidelberg, pp. 372.
- Stokes, M.A., Smiley, T.L., 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago and London, pp. 73.
- Van Deusen, P.C., 1987. Testing for stand dynamics effects on red spruce growth trends. *Can. J. For. Res.* 17, 1487–1495.
- Van Deusen, P.C., 1990. Stand dynamics and red spruce decline. *Can. J. For. Res.* 20, 743–749.
- Van Deusen, P.C., 1992. Growth trends and stand dynamics in natural loblolly pine in the southeastern United States. *Can. J. For. Res.* 22, 660–666.
- Van Deusen, P.C., Reams, G.A., Cook, E.R., 1991. Possible red spruce decline. Contributions of tree ring analysis. *J. For.* 89, 20–24.
- Vins, B., 1961. Störungen der Jahrringbildung durch Rauchschäden. *Naturwissenschaften* 448, 484–485.
- Vins, B., Mrkva, R., 1973. The diameter increment losses of pine stands as a result of injurious emissions. *Acta Universitatis Agriculturae (Brno)* 42, 25–46.
- Warren, W.G., 1990. Some novel statistical analyses relevant to the reported growth decline of pine species in the Southeast. *For. Sci.* 36, 448–463.
- Weber, J.A., Grulke, N.E., 1995. Response of stem growth and function to air pollution. In: Gartner, B.L. (Ed.), *Plant stems: Physiology and functional morphology*. Academic Press, San Diego, pp. 343–363.
- Worbes, M., Bonn, S., Riemer, T., 1995. Methoden zur Erfassung von Zuwachsverlusten und mögliche Einflussfaktoren auf das Jahresringbild von Bäumen in geschädigten Waldbeständen. *Forstwiss. Cent.bl.* 114, 313–325.
- Zahner, R., Saucier, J.R., Myers, R.K., 1989. Tree ring model interprets growth decline in natural stands of loblolly pine in the southeastern United States. *Can. J. For. Res.* 19, 612–621.