Long-Term Growth Trends of Trees: Ten Years of Dendrochronological Studies in France

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in "growth trends in European Forests"
Edited Spiecker et al, 1996, 372 pages

Abstract

The study of long-term growth trends in French forests began 10 years ago at the Phytoecological Laboratory of the National Agronomic Research Institute (INRA). Very large surveys have been carried out in several regions and for many species, allowing the study of changes in radial growth of individual trees during the past 150 years. In all cases, a significant increasing growth trend appeared. It varied between +50% and +160% depending on species and location. Careful analysis of possible bias has been made. Beside these biases, possible causes of such trends are discussed. This chapter summarizes the main methods and results of our laboratory. For additional information, our readers may refer to the cited articles.

1. Introduction

The study of long-term radial growth trends in the French forests began 10 years ago within the framework of the national research programme DEFORPA (*Dépérissement des Forêts et Pollution Atmosphérique*). Consequent to observations of abnormal crown damages on conifers in the eastern France, this programme was launched in 1984 in order to understand forest decline in relation to natural and man-made factors (see a review of research findings since 1985 in Landmann & Bonneau 1995).

The first hypothesis was that a strong increase of the atmospheric pollution levels, especially of acidifying compounds, may have had disastrous consequences on some soil characteristics and on health and growth of trees (Becker 1985). However, while this explanation seemed sufficient in some cases of severe dieback associated with local and heavy pollutions, the role of air pollution was not convincingly established in the majority of the damaged regions studied. The possible role of natural conditions (climatic or edaphic variations) on forest dieback was assessed through large ecological and dendrochronological surveys (Bonneau 1987). The main objective was, on one hand, to describe and to analyse the ecological factors of several sites and, on the other hand, to reconstruct the growth of the trees on the same sites over the past decades. The combination of ecological studies (i.e. the analysis of physical and biotic growth conditions) and dendrochronological studies (i.e. the reconstruction of radial growth) provides a sound basis for the historical assessment of the vitality of the major forest species and the role of ecological factors.

Initially, these dendroecological studies had various goals:

- to analyse the functioning or malfunctioning of forest ecosystems;
- to explain observed crown damages;
- to understand the short-term radial growth dynamics according to climatic factors;
- to quantify the reaction of trees after fertilization.

The study of long-term radial growth trends was, as such, outside the scope of these studies. Nevertheless, a significant increasing growth trend during the last century was brought to light in various situations. The question of global change became a matter of increasing concern. Multilocal and multispecies approaches were needed in order to assess the impact of such changes on the functioning of ecosystems, especially forest ecosystems.

2. Initial Results: a Strongly Increasing Radial Growth Trend

Since the first dendroecological study made by Becker in 1987 on silver fir in the Vosges mountains, nine other surveys have been made in France by the Phytoecological Laboratory of the National Agronomical Research Institute (INRA). These studies concerned several forest species in different regions (Fig. 1 & Table 1): silver fir (*Abies alba* Mill.) in the Vosges and Jura mountains; Norway spruce (*Picea abies* [L.] Karst.) in the Vosges mountains; beech (*Fagus sylvatica* L.) in the Vosges mountains, the acidic Lorraine lowland and the calcareous Lorraine plateau; oaks (*Quercus robur* L. and *Quercus petraea* [Matt.] Liebl.) in the Lorraine lowland; mountain pine (*Pinus uncinata* Mill.) in the Pyrénées mountains, and Corsican pine (*Pinus nigra* Arnold ssp. *laricio* var. *corsicana*) in a region called Pays de la Loire in western France.

All these studies were based on large samples of trees (from 500 to 1500 trees) from stands chosen so as to provide a balanced sample of ecological diversity of the area (elevation, aspect, topography, soil, ground vegetation). Furthermore, the main criterion was to find trees for which the age was as varied as possible (between 20 and 200 years). This is an absolute condition to distinguish between the effects of aging on radial growth and possible trends due to concomitant changes in growth conditions according to calendar dates.

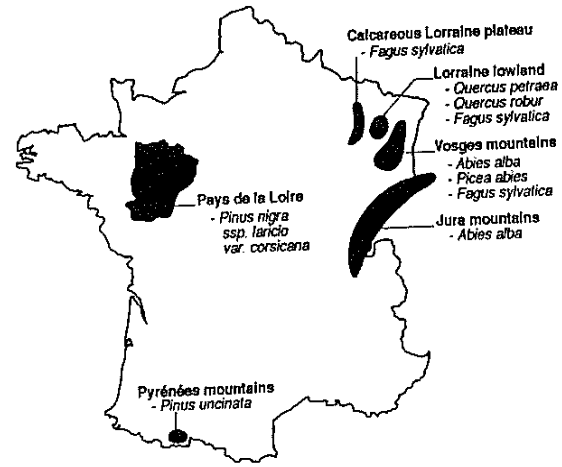

Fig. 1. Geographic location of regions and species studied.

The methods used to extract the part of variation due to ageing have been described comprehensively in various publications (Becker 1987, 1989; Becker *et al.* 1989, 1994, 1995a, b; Bert 1992; Dupouey et al. 1992; Badeau 1995; Lebourgeois 1995) and they will be concisely presented here (see Section 4.1). Annual tree rings are measured using a computerized device, then they are cross-dated carefully with the help of pointer years. Finally, ring widths (or ring areas) are standardized (i.e. converted into indices according to the cambial age of each tree ring) and averaged according to calendar dates in order to obtain a mean chronology excluding the cambial age effect.

Figure 2a to h displays the radial growth level expressed through radial growth indices for eight surveys according to calendar dates. Beside large interannual variations mainly controlled by climatic factors, these curves show a clear and positive long-term trend.

In the Vosges mountains, radial growth indices have increased by:

- +160% from 1850 to 1986 for silver fir (Becker 1987; Fig. 2a);
- +130% from 1865 to 1988 for Norway spruce (Becker et al. 1995b; Fig. 2b);
- +90% from 1850 to 1990 for beech (Picard 1995; Fig. 2c).

The results in the Vosges mountains are consistent with those obtained in the Lorraine lowland, on acid soils (Fig. 2d to f):

- +90% from 1850 to 1987 for sessile oak (Becker et al. 1994; Fig. 2e);
- +55% from 1850 to 1987 for pedunculate oak (Becker et al. 1994; Fig. 2f);
- +120% from 1860 to 1992 for beech (Becker, unpublished data; Fig. 2d).

Table 1. Overview of the data structure of the ten dendroecological studies.

Species	Geographic location	Silvicultural management	Number of sites	Number of trees	Number of rings	Age spectrum
Abies alba Mill.	Vosges mountains	high forest	277	1 475	120 000	50 to 180 years
Abies alba Mill.	Jura Mountains	high forest & selection forest	208	1 248	115 170	20 to 468 years
Picea abies (L.) Karst.	Vosges mountains	high forest	181	1 050	99 750	40 to 180 years
Fagus sylvatica L.	Vosges mountains	high forest	155	947	134 000	30 to 220 years
Fagus sylvatica L.	Lorraine lowland	high forest	66	258	57 300	50 to 180 years
Fagus sylvatica L.	Calcareous Lorraine plateau	high forest & coppice-with-standards	102	1025	93 971	11 tö 203 years
Quercus robur L.	Lorraine lowland	high forest	115	505	80 800	10 to 332 years
Quercus petraea (Matt.) Liebl.	Lorraine lowland	high forest	121	529	91 000	11 to 239 years
Pinus nigra Arnold ssp. *laricio* var. *corsicana*	"Pays de la Loire"	high forest	183	1 808	49 379	15 to 70 years
Pinus uncinata Mill.	Pyrénées mountains	free growing trees	13	521	107 300	10 to 715 years

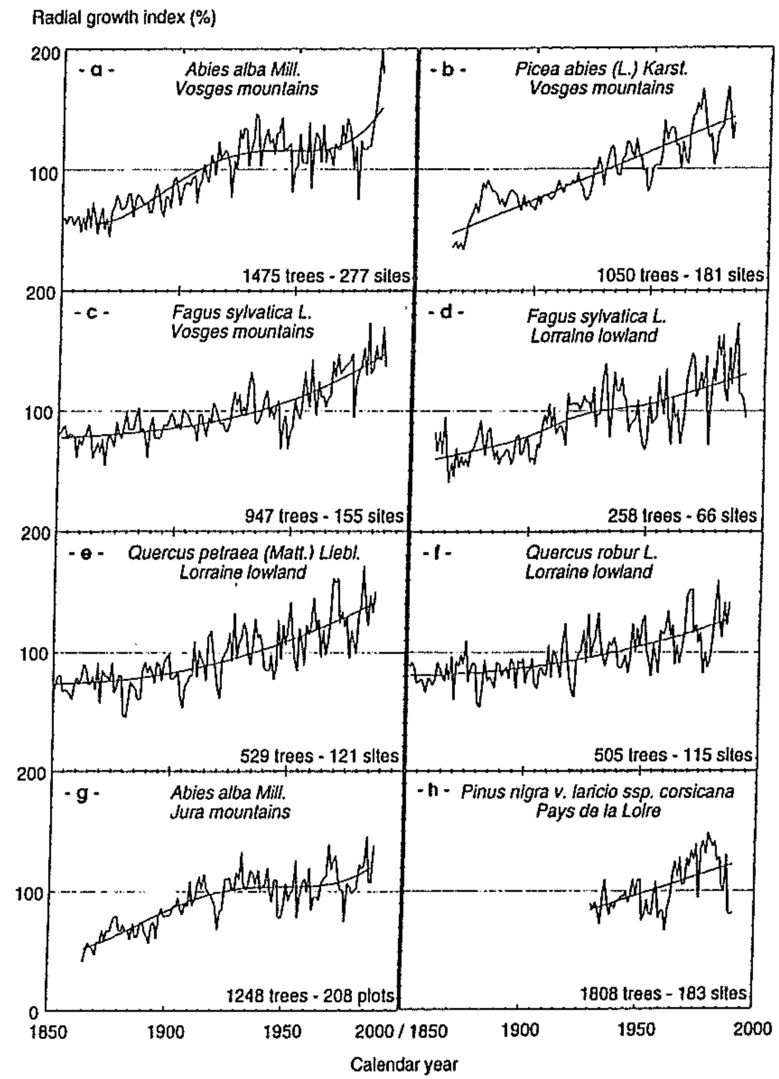

Fig. 2. Radial growth changes since the last century. For each species, radial growth indices are plotted against calendar years and smoothing functions are fitted to highlight the low frequency signal.

In the Jura mountains (Fig. 2g) silver fir showed an increasing trend of +130% (Bert 1993) and in the region Pays de la Loire in western France (Fig. 2h), the radial growth indices of Corsican pine have increased by +50% since 1940 onwards (Lebourgeois and Becker 1996).

3. Possible Causes of the Trends Observed

All these results show that, since the last century, an increasing trend in radial growth, independent of any biological effects related to the ageing processes, seems to be widespread. It has occurred for broadleaved and coniferous species, in plains or mountain regions, on rich or poor lands, etc.

In the context of a slowly and continuously changing environment, three hypotheses could explain these observed trends:

- climatic changes, i.e. temperature or precipitation increase;
- CO_2 fertilization effect;
- pollution effects like nitrogen fertilization through enhanced atmospheric nitrogen deposition.

However, other causes could explain these trends, especially a bias:

- during sampling;
- during the analysis of the data sets;
- finally, silvicultural changes (i.e. changes in stand structures due to thinning frequency or intensity) during the last century could also explain such trends.

The possible role of these non-environmental causes are studied specifically.

4. Attempts to Find Possible Biases

4.1. Methods Used to Identify and Separate the Long-Term Trends

Methods. Various factors may generate growth trends in tree rings: climatic factors, ageing, disturbances, stochastic errors, etc. Graybill (1982) and Cook (1987, 1990) summarized these causes as follow:

$$R_t = A_t + C_t + D_t + E_t$$

R_t is the observed tree ring width; A_t represents the growth trend associated with increasing age and date; C_t is the climatic signal which can vary at both low and high frequencies; and D_t is the tree disturbance signal, often divided into local and stand-wide disturbances. The separation of these different trends is crucial, but this problem has been considered as difficult (Briffa et al. 1988; Visser and Molenaar 1988 and 1990; Cook et al. 1990). In order to take into account the confounding effect between the age trend (i.e. A_t) and the date trend (i.e. D_t the region-wide disturbance associated with large-scale environmental changes), three methods have been tested.

The first method, known as at constant cambial age, is very simple and does not require any transformation of the initial data. It consists of considering simultaneously, in the whole sample, the tree rings developed at a given cambial age but at various calendar dates (Becker 1987; Briffa 1992; *the cambial age of a given tree ring is the age of the tree when this tree ring was built*). This simple method can obviously give interesting results but it is not sufficient. All the information contained in the tree rings is impossible to use and the figures cannot be compared among themselves because the average growth level of each cambial age is not constant, due to the age trend. Nevertheless, the comparison becomes possible if each ring width or ring area is converted against a reference in order to suppress this trend: the removal of A_t from tree ring series is known as standardization (Fritts 1976).

The second method is a calculation of *standardized* radial growth indices using a regional age curve (Mitchell 1967; Becker 1989). After alignment of all the available individual series according to their cambial ages, a regional age curve is built by averaging annual ring widths (or annual basal area increments). A mathematical model is adjusted to this curve. Then each initial ring width or ring area is converted into a growth index, which is the ratio expressed as a percentage of the initial value to the corresponding reference value given by the above model for the same cambial age. In relation to the first method, all the available tree rings can be taken into account. Yet, Cook et al. (1990) point out the main shortcoming of the regional age curve approach: it assumes that the shape of the age curve is independent of the time period. In order to overcome this limitation, a new approach was developed.

The third method is the analysis of variance (Dupouey et al. 1992; Badeau 1995; Badeau *et al.* 1995). Ring areas can be organized in a two-way table with cambial age in rows and calendar dates in columns. The ANOVA ideally requires an equal and sufficiently large number of observations for each combination of age and date. In order to obtain this balanced design, the age and date factors can be divided into a limited number of classes. Then, in each cell of the table, individual annual rings belonging to a given tree can be averaged in order to limit the dependence of the variables for each combination of age and date and in order to give each tree the same weight in the analysis. At last, the following simple linear model is used (Badeau et al. 1995):

$$BAI_{tad} = A_a + D_d + Aa.D_d + E_{tad},$$ where:

BAI_{tad} is the mean basal area increment of tree t at cambial age class a and belonging to date class d;
A_a is the effect of age class a;
D_d is the effect of date class d;
$A_a . D_d$ is the interaction between age class a and date class d;
E_{tad} is the residual.

This method is more demanding in terms of computer processing, but it produces a more reliable extraction of both age and date effects. Finally, although we used averaged BAIs from each core for each combination of age and date classes, some dependencies remain. Statistical models taking into account such dependencies are under development.

Results. Figures 3 to 5 present some results obtained for beech managed in high forest on the calcareous Lorraine plateau in northeastern France, using the three previous methods.

With the method at constant cambial age, ring areas of the same cambial age are plotted against calendar date (Fig. 3a, b). For both examples, ring areas have increased during the period studied. These two plots are only an example: for each available cambial age a figure can be built if there are enough calendar dates. For each study presented in the introduction, these plots were made as a matter of routine for cambial ages ranging for 10 to 100 years. In each case, a significant and positive trend was brought to the fore for each cambial age, using ring width or ring areas.

In the second method, a regional mean relation between radial growth and cambial age is built at first (Fig. 4a). The resulting mean curve is smooth because of the sample size, cambial age and calendar year diversity. Then ring areas of each dendrochronological series are standardized according to this curve and the resulting indices are averaged according to calendar dates in order to obtain a standardized chronology at the regional level (Fig. 4b). As in Fig. 2, this curve displays a high-frequency signal mainly controlled by interannual climatic variations (especially drought); growth depression of varying severity at the decade time scale (e.g. around 1948 or 1976); and finally, a positive and low-frequency trend in radial growth.

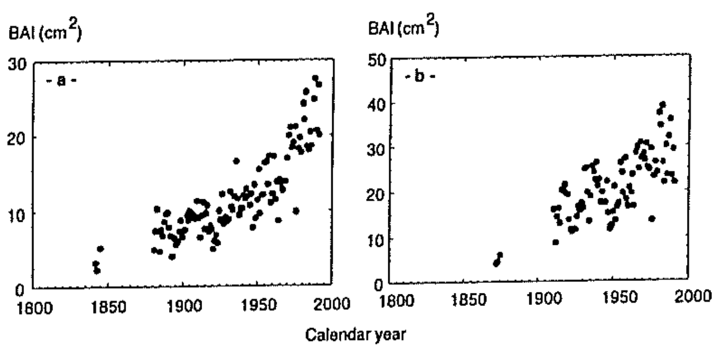

Fig. 3. Long-term trend in radial growth of beech on the calcareous Lorraine plateau at the age of 40 (*a*) and at the age of 70 (*b*).

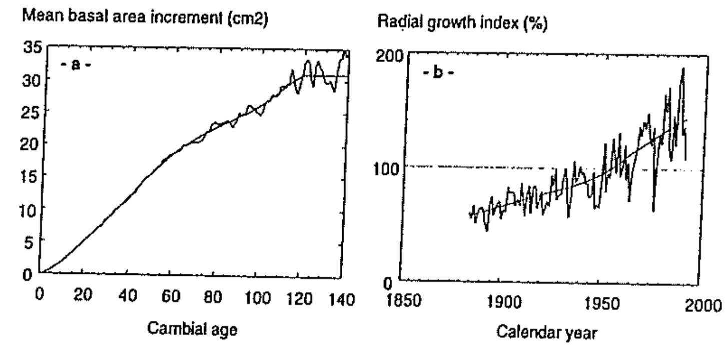

Fig. 4. Standardization from the regional mean relation between radial growth and cambial age for beech on the calcareous Lorraine plateau:

a age trend: regionally averaged basal area increments (BAIs) versus cambial age and fitted polynomial curve;

b date trend: radial growth indices versus calendar years and smoothing function.

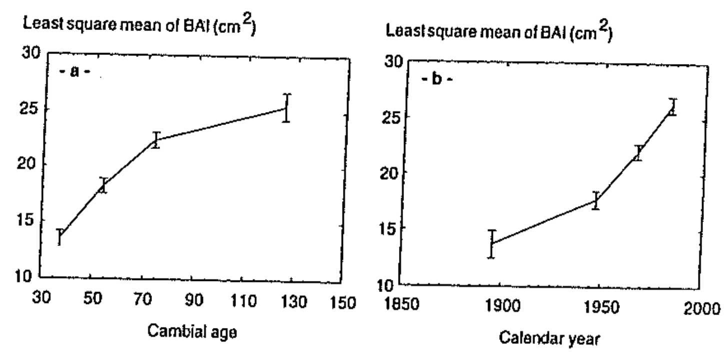

Fig. 5. Least square means of annual BAIs for cambial age effects (a) and calendar date effects (b) computed from an analysis of variance for beech on the calcareous Lorraine plateau. Confidence intervals at the 95% level are plotted.

In the third method, the whole sample of tree rings is divided into four age and date classes and the ANOVA is computed. Table 2 shows that the chosen model is highly significant. The cambial age and the calendar date integrate most of the total variance but, in the case of high forest, the part of variance explained by the inter-

Table 2. Analysis of variance of cambial age and calendar date effects on annual BAIs, computed with the Global Linear Model procedure of SAS (1988), for beeches managed in high forest.

Source of variation	Degrees of freedom	Mean Square	F Value	Pr > F
Model	15	11747.10	116.20	0.0001
Error	3141	101.09		
				$r^2 = 0.3569$

Source of variation	Degrees of freedom	Mean Square	F Value	Pr > F
cambial age effect	3	13587.46	134.40	0.0001
date effect	3	14145.72	139.93	0.0001
interaction	9	133.89	1.32	0.2184

action between age and date effects is not significant. Figure 5a and b shows the age effect means and the date effect means.

Without going into detail, the three methods proved to be effective in bringing to the fore long-term radial growth trends and gave similar results. These three methods have been applied in other studies with the same results, so it is now well established that the positive long-term trends observed are not due to an artefact introduced by the methods used for processing the data, even if each of them has advantages and disadvantages.

4.2. Are the Chosen Trees Representative?

Among the causes which may explain the long-term growth trends, another possible bias is that the productivity in their youth of the very old trees alive now may be not representative of the productivity of the whole forest in the last century. The oldest sampled trees may still be alive because they were not big enough to be harvested. Conversely, the trees of the same age but with a higher productivity may have been harvested already.

In order to check this hypothesis, Dupouey et al. (unpublished data) compared radial growth levels of oaks alive now and archaeological oak samples in the same region for different areas in Europe. In every region, a significant difference was found between living and ancient trees: at a given cambial age, living oaks displayed higher levels of radial growth. The origin and dominance status of ancient trees in such samples was unknown. However, these results are in accordance with trends observed in living tree growth.

Previous observations of increasing radial growth obtained from living trees are confirmed. This archaeological analysis shows that the possible bias during sampling alone cannot explain the observed long-term radial growth trends.

4.3. Changes in Silvicultural Practices

Silvicultural management could affect individual tree radial growth if, in the long term, the thinning intensity or frequency had increased, thus lowering the competition level between trees.

Two studies were carried out in order to test this possible effect on long-term radial growth:

- a comparison of radial growth between high and low density stands of beech (Badeau 1995);
- an analysis of free-growing trees at tree-line in high elevation mountains (Dupouey et al., unpublished data).

Comparison of High and Low Density Stands. In France, beech is managed in high forests. These stands are even-aged, with high competition pressures between trees during the whole of their life. In this case, silvicultural practices may have evolved since the last century. On the other hand, beech is managed in coppice-with-standards. In this type of stand, there are two different strata: the coppice, which is clearcut every 25-30 years, and a few tall trees, the standards, which grow at a very low density level. The standards are allowed to grow for several rotations of the coppice before being harvested. Here, silviculture maintains a constant sparsely populated area, with very low competition pressures between tall trees, and with a stable influence at the century time scale.

Figure 6 shows that a long-term growth trend is observed in both silvicultural systems, but it is stronger and more regular in high forests than in coppice-with-standards. The significant difference observed between the two silvicultural systems implies that the trends cannot be explained entirely by changes in environmental factors. However, the trend observed in the coppice-with-standards treatment implies that changes in silvicultural practices alone cannot explain the trends because an increase in the thinning intensity is unlikely in these stands. Management registers even suggest that the frequency of coppicing has been lowered since the 1960s, thus the stand density of coppice-with-standards has increased. The possible positive influence of nitrogen flushes on growth of the standards, following each removal of the coppice, has disappeared.

Study of Naturally Open Stands. In order to test the influence of silvicultural practices, another study has been carried out at tree line (between 2200 and 2400 m above sea level) in the Pyrénées mountains, with free-growing mountain pine (*Pinus uncinata* Mill.) at a very low competition level and without any human silvicultural practices.

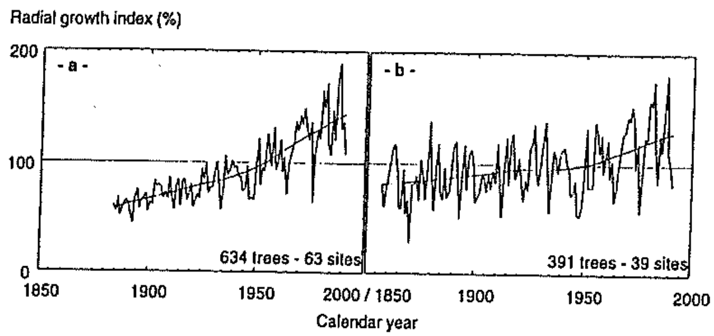

Fig. 6. Radial growth changes since the last century for beech managed in high forest (a) and coppice-with-standards (b) on the calcareous Lorraine plateau.

The increasing radial growth trend observed for the 521 sampled trees (Fig. 7) is still very steep (approximately +120%), so this result corroborates the possible role of environmental changes on radial growth. Nitrogen fertilization cannot explain this radial growth increase because atmospheric nitrogen deposition is low in this region.

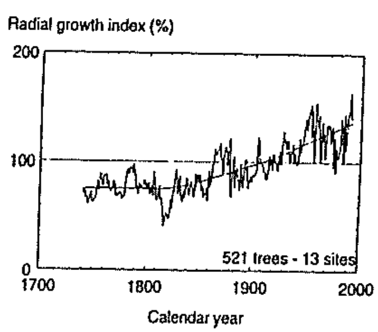

Fig. 7. Long-term growth trend of mountain pine (*Pinus uncinata* Mill.) at tree line in the Pyrénées mountains.

5. Conclusions

Ten studies, concerning seven forest species, have been carried out in France since the early 1980s. In all cases, a significant increasing long-term trend in radial growth appeared during the last 150 years. This trend varies between +50 and +160% for basal area increment indices, depending on the species and the location.

One can legitimately be surprised by the magnitude of the increases observed, and some uncertainties remain about the interpretation of the results. In order to test the reliability of the results, careful analyses of possible biases have been carried out. These analyses show that the results are not due to a bias introduced by the methods used for processing the data.

The chosen trees seem to be representative, according to a comparison between living and archaeological trees. Various attempts to identify a bias in the spatial structure of the sample and the ecological diversity of the corresponding site types have been made. In the Jura mountains for example, the older trees available are mainly located on poor sites, where radial growth is slow. However, for sessile oak, pedunculate oak and beech on the Lorraine plateau, this bias has been limited by a careful selection of trees within a limited ecological range. The stratification of the data in an attempt to isolate more satisfactory subsets did not result in fundamentally different results (Becker et al. 1995a).

Another possible bias, in closed stands, is that some of the currently dominant trees may have been suppressed previously. Such social changes in the hierarchical structure of stands are often considered as infrequent in managed forests, but their exact role on the observed long-term trends remains to be precisely quantified.

Silvicultural practices could explain part of the long-term trends observed, according to the results obtained for beech in high forest and coppice with standards. On the other hand, the results obtained for mountain pine in the Pyrénées mountains strongly suggest the role of environmental changes.

In order to gain a better understanding of the different causes of the long-term increasing growth changes currently observed in different parts of Europe, it may prove useful to extend these studies in different environments where the various factors could be separated. For example, northern boreal forests, which are free from silvicultural disturbances and where nitrogen pollution is very low, offer a good opportunity. It may also be necessary to study height growth trends in addition to radial growth. Dominant height growth is supposed to be lower depending on stand density. It could be an additional indicator of long-term environmental changes.

Whatever the causes, we strongly advocate the use of proper methods of standardization such as the regionally based age curve or the joint analysis of variance of date and age effects for the study of long-term growth trends, which allow reliable conclusions to be drawn.

References

Badeau V (1995) Etude dendroécologique du hêtre (*Fagus sylvatica* L.) sur les plateaux calcaires de Lorraine. Influence de la gestion sylvicole. PhD thesis, University of Nancy I, 224p + annexes.

Badeau V, Dupouey JL, Becker M, Picard JF (1995) Long-term growth trends of *Fagus sylvatica* L. in northeastern France. A comparison between high and low density stands. Acta Œcologica, 16 (5), 571-583.

Becker M (1985) Le dépérissement du sapin dans les Vosges. Quelques facteurs liés à la détérioration des cimes. Rev. For. Fr., 37 (4), 281-287.

Becker M (1987) Bilan de santé actuel et rétrospectif du sapin (*Abies alba* Mill.) dans les Vosges. Etude écologique et dendrochronologique. Ann. Sci. For., 44 (4), 379-402.

Becker M (1989) The role of climate on present and past vitality of silver fir in forest in the Vosges montains of northeastern France. Can. J. For. Res., 19, 1110-1117.

Becker M, Bert GD, Bouchon J, Dupouey JL, Picard, Ulrich E (1995a) Long-term changes in Forest Productivity: the Dendroecological Approach. In: Forest decline and atmospheric deposition effects in the French mountains, G Landmann, M Bonneau (ed), Springer Verlag, 143-153.

Becker M, Bert GD, Bouchon J, Picard JF, Ulrich E (1995b) Growth trends in various broadleaved and coniferous trees in Northeastern France from the mid 19th century. In: Functioning and dynamics of natural and perturbed ecosystems, Bellan-Santini D, Bonin G, Emig C (ed), Lavoisier Publishing, Paris, 35-48.

Becker M, Landmann G, Levy G (1989) Silver fir decline in the Vosges Mountains (France): role of climate and silviculture. Water, Air and Soil Pollution, 48, 77-86.

Becker M, Nieminen TM, Geremia F (1994) Short-term variations and long-term changes in oak productivity in northeastern France. The role of climate and atmospheric CO_2. Ann. Sci. For., 477-492.

Bert GD (1992) Influence du climat, des facteurs stationnels et de la pollution sur la croissance et l'état sanitaire du Sapin pectiné (*Abies alba* Mill.) dans le Jura. Etude phytoécologique et dendrochronologique. PhD thesis, Nancy I University, 200 p + annexes.

Bert GD (1993) Impact of ecological factors, climatic stresses, and pollution on growth and health of silver fir (*Abies alba* Mill.) in the Jura mountains: an ecological and dendrochronogical study. Acta Œcologica, 14 (2), 229-246.

Bonneau M (1987) Genése et contenu du programme DEFORPA. In: Les recherches en France sur le dépérissement des forêts. Programme DEFORPA, 1er rapport, ENGREF, Nancy, 6-10.

Briffa KR (1992) Increasing productivity of "natural growth" of conifers in Europe over the last century. In: Tree rings and Environment. Proceedings International dendrochronological symposium "Tree rings and environment", Ystad (Sweden), 3-9 September 1990, Lundqua report, 34, 64-71.

Briffa KR, Jones PD, Pilcher JR, Hughes MK (1988) Reconstructing summer temperature in Northern Fennoscandinavia back to A.D. 1700 using tree ring data from Scots Pine. Artic and Alpine Research, 20, 385-394.

Cook ER (1987) The decomposition of tree ring series for environmental studies. Tree ring bulletin, 47, 37-59.

Cook ER (1990) A conceptual linear aggregate model for tree rings. In: "Methods of dendrochronology", ER Cook, LA Kairiukstis (ed), Kluwer Academic Publishers, Dordrecht / Boston / London, 98-104.

Dupouey JL Denis JB, Becker M (1992) A new method of standardization for examining long term trends in tree ring chronologies. In: Tree rings and Environment. Proceedings International dendrochronological symposium "Tree rings and environment", Ystad (Sweden), 3-9 September 1990, Lundqua report, 34, 85-88.

Fritts (1976) Tree rings and climate. Academic press, vol. 1 (245p) & vol. 2 (567p).

Graybill DA (1982) Chronology development and analysis. In: Climate from tree rings, Hughes M.K. et al. (ed), Cambridge University Press.

Landmann G, Bonneau M (ed) (1995) Forest decline and atmospheric deposition effects in the French mountains. Springer Verlag, 461p.

Lebourgeois F, Becker M (1996) Dendroécologie du pin laricio de Corse dans l'ouest de la France. Evolution du potentiel de croissance au cours des dernières décennies. Ann. Sci. For., in press.

Lebourgeois (1995) Etude dendroécologique et écophysiologique du pin laricio de Corse (*Pinus nigra* Arnold ssp. *laricio* Poiret var. *corsicana*) en région Pays de la Loire. PhD thesis, University of Paris XI, 209p. + annexes.

Mitchell VL (1967) An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest. Univ. Wisconsin. Dept. Meteorol. Tech. Rep. 33, Task NR 387-022, ONR Contract 1202 (07), NSF GP-5572X, Madison.

SAS Institute Inc. (1988) SAS/STAT® User's Guide. Release 6.03 Edition, Cary, NC: SAS Institut Inc., 1028p.

Visser H, Molenaar J (1988) Kalman filter analysis in dendroclimatology. Biometrics, 44, 929-940.

Visser H, Molenaar J (1990) Estimating trends in tree ring data. Forest Science, 361, 87-100.