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Abstract

Several recent surveys have shown an increasing long-term growth trend for various forest species in western Europe. In order to confirm these growth changes and to study the role of stand density changes, we compared radial growth trends of beech (*Fagus sylvatica* L.) in northeastern France, during the last century, in two different silvicultural systems: high forest (high density stands) and coppice-with-standards (low density stands). The sampling scheme was based on 1025 trees of all age classes from 102 sites. This allowed the separation, in the low-frequency signals, of effects related to the ageing of the trees or stands from other effects. Two standardization techniques were used. Both showed a significant increasing radial growth trend since the last century, independent from biological effects related to age. However, this trend was steeper and began earlier in high forest than in coppice-with-standards stands. This result implies that the current increasing growth trend is partly due to silvicultural effects or interactions between silviculture and environmental changes.

Keywords: *Fagus sylvatica,* beech, silvicultural management, stand density, high forest, coppice-with-standards, dendrochronology, standardization, growth trend.

Résumé

De nombreuses études, réalisées en Europe de l'ouest, ont montré que plusieurs essences forestières présentaient, à long terme, des tendances de croissance positives. Afin de confirmer l'existence de telles dérives et d'analyser le rôle de la sylviculture, nous avons comparé l'évolution de la croissance radiale du hêtre (*Fagus sylvatica* L.) depuis le siècle dernier entre deux types de gestion sylvicole : la futaie (peuplement à forte densité) et le taillis-sous-futaie (peuplement à faible densité). Une centaine de placettes a été installée sur les Plateaux Calcaires de Lorraine (nord-est de la France). Mille arbres d'âges variés ont été échantillonnés afin de pouvoir différencier deux signaux s'exprimant à basse fréquence : les effets relatifs à l'augmentation de l'âge des arbres et les effets environnementaux. Deux techniques de standardisation ont été employées pour séparer ces signaux. Elles conduisent toutes les deux à la mise en évidence d'une tendance positive à long terme de la croissance radiale depuis le siècle dernier indépendamment des effets liés à l'augmentation de l'âge. La tendance que l'on observe pour les arbres de futaie est plus forte et débute plus tôt que celle observée pour le taillis-sous-futaie. Ce résultat laisse supposer que les augmentations observées en ce qui concerne la croissance radiale seraient dues en partie aux effets de la sylviculture ou à l'interaction entre la sylviculture et des changements environnementaux.

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INTRODUCTION

Tree radial growth is a signal which carries different informations at different time scales. The high-frequency components, i.e. the short-term variations, ranging from one year to a decade, have been intensively studied for many species throughout the world (Fritts, 1976; Schweingruber, 1988). They are usually due to stochastic environmental variations, mainly climate and various other disturbances (fire, insects...). The low-frequency components of radial growth, at a time scale of a decade, a century, or longer, remain poorly documented. However, they are of major concern in the context of a slowly, continuously changing environment.

Several recent dendroecological surveys in western Europe have shown a clear increasing long-term trend in forest productivity, or tree radial growth, during the last century, for various species and regions (see a synthesis in Innes, 1991 and also Becker *et al.*, 1990; Briffa, 1992; Hartmann *et al.*, 1992; Kauppi *et al.*, 1992; Bert, 1993; Eriksson & Johansson, 1993; Becker *et al.*, 1995). Four causes could explain these trends: climatic changes (temperature or precipitation increase), increasing atmospheric CO_2 concentration, pollution effects (nitrogen fertilization) or silvicultural changes. Silvicultural management could affect individual tree radial growth if, in the long term, thinning intensity or frequency had increased, thus lowering the competition level between trees. In the present work, in order to separate the possible effect of changing silvicultural practices on radial growth from other causes, we compared long-term growth trends in stands with or without silvicultural effects on tree competition.

Two types of silvicultural systems co-exist for beech in northeastern France. On the one hand, beech is managed in high forests. These stands are even-aged, with high competition pressure between trees throughout their life. In this case, thinning intensity and frequency could trigger radial growth changes and may have varied during the last century. On the other hand, these forest stands can be compared with the more ancient management of coppice-with-standards. In this type of stand, there are two different strata: the coppice, which is clear-cut every 25-30 years, and a few high trees, the standards, which grow at a very low level of density. The standards are allowed to grow for several rotations of the coppice before harvesting. Here, silviculture practices maintain a constant sparsely populated area, with very low competition pressure between high trees once they have reached the dominant stratum, and with a stable influence at the century time-scale. The average basal area for these two silvicultural systems, between 100 and 140 years old, is 27 m^2/ha for the high forest and 15 m^2/ha for the coppice-with-standards.

Briefly, the main aims of this study were:

– to look for low frequency variations of beech radial growth in northeastern France, over the last century;

– to test different methods for the extraction of low-frequency signals from tree-ring series;

– to compare these low-frequency variations between two different management systems in order to identify the possible role of stand density.

METHODS

Sampling

The potential source of variability due to site quality was reduced by sampling 102 sites with similar ecological characteristics (topography, soil, vegetation, micro-climate). Conversely, in order to distinguish between biological effects due to age increase and other trends, 1025 trees of all age classes were bored to the pith (one core per tree) at breast height: 620 trees on 63 sites in high forests (50,509 rings from 11 to 165 years old, between 1832 and 1991) and 391 trees on 39 sites in coppice-with-standards (40,876 rings from 39 to 196 years old, between 1803 and 1991). All trees were chosen from the dominant stratum in natural regeneration stands.

Individual series were pre-dated using well-known regional pointer years such as 1870, 1894, 1952, 1976. Ring widths were measured to 1/100 mm with a binocular microscope and a digitizing tablet coupled to a micro-computer, then synchronised. In all subsequent analysis, tree-ring surface areas were used, instead of tree-ring widths, because the annual basal area increment (BAI) is closer to biomass production than the ring width (see e.g. Federer *et al.*, 1989; Jordan & Lockaby, 1990; LeBlanc, 1990; Briffa, 1992). Moreover, all calculations were also repeated using ring widths instead of BAIs and gave nearly identical results.

Analysis

The separation of low-frequency signals from tree-ring series is rather difficult and methods are still debatable (Wigley *et al.*, 1987; Dupouey *et al.*, 1992). The removal of biological effects related to increasing age of the stands or trees is the key issue. This step of the analysis is called standardization. Classical methods operate on a tree-by-tree basis, thus precluding the separation of environmental low-frequency effects from the biological trend. We used two different methods for this purpose. The first one was based on the calculation of radial growth indices using a regional age curve. This method, presented in Fritts (1976) and Cook *et al.* (1990), has already been successfully applied for the study of long-time trends in chronologies (Becker, 1989; Briffa *et al.*, 1992). The second one was an analysis of variance of ring surface areas, using a model derived from the bilinear model of Dupouey *et al.* (1992).

Calculation of radial growth indices using a regional age curve

After alignment of all the available individual series according to their cambial ages (representing various calendar dates), a regional age curve was built by averaging BAIs. Cambial age of a given tree-ring is the age of the tree when this tree-ring was built. However, the sample number was not equal for all cambial ages at each calendar date. For the young cambial ages, we had a lof of available calendar dates, but this number decreased with increasing cambial ages, due to the distribution of age classes in forest stands. In order to minimize this bias, we calculated mean BAIs for each combination of cambial age and calendar date. Then, the regional growth curve was obtained by averaging, for each cambial age, these mean values over all the available calendar dates at this age. This weighting process gave the same weight to each calendar date, whatever its sample depth. This curve gives an estimate, at the regional scale, of the radial growth trend due to biological factors related to increasing age. The resulting mean curves, for both silvicultural systems, are smooth because of the sample size, cambial age and calendar year diversity (fig. 1).

Then polynomial curves, fitted to these averaged data, were calculated. These fitted curves were used to standardize initial ring surface areas, for all trees in all sites: a growth index was calculated by dividing the raw values by the corresponding reference value for the same cambial age given by the model. For each silvicultural system, growth indices were averaged over calendar years for which more than 30 values were available. This gave regionally standardized BAI chronologies.

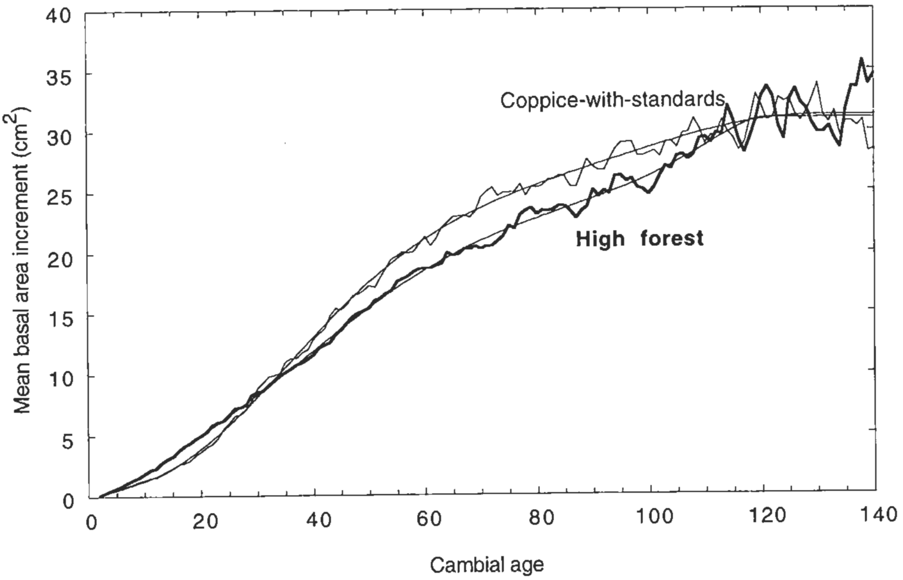

FIG. 1. – Regionally averaged BAIs versus cambial ages for coppice-with-standards (thin line) and high forest (bold line); and fitted polynomial curves (smooth thin lines).

Analysis of variance of BAIs

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. DUPOUEY *et al.* (1992) developed a new approach based on the analysis of variance of BAIs, in order to overcome this limitation. Ring surface areas can be organized in a two-way table with cambial age in rows and calendar date in columns. It is possible to analyse this set of data, using a classical analysis of variance procedure in order to extract age and date effects, and their interaction, separately. However, this analysis ideally requires an equal and sufficiently large number of observations for each combination of age and date. In order to obtain this balanced design, we divided the age and date factors into a limited number of classes. Then, in each cell of the table, individual annual rings belonging to a given tree were averaged in order to limit the dependence of the variables for each combination of age and date and in order to give at each tree the same weight in the analysis. The following simple linear model was used:

$$\mathrm{BAI}_{\mathrm{tad}} = A_a + D_d + A_a \,.\, D_d + E_{\mathrm{tad}}$$

where:

$\mathrm{BAI}_{\mathrm{tad}}$ is the mean basal area increment of tree t at cambial age class a and belonging to date class d;

$\mathrm{A_a}$ is the effect of age class a;

$\mathrm{D_d}$ is the effect of date class d;

$\mathrm{A_a} \,.\, \mathrm{D_d}$ is the interaction between age class a and date class d;

$\mathrm{E_{tad}}$ is the residual.

For each silvicultural system, cambial ages and calendar dates were divided into four classes of approximately same size (table 1). Parameters of this slightly unbalanced model were fitted using the General Linear Model procedure of SAS (1988). Age and date were considered as fixed effects. Least square estimates of marginal means were computed for each age and date class, and their interactions.

TABLE I. – *Data structure for the analysis of variance of annual BAIs. For each silvicultural system, the table gives the number and the percentage of trees analysed. The corresponding cambial age and calendar date classes are indicated, respectively, for each column and row.*

High forest

date	[30,45]	[46,62]	[63,85]	[86,165]	
[1856,1935]	312 9.88%	232 7.35%	92 2.91%	22 0.70%	**658** **20.84%**
[1936,1958]	217 6.87%	261 8.27%	243 7.70%	92 2.91%	**813** **25.75%**
[1959,1975]	175 5.54%	189 5.99%	261 8.27%	232 7.35%	**857** **27.15%**
[1976,1991]	125 3.96%	175 5.54%	217 6.87%	312 9.88%	**829** **26.26%**
	829 26.26%	**857** 27.15%	**813** 25.75%	**658** 20.84%	**3157** 100.00%

cambial age

Coppice-with-standards

date	[30,49]	[50,71]	[72,102]	[103,196]	
[1825,1918]	215 9.68%	162 7.29%	79 3.56%	16 0.72%	**472** **21.24%**
[1919,1949]	168 7.56%	146 6.57%	171 7.70%	79 3.56%	**564** **25.38%**
[1950,1971]	149 6.71%	152 6.84%	146 6.57%	162 7.29%	**609** **27.41%**
[1972,1991]	45 2.03%	149 6.71%	168 7.56%	215 9.68%	**577** **25.97%**
	577 25.97%	**609** 27.41%	**564** 25.38%	**472** 21.24%	**2222** 100.00%

cambial age

RESULTS

Age and date trends using a regionally standardized growth curve

We present the results for the regional age curve first, and then the radial growth changes since the last century. Three phases can be distinguished during the life cycle of coppice-with-standards and high forests (fig. 1). First, before 30 years old, trees in the coppice-with-standards display smaller rings than high forest trees. Then, up to 120 years old, the opposite is observed. Finally, both silvicultural systems display equivalent ring surface areas.

Annual rings of trees from coppice-with-standards before 30 years were discarded from the following analyses because they came from potentially suppressed trees. In the same way, these rings were also removed for the high forest subsample in order to compare equivalent data sets.

Figure 2 (a & b) shows the variation of radial growth indices during the last 150 years for both silvicultural systems. These curves display high frequency signals, mainly controlled by interannual climatic variations. Growth depression of various severity, at the decade time scale, are also visible (around 1948 and 1976).

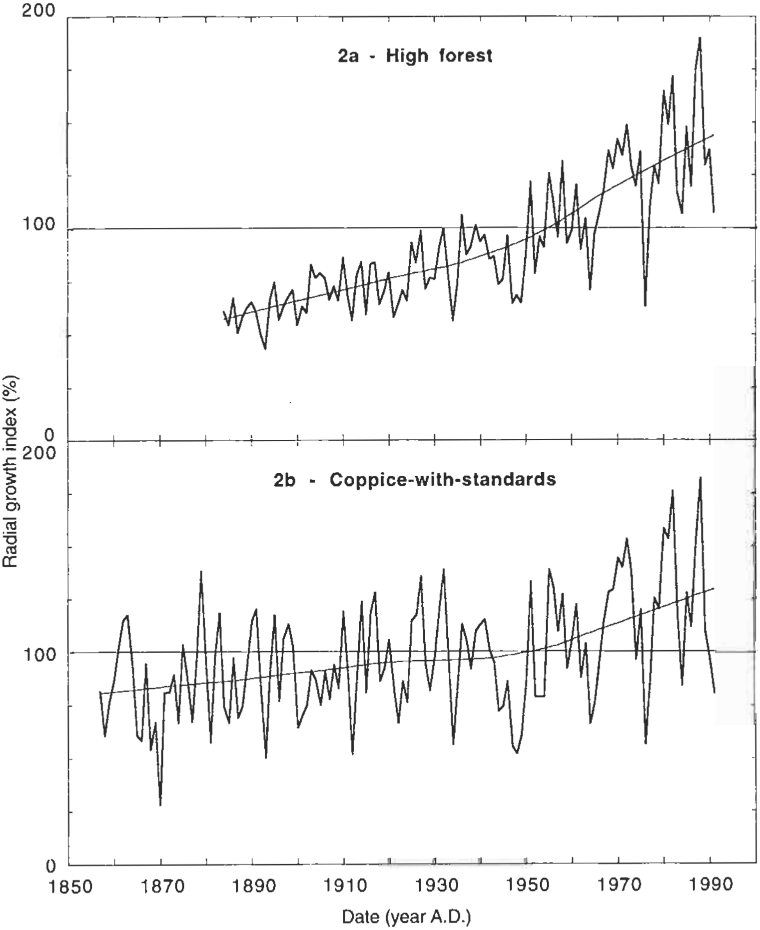

FIG. 2. – Radial growth changes since the last century. For each silvicultural system, growth indices are plotted against calendar dates (bold lines) and a smoothing function (thin lines) is fitted to highlight the low frequency signal.

Trees from coppice-with-standards are more sensitive to these variations than trees from high forest. Statistical models using climatic parameters explain a large part of these signals (BADEAU, 1995), and will be the subject of a separate paper.

However, the most important result is the low-frequency trend in radial growth. High forest shows a clear and regular positive trend since the end of the last century. Coppice-with-standards shows a weaker positive trend between 1860 and 1950. For both silvicultural systems, the increasing trends become significantly steeper after 1950.

Results using the analysis of variance approach

The analysis of variance of BAIs shows that, for both silvicultural systems, the chosen model is highly significant (table 2). The cambial age and the calendar date integrate most of the total variance. For the coppice-with-standards, the part of variance explained by the interaction between age and date effects is significant. However, it is small enough to allow a direct interpretation of age and date effects separately.

TABLE II. – *Analysis of variance of cambial age and calendar date effects on annual BAIs, computed with the Global Linear Model procedure of SAS (1988), for each silvicultural system.*

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 square= 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

Coppice-with-standards

Source of variation	Degrees of freedom	Mean Square	F Value	Pr > F
Model	15	9832.82	64.96	0.0001
Error	2206	151.36		
			r square= 0.3064	

Source of variation	Degrees of freedom	Mean Square	F Value	Pr > F
cambial age effect	3	14551.84	96.14	0.0001
date effect	3	9219.95	60.92	0.0001
interaction	9	704.04	4.65	0.0001

Least square means, with confidence intervals at the 95% level, related to age and date effects are shown in figure 3a. For both silvicultural systems, the age effect means show the same evolution as the mean regional change of radial growth according to cambial ages shown previously.

The date effect, plotted against calendar years (fig. 3b), makes the long-term growth trends more conspicuous, for both silvicultural systems. The trend is more regular and always stronger in high forests than in coppice-with-standards. In comparison with the first method, high and medium frequency signals are removed because classes instead of individual years are used.

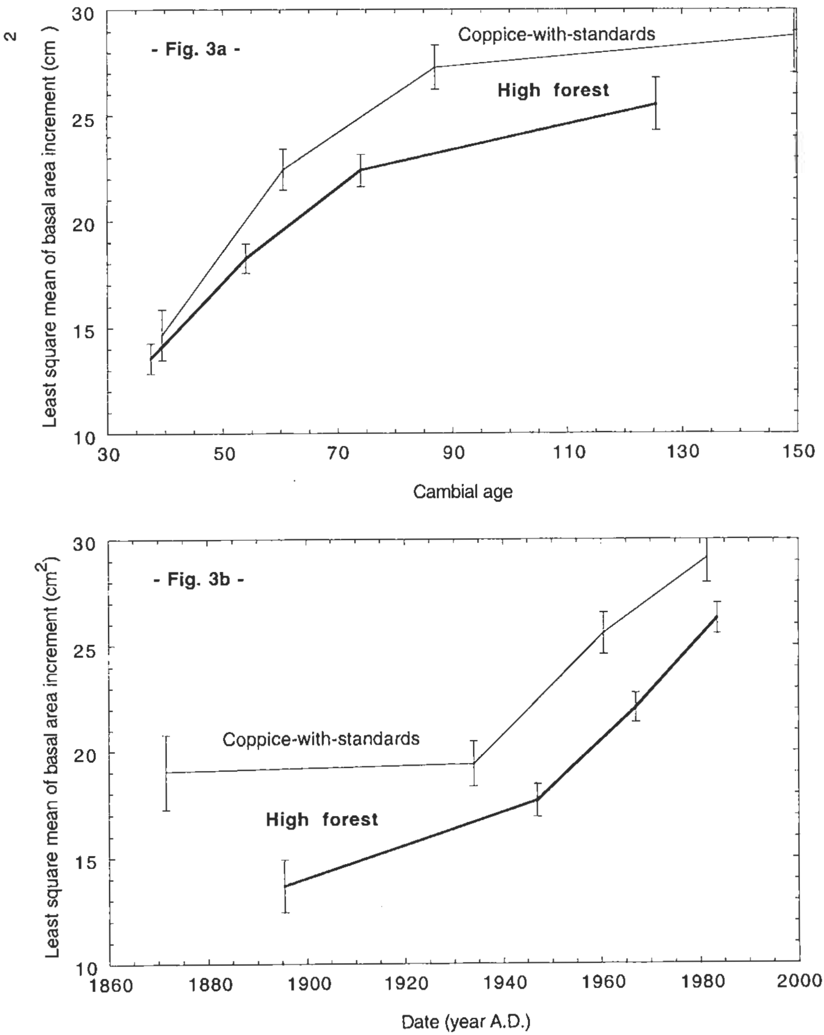

FIG. 3. – Least square means of cambial age effects (3a) and calendar date effects (3b) on annual BAIs, computed from an analysis of variance. Confidence intervals at the 95% level are plotted.

The interaction between age and date effects is higher for coppice-with-standards than for high forest (table 2). In the former system of silviculture, the interaction is mainly due to a steeper trend for young cambial ages (fig. 4). This means that young trees display greater differences in radial growth with time than older trees. These differences do not exist for trees in high forest: the date effect plotted against calendar years and for the four age classes gives parallel lines. This figure is in accordance with the non-significant interaction in high forest.

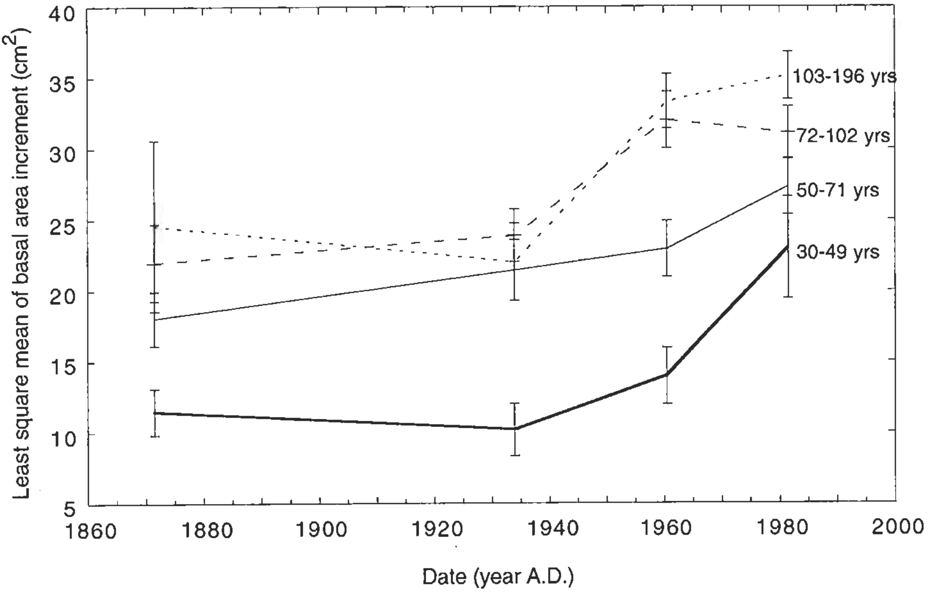

FIG. 4. – Least square means of annual BAIs for all combinations of age and date classes, and confidence intervals at the 95% level, for coppice-with-standards. The lines join the different date classes for each age class.

DISCUSSION AND CONCLUSION

Our study shows a clear increasing trend in radial growth of *Fagus sylvatica* L. in high forests since the last century, independent from any biological effects related to ageing processes. A similar trend also appears in coppice-with-standards, but only after 1950. This result is in accordance with similar observations by PICARD (1995) for beech in the nearby Vosges mountains. In the Black Forest, ABETZ (1988) also showed that younger beech trees, up to an age of 50 years, are currently growing faster than older trees when they were young, both radially and in height.

Regional age curves

The differences observed between the regional age curves for the two silvicultural systems are in agreement with the observed changes in competition levels along time. In coppice-with-standards under favourable conditions, future standards germinate after the thinning of the coppice (once every 30 years on the average). They have to compete with the growing coppice and, to a lesser extent, with the oldest trees still standing, thus exhibiting lower levels of radial growth. Once they have reached the dominant stratum of standards, they grow at a low competition level, whereas trees from high forest stands are submitted to high competition pressures all their life. At 120-130 years old, regenerative felling in high forest stands returns competition pressure to a similar level as that in coppice-with-standards. These differences confirm the first hypothesis of our study: competition levels are not the same in high forest and in coppice-with-standards. The higher radial growth level for trees in coppice-with-standards suggests that the above-ground competition is lower than in high forest. However, below-ground competition could be more important in coppice-with-standards where standards have to compete with coppice for root space, soil water and nutrients.

Methods of extraction of low frequency signals

Both methods used proved to be effective in bringing to the fore long-term, low-frequency signals. However, each has advantages and disadvantages. Analysis of variance allows the interactive effects between age and date to be taken into account, whereas the regional age curve method does not. On the other hand, the need for a balanced data set is highly restrictive. Because of this constraint, the time resolution one can achieve using analysis of variance is directly linked with the sample size. Very large data sets are needed for a reliable analysis of long-term trends. Finally, although we used 20-year blocks of averaged BAIs from each core, some dependencies still exist between each combination of age and date due to the strong tree effects. Statistical models taking into account such dependencies are under development.

Possible causes of the observed trends: interaction with silvicultural management

Our study provides new information about the respective roles of silvicultural management and environmental changes on long-term radial growth trends. First, the significant difference observed between the two silvicultural systems implies that the trends cannot be explained by changes in environmental factors alone (CO_2, climate or nitrogen deposition). Silviculture, through a control over stand density, either plays a direct role in the increasing radial growth trend or interacts with some of these environmental changes.

An increasing frequency and intensity of thinning in high forest stands during the last century could partly explain the observed trend. However, such a lowering of competition levels has not yet been documented and is highly speculative. Moreover, this change could only have occurred during the last decades of intensive management practices. Nevertheless, during these decades, this trend also became apparent in the coppice-with-standards. This can hardly be ascribed to stand density changes, which were supposed to be absent or minimized in these kinds of stands. Management registers even suggest that the frequency of coppicing was lowered during the last decades, thus decreasing the possible positive influence of nitrogen flushes on growth of the standards, following each removal of the coppice.

Among the possible causes for this recent change is nitrogen deposition, which is known to have abruptly increased since 1950 in western Europe (Lövblad &

Erisman, 1992). Current loads have been measured between 14 and 20 $kg.ha^{-1}.yr^{-1}$ in the area (Thimonier, 1994), and were probably higher in the past. Herb-layer vegetation in the same beech forests showed an increasing frequency of nitrogen demanding species (Thimonier *et al.*, 1994). Thus nitrogen fertilization could play an important role in the increasing growth trends since 1950.

Finally, we cannot totally rule out biases due to the sampling method used: currently living old trees are possibly not an adequate sample for the estimation of past levels of growth. Two different bias may interfere with our observations. First, the age structure of currently living trees is linked with site fertility, because fast growing trees, on the more fertile site, may be cut before slow growing ones. This bias has been limited in our case by a careful selection of trees within a limited ecological range. The second possible bias is due to the fact that some of the currently dominant trees may have been previously suppressed. Such social changes in the hierarchical structure of beech stands are often considered as unfrequent, but their exact role on the observed long-term trends remains to be exactly quantified.

Differences between high forests and coppice-with-standards growth trends

Different ecophysiological functioning could explain the weaker trend in coppice-with-standards in comparison with high forests before 1950. The two silvicultural systems probably have different microclimatic characteristics which are largely unknown. Water balance, water-use efficiency and soil processes are very different.

Patterns of carbon allocation also differ. Trees in coppice-with-standards bear fruits earlier in their life than trees in high forest and are more productive. In coppice-with-standards, trees achieve sexual maturity at the age of 40 (Mathieu, 1897; Pardé, 1943); the seed production is 2.5 times more important than in high forests (Becker *et al.*, 1977) and a full fructification can equal up to 60% of the annual carbon investment in wood increment at 100 years (Badeau, 1995). Besides fruits, carbon allocation to the crown and roots is often supposed to be also higher for trees in coppice-with-standards. Thus, the effect of an elevated carbon availability, e.g. through CO_2 fertilization, may be more apparent in these tree compartments in coppice-with-standards than in bole increment.

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. 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 conditions the achievement of reliable conclusions.

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