Ring width and element concentrations in beech (*Fagus sylvatica* L.) from a periurban forest in central Belgium

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**Abstract**

The Forêt de Soignes is a beech high forest located near Brussels (Belgium), established on a strongly acidic soil and subjected to atmospheric pollution and recreational pressure. We investigated variations in ring width and mineral element concentrations (N, P, K, Ca, Mg, Mn, Al) over the last 95 years in five 135-year-old trees, variations in ring width in four 40-year-old trees and tested associations with climatic parameters. Growth curves showed a striking increase in mean sensitivity in the last 20 years in the old trees but not in the young ones, starting with the 1976 summer drought. Mean sensitivity is a statistical measure of the mean relative variability between adjacent ring widths within a tree, which is correlated to susceptibility to climatic stress (Fritts, H.C., 1976. *Tree Rings and Climate*, Academic Press, London, 567pp). May rainfall and, to a lesser extent, soil water recharge (i.e. pooled rainfall from October to May) correlated significantly with ring width. However, two of the five growth depressions in the last 20 years could not readily be accounted for by adverse climatic conditions. Element concentration profiles were suggestive of a decrease in the availability of Mn, Mg and Ca, but no trend of increasing N was obvious. The possible causes of the recent increase in sensitivity of old beech trees are discussed in terms of interactions between ageing and extreme climatic events, aggravated by soil compaction due to logging traffic. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** *Fagus sylvatica*; Dendrochemistry; Dendroecology; Forest decline; Growth–climate relationships

1. Introduction

The recent forest decline syndrome has triggered considerable research aimed at correlating recent deteriorations of tree health with alterations of environmental parameters. Dendroecology and its subdiscipline, dendrochemistry, have emerged as two powerful tools for that purpose. Ring width has long been used to reconstruct historical trends in tree vigour and has been shown to be responsive to various environmental parameters including climate (Fritts, 1976; Becker, 1989; Cook and Kairiukstis, 1992; Biondi, 1993) and forest management (Badeau, 1995). More recently, tree ring mineral element concentrations have been used as biomonitors of chemical parameters of the environment, including soil solution chemistry and atmospheric pollution (Baes and McLaughlin, 1984; Kazmierczakowa et al., 1984; Bondietti et al., 1989, 1990; De Visser, 1992; Hagemeier, 1993; Guyette and Cutter, 1994). Specifically, trends of decreasing availability of base cations and
increasing nitrogen fertility have been documented in forests subject to high inputs of atmospheric pollutants (Lévy et al., 1996).

In this paper, we investigate ring width and mineral element concentrations in beech (Fagus sylvatica L.) in the Forêt de Soignes, a large periurban forest located near Brussels in central Belgium. The Forêt de Soignes is an interesting study site for dendroecology for several reasons. First, being situated in one of the most densely populated and industrialised regions in Europe, this forest is subjected to significant atmospheric pollution and recreational pressure (Meurrens et al., 1995). Secondly, evidence for degradation of soil physico-chemical conditions has been reported, and has been ascribed to 200 years of beech monoculture and to soil compaction by logging traffic (Herbauts et al., 1996). Thirdly, decline symptoms were reported by foresters for the first time 20 years ago. The objectives of the study are (i) to obtain growth curves for the last 95 years, (ii) to investigate relationships between growth and climatic parameters and (iii) to test if radial patterns of macronutrient concentrations provide evidence for an alteration of soil chemical parameters over the last century.

2. Material and methods

2.1. Site description

The forest stands chosen for this study are located in the Forêt de Soignes, south-east of Brussels, in central Belgium. This forest covers 4400 ha of a loessic plateau at about 120 m altitude. The climate is of Atlantic-type, with an average annual rainfall of 780 mm, evenly distributed throughout the year, and a mean annual temperature of 9.8°C (2.6°C in January and 17.1°C in July) (Sneyers and Van Diepenbeeck, 1995). The natural vegetation is a deciduous forest with oaks (Quercus robur L. and Q. petraea (Mattuschka) Lieblein) and beech (Fagus sylvatica L.) as co-dominant species. However, beech has been extensively planted there since the end of the 18th century, so that beech high forest currently covers 80% of the forest area. No natural regeneration, however, occurs. Since 1976, symptoms of beech and oak decline in the Forêt de Soignes have been reported (Vasic et al., 1993; Dulière and Malaisse, 1997). The average annual inputs of atmospheric pollutants in rainfall are as follows: NO$_3^-$=5.1 kg ha$^{-1}$ year$^{-1}$, NH$_4^+$=8.1 kg ha$^{-1}$ year$^{-1}$, SO$_4^{2-}$=15.1 kg ha$^{-1}$ year$^{-1}$, pH=4.93 (averages for meteorological year 1991–1992); the concentration of ozone is 56 μg m$^{-3}$ (daily average May–August 1995) (Meurrens and Lénelle, 1992; Meurrens et al., 1995).

Prevailing soils are Typical or Gleyic argillic brown earth with $A_{ht}EB_{tg}C$ profile (French classification: Sols lessivés and Sols lessivés hydromorphes; Aba(b) and Abc soils series of the Belgian Soil Map: Louis, 1959), developed on calcareous loessic deposits of the Würm age. Most soils have an acid humus layer of moder–mor-type. These soils have been considered for many years as ‘degraded soils,’ with strong surface acidification, bleaching of eluvial horizon and correlative mottling or tonguing of the illuvial B$_t$ (Dudal, 1953; Galoux, 1953; Louis, 1959). Furthermore, it was recently shown that soil compaction due to logging traffic leads to a strong physical and mineralogical degradation through active hydromorphic processes (Herbauts et al., 1996).

Two stands of even-aged beech high forest were studied, one about 135 years old (‘Mésanges’ site, hereafter MES), the other about 40 years old (‘Relais des Dames’ site, hereafter REL). Both are developed on plateau topography (about 100 m above sea level). In the MES stand, the ground layer consists mainly of Pteridium aquilinum (L.) Kuhn, Dryopteris dilatata (Hoffm.) A. Gray and Milium effusum L., while Juncus effusus L. and Carex remota Jusl. ex L. are locally abundant; in the REL site, where tree litter is very thick, the herbaceous layer is quite absent. In both sites, soil is acid (pH H$_2$O around 4.0 in the humus layer and <5.0 in underlying mineral horizons), with low effective base cation saturation rates (<45%) and high concentrations of exchangeable aluminium. They are characterised by an illuvial argillic B$_t$ horizon (clay-leaching ratio=2.1 in the B$_{2t}$ horizon), frequently mottled, due to unfavourable drainage conditions in the winter. Table 1 gives the main analytical data for the soil of the MES site.

2.2. Sampling

Five and four beech trees were randomly sampled in the MES and REL stands, respectively. Discs of about 20 cm in thickness were cut off from the top (i.e. at a
height of about 20 m: MES site) or the base (REL site) of the boles. The samples were collected in early spring after clearing in 1995 (MES) and in 1996 (REL) and were used for dendroecological (MES and REL) and dendrochemical (MES) measurements. The size of the sample is within the range of recent dendrochemical investigations (e.g. Meisch et al., 1986; De Visser, 1992; Momoshima et al., 1995); moreover, the studied beech stands, treated as even-aged high forests, offer homogeneous sampling conditions, since all beech trees were planted simultaneously and are genetically similar.

2.3. Dendroecological methods

The discs were polished to reveal annual growth rings. Ring width was measured along four radii selected so as to avoid growth anomalies (e.g. reaction wood, deformed rings), using an Addo Facit system of 0.01 mm precision (Schweingruber, 1988). For each individual tree, the average of the four series of measurements was used for subsequent analysis. Cross-dating was done both visually and statistically, using the coincidence coefficient (Fritts, 1976). For each individual tree, a dendrochronological curve was obtained using a standardised radial growth index ($I_t$) (Fritts, 1976) and mean site chronologies were calculated by averaging individual curves. The first-order autocorrelation of $I_t$ was highly significant ($r=0.443; p<0.001$) and, accordingly, mean curves were also constructed based on the residuals of the linear regression of $I_{t+1}$ on $I_t$ as recommended by Cropper (1984). Average mean sensitivities ($MS_t$) were calculated for 20-year periods; mean sensitivity is a statistical measure of the mean relative variability between adjacent ring widths within a tree, which is correlated to susceptibility to climatic stress (Fritts, 1976).

2.4. Climatic data

Climatic data were provided by the Institut Royal Météorologique at the Uccle meteorological station (Brussels), 5 km from the Forêt de Soignes. Sixty parameters were considered, including monthly rainfall, mean monthly temperature, monthly absolute minimum temperature, monthly maximum wind velocity and potential evapotranspiration (Penman method).

2.5. Growth–climate relationships

The growth–climate relationships were investigated by means of the Pearson correlation coefficient between standardised growth index and the 60 cli-
matic variables. Correlation analysis was based on the residual growth indices.

2.6. Element analysis of tree rings

For each disc, wood samples representing 5-year growth intervals were cut off with a band saw and a chisel. The samples were dried at 65°C and ground by means of a grinding mill (Janke and Kunkel, type A 10). Mineralization of a 0.7 g sample was done in duplicate, using H₂O₂/H₂SO₄ (with K₂SO₄–CuSO₄) for total nitrogen (Büchi 435 digestion unit) or hot HNO₃/HClO₄ for P, Ca, Mg, K, Mn and Al (Tecator 2040 digestor). N was determined by the semi-micro Kjeldahl method, P by colorimetry (Scheel method: Cottenie et al., 1982), Ca, Mg, K and Mn by atomic absorption spectrometry (AAS) and Al by induced coupled plasma emission spectroscopy (ICPES). Aluminium results were, however, discarded in view of the very low concentrations (<10 mg kg⁻¹) and the high variability between samples, which precluded the use of Ca/Al ratio as an indicator of environmental changes. Difficulties with Ca/Al ratios in wood due to analytical problems, low concentrations and artefacts were already pointed out by McClenahen et al. (1989) and Cronan and Grigal (1995).

Pearson correlation coefficients were computed between element concentrations (averaged over individuals) and climatic parameters pooled over 5-year intervals. The climatic parameters included were monthly temperatures and rainfall for the growth season. Correlations between element concentrations and standardised growth index (Iₓ) were also computed.

3. Results and discussion

3.1. Ring width

Individual and mean tree-ring chronologies for the last 95 years in the MES site (n=5), are given in Fig. 1. The interannual variations of the growth index were generally consistent across the five trees, as reflected by moderate standard deviations of average values. A striking result is the increase in frequency of sharp fluctuations of the growth index in the last 20 years. In this respect, 1976 seems to act as a ‘starting’ year. The amplitude of short-term fluctuations of the growth index are well expressed through MSₓ, the mean sensitivity coefficient (Fritts, 1976). In the MES site, mean MSₓ based on 20-year intervals was consistently less than 0.16 before 1975 and reached 0.328 in the last 20-year time period (Table 2), providing evidence of a strong increase in sensitivity of this beech stand. In the REL site, by sharp contrast, all four individual trees showed less sensitivity throughout the time period, with a mean MSₓ of 0.23 in the last 20-year interval.

‘Event years,’ that is, years during which ring width was exceptionally low or high can be easily detected on the mean residual curve as shown in Fig. 2. We define ‘event years’ as those with a residual growth index exceeding the 95% confidence interval. In the MES site, event years were markedly more frequent over the last two decades (12 event years between 1975 and 1994: 7 with high and 5 with low radial growth) than during each of the previous 20-year periods (1900–1914: 3; 1915–1934: 2; 1935–1954: 1).

Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>MES site</th>
<th>REL site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fagus A</td>
<td>Fagus B</td>
</tr>
<tr>
<td>1900–1914</td>
<td>0.139</td>
<td>0.093</td>
</tr>
<tr>
<td>1915–1934</td>
<td>0.131</td>
<td>0.086</td>
</tr>
<tr>
<td>1935–1954</td>
<td>0.191</td>
<td>0.122</td>
</tr>
<tr>
<td>1955–1974</td>
<td>0.160</td>
<td>0.138</td>
</tr>
<tr>
<td>1975–1994</td>
<td>0.407</td>
<td>0.331</td>
</tr>
</tbody>
</table>

Stand mean

Fagus A  | Fagus B  | Fagus C  | Fagus D  | Fagus E  | Fagus F  | Fagus G  | Fagus I  | Fagus J  |
---------|----------|----------|----------|----------|----------|----------|----------|----------|
0.139    | 0.093    | 0.124    | 0.151    | 0.112    | 0.124    | 0.212    | 0.120    | 0.271    |
0.131    | 0.086    | 0.111    | 0.108    | 0.144    | 0.116    | 0.180    | 0.144    | 0.228    |
0.191    | 0.122    | 0.189    | 0.120    | 0.113    | 0.147    | 0.183    | 0.293    | 0.246    |
0.160    | 0.138    | 0.139    | 0.136    | 0.197    | 0.154    | 0.183    | 0.293    | 0.246    |
0.407    | 0.331    | 0.286    | 0.286    | 0.305    | 0.328    | 0.183    | 0.293    | 0.246    |

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Fig. 1. Individual (above) and mean (below) tree-ring chronologies of Fagus sylvatica in the MES site (r=radial growth index; vertical bars=standard deviations).
Moreover, four of five trees in the MES stand have shown the same growth trend during 17 years of the last two decades (1975–1994) against less than 13 for each of the preceding 20-year periods. Between 1900 and 1994, 11 years show exceptionally low radial growth (1914, 1915, 1944, 1947, 1948, 1960, 1976, 1979, 1980, 1986 and 1990), but it is striking that the four absolutely lowest values were recorded in the last 20 years. The strong, negative impact of the exceptionally dry growth season in 1976 on the growth of trees in north-western Europe is well documented (e.g. Aussenac, 1978; Becker et al., 1990). In order to assess if the other recent growth depressions can also be explained by adverse climatic conditions, general growth–climate relationships were investigated.

3.2. Growth–climate relationships

Of the 60 climatic parameters tested, only two were significantly correlated with growth, that is, May rainfall \( (r=0.353, p<0.001) \) and soil water recharge (calculated as the sum of monthly rainfalls from October to May) \( (r=0.233, p<0.01) \). These results fit in relatively well with the few studies which have investigated growth–climate relationships in European beech; all of them point to water availability as the most limiting factor even though the critical period apparently differs depending on the geographical area (Holmsgaard, 1955 in Biondi, 1993; Gutierrez, 1988; Le Goff and Ottorini, 1993; Dupouey et al., 1993). Even though the May rainfall curve and the residual growth curve in the MES site are strikingly congruent particularly during the last two decades (Fig. 2), it is obvious that this parameter alone cannot account for all the lean event years. Other climatic or environmental factors – and their possible interactions – may have negatively affected the growth of the studied beech stands. Low annual ring growth can be triggered by climatic stress dating back to the preceding years (Amorini et al., 1996). In the MES site, three of the most severe growth reductions in the last 20 years (1976, 1986 and 1990) are most likely due to the combined effects of several adverse climatic parameters. Specifically, 1976 was characterised by severe rainfall deficits (during April and May, and for the whole year), associated with very low temperatures in January and April; moreover, May 1975 also showed a marked rainfall deficit and the soil water recharge was also very low between 1969 and 1973. May rainfall was lower than average in 1986, 1989 and 1990 (respectively, 16, 68 and 70% below the normal). Rainfall parameters, however, fail to explain the 1979 and 1980 lean event years. Even though 1979 was characterised by a cold winter, with deep frosts in January, these climatic conditions are not really
uncommon and cannot explain by themselves the poor growth during these 2 years. Clearly, a more detailed climatic interpretation of the recent lean years would require a larger sample size. In fact, beyond a regular increase in mean annual temperature (dating back to the 19th century) there is no evidence for a change in climatic conditions over the last 20 years in Belgium (Sneyers and Van Diepenbeeck, 1995). An alternative, non-climatic hypothesis is that an intrinsic factor, possibly related to ageing, may have increased sensitivity in the last 20 years. This hypothesis receives strong support from the fact that the 40-year-old stand (REL site) showed no comparable increase in sensitivity. Aged trees are actually more likely to suffer from water stress, due to a larger ratio between transpiring surfaces and root absorption capacity. El Bayad (1996) found evidence for a severe reduction of macroporosity and, hence, to a 25% lower water storage capacity of the loessic soils of the Forêt de Soignes, which was ascribed to repeated logging operations. Herbauts et al. (1996) reported that soil compaction by mechanised forest management (with a silvicultural rotation of 8 years) and subsequent surface waterlogging have actually been increasing in the last decades, most likely because low pH conditions and poor biological activity impede spontaneous soil structure regeneration. We therefore hypothesise (i) that the alterations of the soil water balance and the rooting conditions have gradually increased the environmental restraints for beech up to a critical threshold in the last 20 years and (ii) that the exceptionally dry growth season in 1976 has triggered beech sensitivity due the unfavourable conditions created by physical soil damages. Soil compaction due to machine traffic has already been pointed out as an aggravating factor in beech dieback (Nageleisen, 1993).

3.3. Variation pattern of element concentrations

For all elements except K, the variation pattern was fairly consistent among the five trees (Fig. 3). Overall, there was no evidence for a sharp heartwood/sapwood transition, contrary to oak, where three- to tenfold concentration ratios between outer and inner wood are usually found for N, P, K and Mg (De Visser, 1992; Lévy et al., 1996). Tree species which lack a sharp heartwood/sapwood transition are not usually regarded as most suitable for dendrochemical inves-

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tigations because of a supposedly higher radial mobility of elements in their trunk (Cutter and Guyette, 1993). However, the marked increase in phosphorus and nitrogen in the last 15 years (Fig. 3) might still be explained by a higher proportion of living cells in the outer wood. There is no clear indication of a steady increase in nitrogen availability in the last 30 years, due to atmospheric deposition, as found, for instance, in the oak forests in northern France (Lévy et al., 1996).

Manganese and calcium showed a constant decrease throughout the time period with a 2- and 1.5-fold difference between maximum and minimum concentration, respectively (Fig. 3). The pattern of variation of magnesium was somewhat more complex, showing a two-fold increase from 1930–1965, followed by a subsequent decrease of about the same magnitude.

Several possible endogenous and exogenous factors can account for the radial variations in wood cation concentrations. First, endogenous factors include wood cation binding capacity (CBC). Systematic declines in CBC from pith to bark have been documented in other species (Momoshima and Bondietti, 1990; Momoshima et al., 1995), but no data seem to be available for Fagus sylvatica. The observed profile for Mn and Ca might conceivably reflect such a constant decline in CBC. A second endogenous factor is the pattern of radial variation in the number of living cells in the wood (Marschner, 1994). Specifically, as an element usually associated with living cells (De Visser, 1992), magnesium would have been expected to increase in concentration from pith to bark following the same profile as nitrogen and phosphorus. The finding of a steady decrease in the last 30 years is strongly suggestive of an extrinsic, environmental influence on the concentration profile of Mg, which will be further discussed below. Thirdly, variations in wood cation concentrations can reflect changes in sap chemistry, possibly due to corresponding alterations to soil solution. A transient increase in the concentration of certain cations in wood in the mid-1900s, followed by a sharp decrease in the late 1900s has been well documented for forest trees in areas subject to strong atmospheric deposition of acidifying pollutants (Bondietti et al., 1990). Such radial patterns have been interpreted in terms of cation mobilisation, followed by depletion through leaching. The variation pattern of
Mg in this study might tentatively be ascribed to the same causes. Magnesium deficiency has often been proposed as one of the possible causes of the recent forest decline in Europe, including in Belgium (Weissen et al., 1992).

Acidification of soil profile by atmospheric deposition usually results in the mobilisation of specific metals, including aluminium and manganese. Based on the fact that its availability strongly increases with decreasing pH, manganese concentration in wood has been proposed as a reliable bioindicator of pH variations in the soil (Guyette et al., 1992). In the context of a forest ecosystem in a polluted area, developed on a poorly buffered soil, the finding of a decrease in Mn concentration, associated to an increase in the Ca/Mn ratio (Fig. 4) is surprising. In view of the low soil pH values (pH <4 in the upper 25 cm, see site description), the observed decrease in Mn concentration in wood is
unlikely to be explained by a corresponding increase in soil pH. An alternative hypothesis is that available Mn within rooting depth is being exhausted by long-term leaching because of a limiting pool of readily soluble Mn. This hypothesis is consistent with the relatively low concentrations of extractable Mn in the soil profile (Table 1). Meisch et al. (1986) also found a recent decrease in the concentrations of Ca, Mg and Mn in beech wood in Germany. For Ca, they ascribed this to a well-documented decrease in the emission of dust by local industry, whereas a depletion of the soil was not excluded for Mg and Mn.

3.4. Correlations of element concentrations with climatic parameters and ring width

In agreement with Meisch et al. (1986), the growth index did not correlate significantly with element concentrations. Specifically, there was no evidence that the transient increase in Mg in the 1960s (Fig. 3) correlated with improved growth as found by Bondietti et al. (1990) for North American forest trees. However, a deficiency in divalent cation in the soil might still be one of the factors involved in the steady increase in sensitivity of beech from 1976 onwards in the Forêt de Soignes.

Finally, there were few significant correlations between element concentrations and climatic parameters (Table 3). Interestingly, the strongest correlation was found between calcium and March rainfall ($r = -0.727$, $p<0.001$). This result is in line with the annual variation pattern of Ca concentration in beech xylem sap with ten times higher concentrations in early spring than in the rest of the year (Glavac et al., 1990). Thus, high rainfall during periods of intense root absorption of Ca might conceivably depress Ca uptake through a dilution effect of the soil solution. This hypothesis needs further investigation as links between element concentrations in the wood and climatic parameters have not been frequently reported (McClenahen and Vimmerstedt, 1993).

4. Conclusion

Old beech trees in the Forêt de Soignes have shown a steady increase in sensitivity of radial growth starting with the exceptionally dry year, 1976. Water stress due to low rainfall in May, possibly aggravated by decreased soil porosity resulting from compaction by logging traffic can explain some but not all lean years after 1976. Finally, wood concentration profiles are suggestive of a decreasing availability of divalent cations in the soil. This will have to be confirmed using another tree species with a sharper heartwood/sapwood transition than beech.

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References


