RELATIONSHIPS BETWEEN CROWN CONDITION OF BEECH (*Fagus sylvatica* L.) AND THROUGHFALL CHEMISTRY

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Abstract. A two-step regression procedure was used to predict the impact of throughfall chemistry on the defoliation of *Fagus sylvatica* L. over a J O-year-monitoring period at three plots in northem Belgium. The impact of throughfall chemîstry on crown condition was examined after accounting for influences of site, stand, climate and diseases. In a first step, defoliation was regressed on site, stand, climate and disease parameters. The residual defoliation of this standard set was correlated with 27 throughfall variables.

Climatic variables of the year preceding the year of crown assessment accounted for 79% of the variation in current defoliation. Site, stand and disease factors were not included and were still part of the residual defoliation. The study of the residual defoliation revealed that high throughfall depositions of sulphate and ammonium and high throughfall ratios of SO.JMg enhanced defoliation.

Keywords: climate, crown condition, *Fagus sylvatica* L., residual defoliation, throughfall chernistry

1. Introduction

Forest health bas been one of the major concerns in sylviculture for many years. As a consequence of the occurrence of new types of forest decline in Europe and North America in the early 1980s (Olson *et al.,1992;* Innes,1993; Hüttl and Mueller-Dombois, 1994), emphasis has been put on recording the visual assessment of crown condition as an indicator of forest health. The crown condition of sample trees has been recorded using different indices to monitor tree vitality. The acquisition of such a long time series can help to reveal if forest health is liable to a slowly developing long-term decline or if changes in vitality are merely due to natura! (short or long term) fluctuations.

The data from such surveys have often been used to assess the impacts of pollution stress factors on stand nutrition or on crown condition (Freer-Smith and Read, 1995; Solberg and Tmseth, 1997; Audley *et al.*, 1998; Thomas and Büttner, 1998).

Leaf losses can be attributed to several biotic as well as abiotic stress factors. Climate stresses have become increasingly accepted as key factors influencing the crown condition of trees, although they were initially ignored (Innes, 1993; Landmann, 1995). Innes (1993) emphasised the importance of climate and stand management factors which may mask possible chronic pollution effects. Burton *et al.* (1991) stated that statistically verifiable effects of pollution on leaf area might be lost in the "noise" created by the vagaries of nature. Changes in leaf area resulting from acid deposition may be quite small compared to 20 to 30% leaf area reductions during heavy seed years. Effects of (air pollution) stress factors can, in principle, only be estimated or tested properly if all other relevant effects are taken into account (De Vries *et al.,* 1998). Because of the predominant role of climate in forest health, climate variables should be involved in pollution effect studies. This study aimed to explore relationships between throughfall chemistry and leaf losses of three *Fagus sylvatica* L. plots over a 10-year monitoring period in northern Belgium. The impact of throughfall chemistry was examined after **accounting for the effects of site, stand, climate and diseases.**

2. Materials and Methods

The data were collected in three plots which are part of the 'EU-UN/ECE intensive monitoring of the forest ecosystem' study in the Flemish Region (level II). The first plot is located at the forest of Wijnendale (280 ha, 51°04'10" N; 3°02'10" E) which is situated in the low plain of sandy Flanders. The soil is a moderately wet loam/sand with a partly destroyed textural B-horizon, with a sandy clay substrate beginning at moderate depth. (FAO classification = Gleyic Distric Cambisol). The second plot is located at Gontrode (30 ha, 50°58'35" N; 3°48'19" E) which is situated in the northern low plain of Flanders. The soil is a strongly gleyed (poorly drained) sandy loam with a partly destroyed textural B-horizon, with a clay substrate beginning at a depth of 60 cm (FAO classification = Dystric Podzoluvisol). The third plot is situated at the forest of Zoniën (4400 ha, 50°44'50" N, 4°24'53" E) located on a gently undulating plateau south-east of Brussels. The moderately to well drained loamy soil has a partly destroyed textural B-horizon beginning at a depth of ca. 40 cm (FAO = Dystric Podzoluvisol).

Soils at all sites are acidic with pHc,c_{12} not exceeding 4 throughout the soil column. **Base saturation is lower than 25% except at the deeper horizons in Gontrode and Zoniën.**

The climate of the sites is characterised as moderate Atlantic. Data from neighbouring **meteorological weather stations display little differences in climatic features between the** plots. Mean annual temperature and precipitation are 9.7°C and 754 mm, respectively. Precipitation during the growing season (May-October) averages 414 mm. There are on average 66 frost days each year.

The stands of the plots at Wijnendale and Zonien are homogeneous beech *(Fagus sylvatica* L.), age 75 and 89 years, respectively, with a basal area of 37.7 and 31.7 m^2 ha^{-1}, respectively. The standing volume amounts to 425 and 536 m^3 ha-1, respectively. The stand in Gontrode is a 89-year-old mixed common aak *(Quercus robur* L.)-beech stand with a basal area and standing volume of 31.3 $m^2 ha^{-1}$ and 391 $m^3 ha^{-1}$, respectively.

Average annual defoliation rates over a 10-year-monitoring period are 24% in Wijnendale (range: 16 to 30%) and 15% in Gontrode (range: 12 to 22%) and Zoniën (range: 11 to 23%). Tree mortality has not been observed.

All plots are part of the intensive 'level II' monitoring network in Flanders. Crown condition is assessed on 29 (Wij.), 8 (Gon.) and 25 (Zon.) sample trees situated along the N-S and E-W axes of the circular plots (area 0.25 ha). Crown condition is assessed by measuring defoliation (5% classes), discoloration and the presence and intensity of insects and fungi (UN/ECE, 1994). Assessments are carried out in July-August. The evaluation of crown condition in Wijnendale and Gontrode started in 1988 and continued until 1997 (with the exception of 1989). Crown condition assessment in Zoniën started in 1991. Bulk rainfall and throughfall has been sampled since 1992 every two weeks. The water samples have been analysed for pH, Ca, Mg, K, Na, $HC0_3$, $S0_4$, NR,, $N0_3$ and Cl. Deposition estimates were also available for the plots of Gontrode and Wijnendale for 1988.

The meteorological predictor variables were derived from an extensive data set of daily variables of rainfall, maximum and minimum temperature, relative humidity, wind **speed and sunshine duration, from three neighbouring meteorological weather stations at**

TABLE I

Set of meteorological predictor variables derived from meteorological weather stations

Meteorological predictor variable	abbreviation
average daily rainfall in month i (mm day^{-1})	Ri
average monthly minimum temperature in month i (°C)	Tmini
average monthly minimum temperature in month i (°C)	Tmaxi
average monthly relative humidity in month i (%)	RHi
average monthly wind speed in month *i* (km h^{-1})	Vi
average daily sunshine duration in month *i* (min day^{-1})	SUNi
number of rainless days in month *i* (days $month^{-1}$)	Rai
number of frost days in month i (days $month^{-1}$)	Tminai
number of days with Tmax >= 25 °C in month *i* (days $month^{-1}$)	Tmaxai
number of days with RH < 65% in month i (days $month^{-1}$)	RHai
number of days with V > 90 km h^{-1} in month *i* (days $month^{-1}$)	Vai
number of days with sunshine duration > 700 min day^{-1} in month *i* (days $month^{-1}$)	SUNai
Σ, Tmin of frost days in month i (degree days)	frost-indexi
Σ, Tmax of days with Tmax >== 25 °C in month *i* (degree days)	heat-indexi

Middelkerke, Munte and Zaventem (locations respectively 51°11'53"N; 2°52'04"E, 50°56'00"N; 3°44'00"E and 50"53'46"N; 5°28'00"E; the distance between each plot and the nearest weather station was 11, 4 and 6 km, respectively). From this database a set of monthly climatic variables from 20 months preceding the month of crown condition assessment was calculated (Table I).

The annual radial growth indices from each stand were included as a stand factor. The yearly transpiration stress (calculated as the difference between potential and actual transpiration) and drainage flux at 50 and 240 cm were obtained from a hydrological model (Hubrechts *et al"* 1997) and were introduced as site variables. The annual average intensity of insect attack and the percentage of sample trees affected by fungi were recorded at the same time as the crown condition assessment. The two-weekly deposition fluxes and ratios have been aggregated over a whole year (Table II).

The impact of throughfall chemistry was tested after making an allowance for the effects of site, stand, climate and pathogens. A two-step regression procedure was used to analyse the influence of deposition on average defoliation (Brooks, 1994). In a first step the annual average defoliation values from the three plots over 9, 9 and 7 years, respectively (n = 25) were regressed on a standard set of time-dependent site, stand, climate and disease predictor variables using a stepwise regression with a forward selection procedure. The problems related to multi-collinearity were avoided by omitting variables that were correlated with the variables included in the best-fit model. Therefore, prior to the regression analysis, a correlation study was performed. Positive residuals from this regression model implied that defoliation is underestimated by the set of predictor variables; it meant that there was a defoliation stimulating factor which had not been taken into account. Negative residuals indicated the presence of a factor which suppressed defoliation. The residual defoliation obtained from this multiple regression model was correlated individually with throughfall variables.

3. Results

A standard set of 4 monthly climatic variables from the year preceding the crown condition assessment explained 79% of the variability in defoliation (Table III). A low heat-index in May, high number of rainless days in June, high wind speed in August and

TABLE II

Annual means of throughfall from 3 beech plots involved in the regression analysis (coefficient of variation in parentheses)

Throughfall variable	Wijnendale (n = 7)	Gontrode {n = 7)	Zoniën (n = 6)
throughfall fluxes			
H (kg ha·' year-¹)	0.003 (61%)	0.011 (55%)	0.044 (99%)
HC0₃ (kg ha-¹ year-)¹	77.5 (39%)	84.2 (33%)	72.6 (35%)
S04-S (kg ha·' year-)¹	19.4 (44%)	26.2 (31%)	18.5 (38%)
N0₃-N (kg ha-¹ year"¹)	6.3 (37%)	7.8 (32%)	7.6 (19%)
NH4-N (kg ha-¹ year-¹)	20.8(28%)	21.2 (23%)	14.6 (13%)
Cl (kg ha-¹ year-¹)	41.2 (25%)	40.0 (17%)	32.3 (13%) .
Ca (kg ha-¹ year-¹)	10.9 (46%)	17.2 (29%)	18.5 (40%)
Mg (kg ha-¹ year"¹)	3.7 (26%)	5.1 (16%)	4.3 (21%)
K (kg ha-¹ year-¹)	23.5 (26%)	33.0 (33%)	25.8 (25%)
Na (kg ha·' year-¹)	21.9 (26%)	22.2 (16%)	17.6 (24%)
Throughfall ratios			
NO,_ICI (mg mg.¹)	1.17 (44%)	1.82 (58%)	1.95 (44%)
Süi/CI (mg mf ¹l	2.16 (27%)	3.27 (35%)	2.61 (35%)
Ca/K (mg mg·)	0.73 (77%)	0.79 (89%)	1.20 (32%)
Mg/K (mg mg.¹)	0.28 (99%)	0.24 (97%)	0.29 (23%)
Ca/Mg (mg mg.¹)	3.19 (28%)	3.53 (29%)	4.53 (32%)
NH.i/K (mg mg-¹)	2.36 (35%)	1.73 (46%)	1.39 (25%)
NH.fMg (mg mg.¹)	9.52 (21%)	6.38 (15%)	5.28 (30%)
NHJCa (mg mg-¹)	3.43 (25%)	2.05 (11%)	1.35 (26%)
NO;/K (mg mg-¹)	2.82 (49%)	2.16 (53%)	2.53 (43%)
NO;/Mg (mg mg.¹)	10.1 (32%)	7.90 (28%)	9.5 (28%)
N0₃/Ca (mg mg-¹)	4.14 (49%)	2.59 (30%)	2.33 (19%)
N03/Nfü (mg mg·¹)	1.24 (24%)	1.44 (29%)	2.01 (27%)
SO.i/K (mg mg.¹)	4.92 (35%)	4.94 (52%)	3.68 (16%)
SO.iMg (mg mg.¹)	18.9 (24%)	17.7 (22%)	14.2 (21%)
SO,JCa (mg mg-¹)	7.20 (22%)	5.78 (18%)	3.79(24%)
S04'NH., (mg mg.¹)	2.36 (21%)	3.21 (18%)	3.49 (21%)
S04/'N0₃ (mg mg-¹)	3.12 (57%)	3.58 (56%)	2.50 (29%)

a low relative humidity in November resulted in large leaf losses the subsequent year at all three beech plots. The relative humidity in November explained only a small portion of the total variability (5%). Site, stand and pathogens were not included in the model. Their minor components are still part of the residual.

The study of residual defoliation revealed that defoliation was generally underestimated for Wijnendale and Gontrode *(L* residuals resp. 2.8% and 3.9%) and overestimated for Zoniën *(L* residuals = -6.7%) (Figure 1). The residuals were regressed individually on throughfall data. Three out of 27 tested variables were found to be significantly correlated with the residual defoliation. Throughfall fluxes of NH_4-N and $S0_4$-S and the SOJMg ratio in the throughfall ($p<0.01$, <0.01 and <0.05, respectively) were positively correlated with the residual defoliation (Table III; Figure 2). This implied that leaf loss rates were increasingly underestimated by the standard set of climatic variables in the presence of increasing deposition of sulphate and ammonium and increasing ratios of SOJMg in throughfall.

4. Discussion

Changes in defoliation could be largely attributed to a combination of climatic **variables from the year preceding the crown condition assessment. Summer droughts are**

TABLE III

Statistics of two-step regression procedure on defoliation and residual defoliation

Independent variable	regression coefficient	standard error	t-value	*p*	*F-ratio*	*R2otlj*
defoliation (n =25)					23.62	0.79
Constant	60.585	24.240	2.52	0.0202		
Heat-indexs*	-1.519	0.125	-7.41	0.0000		
v3•	0.566	0.008	5.13	0.0001		
Ra6*	0.562	0.111	4.56	0.0002		
RHll*	-0.640	0.268	-2.41	0.0257		
residtial defoliation						
NH4 deposition (n=17)					9.65	0.56
Constant	-4.156	1.379	-3.01	0.0087		
Slope	0.206	0.066	3.11	0.0072		
S04 deposition (n =16)					10.63	0.45
Constant	-1.343	0.606	-2.22	0.0451		
Slope	0.086	0.026	3.26	0.0062		
SO,!Mg (n =18)					5.14	0.26
Constant	-2.226	1.447	-1.538	0.1448		
Slope	0.188	0.083	2.268	0.0385		

* meteorological variables from year preceding year of crown condition assessment

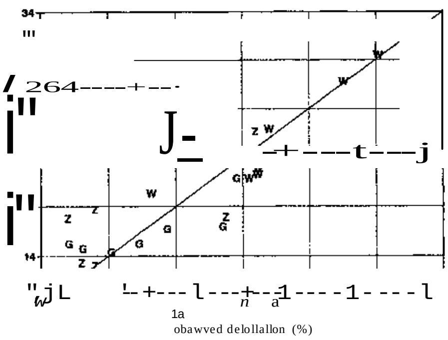

Fig. 1. Predicted (met. data) vs observed defoliation.

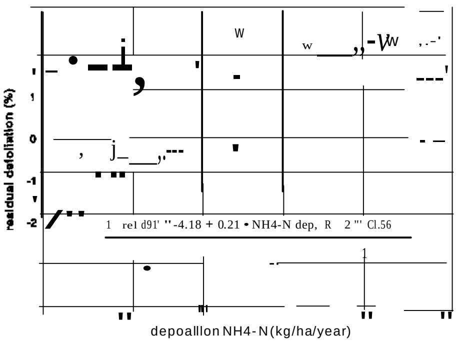

Fig. 2. Residual defoliation vs. NH4-N deposition

reducing the twig growth (Roloff, 1984; Power, 1994) of beech in the following year. The relationship between previous summer drought and leaf loss is aften connected with the occurrence of heavy mast years (Schröck, 1995; Hilton and Packham, 1997). This can lead to decreases in foliation due to allocation of assimilates to reproductive tissues (Burton *et al"* 1991). High cupule production in the 16 x 16 km network of Flanders was noticed in 1991 and 1995 (Sioen and Roskams, 1998).

The study of the residual defoliation suggests a decoupling of the relationship between foliation and climate in the presence of high throughfall deposition of ammonium, sulphate and high $S0_4$ to Mg ratios in throughfall (Figure 2). The results suggest adverse effects of ammonium and sulphate deposition on crown condition. Ammonium and sulphate deposition ranged from 12 to 32 kg N ha-^{1} yr-^{1} and from 13 to 44 kg S ha·' yr-^{1} and declined during the monitoring period. Ammonium and sulphate were highly correlated in throughfall (r = 0.68, p < 0.001). Residual defoliation was set to zero at NH_4-N and $S0_4$-S deposition of 20.2 and 15.6 kg ha-' yf^1 respectively. Values exceeding these rates lead to positive values of residual defoliation, implying additional leaf losses superimposed on the natura!, climatic induced defoliation. Forest health could have been affected indirectly by the depletion of base cations from soils (nutrient deficiency and imbalances), increasing mobilisation of aluminium (increasing toxicity), inhibition of soil biologica! processes or increased bioavailability of nitrogen (Lucier and Haines, 1990).

Increasing ratios of SOJMg in throughfall were also associated with defoliation. High ratios of $S0_4$ to Mg may result from decreased canopy teaching rates of magnesium owing to depletion of mineral and forest floor magnesium pools or decreased ·dry deposition of Mg-bearing particles relative to gaseous or particulate interception of sulphur. Deposition of Mg and other base cations, on the contrary, did not contribute to the changes in residual defoliation. Base cation deposition in these regions of Europe is declining (Hedin *et al.*, 1994). It is not clear to what extent future decline wil! exacerbate stand nutrition and tree health at these base cation-poor sites.

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