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**Original article**

# Regional scale effects of base cation fertilization on Norway spruce and European beech stands situated on acid brown soils: soil and foliar chemistry

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**Abstract** – Ten experiments were installed on acid soils in different ecoclimatic conditions of the Belgian Ardenne. Soil pH, exchangeable cations and P contents as well as foliar nutrient concentrations were monitored 1 and 3 years following the application of either (1) 3 t $ha^{-1}$ of a dolomitic limestone or (2) 3 t $ha^{-1}$ of a dolomitic limestone plus different amounts of P (0–800 kg natural phosphate) and/or K (0–250 kg $K_2SO_4$). Dolomite rapidly increased Ca and Mg concentrations in the 0–10 cm soil layer and in the tree leaves. After three years, exchangeable Al was significantly lower in the first soil layer but it still represented more than 50% of the exchangeable cations. Mean pH increase in the 0–10 cm layer was less than 0.5 pH units. Dolomite alone tended to reduce mean K concentrations in the soils and/or leaves of the beech stands. The addition of potassium sulphate to dolomite generally increased the soil and foliar K contents in the spruce stands contrary to the beech stands. It also tended to increase the resaturation of the exchange complex with Ca and Mg ions. The effects of natural phosphate addition were restricted to a slight increase of P foliar concentrations. The B foliar concentrations were reduced by both treatments, whereas Zn concentrations increased significantly. The between stands variability of soil and foliage chemical properties was important but did not influence the effects of the treatments.

**base cation fertilization / micronutrient / *Picea abies* / *Fagus sylvatica***

**Résumé – Effets à l'échelle régionale de la fertilisation en cations basiques sur des peuplements d'épicéa commun et de hêtre situés sur des sols bruns acides : analyses de sols et feuilles.** Dix dispositifs ont été installés dans différentes conditions écoclimatiques de l'Ardenne belge. Les cations échangeables, le pH, la concentration en P dans le sol et les teneurs foliaires en éléments ont été déterminés 1 et 3 ans après l'application de (1) 3 t $ha^{-1}$ de dolomie ou (2) 3 t $ha^{-1}$ de dolomie plus différentes doses de P (0–800 kg de phosphates naturels) et/ou de K (0–250 kg $K_2SO_4$). La dolomie permet d'accroître rapidement la concentration en Ca et Mg dans les dix premiers cm du sol et dans les feuilles. Après 3 ans, l'Al échangeable diminue mais seulement dans la première couche de sol. Dans cette même couche, l'accroissement de pH est limité à une demi unité. La dolomie seule a tendance à réduire les teneurs en K échangeable dans le sol et les feuilles des arbres en hêtraies. L'application de $K_2SO_4$ permet finalement d'accroître la concentration en K dans le sol et les feuilles des peuplements d'épicéa. De plus, ce traitement entraîne une plus grande resaturation du complexe d'échange en Ca et Mg. Les phosphates naturels augmentent légèrement les teneurs foliaires en P. Le B dans les feuilles diminue suite aux deux traitements et le Zn augmente significativement. La variabilité des propriétés chimiques des sols et des feuilles est importante entre les dispositifs expérimentaux mais n'influence pas l'effet des traitements.

**fertilisation en cations basiques / micronutriments / *Picea abies* / *Fagus sylvatica***

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## 1. INTRODUCTION

During the 1970s the forest condition deteriorated severely in different parts of Europe and North America. In Belgium, great concern arose after the severe decline of Norway spruce during the winter 1982–1983 [36]. The symptoms of foliage discoloration and loss were the same as observed in West Germany since the mid-1970s. These symptoms were partly attributed to the direct effect of atmospheric pollution that had an important impact in Germany [36]. With the benefit of hindsight, it has been demonstrated that several stress factors could impair forest health and that a complex system of ecological interrelationships had to be taken into account [21].

Since then, different studies have shown that nutritional imbalance was a predisposing factor of forest decline for stands situated on acid soils [12, 39]. The foliar yellowing of Norway spruce associated with forest dieback was identified as a symptom of magnesium deficiency [9, 37]. It has been postulated that these deficiencies could be reinforced by acid and nitrogen inputs from the atmosphere, which accelerate the processes of soil acidification and cation leaching [35]. In South Belgium, several studies demonstrated that besides the well known cases of low concentrations in phosphorous and calcium, magnesium was also at a critical level in 70% of the sampled soils [17].

Improving the chemical and biological status of the soil by fertilization is thought to be an efficient tool to prevent forest degradation or restore damaged ecosystems [1, 11]. Controlled laboratory experiments are suitable for the identification of individual soil processes [28, 29] but should be corroborated by field experiments. In order to settle management tools to impede forest decline, diagnostic fertilization trials were installed in several countries during the two last decades [5, 11, 14, 15, 20]. Besides this, interpretation of previous experiments was carried out [24, 30, 33]. Generally, these studies lacked regional representativeness since they were based on a small number of experimental stands. As a consequence, it was not always clear if stands in the same region but differing in ecoclimatic conditions or species composition would react similarly to fertilization.

The objectives of this study were (i) to test base cation fertilization on acid soil as a method to prevent forest dieback and/or restore forest health in adult stands, (ii) to assess how different ecoclimatic conditions within a geographically limited region could influence the response of stands, and (iii) to compare the response of two commercially important forest-tree species to fertilization.

One and the same experimental design was applied in a network of spruce (*Picea abies* (L.) Karst.) and beech (*Fagus sylvatica* L.) adult stands. Various fertilization treatments were tested on replicated plots. Each two-year, soil as well as foliar analyses were performed. Crown condition was assessed each year and the floristic composition each four years. This article presents the general methodology of the research programme and the results of soil and foliar analyses obtained one and three years after fertilization. A second paper deals with fertilizer effects on the ground vegetation [22].

## 2. MATERIALS AND METHODS

### 2.1. Stand selection and description

Five monospecific even-aged stands of Norway spruce and European beech were selected throughout the Belgian Ardenne according to several criteria. First, experimental stands had to be located on acid and magnesium poor soils. This was tested by foliar and soil analyses before fertilizer application. Second, soil type (Belgian legend, IRSIA 1:20,000 soil map) and topography had to be homogeneous at the stand level. Third, sampling should take into account the ecoclimatic diversity of the region: for each species, stands were chosen in various Ecological Sectors of the Belgian Ardenne as defined by Onclinkx et al. 1987. Selected characteristics of the experimental stands are listed in *table I*.

The spruce stands were approximately 50 years old while the beech stands were around 100 years old at the beginning of the experiment (1995). The altitude of the stands varies between 380 m and 560 m. Depending on the ecological sector (*table I*), the mean annual temperature ranges between 6.5 ºC and 8.0 ºC, and total annual precipitation varies between 1030 mm and 1200 mm [26]. The soils are classified as *Gbb* (Belgian legend) for all the stands, which means well drained acid brown soils dominated by clay/silt, with a stony load > 5%. Following the FAO classification, the selected stands are on *Dystric* and *Eutric cambisol*. Humus type is moder. The natural association of the beech stands is *Luzulo-Fagetum* and the sub-association varies between *typicum* and *vaccinietosum* (*table I*) [25]. There is no ground vegetation data for the spruce stands since understorey plants are very scarce.

The range of site indexes (SI), based either on dominant height at 50 (spruce) or 100 (beech) years old

**Table I.** Selected characteristics of the experimental stands.

| Stand code | Species | Altitude (m) | Ecological sectors[1] | Phytosociological associations[2] | SI[3] | BA[4] |
|---|---|---|---|---|---|---|
| 1S | Norway spruce | 470 | Ardenne centro-orientale | | 2.3 | 39.0 |
| 2S | Norway spruce | 510 | Haute Ardenne | | 3.2 | 37.6 |
| 3S | Norway spruce | 560 | Haute Ardenne | | 3.8 | 40.2 |
| 4S | Norway spruce | 430 | Ardenne méridionale | | 2.4 | 40.9 |
| 5S | Norway spruce | 420 | Ardenne méridionale | | 2.8 | 52.8 |
| 6B | European beech | 470 | Ardenne occidentale | *LF – deschampsietosum* | 1.7 | 20.3 |
| 7B | European beech | 420 | Ardenne centro-orientale | *LF – vaccinietosum* | 1.0 | 21.7 |
| 8B | European beech | 380 | Ardenne atlantique | *LF – typicum* | 1.2 | 23.5 |
| 9B | European beech | 400 | Ardenne atlantique | *LF – deschampsietosum* | 1.2 | 18.4 |
| 10B | European beech | 445 | Ardenne méridionale | *LF – deschampsietosum* | 1.5 | 22.9 |

[1] according to [26].
[2] according to [25]. LF = *Luzulo fagetum*. No ground vegetation data for the spruce stands.
[3] SI = Site Index according to [3], [27].
[4] BA = basal area in $m^2$ per ha (winter 1994–1995).

(*table I*), reflects the diversity of ecoclimatic conditions or site specificity. Differences in basal area (BA, *table I*) between stands for a given species (winter 1994–1995) result from different thinning regimes.

### 2.2. Fertilization treatments

Preliminary soil (*table II*) and foliar (*table III*) analyses were performed on each experimental stand in 1994. Based on these results, two kinds of treatments (*table IV*) were specified in addition to a control (no fertilization). The F1 treatment brought 3 000 kg $ha^{-1}$ of dolomitic limestone (55% $CaCO_3$ / 40% $MgCO_3$) in order to raise the Mg and Ca deficiencies observed in most stands; in the 3S stand it was limited to 2 650 kg $ha^{-1}$ due to an error during the field work. The F2 treatment consisted of the standard dolomite application plus varying amounts of P (as natural phosphate) and/or K (as $K_2SO_4$), depending on the site susceptibility to specific induced deficiencies.

The treatments were applied on 45 × 45 m square plots for spruce and 50 × 50 m square plots for beech, with a buffer zone of at least 25 m between plots. Two to 4 replications per treatment were made, depending on the stand (*table IV*). The fertilizer was applied with a blowing engine towed by a Buurnett forwarder during the winter season 1994–1995.

### 2.3. Soil sampling and analyses

The soil was sampled twice after the treatments were applied, respectively during the winter 1995–1996 (one year after treatment) and during the winter 1997–1998 (three years after treatment). Nine core samples per plot and per soil layer (0–10 cm and 10–20 cm) were pooled for soil analysis. They were extracted at the nodes of a 15 × 15 m grid settled 2 m apart at each sampling date in order to avoid extracting previously disturbed soil.

For the chemical analyses, we used the harmonised methods of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forest [13]. The soil samples were air-dried at 20 °C and ground to pass a 2 mm sieve prior to analysis. The moisture content of air-dried soils was determined on a subsample of 5 g dried overnight at 105 °C. The pH ($H_2O$) was measured with an electrode, using a soil: solution ratio of 1:5 (m:v). The exchangeable base cations (Ca, Mg, K) were extracted with a 0.1 m $BaCl_2$ agent, with a soil: solution ratio of 1:10 (m:v). Soil P was extracted by aqua regia agent. Extracted base cations (Ca, Mg, K) and P were determined by inductively-coupled plasma emission spectrometry. For the 1997 sampling, the exchangeable acid cations (Al+H) were extracted using a 1 m KCl agent with a soil: solution ratio of 1:2.5 (m:v). Al and H were measured by titration with 0.1 m NaOH.

**Table II.** Soil chemical properties of the stands[a] before fertilization (1994) compared to deficiency thresholds (Ca, Mg, K cmol+/kg; P mg/kg).

| Stand code | Ca [1] | Mg [1] | K [1] | P [2] | pH $H_2O$ [3] |
|---|---|---|---|---|---|
| 1S | 0.21 * | 0.15 * | 0.11 | 52.1 | 4.17 * |
| 2S | 0.18 * | 0.11 * | 0.11 | 49.5 | 4.47 |
| 3S | 0.30 * | 0.18 | 0.19 | 74.3 | 4.03 * |
| 4S | 0.25 * | 0.15 * | 0.15 | 57.3 | 4.25 |
| 5S | 0.25 * | 0.14 * | 0.16 | 52.2 | 4.06 * |
| 6B | 0.21 * | 0.18 * | 0.19 | 67.8 | 3.97 * |
| 7B | 0.44 * | 0.19 * | 0.24 | 57.2 * | 3.83 * |
| 8B | 0.31 * | 0.12 * | 0.15 | 42.6 * | 3.86 * |
| 9B | 0.60 | 0.29 | 0.28 | 73.7 | 3.86 * |
| 10B | 0.22 * | 0.19 * | 0.17 | 79.8 | 4.33 |
| Deficiency thresholds for the 0–20 cm soil layer according to [34], [37] | | | | | |
| Norway spruce | < 0.50 | < 0.16 | < 0.08 | < 40 | < 4.2 |
| Beech | < 0.50 | < 0.25 | < 0.10 | < 60 | < 4.2 |

[a] Means determined from 18 to 24 samples per stand.
* < deficiency threshold.
[1] Extraction with 0.5 M $NH_4$ Acetate+0.2 M EDTA at pH = 4.65. Measured by AAS.
[2] Extraction with citric acid (Dyer method). Measured by colorimetry.
[3] Soil: solution ratio of 1:5 (m:v).

**Table III.** Foliar nutrient concentrations[a] at the stand level[b] before fertilization (1994) compared to deficiency thresholds (% of dry matter).

| Stand code | Ca | Mg | K | P |
|---|---|---|---|---|
| 1S | 0.15 ** | 0.08 ** | 0.44 * | 0.12 * |
| 2S | 0.11 ** | 0.06 ** | 0.51 * | 0.12 * |
| 3S | 0.13 ** | 0.05 ** | 0.50 * | 0.10 ** |
| 4S | 0.13 ** | 0.08 * | 0.41 * | 0.16 |
| 5S | 0.15 ** | 0.06 ** | 0.51 * | 0.12 * |
| 6B | 0.36 ** | 0.10 * | 0.52 ** | 0.16 * |
| 7B | 0.36 ** | 0.06 ** | 0.57 * | 0.14 * |
| 8B | 0.56 * | 0.06 ** | 0.91 * | 0.17 * |
| 9B | 0.45 ** | 0.07 ** | 0.71 * | 0.11 * |
| 10B | 0.46 ** | 0.13 * | 0.60 * | 0.19 * |
| Deficiency threshold of nutrient foliar concentrations after [34], [37] | | | | |
| Spruce – deficiency | < 0.20 | < 0.06 | < 0.40 | < 0.10 |
| Spruce – optimum | > 0.50 | > 0.11 | > 0.80 | > 0.15 |
| Beech – deficiency | < 0.50 | < 0.08 | < 0.55 | < 0.10 |
| Beech – optimum | > 0.80 | > 0.15 | > 1.00 | > 0.20 |

[a] Digestion by $HNO_3$; determination by ICP.
[b] Means from 7 to 15 trees per stand (Norway spruce: 1-year-old needles).
** < deficiency threshold. * Values between deficiency and optimum thresholds.

**Table IV.** Applied treatments and experimental design (kg ha$^{-1}$).

| Stand Code | Treatment | Number of Plots | Dolomite Lime[1] | Natural Phosphate[2] | Potassium Sulphate[3] |
|---|---|---|---|---|---|
| 1S | Control | 4 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 2 | 3000 | 800 | 200 |
| 2S | Control | 4 | | | |
| | F1 | 4 | 3000 | | |
| | F2 | 4 | 3000 | 400 | 200 |
| 3S | Control | 3 | | | |
| | F1 | 3 | 2650 | | |
| | F2 | 3 | 2650 | 350 | |
| 4S | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | 400 | 200 |
| 5S | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | 400 | 200 |
| 6B | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | 400 | 200 |
| 7B | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | 400 | 200 |
| 8B[a] | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 2 | 3000 | 800 | |
| | F2’ | 1 | 3000 | 400 | 250 |
| 9B | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | 400 | 200 |
| 10B | Control | 3 | | | |
| | F1 | 3 | 3000 | | |
| | F2 | 3 | 3000 | | 200 |

[1] $CaMg(CO_3)_2$ (55% Ca $CO_3$ and 40% Mg $CO_3$) of particle size < 100 µm.
[2] 31% of $P_2O_5$ in powder.
[3] 50% of $K_2O$ in powder.
[a] F2 and F2’ were combined for the statistical analyses.

### 2.4. Foliar sampling and analyses

The tree leaves were sampled by shooting in the upper third of the crowns one and three years after treatment application. They were collected from the same 4 or 8 dominant and permanently marked beech– or spruce-trees per plot, respectively. The leaves were sampled during the second part of August for beech, and in winter for spruce; for the latter species, 1- and 2-year old needles were separated. One composite sample per plot and per needle age (spruce) was analysed.

Analyses were made according to the harmonised procedures of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forest [13]. Each composite sample was oven-dried at 65 °C during three days and ground to pass a 0.2 mm sieve prior to analysis. For the digestion, we used the dry-ashing procedure at 450 °C during 4 hours. Digests were made soluble in HCl solution. Element concentrations were determined by inductively-coupled plasma emission spectrometry for Ca, Mg, K, P, Al, B, Cu, Fe, Na, and Zn. Total N was determined by the Kjeldahl procedure.

### 2.5. Statistical analyses

Differences between treatments and stands for a given species and sampling date were tested with a two-way ANOVA, including the interaction term. We then performed Dunnett's two-tailed *t* tests on least square means, to test for any difference between treatments and the control for all main effects. We used the SAS statistical package for all calculations (GLM procedure with LSMEANS statement) [31].

## 3. RESULTS AND DISCUSSION

### 3.1. Soils

Dolomite lime, either alone (F1) or combined with others products (F2), had a rapid effect on the exchangeable Ca-Mg content of the topsoil layer (0–10 cm) (*table V*). The mean concentrations of both elements were significantly higher in the F1 and F2 treatments compared to the CONTROL already one year after fertilizer application (*table VI*). The difference in Ca and Mg

**Table V.** Values of $p$ (F > F obs) from Anova 2 calculated on the soil data.

| Soil layer | Species | Year | Effect[1] | Df [2] | Ca | Mg | K | Al | H | P | pH $H_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0–10 cm | Spruce | 1995 | T | 2 | < 0.001[b] | < 0.001[b] | < 0.001[b] | ND | ND | 0.453 | 0.141 |
| | | | S | 4 | 0.003[b] | 0.002[b] | 0.015[a] | ND | ND | 0.994 | < 0.001[b] |
| | | | T × S | 8 | 0.156 | 0.012[a] | 0.061 | ND | ND | 0.227 | 0.192 |
| | | 1997 | T | 2 | < 0.001[b] | < 0.001[b] | 0.009[b] | 0.002 [b] | 0.066 | 0.126 | < 0.001[b] |
| | | | S | 4 | 0.002[b] | 0.029[a] | 0.685 | < 0.001[b] | < 0.001[b] | < 0.004[b] | < 0.001[b] |
| | | | T × S | 8 | 0.202 | 0.181 | 0.766 | 0.428 | 0.146 | 0.490 | 0.093 |
| | Beech | 1995 | T | 2 | 0.005[b] | < 0.001[b] | 0.117 | ND | ND | 0.998 | 0.055 |
| | | | S | 4 | < 0.001[b] | < 0.001[b] | 0.007[b] | ND | ND | < 0.001[b] | 0.148 |
| | | | T × S | 8 | 0.105 | 0.001[b] | 0.090 | ND | ND | 0.019[a] | 0.463 |
| | | 1997 | T | 2 | < 0.001[b] | < 0.001[b] | 0.019[a] | < 0.001[b] | < 0.001[b] | 0.541 | < 0.001[b] |
| | | | S | 4 | 0.012[a] | 0.076 | < 0.001[b] | < 0.001[b] | 0.880 | < 0.001[b] | 0.071 |
| | | | T × S | 8 | 0.167 | 0.169 | 0.904 | 0.022[a] | 0.133 | 0.417 | 0.118 |
| 10–20 cm | Spruce | 1995 | T | 2 | 0.184 | 0.001[b] | 0.017[a] | ND | ND | 0.706 | 0.678 |
| | | | S | 4 | 0.001[b] | 0.001[b] | 0.129 | ND | ND | 0.592 | 0.007[b] |
| | | | T × S | 8 | 0.142 | 0.004[b] | 0.093 | ND | ND | 0.316 | 0.068 |
| | | 1997 | T | 2 | < 0.001[b] | < 0.001[b] | 0.001[b] | 0.502 | 0.339 | 0.016[a] | < 0.001[b] |
| | | | S | 4 | 0.006 [b] | < 0.001[b] | 0.012[a] | < 0.001[b] | 0.031[a] | 0.013[a] | < 0.001[b] |
| | | | T × S | 8 | 0.111 | 0.039[a] | 0.126 | 0.407 | 0.470 | 0.077 | 0.052 |
| | Beech | 1995 | T | 2 | 0.899 | 0.716 | 0.054 | ND | ND | 0.769 | 0.436 |
| | | | S | 4 | 0.188 | 0.573 | 0.283 | ND | ND | < 0.001[b] | 0.393 |
| | | | T × S | 8 | 0.633 | 0.622 | 0.803 | ND | ND | 0.006 | 0.120 |
| | | 1997 | T | 2 | 0.199 | 0.108 | 0.474 | 0.201 | 0.548 | 0.474 | 0.155 |
| | | | S | 4 | 0.121 | 0.475 | < 0.001[b] | 0.400 | 0.367 | < 0.001[b] | 0.521 |
| | | | T × S | 8 | 0.355 | 0.249 | 0.731 | 0.135 | 0.481 | 0.256 | 0.199 |

[1] T = TREATMENT; S = STAND; T × S = TREATMENT × STAND interaction.
[2] Df: degree of freedom.
[a] $0.01 < p \leq 0.05$; [b] $p \leq 0.01$
ND = no data.

**Table VI.** Means and coefficient of variation (CV%) of the soil chemical properties by soil layer, species, year and treatment. (Ca, Mg, K, Al, H in cmol+/kg; P in mg/kg).

| Layer | Species | Year | Treatment | Ca | CV | Mg | CV | K | CV | Al | CV | H | CV | P | CV | pH $H_2O$ | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0–10 cm | Spruce | 1995 | Control | 0.19 | 22 | 0.13 | 17 | 0.10 | 8 | ND | ND | ND | ND | 715.1 | 5 | 4.35 | 1 |
| | | | F1 | 0.41 * | 10 | 0.32* | 7 | 0.09 | 9 | ND | ND | ND | ND | 747.0 | 5 | 4.38 | 1 |
| | | | F2 | 0.42 * | 10 | 0.35* | 7 | 0.15 * | 6 | ND | ND | ND | ND | 776.6 | 5 | 4.42 | 1 |
| | | 1997 | Control | 0.21 | 65 | 0.16 | 62 | 0.11 | 6 | 5.75 | 3 | 1.09 | 4 | 786.9 | 5 | 4.17 | 1 |
| | | | F1 | 1.08 * | 13 | 0.92* | 11 | 0.11 | 6 | 5.40. | 4 | 0.99 | 5 | 818.9 | 5 | 4.45 * | 1 |
| | | | F2 | 1.40 * | 11 | 1.14* | 9 | 0.13 | 5 | 4.71 * | 4 | 0.92 * | 6 | 901.2 | 5 | 4.53 * | 1 |
| | Beech | 1995 | Control | 0.29 | 25 | 0.15 | 23 | 0.1 | 8 | ND | ND | ND | ND | 616.5 | 3 | 4.32 | 1 |
| | | | F1 | 0.64 * | 11 | 0.37* | 9 | 0.12 | 8 | ND | ND | ND | ND | 614.7 | 3 | 4.46 | 1 |
| | | | F2 | 0.55 * | 14 | 0.40* | 9 | 0.14 | 7 | ND | ND | ND | ND | 615.4 | 3 | 4.39 | 1 |
| | | 1997 | Control | 0.44 | 42 | 0.25 | 55 | 0.15 | 5 | 5.89 | 3 | 1.47 | 6 | 808.8 | 3 | 4.05 | 1 |
| | | | F1 | 1.50 * | 12 | 1.06* | 13 | 0.12 * | 7 | 4.64 * | 4 | 0.85 * | 10 | 794.0 | 3 | 4.46 * | 1 |
| | | | F2 | 1.59 * | 12 | 1.19* | 12 | 0.13 * | 7 | 4.68 * | 4 | 1.06 * | 9 | 836.0 | 3 | 4.37 * | 1 |
| 10–20 cm | Spruce | 1995 | Control | 0.12 | 17 | 0.07 | 17 | 0.06 | 10 | ND | ND | ND | ND | 698.4 | 5 | 4.51 | 0 |
| | | | F1 | 0.16 | 13 | 0.13 * | 9 | 0.06 | 10 | ND | ND | ND | ND | 709.7 | 5 | 4.54 | 0 |
| | | | F2 | 0.17 | 13 | 0.13 * | 10 | 0.08 * | 7 | ND | ND | ND | ND | 739.1 | 5 | 4.53 | 1 |
| | | 1997 | Control | 0.08 | 28 | 0.06 | 24 | 0.05 | 6 | 3.72 | 4 | 0.54 | 9 | 761.5 | 8 | 4.42 | 0 |
| | | | F1 | 0.20 * | 11 | 0.20 * | 8 | 0.05 | 6 | 3.79 | 4 | 0.48 | 10 | 776.6 | 8 | 4.52 * | 0 |
| | | | F2 | 0.22 * | 11 | 0.21 * | 8 | 0.07 | 5 | 3.56 | 4 | 0.44 | 11 | 1015.0 | 7 | 4.55 * | 0 |
| | Beech | 1995 | Control | 0.26 | 31 | 0.11 | 22 | 0.07 | 11 | ND | ND | ND | ND | 562.3 | 3 | 4.55 | 1 |
| | | | F1 | 0.21 | 38 | 0.13 | 19 | 0.07 | 11 | ND | ND | ND | ND | 578.6 | 3 | 4.60 | 1 |
| | | | F2 | 0.22 | 39 | 0.14 | 18 | 0.10 | 9 | ND | ND | ND | ND | 567.0 | 3 | 4.54 | 1 |
| | | 1997 | Control | 0.14 | 67 | 0.10 | 53 | 0.06 | 8 | 4.55 | 5 | 0.48 | 50 | 722.5 | 3 | 4.44 | 1 |
| | | | F1 | 0.26 | 36 | 0.19 | 29 | 0.05 | 10 | 4.15 | 6 | 0.83 | 29 | 712.4 | 3 | 4.55 | 1 |
| | | | F2 | 0.39 | 25 | 0.28 | 21 | 0.06 | 10 | 3.95 | 6 | 0.54 | 44 | 750.5 | 3 | 4.54 | 1 |

* Significant difference compared to the control (Dunnett's test, α level = 5%).
ND = no data.

concentrations between fertilized and control plots further increased in 1997: mean Ca-Mg concentrations were 3 to 7 times higher in the F1 and F2 treatments than in the CONTROL (*table VI*). Considering mean concentrations, there was no evidence for differences between the migration of Ca and Mg at this depth.

These results are consistent with those of Dulière et al. (1999) who reported a 3 to 9 fold increase in Ca and Mg concentrations in the 0–10 cm soil layer 6 months after a 5 t $ha^{-1}$ dolomite application, compared to the control. An important part of Ca and Mg is however likely to remain within the holorganic horizons [28, 30]. At a larger time scale, liming has been reported to have a positive effect on humus mineralization, with increased cation mobilization and migration down to the mineral layers [16].

At larger depth, dolomite lime influenced exchangeable Ca and Mg of the 10–20 cm layer more quickly under spruce than under beech. In 1997 for example, the TREATMENT effect was significant for both elements for spruce, but not for beech (*table V*). Closer examination of the data, however, showed comparable Ca and Mg increase for both species (*table VI*). This apparent difference in TREATMENT effects was therefore probably due to the greater variability of exchangeable cation contents in the beech compared to the spruce stands, as illustrated by the respective coefficients of variation.

In the surface layer, dolomite had a negative effect on exchangeable K concentration in the soil of the beech stands as indicated by the small but significant decrease in mean K concentrations in the F1 treatment in 1997 (*table VI*). The addition of potassium sulphate (F2 treatment) was apparently not sufficient to maintain K concentrations at levels similar to those of the control (*table VI*, 1997). Such decrease probably resulted from the displacement of resident K by Ca [2, 30]. By contrast, dolomite did not decrease exchangeable K contents at the 0–10 cm level in the spruce stands, whatever the period (*tables V* and *VI*). Furthermore, the addition of potassium sulphate significantly increased the K concentrations of this layer in 1995 *(table VI*). In the 10–20 cm layer, the TREATMENT effect on soil K concentrations was limited to the spruce stands (*table V*). More detailed studies would be necessary to understand the difference of soil response between beech and spruce stands.

For all species and soil depths, P concentrations did not show any significant change following the application of natural phosphate (*tables V* and *VI*, F2 treatments). Two main reasons could account for this observation: phosphorous retention in the organic layer and/or change in phosphorous concentrations insufficient to be detected by the extraction method used in this study.

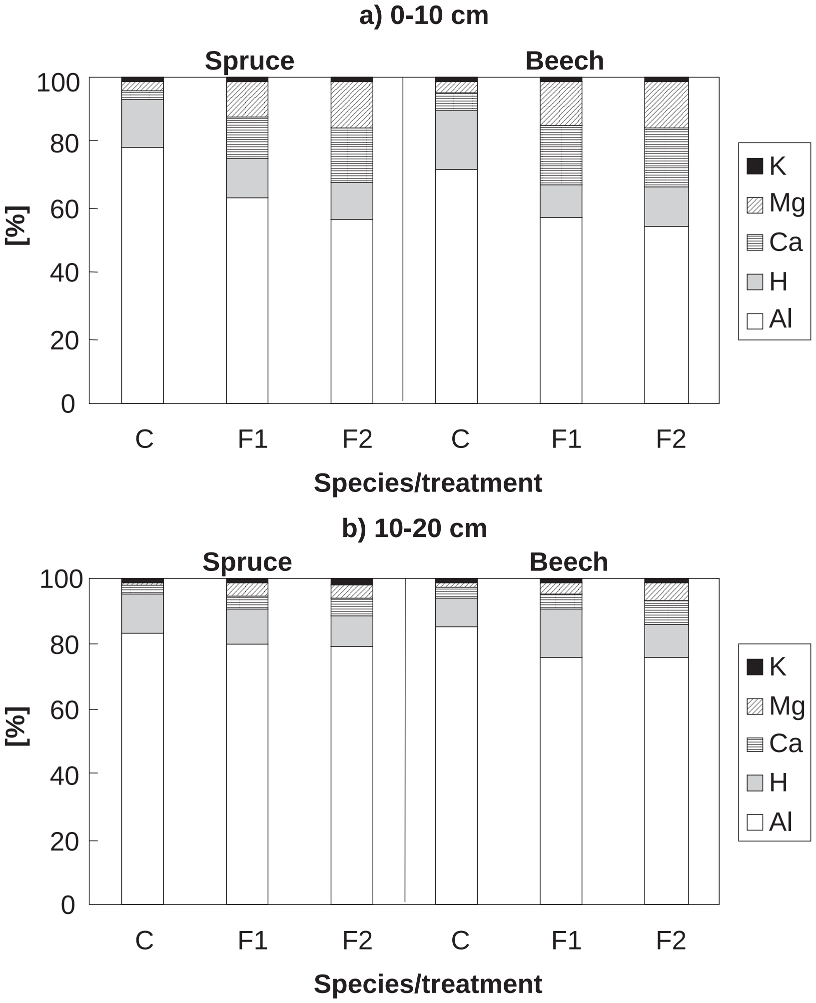

**Figure 1 (a,b)**. Mean proportions of cations on the exchangeable complex (exch. cations/ECEC and ECEC = ∑ Ca, Mg, K, Al, H) in the 0–10 and 10–20 cm soil layers of each treatment (1997). (C: CONTROL; F1: Dolomite Lime; F2: Dolomite Lime + Natural Phosphate + Potassium Sulphate).

Three years after fertilizer application, the TREATMENT effect was significant in the 0–10 cm layer for pH, Al (spruce, beech) and H (beech) (*table V*). In the F1 and F2 treatments (0–10 cm), the increase of exchangeable (Ca+Mg) following dolomite application was balanced by the decrease of exchangeable (Al+H) in the beech stands, whereas it was associated with a limited ECEC increase (≅ 1 cmol + $kg^{-1}$) in the spruce stands. Depending on factors such as the organic carbon content of the soil and the amount of applied alkalinity, exchangeable Al and H in the mineral soil may be neutralised without important change of the dissociated charge [19, 23, 30].

At deeper soil layers, there was no significant TREATMENT effect for Al or H, for any species (*table V*). The rise in pH following fertilization was limited to the spruce stands in 1997, and mean pH in the F1 and F2 treatments differed from the control by only one tenth of pH unit (*tables V* and *VI*).

Despite the decrease of exchangeable Al following base cation fertilization, Al still remained largely dominant on the ECEC of both layers. For instance, exchangeable Al still accounted for 57% (spruce) and 54% (beech) of the ECEC in the 0–10 cm layer of the F2-treated plots (*figure 1a*). The proportion of Al was still higher in the 10–20 cm soil layer, being around 80% and 75% for the spruce and beech stands, respectively (*figure 1b*).

The overall limited downward migration of base cations and alkalinity through the soil profiles in the short term can be attributed to the kinetics of dissolution of the amendments and to the formation of exchangeable sites in the holorganic horizons, as shown by different studies [23, 29, 30]. At longer time scale, however, the rate of humus mineralization would probably increase in the fertilized plots and this re-acidification would favour the supply of cations to deeper mineral horizons [16].

From *figure 1a* it can be seen that the proportional decrease of the acid cations (Al+H) was more important when complete base cation fertilization (F2) was applied instead of dolomite alone (F1), despite comparable Ca and Mg application. This can be explained by the migration of part of Ca and Mg ions with the mobile $SO_4^{2-}$ anions originating from the potassium sulphate fertilizer [28, 29]. On the other hand, several authors observed considerable changes in the decomposers population after P and/or K fertilization [7, 32]. This phenomenon could also contribute to the increased release of Ca and Mg cations [38].

A significant STAND effect was detected for most soil variables, for spruce as well as for beech (0–10 cm) (*table V*). The factors acting locally, such as local climate or stand history, all have a potential influence on the soil chemical properties of the stands. Nevertheless, the limited number of TREATMENT × STAND interactions indicates that in most cases the different stands reacted similarly to fertilization, showing comparable trends (*tables V* and *VI*). Thus, even if the ecoclimatic conditions as well as the initial soil chemical properties were heterogeneous between stands, the forcing effects of the treatments were strong enough to account for the similarities of response.

### 3.2. Trees

The response of trees to fertilization was particularly rapid for Ca whatever the species since the TREATMENT effect was already significant during the vegetation period just following fertilization (1995) (*table VII*). For Mg, the difference between treatments was not significant until 1997 (*table VII*). In addition, the increase of foliar Ca after fertilization was proportionally more important than that of Mg (*table VIII*, 1997 data), despite comparable soil evolution (*table VI*).

In some cases, the mean foliar concentrations of Ca and/or Mg exceeded the deficiency threshold following application of the fertilizers. In the beech stands for example, Ca concentrations reached 0.43% (CONTROL), 0.55% (F1) and 0.52% (F2) in 1995, the last two values being higher than the deficiency threshold (0.50%) (*tables III* and *VIII*). Nevertheless, inter-annual variability of foliar concentrations was important, as also shown in other studies [18]. It is interesting to see that for both elements mean foliar concentrations were relatively similar between treatments, whatever the species (*table VIII*).

Addition of dolomite alone tended to decrease slightly (Dunnett's test not significant) the mean K foliar concentrations in the beech stands, compared to the control. This could be due to an increased Ca-K absorption antagonism at the plant level resulting from the relative increase of exchangeable Ca in the soil. This suggests a risk of induced-K deficiency following liming in case of low initial K concentrations in the soil [2, 4, 10, 33]. The simultaneous application of potassium sulphate with dolomite (F2 treatment) tended to raise the K foliar concentrations for both species, in comparison to the CONTROL (*table VIII*). The Dunnett's test was however only significant in the spruce stands (*table VIII*).

Even if the P concentration at the soil level was not significantly improved by natural phosphate addition (F2 treatment), the foliar concentration increased

**Table VII.** Values of *p* (F > F obs) from Anova 2 calculated on foliar analysis data.

| Species | Year | Age of needles | Effect[1] | Df[2] | Ca | Mg | K | P | Al | B | Cu | Fe | Na | Zn | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spruce | 1995 | 1 | T | 2 | 0.030[a] | 0.739 | 0.026[a] | 0.089 | 0.841 | 0.642 | ND | 0.237 | ND | 0.008[b] | 0.136 |
| | | | S | 4 | 0.001[b] | 0.001[b] | 0.002[b] | 0.059 | 0.001[b] | 0.001[b] | ND | 0.003[b] | ND | 0.001[b] | 0.681 |
| | | | T × S | 8 | 0.841 | 0.205 | 0.578 | 0.567 | 0.955 | 0.641 | ND | 0.101 | ND | 0.609 | 0.288 |
| | | 2 | T | 2 | 0.107 | 0.771 | 0.004[b] | 0.001[b] | 0.432 | 0.686 | ND | 0.887 | ND | 0.002[b] | ND |
| | | | S | 4 | 0.001[b] | 0.001[b] | 0.019[a] | 0.001[b] | 0.001[b] | 0.014[b] | ND | 0.023[a] | ND | 0.001[b] | ND |
| | | | T × S | 8 | 0.800 | 0.147 | 0.188 | 0.060 | 0.785 | 0.862 | ND | 0.865 | ND | 0.755 | ND |
| | 1997 | 1 | T | 2 | 0.001[b] | 0.001[b] | 0.002[b] | 0.001[b] | 0.002[b] | 0.001[b] | 0.036[a] | 0.286 | 0.002 [b] | 0.001[b] | 0.856 |
| | | | S | 4 | 0.003[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] | 0.001[b] |
| | | | T × S | 8 | 0.252 | 0.964 | 0.003[b] | 0.153 | 0.063 | 0.674 | 0.153 | 0.920 | 0.399 | 0.775 | 0.180 |
| | | 2 | T | 2 | 0.001[b] | 0.001[b] | 0.169 | 0.001[b] | 0.001[b] | 0.001[b] | 0.061 | 0.032[a] | 0.045[a] | 0.001[b] | 0.795 |
| | | | S | 4 | 0.201 | 0.001[b] | 0.257 | 0.004[b] | 0.001[b] | 0.001[b] | 0.002[b] | 0.001[b] | 0.001[b] | 0.005[b] | 0.001[b] |
| | | | T × S | 8 | 0.863 | 0.344 | 0.062 | 0.136 | 0.087 | 0.725 | 0.973 | 0.008[b] | 0.246 | 0.366 | 0.332 |
| Beech | 1995 | | T | 2 | 0.004[b] | 0.327 | 0.048[a] | 0.067 | 0.131 | 0.001[b] | 0.002[b] | 0.206 | 0.021[a] | 0.089 | 0.207 |
| | | | S | 4 | 0.001[b] | 0.001[b] | 0.001[b] | 0.008[b] | 0.001[b] | 0.001[b] | 0.007[b] | 0.071 | 0.001[b] | 0.521 | 0.003[b] |
| | | | T × S | 8 | 0.350 | 0.431 | 0.347 | 0.556 | 0.420 | 0.252 | 0.144 | 0.524 | 0.262 | 0.636 | 0.856 |
| | 1997 | | T | 2 | 0.001[b] | 0.009[b] | 0.464 | 0.037[a] | 0.129 | 0.001[b] | 0.981 | 0.311 | 0.733 | 0.001[b] | 0.240 |
| | | | S | 4 | 0.017[a] | 0.001[b] | 0.001[b] | 0.082 | 0.163 | 0.002[b] | 0.755 | 0.021[a] | 0.001[b] | 0.445 | 0.001[b] |
| | | | T × S | 8 | 0.021[a] | 0.127 | 0.243 | 0.422 | 0.876 | 0.341 | 0.230 | 0.790 | 0.451 | 0.648 | 0.632 |

[1] T = TREATMENT; S = STAND; T × S = TREATMENT × STAND interaction.
[2] Df: degree of freedom.
[a] $0.01 < p \leq 0.05$.
[b] $p \leq 0.01$.
ND = no data.

significantly in 1997 for both species (*table VIII*). This increase was however very limited, as the maximum difference between the CONTROL and the F2 treatment was 0.02% (spruce 1997, 2-year old needles) (*table VIII*).

An important decrease of mean Al foliar content was noticed 3 years after base cation fertilization, but it was only significant for spruce (both age classes of needles) (*table VIII*), probably because of a lower variability of Al concentrations for this species compared to beech (compare the 1997 coefficients of variation).

Foliar concentrations of B and Zn showed a distinct significant pattern. We noticed an important decrease of the B concentration 2 years after fertilization, this decrease tending to be higher in the F2-treated plots compared to the F1-treated plots (*table IX*). For the beech stands, the decrease was already significant in 1995 and remained significant in 1997 (*tables VII* and *IX*). As postulated by Gupta et al. (1985) and Kreutzer (1995), this phenomenon probably results from the formation of organic complexes, promoting the insolubilisation of B and low availability for plant uptake.

On the opposite, fertilization activated Zn uptake for spruce and beech. In the spruce stands, the TREATMENT effect was already significant in 1995 for both years of needles (*table VII*). In addition, mean Zn concentrations were higher for the F2- than for the F1-treatments (*table IX*). The great inter-annual variability of Zn foliar concentrations must however be noticed. In the CONTROL treatment of the beech stands for instance, values reported for 1997 were about half those of 1995. These differences could be due to various factors such as climate or sampling variability. Contradictory results are found in the literature concerning the effects of

**Table VIII.** Means (% of dry matter) and coefficient of variation (CV%) of the nutrient foliar concentrations by species, year and treatment.

| Species | Year | Age of needles | Treatment | Ca | CV | Mg | CV | K | CV | P | CV | Al | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spruce | 1995 | 1 | Control | 0.20 | 9 | 0.08. | 4 | 0.56 | 5 | 0.14 | 3 | 68.01 | 6 |
| | | | F1 | 0.26 | 7 | 0.09. | 4 | 0.55 | 5 | 0.14 | 3 | 65.13 | 6 |
| | | | F2 | 0.27 | 7 | 0.08. | 4 | 0.65 * | 4 | 0.15 | 3 | 67.94 | 6 |
| | | 2 | Control | 0.21 | 8 | 0.06. | 4 | 0.49 | 5 | 0.12 | 2 | 103.71 | 4 |
| | | | F1 | 0.26 | 6 | 0.06. | 4 | 0.50 | 5 | 0.12 | 2 | 101.11 | 5 |
| | | | F2 | 0.25 | 7 | 0.06. | 4 | 0.60 * | 4 | 0.14 * | 2 | 109.64 | 4 |
| | 1997 | 1 | Control | 0.17 | 4 | 0.08. | 4 | 0.48 | 3 | 0.16 | 2 | 52.31 | 3 |
| | | | F1 | 0.29 * | 3 | 0.10 * | 3 | 0.45 | 3 | 0.15 | 2 | 43.76 * | 4 |
| | | | F2 | 0.28 * | 3 | 0.09 * | 4 | 0.53 * | 3 | 0.17 * | 2 | 46.27 * | 4 |
| | | 2 | Control | 0.18 | 7 | 0.05. | 6 | 0.40 | 4 | 0.13 | 2 | 79.13 | 3 |
| | | | F1 | 0.32 * | 4 | 0.08 * | 4 | 0.39 | 4 | 0.14 | 2 | 61.28 * | 4 |
| | | | F2 | 0.30 * | 4 | 0.06 * | 5 | 0.43 | 4 | 0.15 * | 2 | 65.97 * | 4 |
| Beech | 1995 | | Control | 0.43 | 6 | 0.05. | 8 | 0.64 | 3 | 0.12 | 3 | 45.45 | 3 |
| | | | F1 | 0.55 * | 4 | 0.06. | 7 | 0.59 | 4 | 0.12 | 3 | 42.80 | 4 |
| | | | F2 | 0.52 * | 5 | 0.06. | 8 | 0.67 | 3 | 0.13 | 3 | 40.92 | 4 |
| | 1997 | | Control | 0.30. | 5 | 0.07 | 8 | 0.54. | 6 | 0.13 | 3 | 38.31 | 9 |
| | | | F1 | 0.50 * | 3 | 0.09 * | 6 | 0.50 | 7 | 0.13 | 3 | 31.66 | 11 |
| | | | F2 | 0.47 * | 3 | 0.09 * | 7 | 0.56 | 6 | 0.14 * | 3 | 28.43 | 12 |

* Significant difference compared to the control (Dunnett's test, $\alpha$ level = 5%).

base cation fertilization on Zn foliar concentrations. Several authors report that Zn is less soluble in the soil and thus less available for the plant in case of pH increase [6]. According to Fiedler (1988), pH should not exceed 5.0–5.5 otherwise Zn availability would decrease considerably. On the other hand, data from studies on acid soils show an increase of Zn foliar concentration following lime application [12, 33]. Synthetising these results, it seems that a moderate pH increase after base cation fertilization on acid soils is likely to produce an increase of Zn plant uptake. Bakker (1999) showed that the uptake of different micronutrients could be improved after fertilization by positive effect on mycorrhizae. With further increase in pH, however, insolubilisation of soil Zn could cause a decrease in Zn availability.

As for the soil, the analyses of variance showed a significant STAND effect for most of the foliar chemical properties. On the other hand, the TREATMENT × STAND interaction was rarely significant (*table VII*). The effects of the treatments were strong enough to account for the similarities of response between stands, despite possible initial differences in stand and/or site conditions.

## 4. CONCLUSIONS

This study demonstrated that base cation fertilization may be an efficient tool to restore the soil and foliar chemical status of stands situated on acid and nutrient poor soils. Application of 3 t ha$^{-1}$ of dolomite lime quickly corrected nutritional imbalances, which are known to be important contributing factors to forest dieback.

Preliminary soil and foliage analyses are necessary to select the appropriate treatments. For instance, it was shown that dolomite application alone tended to reduce K concentrations in the soils and the leaves of the beech stands. In case of low initial K concentrations, this could lead to induced deficiencies. Addition of even a low quantity of potassium sulphate (maximum 250 kg ha$^{-1}$)

**Table IX.** Means (mg kg$^{-1}$ of dry matter) and coefficient of variation (CV%) of the nutrient foliar concentration by species, year and treatment.

| Species | Year | Age of Needles | Treat-ment | B | CV | Cu | CV | Fe | CV | Na | CV | Zn | CV | N | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spruce | 1995 | 1 | Control | 28.61 | 5 | ND | ND | 31.28 | 4 | ND | ND | 17.13 | 8 | 1.63 | 1 |
| | | | F1 | 27.07 | 5 | ND | ND | 28.99 | 4 | ND | ND | 19.76 | 7 | 1.68 | 1 |
| | | | F2 | 26.98 | 5 | ND | ND | 28.30 | 5 | ND | ND | 24.13 * | 6 | 1.66 | 1 |
| | | 2 | Control | 23.22 | 5 | ND | ND | 33.64 | 5 | ND | ND | 10.96. | 8 | ND | ND |
| | | | F1 | 22.77 | 5 | ND | ND | 34.87 | 5 | ND | ND | 12.87 | 7 | ND | ND |
| | | | F2 | 21.76 | 6 | ND | ND | 34.36 | 6 | ND | ND | 15.88 * | 6 | ND | ND |
| | 1997 | 1 | Control | 18.15 | 2 | 3.30 | 4 | 26.18 | 3 | 144.08 | 6 | 9.62 | 5 | 1.48 | 1 |
| | | | F1 | 15.81 * | 3 | 3.15 | 4 | 27.16 | 3 | 154.54 | 6 | 15.59 * | 3 | 1.47 | 1 |
| | | | F2 | 14.73 * | 3 | 3.63 | 4 | 28.04 | 3 | 194.13 * | 5 | 16.48 * | 3 | 1.49 | 1 |
| | | 2 | Control | 15.48 | 3 | 2.70 | 6 | 31.77 | 2 | 150.33 | 5 | 7.17 | 9 | 1.47 | 1 |
| | | | F1 | 12.51 * | 4 | 2.19 * | 7 | 29.60 * | 2 | 147.16 | 5 | 12.51 * | 5 | 1.47 | 1 |
| | | | F2 | 11.83 * | 4 | 2.62 | 6 | 31.92 | 2 | 174.01 | 5 | 14.15 * | 5 | 1.45 | 1 |
| Beech | 1995 | | Control | 29.80 | 3 | 4.78 | 7 | 83.59 | 4 | 167.50 | 7 | 18.36 | 7 | 2.17 | 1 |
| | | | F1 | 24.74 * | 3 | 3.38 * | 10 | 76.55 | 4 | 143.49 | 8 | 20.37 | 7 | 2.16 | 1 |
| | | | F2 | 23.07 * | 4 | 2.86 * | 13 | 75.90 | 5 | 118.35 * | 10 | 22.94 | 6 | 2.23 | 1 |
| | 1997 | | Control | 19.48 | 3 | 5.59 | 14 | 47.51 | 6 | 116.95 | 5 | 10.89 | 5 | 2.22 | 2 |
| | | | F1 | 16.50 * | 4 | 5.73 | 14 | 47.33 | 6 | 111.75 | 5 | 14.73 * | 4 | 2.15 | 2 |
| | | | F2 | 15.77 * | 4 | 5.82 | 14 | 42.03 | 7 | 118.17 | 5 | 16.27 * | 4 | 2.14 | 2 |

* Significant difference compared to the control (Dunnett's test, α level = 5%).
ND = no data.

to dolomite proved to be a tool to avoid this problem. On the other hand, the addition of natural phosphate (maximum 800 kg ha$^{-1}$) did not result in any systematic increase in soil and foliar P concentrations.

For a given species, variations in site and/or ecoclimatic conditions only had a minor influence on the effects of base cation fertilization. This allows us to generalise the results of this study at the regional scale of the Belgian Ardenne for adult Norway spruce and European beech forests situated on acid brown soils.

Differences between species are to be taken into account when planning fertilizer treatment. Our study showed that migration of Ca-Mg ions through the soil profile after dolomite application was more rapid for the spruce than for the beech stands. On the other hand, dolomite tended to reduce soil and leave K concentration only in the beech stands. Better understanding of the contrasting pattern observed between the two species would need more detailed studies. In addition, it should be important to assess the response of stands to base cation fertilization on larger time scale before concluding unequivocally about these results.

Another important issue of this study concerns the indirect effect of base cation fertilization on micronutrient nutrition. Particularly, it has been shown that the Zn foliar content increased and that the B foliar concentration decreased following application of the treatments. Risks of induced Zn toxicity and induced B deficiency should be investigated.

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