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Journal

Annals of Forest Science, 58

Author

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Publication Date

2001

Peer reviewed

Ann. For. Sci. 58 (2001) 829–842

Original article

Effects of fertilization on the vascular ground vegetation of European beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Lieb.) stands

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(Received 12 February 2001; accepted 9 August 2001)

Abstract – The objective of this study was to assess the effects of base cation (Ca, Mg, K) and phosphorous (P) fertilization on the vascular ground vegetation in mature European beech and sessile oak stands located on acid brown soils. Two types of treatment were applied next to control plots (dolomite lime, dolomite lime + natural phosphate + potassium sulphate). Specific richness, total cover (%), equitability coefficient as well as the Ecological Group of the ground vegetation were studied. Four years after dolomite application, new N-demanding and ruderal species appeared and increased the specific richness. The natural phosphate application combined with potassium sulphate positively influenced the emergence of new mesotrophic plant species. In the beech stands the total cover tended to increase while in the oak stand the equitability coefficient decreased. The specific richness of the initial acidophilous vegetation remained unchanged but the total cover decreased. Differences between the response of the ground vegetation in the oak and the beech stands were attributed to a difference in stand density.

base cation / phosphorous / acid brown soil / plant diversity / ecological group

Résumé – Effets de la fertilisation sur les plantes vasculaires du sous-bois dans des peuplements de hêtre (*Fagus sylvatica* L.) et de chêne sessile (*Quercus petraea* (Matt.) Lieb.). L'objectif de cette étude est d'évaluer les effets d'une fertilisation en cations basiques (Ca, Mg, K) et P sur les plantes vasculaires du sous-bois dans des peuplements adultes de hêtre et de chêne sessile situés sur des sols bruns acides. Deux types de traitement ont été appliqués et comparés à un témoin (dolomie, dolomie + phosphate naturel + sulfate de potassium). La richesse spécifique, le recouvrement total, le coefficient d'équitabilité ainsi que les groupes écologiques de la végétation au sol ont été étudiés. Quatre ans après l'application de dolomie, de nouvelles espèces nitrophiles et rudérales apparaissent, augmentant ainsi la richesse spécifique. Le phosphate naturel combiné au sulfate de potassium influence positivement l'émergence de nouvelles espèces mésophiles. Dans les peuplements de hêtre, le recouvrement total tend à s'accroître et dans le peuplement de chêne le coefficient d'équitabilité diminue. La richesse spécifique de la végétation initiale acidophile reste inchangée mais le recouvrement total diminue. Des différences entre la réponse de la végétation au sol dans les peuplements de chêne et de hêtre ont été mises en évidence et ont été attribuées à la différence de densité de peuplement.

cation basique / phosphore / sol brun acide / diversité floristique / groupe écologique

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1. INTRODUCTION

Since the 1970s, forest decline is a matter of concern in different parts of Europe and North America. Many biotic and abiotic stress factors seem to influence forest dieback [21]. In particular, nutritional imbalances have been pointed to as a predisposing factor in certain regions [16, 20, 47]. For example, it has been demonstrated that Mg deficiency positively influences the yellowing and the crown defoliation of Norway spruce [14, 46].

In this context, base cation fertilization is thought to be an efficient tool against forest degradation [1, 17, 32, 34]. Many studies have been conducted to assess the effects of fertilization or liming on different parts of the forest ecosystem. In this context, information is available about the concentration of nutrients in the soil and the leaves, the crown condition and the tree growth [3, 4, 15, 23, 28, 41]. Some authors studied the effect of fertilization on the stocks of elements in different parts of the ecosystem, sometimes taking into account fluxes such as throughfall and/or soil solution [17, 24, 30, 31, 38].

The response of the ground vegetation has received less attention [5, 6, 25, 35, 36] though, in some cases, the ground flora contributes more to the annual nutrients cycling than the old trees [10, 36]. Furthermore, if liming tends to be generalised, questions arise about the impact of this practice on the floristic composition, structure and diversity of plant communities [13]. Great concerns about such impacts arise in regions like the Belgian Ardenne, where studies show that some important nutrients (Ca, Mg, P) are at low concentration in 70% of the soils [19].

During the 1990s, diagnostic fertilization trials were installed in the Belgian Ardenne on acid and poor-nutrient soils [23]. The aims of the experiment were (i) to test on a regional scale base cation (Ca, Mg, K) and phosphorous (P) fertilization as a method to prevent forest dieback and/or restore forest health on adult stands, and (ii) to compare the response of different ecosystems. The experimental design was suited to investigating the treatments effect on the ground vegetation. The aim of this paper is to present the results concerning the response of the vascular plant community. This response is analysed from different points of view: species diversity, cover, equitability and Ecological Group. Another paper presents the general methodology of the study and the results of soil and foliar analysis [23].

2. MATERIALS AND METHODS

2.1. Stands description

The ground vegetation surveys were conducted in 5 even-aged stands of European beech (*Fagus sylvatica* L.) and 1 stand of sessile oak (*Quercus petraea* (Matt.) Lieb.) located in the Belgian Ardenne (*figure 1* and *table I*). According to the management plan, the trees were approximately 100 years old at the beginning of the experiment (1994). These stands were selected throughout the Belgian Ardenne according to several criteria [23]. First, they had to be located on acid and magnesium poor soils. This was tested by foliar and soils analyses before fertilizer application. Second, soil type (Belgian legend, IRSIA 1:20 000 soil map) and topography had to be homogeneous at stand level. Third, sampling should take into account the ecoclimatic diversity of the region: stands were chosen in various Ecological Sectors of the Belgian Ardenne as defined by Onclinkx et al. 1987 (*table II*).

The altitude ranges between 380 and 470 m (*table I*). The mean temperature varies between 6.5 and 7.9 °C and the annual precipitation between 1030 and 1200 mm (*table II*). The stands are on *Dystric Cambisol* [9] and the humus type is moder for the beech and acid mull for the oak. In 1994, the pH of the mineral soil (0–20 cm layer) was between 3.83 and 4.35 (*table I*). In the winter 1994–1995, the basal area was between 18.4 and 23.5 $m^2\ ha^{-1}$.

The study sites are situated in the medio-European phytogeographical domain. The natural association of the beech stands is *Luzulo-Fagetum* with sub-association

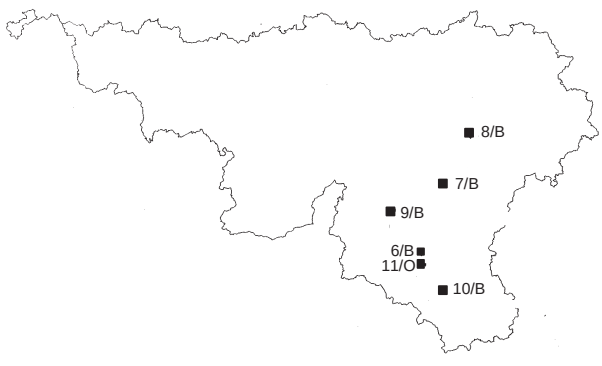

Figure 1. Location of the experimental stands in Southern Belgium (Beech: 6/B, 7/B, 8/B, 9/B, 10/B; Oak: 11/O).

Table I. Selected characteristics of the experimental stands (1994).

Stand code	Species	Altitude (m)	Soil pH[1] (0–20 cm)	*BA*[2] ($m^2 ha^{-1}$)	Phytosociological Associations[3]
6B	European beech	470	3.97	20.3	*LF – deschampsietosum*
7B	European beech	420	3.83	21.3	*LF – vaccinietosum*
8B	European beech	380	3.86	23.0	*LF – typicum*
9B	European beech	400	3.86	18.4	*LF – deschampsietosum*
10B	European beech	445	4.33	22.9	*LF – deschampsietosum*
11O	Sessile oak	400	4.35	18.8	*LQ – typicum*

[1]: Means of pH H_20 determined for 18 to 24 soils samples per stand;
[2]: *BA* = basal area (winter 1994-1995);
[3]: after [26]. LF = *Luzulo fagetum*, LQ = *Luzulo quercetum.*

Table II. Location of the experimental stands in the Ecological Sectors of the Belgian Ardenne and climatic characteristics.

Stand code	Ecological Sectors[1]	Mean Temperature (°C)	Annual Precipitation (mm)	Vegetation period (days)
6B	Ardenne occidentale	7.5	1150	142
7B	Ardenne occidentale	7.5	1150	142
8B	Ardenne centro-orientale	7.6	1030	152
9B	Ardenne atlantique	7.9	1080	150
10B	Ardenne méridionale	8.0	1150	153
11O	Ardenne méridionale	8.0	1150	153

[1]: after [27, 45].

typicum, *vaccinietosum* or *deschampsietosum* (*table I*) [26]. The oak stand belongs to the *Luzulo-Quercetum* (subass. *typicum*), which is an anthropic substitution of the former association [26].

2.2. Fertilization treatment

The methodology applied in the prescription of the fertilization treatments can be found in Misson et al. (2001). *Table III* presents the general characteristics of the products and doses applied during winter 1994–1995. The first treatment (F1) spread 3000 kg ha^{-1} of dolomitic limestone 55/40 with a particle size < 100 μm. The second treatment (F2) consisted of the standard dolomite application (F1) plus an addition of 0 to 800 kg ha^{-1} of natural phosphate as well as between 200 and 250 kg ha^{-1} of potassium sulphate. The amount of natural phosphate and potassium sulphate depends on the site susceptibility to specific induced deficiencies [23]. A control treatment (CONTROL) is characterised by the absence of fertilization.

In each stand, three replications per treatment were made. Each replicate was a square plot, which is 50 × 50 m for beech and 55 × 55 m for oak. Between the plots, a buffer zone of at least 25 m wide was kept without any treatment. A blowing engine towed by a Buurnett forwarder was used to spread the fertilizers, using a flow independent of the speed of the forwarder. To ensure the spatial homogeneity of fertilizer application [22], the spreading was carried out in two applications, from the opposite sides of each plot. It was done on days without wind, rainfall, snowfall or snow cover of the soil.

In 1994 and 1997, the soils were sampled and analysed. *Figure 2* shows the mean concentration of the soil exchangeable cations for each treatment in 1997. After fertilization, Ca and Mg concentrations in the 0–10 cm soil layer were higher in the treated plots than in the CONTROL plots. In parallel, Al and H concentrations tended to decrease. In the beech stands, the mean pH-H_2O varied from 4.05 (CONTROL) to 4.46 (F1) and 4.37 (F2). In the oak stand, the pH-H_2O varied from 3.94 (CONTROL) to 4.40 (F1) and 4.65 (F2).

Table III. Applied treatments and doses (kg ha^{-1}).

Stand Code	Treatment	Number of plots	Dolomite Lime[1]	Natural Phosphate[2]	Potassium Sulphate[3]
6B	CONTROL	3			
	F1	3	3000		
	F2	3	3000	400	200
7B	CONTROL	3			
	F1	3	3000		
	F2	3	3000	400	200
8B	CONTROL	3			
	F1	3	3000		
	F2	2	3000	800	
	F2' [4]	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
11O	CONTROL	3			
	F1	3	3000		
	F2	3	3000	400	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;
[4]: because of an error during fieldwork.

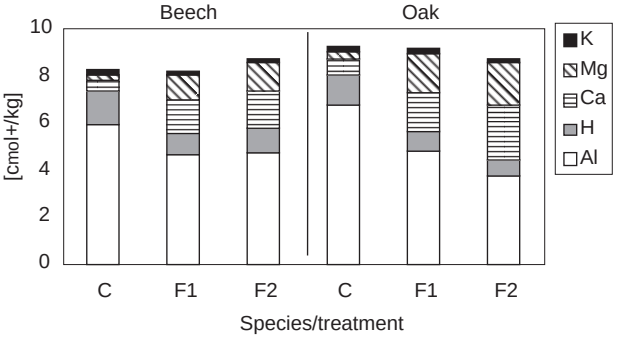

Figure 2. Mean concentration of exchangeable cations[1] in the 0–10 cm soil layer of each treatment[2] (1997) [23].
[1]: K, Mg, Ca = extraction with 0.1 M $BaCl_2$ agent, soil:solution ratio of 1:10 (m:v), measured by ICP; H, Al = extracted with 1 M KCl agent, soil:solution ratio of 1:2.5 (m:v), measured by titration with 0.1 M NaOH;
[2]: C: CONTROL; F1: Dolomite Lime; F2: Dolomite Lime + Natural Phosphate + Potassium Sulphate.

2.3. Vegetation survey and floristic indices

In each of the 54 plots, the vascular plants were recorded using the Braun-Blanquet method. The plants were classified in 3 vertical layers: canopy, shrub and ground vegetation. The survey was done twice: once at the end of June 1994 (before the fertilization), and once at the end of June 1998 (four years after the treatment). The stands were not thinned between these dates.

Three floristic indices were calculated per plot in order to assess the changes in the ground vegetation from different angles after fertilization: the specific richness (S), the total cover (C) and the equitability coefficient ($\bar{e}$). The specific richness (S) is the number of different species present in the plot. The total cover (C in %) is the sum of the individual cover per species, which requires the transformation of the Braun-Blanquet dominance

values into percentage according to Tüxen (1937) (0.5 = 0.5%, 1 = 3%, 2 = 15%, 3 = 37.5%, 4 = 62.5%, 5 = 87.5%).

Furthermore, two plant communities can have the same total cover and the same number of species, despite very different individual species cover. The equitability coefficient ($\overline{e}$) provides an insight into the taxonomic structure of the population [33]. It tends to 0 when all the cover is from the same species. It tends to 1 when each species has the same cover. This coefficient is derived from the Shannon-Wiener indices of diversity ($\overline{H}$):

$$\overline{H} = \sum_{i=1}^{S} \frac{c_i}{C} \log_2 \frac{c_i}{C}$$

where c_i is the cover of the i-th species (%). If $\overline{H}$ is calculated for a population where all the species are represented by the same cover, the equitability is maximum and $\overline{H} = \overline{H'} = \log_2 S$. The knowledge of $\overline{H}$ and $\overline{H'}$ allows us to calculate the equitability coefficient as:

$$\overline{e} = \frac{\overline{H}}{\overline{H'}} = \frac{\overline{H}}{\log_2 S}$$

Finally, to interpret the possible changes of species in terms of ecological variation after fertilization, we classified each plant in the survey into the Ecological Groups described for southern Belgium [7]. These groups define different trophic and hydric categories characterised by their humus type. Species recorded in our surveys belong to the Moder/Mor, Acid Mull, Mesotrophic Mull, Polytrophic Mull, Helionitrophyte, Hygrophyte and Hydromoder groups. Some species were not classified insides these groups, which doesn't means that they are indifferent species. For each treatment and each Ecological Group, we calculated and plotted the mean difference of specific richness and total cover (%) between 1998 (after fertilization) and 1994 (before fertilization).

2.4. Statistical analyses

The difference between treatments was tested for each floristic index (S, C and $\overline{e}$) in 1994 in order to assess the initial spatial homogeneity of these indices before fertilization. For beech, this was done with ANOVA using a two-way design with STAND and TREATMENT as categorical variables. For oak, a one way ANOVA with TREATMENT as categorical variable was performed because only one stand was available for this species.

For each floristic index, the differences between treatments in 1998 were tested taking into account differences in 1994. For beech, this was done by Covariance Analysis with STAND and TREATMENT as categorical variables, using 1994 data as the covariable. For oak, a Covariance Analysis with TREATMENT as categorical variable and 1994 data as covariable was performed.

The data from the 8B stand were not used in the statistical analyses because the presence of an important regeneration stratum of beech in some plots impeded the development of herbaceous plants. Therefore, we finally analysed the data of 9 plots from the oak stand (3 per treatment) and 36 plots from the beech stands (12 per treatment).

Other statistical analyses were undertaken to test, for each floristic index, which treatment (F1, F2) differed from the CONTROL. For the beech stands, we calculated Least Square Means (LSM) for the floristic indices, which are better than arithmetical means when performing two-way analysis of variance [11]. For oak, we calculated arithmetical means since we performed one-way ANOVA. For the comparison of means, we used the Dunnett's two-tailed t-test to see if any treatment is significantly different from a single control for all main effects. The Dunnett's test was particularly suited to this kind of comparison [8]. We used the SAS statistical package for all calculations (GLM procedure with MEANS or LSMEANS statement) [37].

3. RESULTS AND DISCUSSION

3.1. Floristic indices

For the three floristic indices, the initial conditions prior to fertilization (1994) were statistically the same across the different treatments: for beech as for oak, no significant TREATMENT effect was calculated in 1994 (*table IV*). It has been shown in a previous paper [23] that the TREATMENT effect was also not significant in 1994 for the soil pH, exchangeable cations and total P concentration. Using the same statistical analysis, initial differences of basal area were tested and the p value for the TREATMENT effect was found to equal 0.619 for the oak and 0.822 for the beech stands. Then, the initial spatial homogeneity of the floristic indices, the chemical soil properties and the basal area was considered to be satisfactory across treatments and therefore future comparisons can be made.

Four years after fertilization in the beech stands (1998), the TREATMENT effect was almost significant but for the specific richness only: the p value was 0.075,

Table IV. Values of p ($F > F$ obs) from Anova 1 (oak) and Anova 2 (beech) calculated on the floristic indices.

Specie	Year	Effect [1]	*Df* [2]	(*S*)	(*C*)	($\bar{e}$)
Beech	1994	T	2	0.943	0.840	0.963
		S	3	< 0.001 [b]	0.101	0.223
		T × S	6	0.717	0.882	0.935
	1998	COV	1	0.523	0.489	0.002 [b]
		T	2	0.075	0.332	0.301
		S	3	< 0.001 [b]	< 0.001 [b]	0.458
		T × S	6	0.793	0.504	0.034 [a]
Oak	1994	T	2	0.308	0.251	0.711
	1998	COV	1	0.757	0.034 [a]	0.007 [b]
		T	2	0.066	0.476	0.075

[1]: COV = covariable (1994 data); T = TREATMENT; S = STAND; T × S = TREATMENT × STAND interaction;
[2]: *Df*: degree of freedom;
S = specific richness; *C* = cover (%); $\bar{e}$ = equitability;
[a]: $0.01 < p \leq 0.05$; [b]: $p \leq 0.01$.

Table V. Mean and coefficient of variation (*CV* %) of the floristic indices per species and year.

Specie	Year	Treatment	(*S*)	*CV*	(*C*)	*CV*	($\bar{e}$)	*CV*
Beech	1994	CONTROL	8.2	9	41.2	21	0.63	8
		F1	8.2	9	40.9	22	0.63	8
		F2	8.5	8	47.5	19	0.61	8
	1998	CONTROL	11.6	8	37.0	17	0.67	5
		F1	13.2	7	48.3	13	0.73	5
		F2	14.8 *	6	49.9	13	0.64	6
Oak	1994	CONTROL	8.7	29	80.3	60	0.75	2
		F1	10.7	29	72.7	28	0.68	27
		F2	12.7	24	123.2	27	0.73	4
	1998	CONTROL	9.3	12	100.7	74	0.75	11
		F1	17.7	21	67.0	42	0.63	31
		F2	19.3 *	23	109.8	27	0.59 *	10

*: Significant difference compared to the control (Dunnett's test, α level = 5%);
S = specific richness; *C* = cover (%); $\bar{e}$ = equitability.

which was near the 5% level (*table IV*). The mean number of species ranged from 11.6 (CONTROL) to 13.2 (F1) and 14.8 (F2), F2 being significantly different from the CONTROL (*table V*).

In the oak stand, the difference of specific richness between treatments was almost significant at 5% level in 1998 (*table IV*). At this time the mean number of species ranged from 9.3 (CONTROL) to 17.7 (F1) and 19.3 (F2), F2 being significantly different from the CONTROL (*table V*). The difference between treatments was already important in 1994 and in favour of the fertilized plots. Nevertheless, the increase in the mean number of species from 1994 to 1998 reached 6.7 for the F1 treatment, 6.0 for the F2 treatment and only 0.6 for the CONTROL.

Note that the initial differences between treatments in 1994 are taken into account in the Covariance Analysis of the 1998 data (see 2.4).

Others authors have reported an increase in the number of ground vegetation species after base cation and/or P fertilization [5, 25, 29, 35]. Fehlen and Picard (1994) tested, among others, P, Ca and P + Ca applications in a Norway spruce stand situated on acid brown soil in the French Ardenne. They reported that the mean number of species was only 13 in the control plots and reached respectively 24, 30 and 28 for the 3 treatments cited above. They observed that the total cover of the herbaceous plants increased after fertilization. In our beech stands, total cover also showed a tendency to increase over time with fertilization: from 1994 to 1998 it rose by 7.4% in the F1 and 2.4% fin the F2 treatment, while it decreased of 4.2% in the CONTROL (*table V*). Nevertheless, at statistical level the total cover and the equitability didn't show any significant TREATMENT effect in 1998 (*table IV*).

In the oak stands, statistical analysis shows no treatment effect for the total cover in 1998 but the equitability is affected by the treatment: while it remained constant from 1994 to 1998 in the CONTROL, it decreased by 0.05 in the F1 and 0.14 in the F2 treatment (*table V*). The *p* value for the TREATMENT effect was 0.075, which becomes almost significant at 5% level and the Dunnett's test is significant for the F2 treatment (*table IV* and *table V*).

The difference between the equitability coefficient response in the beech and oak stands was probably due to a higher density and cover of the dominant tree layer in the beech stands. As an indicator, before treatment (1994), the mean basal area of the plots in the beech stands came to 21.9 $m^2\ ha^{-1}$ and only 18.8 $m^2\ ha^{-1}$ in the oak stand, or a difference of 3.1 $m^2\ ha^{-1}$ (values from *table I*). The higher stand density in the beech stand could have impeded the development of the initial ground vegetation. In 1998 for example, plants such *Deschampsia flexuosa*, *Luzula luzuloides*, *Pteridium aquilinum*, *Vaccinium myrtillus*, *Rubus idaeus* and *Rubus fruticosus* didn't have a mean cover > 9% (*table VI*). The lower cover of the dominant tree layer in the oak stand encouraged greater development of the initial ground vegetation. After fertilization, the emergence of new species with low individual cover contributed to the heterogeneous taxonomic structure of the plant community and decreased the equitability coefficient. In 1998, the oak F2 treatment was characterised by 3 species over 36 that had a mean cover > 14% (*Pteridium aquilinum* 18.5%, *Rubus idaeus* 14.5% and *Rubus fruticosus* 45.83%), the others having a mean cover < 3% (*table VII*).

A similar response is discussed by Dulière et al. (1999), who have compared the ground vegetation after dolomite application in a Norway spruce and a sessile oak stands. They observed that the number of vascular plants increased very rapidly in both stands, already 1 year after liming. Nevertheless, the reaction in the oak stand was less spectacular than in the spruce stand, owing to greater competition between new seedlings and *Molinia caerula* or *Pteridium aquilinum*. For the oak stand, Dulière et al. (1999) reported no change in the total cover.

Besides the increase in the specific richness after fertilization, there is a variation between the two sampling dates in the CONTROL plots. *Table V* shows that the mean number of species in the oak and the beech stands (CONTROL plots) was higher in 1998 than in 1994. No thinning was applied between these dates. The increase in the number of species in 1998 is probably due to a more favourable climate than in 1994. *Table VIII* shows that the month of May was warmer in 1998, favouring the germination of the herbaceous plants. June was moister in 1998 and this may also have favoured their development.

The analyses of variance reveal a significant STAND effect for the specific richness and the total cover calculated in the beech experimental sites (*table IV*). The effects of local factors such as climate, stand history and soil characteristics have a significant influence on these floristic indices and make them differ from stand to stand. For instance, the number of species varies from 14 in the 9B stand to 21 in the 7B stand (detailed data not given). Nevertheless, there is a general lack of significant TREATMENT × STAND interaction, which means that the floristic indices react with the same magnitude on all the beech stands after the treatments. Similar results were obtained for several soil and foliar chemical properties [23].

3.2. Ecological Groups

The evolution between 1994 and 1998 in the number of species and total cover (%) in the different Ecological Groups [7] was greatly influenced by fertilization in both the oak and the beech stands. The number of new species appearing in the Helionytrophyte and Mesotrophic + Polytrophic Mull groups was greater in the fertilized plots than in the CONTROL plots (*figure 3*). For both of these Ecological Groups, this evolution was more

Table VI. Mean cover[1] (%) per species and number of plots where species is present (parenthesis) per year and treatment[2] in the beech stands.

Species	Ecological Group (after [7])	1994			1998		
		C	F1	F2	C	F1	F2
Carex pilulifera	Moder-Mor				0.21 (5)	0.17 (4)	0.17 (4)
Cytisus scoparius	Moder-Mor					0.04 (1)	0.04 (1)
Deschampsia flexuosa	Moder-Mor	17.5 (11)	21.5 (12)	19.4 (7)	13.2 (12)	6.8 (9)	8.9 (9)
Digitalis purpurea	Moder-Mor	0.08 (2)	0.17 (4)	0.17 (4)	0.13 (3)	0.63 (5)	0.21 (5)
Frangula alnus	Moder-Mor				0.04 (1)	0.04 (1)	0.29 (2)
Holcus mollis	Moder-Mor					0.33 (3)	0.13 (3)
Ilex aquifolium	Moder-Mor		0.08 (2)	0.04 (1)	0.04 (1)		
Lonicera periclymenum	Moder-Mor	0.04 (1)			0.25 (1)		
Luzula luzuloides	Moder-Mor	5.21 (11)	5.38 (12)	5.58 (12)	3.17 (12)	4.17 (12)	4.17 (12)
Maianthemum bifolium	Moder-Mor	0.04 (1)					
Pteridium aquilinum	Moder-Mor	0.5 (2)	0.5 (2)	2.75 (3)	0.33 (3)	1.5 (2)	1.29 (2)
Sorbus aucuparia	Moder-Mor	0.13 (3)	0.21 (5)	0.17 (4)	0.13 (3)	0.17 (4)	0.38 (4)
Vaccinium myrtillus	Moder-Mor	0.83 (5)	0.33 (3)	6.96 (4)	1.63 (5)	0.29 (2)	6.54 (4)
Athyrium filix-femina	Acid Mull	0.46 (6)	0.25 (6)	0.17 (4)	1.88 (6)	0.04 (1)	0.13 (3)
Dryopteris carthusiana	Acid Mull	0.88 (11)	0.83 (10)	0.88 (11)	2.67 (6)	1.71 (7)	0.75 (8)
Dryopteris dilatata	Acid Mull	0.58 (4)	1.63 (5)	0.58 (4)	2.67 (6)	1.58 (4)	0.63 (5)
Oxalis acetosella	Acid Mull	0.25 (1)	0.29 (2)	0.04 (1)	0.08 (2)	1.25 (1)	0.33 (3)
Polygonatum verticillatum	Acid Mull	0.04 (1)		0.25 (1)	0.13 (3)	0.08 (2)	0.13 (3)
Epilobium angustifolium	Helionitrophyte	0.04 (1)		0.04 (1)	0.21 (5)	0.17 (4)	0.92 (7)
Galeopsis tetrahit	Helionitrophyte			0.08 (2)		0.04 (1)	0.04 (1)
Galium aparine	Helionitrophyte						0.29 (2)
Rubus idaeus	Helionitrophyte	1.29 (6)	1.13 (7)	0.38 (4)	2.17 (8)	4.88 (9)	7.08 (9)
Sambucus racemosa	Helionitrophyte					0.33 (3)	0.38 (4)
Stachys sylvatica	Helionitrophyte	0.04 (1)			0.04 (1)	0.08 (2)	0.04 (1)
Urtica dioica	Helionitrophyte				0.04 (1)	0.33 (3)	0.13 (3)
Anemone nemorosa	Mesotrophic Mull						0.04 (1)
Dryopteris filix-mas	Mesotrophic Mull		0.04 (1)		0.04 (1)		0.25 (1)
Epilobium montanum	Mesotrophic Mull						0.08 (2)
Milium effusum	Mesotrophic Mull						0.08 (2)
Polygonatum multiflorum	Mesotrophic Mull	0.08 (2)			0.04 (1)	0.04 (1)	
Scrophularia nodosa	Mesotrophic Mull	0.04 (1)				0.13 (3)	0.17 (4)
Circaea lutetiana	Polytrophic Mull	0.04 (1)					
Carex ovalis	Hygrophyte-Hydromoder				0.04 (1)	0.42 (5)	0.25 (6)
Carex pallescens	Hygrophyte-Hydromoder				0.17 (4)	0.13 (3)	0.17 (4)
Carex remota	Hygrophyte-Hydromoder	0.29 (2)			0.42 (5)	3.88 (9)	1 (9)
Carex sylvatica	Hygrophyte-Hydromoder				0.04 (1)	0.25 (1)	0.08 (2)
Deschampsia cespitosa	Hygrophyte-Hydromoder			1.25 (1)	0.58 (4)	2.54 (3)	2.54 (3)
Juncus effusus	Hygrophyte-Hydromoder				0.29 (7)	4.63 (8)	0.54 (8)

[1]: Including absent species with a zero cover, empty cases is when the species is absent from all the plots;
[2]: C = CONTROL; F1 = Dolomite Lime; F2 = Dolomite Lime + Natural Phosphate + Potassium Sulphate.

Table VI. (continued).

Species	Ecological Group (after [7])	1994			1998		
		C	F1	F2	C	F1	F2
Agrostis stolonifera	Non classified					0.04 (1)	
Betula pubescens	Non classified				0.04 (1)	0.04 (1)	
Fagus sylvatica	Non classified	4.08 (10)	1.5 (11)	2.67 (10)	0.88 (6)	1.13 (7)	2.38 (8)
Holcus lanatus	Non classified					0.04 (1)	0.04 (1)
Lapsana communis	Non classified					0.08 (2)	
Picea abies	Non classified	0.25 (6)	0.38 (4)	0.75 (8)	0.29 (7)	0.38 (9)	0.25 (6)
Poa nemoralis	Non classified					0.5 (2)	0.17 (4)
Poa trivialis	Non classified				0.04 (1)	0.33 (3)	0.13 (3)
Quercus sp.	Non classified	0.04 (1)	0.13 (3)	0.5 (7)	0.08 (2)	0.08 (2)	0.08 (2)
Rubus fruticosus	Non classified	8.42 (7)	6.29 (6)	4.42 (9)	4.54 (7)	8.42 (7)	8.17 (9)
Salix caprea	Non classified						0.08 (2)
Veronica officinalis	Non classified				0.04 (1)	0.13 (3)	0.04 (1)

[1]: Including absent species with a zero cover, empty cases is when the species is absent from all the plots;
[2]: C = CONTROL; F1 = Dolomite Lime; F2 = Dolomite Lime + Natural Phosphate + Potassium Sulphate.

Table VII. Mean cover[1] (%) per species and number of plots where species is present (parenthesis) per year and treatment[2] in the oak stand.

Species	Ecological Group (after [7])	1994			1998		
		C	F1	F2	C	F1	F2
Betula pendula	Moder-Mor			1 (1)		0.17 (1)	
Carex pilulifera	Moder-Mor				0.33 (2)	1.17 (2)	0.5 (3)
Convallaria majalis	Moder-Mor		1 (1)	1 (1)		1 (1)	1 (1)
Cytisus scoparius	Moder-Mor						0.17 (1)
Deschampsia flexuosa	Moder-Mor	10 (2)	12.67 (2)	18.5 (3)	11 (3)	7 (3)	3 (3)
Digitalis purpurea	Moder-Mor			0.17 (1)			0.17 (1)
Frangula alnus	Moder-Mor				1 (1)	0.17 (1)	0.17 (1)
Galium saxatile	Moder-Mor				0.17 (1)		0.17 (1)
Holcus mollis	Moder-Mor						0.17 (1)
Hypericum pulchrum	Moder-Mor					0.17 (1)	
Lonicera periclymenum	Moder-Mor	2 (2)	2 (2)	2 (2)	2.17 (3)	1.17 (2)	1.17 (2)
Luzula luzuloides	Moder-Mor					0.33 (2)	
Maianthemum bifolium	Moder-Mor		1 (1)	1.17 (2)		1 (1)	2 (2)
Melampyrum pratense	Moder-Mor						0.17 (1)
Pteridium aquilinum	Moder-Mor	26 (3)	11 (3)	22.5 (3)	26 (3)	11 (3)	18.5 (3)
Sorbus aucuparia	Moder-Mor	2 (2)	2.17 (3)	1.33 (3)	0.17 (1)	0.33 (2)	0.17 (1)
Dryopteris carthusiana	Acid Mull	0.17 (1)		0.17 (1)	0.17 (1)	0.17 (1)	0.17 (1)
Dryopteris dilatata	Acid Mull					0.33 (2)	0.17 (1)
Oxalis acetosella	Acid Mull	1 (1)	0.17 (1)	2 (2)	0.17 (1)	1.17 (2)	1.17 (2)
Polygonatum verticillatum	Acid Mull		0.17 (1)		0.17 (1)	0.17 (1)	0.17 (1)

[1]: Including absent species with a zero cover, empty cases is when the species is absent from all the plots;
[2]: C = CONTROL; F1 = Dolomite Lime; F2 = Dolomite Lime + Natural Phosphate + Potassium Sulphate.

Table VII. (continued).

Species	Ecological Group (after [7])	1994			1998		
		C	F1	F2	C	F1	F2
Epilobium angustifolium	Helionitrophyte					1.33 (3)	1.33 (3)
Galeopsis tetrahit	Helionitrophyte						0.17 (1)
Galium aparine	Helionitrophyte					0.17 (1)	0.33 (2)
Moehringia trinervia	Helionitrophyte						0.17 (1)
Rubus idaeus	Helionitrophyte	2 (2)	2.17 (3)	6.17 (3)	7 (3)	7 (3)	14.5 (3)
Sambucus nigra	Helionitrophyte					1 (1)	0.17 (1)
Acer pseudoplatanus	Mesotrophic Mull		0.17 (1)				
Anemone nemorosa	Mesotrophic Mull		0.17 (1)				
Corylus avellana	Mesotrophic Mull						0.17 (1)
Malus sylvestris	Mesotrophic Mull	0.17 (1)					
Polygonatum multiflorum	Mesotrophic Mull						0.17 (1)
Scrophularia nodosa	Mesotrophic Mull					0.17 (1)	0.17 (1)
Arum maculatum	Polytrophic Mull						0.17 (1)
Carex pallescens	Hygrophyte-Hydromoder						0.17 (1)
Deschampsia cespitosa	Hygrophyte-Hydromoder					0.33 (2)	0.17 (1)
Juncus effusus	Hygrophyte-Hydromoder						0.17 (1)
Betula pubescens	Non classified			1 (1)			
Fagus sylvatica	Non classified	1.33 (3)	3 (3)	1.33 (3)		0.33 (2)	0.33 (2)
Holcus lanatus	Non classified					0.17 (1)	0.17 (1)
Picea abies	Non classified		1.17 (2)	0.5 (3)	0.33 (2)	0.5 (3)	1.17 (2)
Poa nemoralis	Non classified					0.33 (2)	0.17 (1)
Poa trivialis	Non classified					0.17 (1)	
Quercus sp.	Non classified	2.17 (3)	3 (3)	11 (3)	0.17 (1)	1.17 (2)	0.33 (2)
Rubus fruticosus	Non classified	22.5 (3)	30.83 (3)	38.33 (3)	34.33 (3)	22.83 (3)	45.83 (3)

[1]: Including absent species with a zero cover, empty cases is when the species is absent from all the plots;
[2]: C = CONTROL; F1 = Dolomite Lime; F2 = Dolomite Lime + Natural Phosphate + Potassium Sulphate.

Table VIII. Mean temperature (*MT*) and precipitation (*P*) in May and June 1994 and 1998.

Month	*MT* (°C)	*P* (mm)
May 1994	12.9	69.4
June 1994	16.4	55
May 1998	15.6	35.5
June 1998	16.3	87.7

pronounced in the F2 plots than in the F1. Furthermore, in the beech stands, some species of the Moder/Mor + Acid Mull group disappeared from the F1 plots while some species of the Mesotrophic + Polytrophic Mull group disappeared from the CONTROL plots (*figure 3*). In the beech stands, species from the Hygrophyte + Hydromoder group appeared in 1998, whatever the treatment. In the oak stand, species from the Moder/Mor + Acid Mull group appeared in 1998, whatever the treatment.

The colonisation of limed plots by nitrophilic species has been reported in various studies [5, 6, 12, 25, 29, 35, 39, 42–44]. In our beech stands, N-demanding species such as *Galium aparine* and *Sambucus racemosa* appeared in some of the fertilized plots (*table VII*). In the oak stand, we observe the emergence of ruderals and N-demanding species such as *Epilobium angustifolium*,

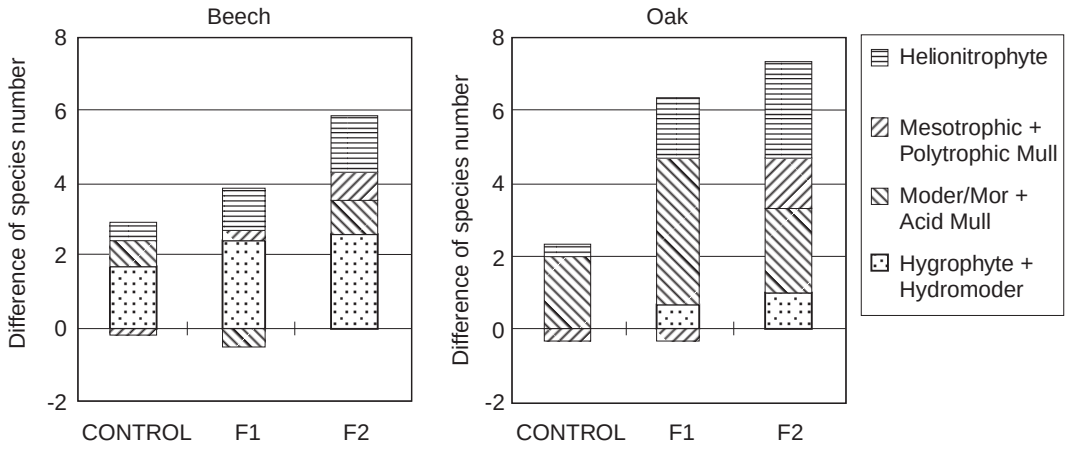

Figure 3. Difference between 1998 and 1994 in the mean number of species per Ecological Group [7] and treatment (C: CONTROL; F1: Dolomite Lime; F2: Dolomite Lime + Natural Phosphate + Potassium Sulphate).

Galeopsis tetrahit, *Galium aparine*, *Moehringia trinervia* and *Sambucus nigra*, (*table VIII*). The development of seedlings from such plants was due to an improvement in the organic matter mineralization. Different authors have shown that liming and/or P fertilization lead to a significant increase in nitrification on the forest floor and upper mineral soil horizons [5, 18, 35, 36].

The colonisation of fertilized plots by species from the Mesotrophic + Polytrophic Mull group is due to the increase in soil pH and nutrient supply after base cation and P fertilization [23]. This effect was more important in the F2 treatment than in the F1 treatment because of the addition of potassium sulphate and natural phosphate to dolomite (*figure 3*). In the beech stands, species such as *Anemone nemerosa*, *Epilobium montanum* and *Millium effusum* emerged in some plots receiving the F2 treatment in 1998 (*table VII*). *Scrophularia nodosa* disappeared from the only beech CONTROL plot where it was present in 1994 and appeared in several F1 and F2 plots (*table VII*). In the oak stand, *Coryllus avellana*, *Polygonatum multiflorum*, *Scrophularia nodosa* and *Arum maculatum* emerged following the F2 treatment in 1998 (*table VIII*).

Apart from the emergence of new species, the number of species in the initial vascular vegetation was not affected by the treatments four years after fertilization. Others authors reported the same results [2, 5, 25]. The number of dominant herbaceous species, which usually characterises acid humus type (Moder/Mor group and Acid Mull group), does not regress notably after base cation and/or P fertilization. In our beech stands, these species were for example *Deschampsia flexuosa*, *Luzula luzuloides*, *Pteridium aquilinum*, *Sorbus aucuparia*, *Vaccinium myrtillus*, *Dryopteris dilatata* and *Oxalis acetosella* (*table VII*). For the oak stand, species such *Pteridium aquilinum*, *Deschampsia flexuosa*, *Lonicera periclymenum* and *Oxalis acetosella* remained present after fertilization (*table VIII*). Only *Ilex aquifolium*, which was present in 1994 in a few beech plots, disappeared in 1998 after fertilization (*table VII*). Considering that pH is still low in the fertilized plots (pH-H_2O < 4.4 in the beech stands), the disappearance of species from the initial acidophilous vegetation is not likely to occur four years after fertilization.

Considering the evolution of the mean cover (%) per Ecological Group, *figure 4* clearly shows that, for both fertilized treatments, the cover of Helionitrophyte group increased while the cover of the Moder/Mor + Acid Mull group decreased. This trend is visible for the oak as for the beech stands and is even more pronounced in the F2 treatment than in the F1 (*figure 4*).

The regression of cover in the initial acidophilous vegetation was due principally to the regression of a limited number of species with high initial cover. In the beech stands, this decrease affected *Deschampsia flexuosa* and *Luzula luzuloides* in the F1 and F2 treatment and *Pteridium aquilinum* in the F2 treatment (*table VII*). Note too that the cover of these species, except for *Luzula luzuloides*, also regressed in the CONTROL plots but to a

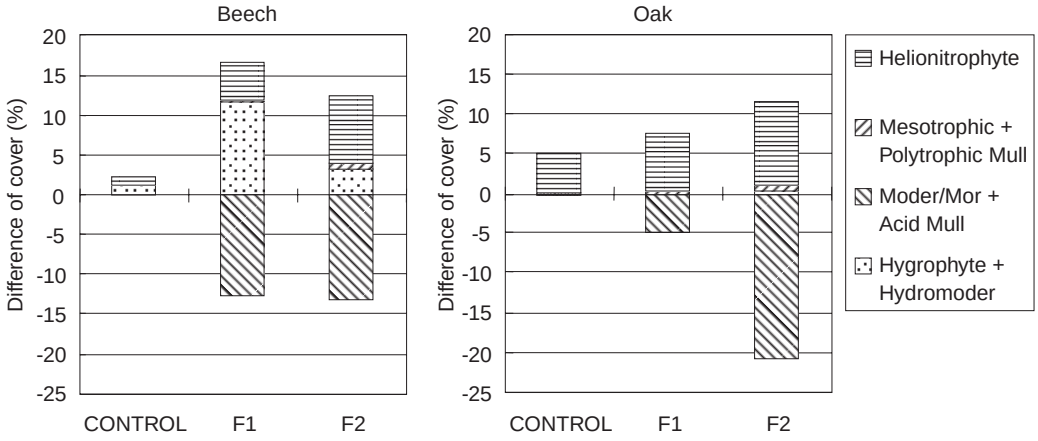

Figure 4. Difference between 1998 and 1994 in the mean cover (%) per Ecological Group [7] and treatment (C: CONTROL; F1: Dolomite Lime; F2: Dolomite Lime + Natural Phosphate + Potassium Sulphate).

lesser extent. In the oak stands, the mean individual cover of species like *Deschampsia flexuosa*, *Lonicera peryclimenum* and *Pteridium aquilinum* decreased greatly after fertilization, above all in the F2 treatment (*table VIII*).

On the other hand, the increase in cover from the Helionitrophyte group was due to the emergence of numerous new species with a small individual contribution. As shown in *tables VII* and *VIII*, the mean cover of new Helionitrophyte species in the F1 and F2 plots never exceeds 1.33%. For the new species belonging to the Mesotrophic+Polytrophic group, the mean cover is even smaller and not greater than 0.17% (*tables VII* and *VIII*).

4. CONCLUSION

This study deals with the response of the vascular ground vegetation after base cation and P fertilization in European beech and sessile oak stands located on acid brown soils. We demonstrate that herbaceous plants react with sensitivity to fertilization carried out in order to restore forest health degraded by nutritional imbalances.

Four years after treatment, the application of 3 T ha^{-1} dolomite not only increases the specific richness of the ground vegetation (in the oak and beech stands), but also modifies the taxonomic structure or equitability (in the oak stands) and tends to increase the total cover (%) (in the beech stands). The addition of 200 Kg ha^{-1} potassium sulphate and 400 Kg ha^{-1} natural phosphate to dolomite reinforces the effects of dolomite. At this first stage of colonisation, the new N-demanding, ruderals and mesotrophic species have a low individual cover (%) and encounter competition from initial acidophilous vegetation. The plant diversity of this initial acidophilous vegetation doesn't decrease but species that have a high initial cover (%) tend to regress. These changes in the composition and taxonomic structure of the ground flora communities could affect the biogeochemical cycle of the forest ecosystem. Further observations should give us more information about developments during the coming years.

The response of the ground vegetation plants is a function of their autoecology but also of interspecific competition. The study reported here shows that the forest type, oak vs. beech stands, influences the vegetational response. In the oak stands, a lower stand density (BA ha^{-1}) promotes greater development of the initial ground vegetation, which imposes higher competition on the species appearing after fertilization. More detailed studies would be necessary to understand the difference in the ground vegetation response between the beech and oak stands.

Acknowledgements: This study was conducted with the support of the "Division Nature et Forêts" of the Walloon Region and the European Commission. We would like to thank Frédéric Hardy and Olivier Bouchez for their technical help during this project. We also thank the two reviewers who contributed greatly to the improvement of the original manuscript.

REFERENCES

[1] Andersson F., Nihlgard B., Forest liming: goals and means, in: Andersson F. and Persson T. (Eds.), Liming as a measure to improve soil and tree condition in areas affected by air pollution. Report No. 3518, National Swedish Evironmental Protection Board, Solna, 1988, pp. 14–19.

[2] Becker M., Bonneau M., LeTacon F., Long-term vegetation changes in an Abies alba forest: natural development compared with response to fertilization, J. Veg. Sci. 3 (1992) 467–474.

[3] Bonneau M., La fertilisation en forêt tempérée, Inra, Nancy, 1995.

[4] Boxman A.W., Cobben P.L.W., Roelofs J.G.M., Does (K+Mg+Ca+P) fertilization lead to recovery of tree health in a nitrogen stressed *Quercus rubra* L. stand?, Environ. Pollut. 85 (1994) 297–303.

[5] Dulière J.-F., Carnol M., Dalem S., Remacle J., Malaisse F., Impact of dolomite lime on the ground vegetation and on potential net N transformations in Norway spruce (*Picea abies* (L.) Karst.) and sessile oak (*Quercus petraea* (Matt.) Lieb.) stands in the Belgian Ardenne, Ann. For. Sci. 56 (1999) 361–370.

[6] Dulière J.-F., De Bruyn R., Malaisse F., Changes in the moss layer after liming in a Norway spruce (*Picea abies* (L.) Karst.) stand of Eastern Belgium, For. Ecol. Manag. 136 (2000) 97–105.

[7] Dulière J.-F., Tanghe M., Malaisse F., Répertoire des groupes écologiques du fichier écologique des essences, Ministère de la Région Wallonne, Namur, 1995.

[8] Dunnett C.W., A multiple comparisons procedure for comparing several treatments with a control, J. Am. Statist. Ass. 50 (1955) 1096–1121.

[9] FAO, FAO-Unesco soil map of the world. Revised legend, FAO, Rome, 1990.

[10] Finér L., Nieminen M., Dry mass and the amounts of nutrients in understorey vegetation before and after fertilization on a drained pine bog, Silva Fennica 31 (1997) 391–400.

[11] Goodnight J.H., Harvey W.R., Least-Squares Means in the fixed-effects General Linear Models. SAS Technical Report R-103, SAS Institute, Cary, 1978.

[12] Guzikowa M., Latocha E., Pancer-Kotejowa E., Zarzycki K., The effects of fertilization on a pine forest ecosystem in an industrial region, Herbs. Ekol. Pol. 24 (1976) 307–318.

[13] Hallbäcken L., Zhang L., Effects of experimental acidification, nitrogen addition and liming on ground vegetation in a mature stand of Norway spruce (*Picea abies* (L.) Karst) in SE Sweden, For. Ecol. Manag. 108 (1998) 201–213.

[14] Hannick A.-F., Waterkeyn L., Weissen F., Van Praag H.J., Vascular tissue anatomy of Norway spruce needles and twigs in relation to magnesium deficiency, Tree Physiol. 13 (1993) 337–349.

[15] Huettl R.F., Liming and fertilization as mitigation tools in declining forest ecosystems, Water Air Soil Pollut. 44 (1989) 93–118.

[16] Huettl R.F., Fink S., Lutz H.J., Poth M., Wisniewski J., Forest decline, nutrient supply and diagnostic fertilization in southwestern Germany and southern California, For. Ecol. Manag. 30 (1990) 341–350.

[17] Ingerslev M., Effects of liming and fertilization on growth, soil chemistry and soil water chemistry in a Norway spruce plantation on a nutrient-poor soil in Denmark, For. Ecol. Manag. 92 (1997) 55–66.

[18] Kreutzer K., Effect of forest liming on soil processes, Plant Soil 168–169 (1995) 447–470.

[19] Lambert J., Parmentier M., Léonard C., Weissen F, Reginster P., Premiers enseignements de l'analyse des sols forestiers en région wallonne, Silva Belgica 97 (1990) 7–12.

[20] Liu J.C., Huettl R.F., Relations between damage symptoms and nutritional status of Norway spruce stands (*Picea abies* (L.) Karst.) in Southwestern Germany, Fert. Res. 27 (1991) 9–22.

[21] Manion P.D., Tree Disease Concepts, Prentice-Hall, Englewood Cliffs, 1991.

[22] Maréchal P., Étude des performances d'un épandeur-souffleur pour le traitement des peuplements dépérissants, Silva Belgica 100 (1991) 21–28.

[23] Misson L., Ponette Q., André F., Regional scale effects of base cation fertilization on Norway spruce and European beech forests situated on acid brown soils: results on soil and foliar chemistry, Ann. For. Sci. 58 (2001) 699–712.

[24] Mohamed A.D., Ranger J., Dambrine E., Bonneau M., Gelhaye D., Granier A., The effects of limestone and of limestone plus NPK fertilization on the soil and mass balance of a spruce stand (*Picea abies* (L.) Karst.) in the Vosges moutains, For. Ecol. Manag. 60 (1993) 291–310.

[25] Fehlen N., Picard J.F., Influence de la fertilisation sur la végétation spontanée et la croissance radiale de l'épicéa commun (*Picea abies* (L) Karst) dans une plantation adulte des Ardennes françaises, Ann. Sci. For. 51 (1994) 569–580.

[26] Noirfalise A., Forêts et stations forestières en Belgique, Les Presses Agronomiques de Gembloux, Gembloux, 1984.

[27] Oncklincx F., Tanghe M., Galoux A., Weissen F., La carte des territoires écologiques de la Wallonie, Revue Belge de Géographie 1 (1987) 51–60.

[28] Ouimet R., Fortin J.M., Growth and foliar status of sugar maple: incidence of forest decline and reaction to fertilization, Can. J. For. Res. 22 (1992) 699–706.

[29] Picard J.-F., Becker M., Lebourgeois F., Modifications de la flore et de l'humus induites par un apport de calcium dans différents écosystèmes forestiers du nord-est de la France, in : Nys C. (Éd.), Forêts et amendements calcaires, Inra, Champenoux, 1993, pp. 61–73.

[30] Ponette Q., Belkacem S., Nys C., Ion dynamics in acid forest soils as affected by addition of Ca fertilizers, Geoderma 71(1996) 53–76.

[31] Ponette Q., Dufey J.E., Weissen F., Downward movement of dolomite, kieserite or a mixture of $CaCO_3$ and Kieserite through the upper layers of an acid forest soil, Water Air Soil Pollut. 95 (1997) 353–379.

[32] Ponette Q., Frankart R., Poma Rojas W., Petit C., Évolution physico-chimique d'un sol brun acide ardennais sous hêtraie suite à l'apport d'amendement minéraux, Pédologie 41 (1991) 89–100.

[33] Ramade F., Éléments d'écologie. Écologie fondamentale, McGraw-Hill, Paris, 1984.

[34] Ranger J., Mohamed AD., Gelhaye D., Effect of liming with or without fertilizer on the biogeochemical cycle of nutrients in a declining spruce stand (*Picea abies* (L.) Karst.) in the Vosges, Ann. Sci. For. 51(1994) 455–475.

[35] Rodenkirchen H., Effects of acidic precipitation, fertilization and liming on the ground vegetation in coniferous forest of southern germany, Water Air Soil Pollut. 61(1992) 279–294.

[36] Rodenkirchen H., Nutrient pools and fluxes of the ground vegetation in coniferous forest due to fertilizing, liming and amelioration, Plant Soil 168–169 (1995) 383–390.

[37] SAS Institue Inc., SAS/Stat User's Guide, Version 6, Vol. 1, Cary, NC, USA, 1989.

[38] Schaaf W., Effects of $Mg(OH)_2$-fertilization on nutrient cycling in a heavily damaged Norway spruce ecosystemn (NE Bavaria/FRG), Plant Soil 168–169 (1995) 505–511.

[39] Sougnez N., Weissen F., Évolution de la couverture morte et de la couverture vivante après fumure en vieille forêt d'épicéa commun, Bull. Rech. Agron. Gemboux 12 (1977) 233–248.

[40] Tüxen R., Die Pflantzengesellschaften Nordwest-Deutschlands, Mittl. Florist. -Soziol. Arbeitsgem. N. F. 5 (1937) 155–176.

[41] Van Praag H.J., Weissen F., Foliar mineral composition, fertilization and dieback of Norway spruce in the Belgian Ardennes, Tree Physiol. 1 (1986)169–176.

[42] Weissen F., Évolution d'une litière de hêtraie après fertilisation, Bull. Rech. Agron. Gembloux 8 (1973) 42–55.

[43] Weissen F., Dix années d'évolution d'une deuxième génération d'épicéas fertilisés à la plantation. 1. Effets généraux des traitements, Bull. Rech. Agron. Gembloux 12 (1977) 135–158.

[44] Weissen F., Développement et signification de quelques effets secondaires de la fumure en forêt ardennaise, Bull. Soc. Roy. Forest. Belgique 87 (1980) 316–319.

[45] Weissen F., Bai, Ph., Boseret J., Bronchart L., Lejeune M., Maquet P., Marchal J., Masson Ch., Oncklincx F., Sandron, Schmitz L., Godeau P., Lambert D., Marneffe C., Piret A., Le fichier écologique des essences. Vol. 1 et 2. Ministère de la Région Wallonne, Jambes, 1991.

[46] Weissen F., Maréchal P., Le sol, un élément stabilisateur de l'écosystème forestier ardennais, Pédologie 51 (1991) 69–87.

[47] Zoettl H.W., Huettl R.F., Fink S., Tomlinson G.H., Wisniewski J., Nutritional disturbances and histological changes in declining forests, Water Air Soil Pollut. 48 (1989) 87–109.