Ann Sci For (1996) 53, 605-613

Original article

Sessile oak seedling fertilization and leaf mineral composition in western France

M Bonneau

Département des recherches forestières, Centre Inra de Nancy, 54280 Champenoux, France

(Received 6 September 1994; accepted 31 October 1995)

Summary — Three experiments were conducted in the Forêt de Blois, in western France, on leached chemically poor soils with limited water drainage (stagnic luvisols in the FAO classification), in young (2–10-year-old) sessile oak seedlings from natural regeneration. The main limiting factors for growth were phosphorus and nitrogen. In the better soils (0.09 $g.kg^{-1}$ P_2O_5 in the A_1 horizon extracted by H_2SO_4 extraction followed by OHNa extraction, according to the Duchaufour method), PKCa fertilization was not efficient and addition of N was necessary to improve height and diameter growth. In the poorest soils (0.03 $g.kg^{-1}$-P_2O_5 in the A_1 horizon), PKCa fertilization without N enabled a 40% gain in height and a complete NPKCa fertilization enabled a 100% gain during at least 5 years. Optimum composition for leaves sampled in August and ratios between elements were estimated as: N: 23 $mg.g^{-1}$; P: 1.5 $mg.g^{-1}$; K: 8.6 $mg.g^{-1}$; Ca: 9 $mg.g^{-1}$; N/P: 15; N/K: 2.7; K/P: 5.6.

fertilization / leaf mineral composition / natural seedlings / *Quercus petraea* / leached soils with pseudogley

Résumé — Essais de fertilisation et composition foliaire de chênes sessiles dans l'ouest de la France. *Trois essais de fertilisation ont été effectués en forêt de Blois, dans l'ouest de la France, sur des sols lessivés à pseudogley (luvisols stagniques de la classification FAO), sur de jeunes (2 à 10 ans) semis de chêne sessile* (Quercus petraea) *issus de régénération naturelle. Le phosphore et l'azote sont les deux principaux éléments limitants pour la croissance en hauteur et en diamètre. Dans les meilleurs sols (0,09 $g.kg^{-1}$ de P_2O_5 dans l'horizon A_1, extrait par une extraction à H_2SO_4 suivie d'une extraction à OHNa, selon la méthode Duchaufour), une fertilisation PKCa n'est pas efficace et l'addition d'azote est nécessaire pour améliorer la croissance en hauteur et en diamètre. Dans les sols les plus pauvres (0,03 $g.kg^{-1}$ de P_2O_5 en A1), une fertilisation PKCa sans azote permet un gain d'accroissement en hauteur de 40% et une fertilisation complète NPKCa, un gain de 100 % pendant au moins 5 ans. La composition foliaire optimale, pour des feuilles prélevées en août, est la suivante : N: 23 $mg.g^{-1}$; P: 1,5 $mg.g^{-1}$; K: 8,6 $mg.g^{-1}$; Ca: 9 $mg.g^{-1}$; N/P: 15; N/K: 2,7; K/P:5,6.*

composition foliaire / fertilisation / régénération naturelle /* Quercus petraea */ sols lessivés à pseudogley

INTRODUCTION

Little research has been devoted to the mineral demands of sessile oak (*Quercus petraea* Matuschka, Liebl) concerning soil fertility and leaf composition in natural conditions. Newnham and Carlisle (1969) gave only indications concerning seedlings in the nursery (optimum leaf composition: 29 $mg.g^{-1}$ N, 2.2 $mg.g^{-1}$ P). Van den Burg (1974) indicated an optimum value of N concentration in leaves of 22 to 26 $mg.g^{-1}$. Keller (in Van den Burg, 1990) suggested an optimum level of 26 $mg.g^{-1}$ N and 1.4–1.9 $mg.g^{-1}$ P. Garbaye and Bonneau (1975), on the basis of a fertilizer experiment in central France, found 23 $mg.g^{-1}$ N, 2 $mg.g^{-1}$ P, 7.5 $mg.g^{-1}$ K and 8 $mg.g^{-1}$ Ca as the foliar composition associated to the optimal growth of 7-year-old planted oaks.

In France, the first research by Leroy (1968) showed that, in the most frequent ecological conditions *(sols lessivés à pseudogley)* [= stagnic luvisols] developed on loamy material with poor water drainage and humus from mull to moder) for adult stands, the main limiting factor for growth was nitrogen availability. He suggested the occurrence of a threshold of 17–18 $mg.g^{-1}$ in dry years and 19–20 $mg.g^{-1}$ in years with normal rainfall for very poor production levels. A good growth level corresponded to 22 $mg.g^{-1}$ N, 1.8 $mg.g^{-1}$ P, 11.5 $mg.g^{-1}$ K and 6.4 mg g^{-1} Ca. Following this assessment, he established several fertilization experiments in the Forêt de Bercé (Sarthe, France) on oak stands at the pole stage; treatments were calcium (Ca) calcium and nitrogen (NCa) or complete fertilization (NPKCa). The NCa treatment had the best effect on growth (Garbaye et al, 1974), but did not last long. Furthermore, it produced heterogeneities in the annual ring width and consequently had a deleterious effect on wood quality.

New experiments were set up in the Forêt de Blois (central France), in young natural regenerations. In this forest, humus under old pure oak stands (180–200 years old) is most often moder, and soils are acidic, poor in calcium and phosphorus. These experiments had two main objectives: i) A long-term objective was to check whether copious mineral fertilization was able to induce a long-term evolution of humus towards mull, providing an adequate supply of N and Ca to adult stands. ii) A short-term objective was to investigate responses of young oak seedlings to mineral fertilization and to more accurately determine their optimum leaf composition.

MATERIALS AND METHODS

The Forêt de Blois is located 150 km south of Paris, just north of the Loire Valley, on a plateau which is the southern part of the Beauce region. Soils are developed from thick dissolution residues of cretaceous limestone called *argile à silex* (flint clay), while the Beauce plateau itself corresponds to more recent continental limestone.

Under a moder layer which, after cutting old trees, develops into mull under better exposure to light, soils were made of two main horizons: i) E horizon: light brown, silty, with about 15% clay; ii) Btg horizon: more clayey (35–40% clay), brown with grey and reddish mottling due to poor water drainage in winter. Table I gives the main chemical and physical properties of soils of the three experiments.

The climate is typical of the Atlantic plains of France, with a mild winter, moderately warm summer and an annual rainfall of about 650 mm, but with occasional drought periods in spring or summer.

Three experiments were set up.

Experiment 1 (Compartment 159)

Two treatments, PKCa and NPKCa, were tested in comparison with a control (table II): four replicates (12 50 x 50 m individual plots) were made. At the beginning of the experiment, seedlings were of different ages, mainly 2 (1979 mast) and 10 years old (1971 mast). Ages were heteroge-

Table I. Physical and chemical properties of soils in the Forêt de Blois. pH in water; exchangeable elements in cmolc. kg^{-1}.

Experiment, horizons		*Clay (%)*	*Silt (%)*	*Sand (%)*	*OM (%)*	*C/N*	*pH*	*Exchangeable elements*			*P_2O_5 g.kg^{-1}*
								Ca	*Mg*	*K*	
Exp 1	A_1	–	–	–	7.8	18	4.5	2.6	1.03	0.31	0.09
	E	22	60	18	–	–	4.6	0.09	0.97	0.17	0.05
Exp 2	A_1	–	–	–	14	23	4.5	2.3	0.60	0.27	0.03
	E	18	74	8	1	20	4.5	0.20	0.31	0.08	0.01
	Btg	36	57	7	–	–	4.5	0.60	2.12	0.23	0.01
Exp3	A_1/E	15	69	16	16	28	4.5	1.5	0.42	0.25	0.03
	B	16	65	19	2.3	26	4.5	0.10	0.07	0.07	0.02

P_2O_5 is determined by the Duchaufour method: two successive extractions by H_2SO_4 0.004 N and OHNa 0.1 N.

neously represented in each individual plot; however, several m^2 large, homogeneous elemental areas could be found in each plot. Thus, ten homogeneous 10 x 3 m large subplots were chosen in each plot, so that each treatment was represented by a population of 4 x 10 = 40 subplots. In each subplot, height of the highest seedling in each square meter ('dominant' population) was measured at the beginning of the experiment.

For comparing seedling growth, 30 subplots were chosen among these 40 subpots in order to equalize the mean initial height in the three treatments, and the 30 subplots were classified by initial mean height in order to create 30 small dissociated blocks of three treatments with approximately equal initial heights. Height of the dominant seedlings (not the same seedlings as at the beginning of the experiment because of the very severe competition between seedlings) was measured again in the same way 2 years later, in autumn 1982. In 1991, 9 years after setting up the experiment, the diameter of 15 dominant trees, evenly distributed, was measured in each subplot. Statistical tests were performed from mean values of height, height increment or diameter of each subplot (Snedecor test).

Leaf samples were taken in August 1983, 1987 and 1991 from 20 seedlings per treatment chosen in each block in different subplots, the height of which was approximately the mean height of the subplot. Completely developed leaves were taken in August, from branchlets of the upper part of the seedling crown. Analyses (N by Kjeldahl method, P, K, Ca, Mg by ICP after digestion in cold H_2O_2 followed by a digestion in hot $HClO_4$) were performed on two mixed samples of ten seedlings corresponding to two blocks. This method did not make it possible to perform statistical tests for leaf composition as only two composite samples were analysed in each treatment; it was only possible to examine trends.

Experiment 2 (Compartment 81)

The same treatments, and a similar design as for experiment 1, were applied on natural seedlings of the same age as in experiment 1. Details of the treatments are described in table II. As the suitable area was smaller than in experiment 1, there were only two replicates. In each plot, 16 homogeneous subplots were chosen. Height of the 25 highest and evenly distributed seedlings of each subplot was measured at the beginning of the experiment in autumn 1981, 1983 and 1986. Diameter was not measured. Leaf samples were collected in August 1983 and 1987, and analysed as in experiment 1.

Table II. Doses, forms and dates of fertilizer applications. All fertilizers were distributed without tillage.

	Dose	*Form*	*Date of application*
Experiment 1			
P	200 $kg.ha^{-1}$ P_2O_5	Treble superphosphate	Spring 1981
K	100 $kg.ha^{-1}$ K_2O	Potassium sulphate	Spring 1982
Ca	1 120 $kg.ha^{-1}$ CaO	Calcium carbonate	Autumn 1980
N	184 $kg.ha^{-1}$ N	Urea	Spring 1982
	200 $kg.ha^{-1}$ N	Ammonium nitrate	Spring 1991
Experiment 2			
P	210 $kg.ha^{-1}$ P_2O_5	50% treble superphosphate 50% calcium phosphate	Autumn 1982
K	100 $kg.ha^{-1}$ K_2O	Potassium chloride	Autumn 1982
Ca	1 100 $kg.ha^{-1}$ CaO	Calcium carbonate	Autumn 1982
N	184 $kg.ha^{-1}$ N	Ammonium nitrate	Spring 1983
Experiment 3			
P	200 $kg.ha^{-1}$ P_2O_5	Basic slag	Autumn 1987
Ca	784 $kg.ha^{-1}$ CaO	Calcium carbonate	Autumn 1987
K_1	50 $kg.ha^{-1}$ K_2O	Potassium sulphate	Spring 1987
	20 $kg.ha^{-1}$	"	Spring 1991
K_2	100 $kg.ha^{-1}$	"	"
	40 $kg.ha^{-1}$	"	"
K_3	150 $kg.ha^{-1}$	"	"
	60 $kg.ha^{-1}$	"	"
N_1	150 $kg.ha^{-1}$	Ammonium nitrate	April 1988
	30 $kg.ha^{-1}$	"	April 1991
N_2	150 $kg.ha^{-1}$	"	April 1988
	150 $kg.ha^{-1}$	"	June 1988
	60 $kg.ha^{-1}$	"	April 1991

Experiment 3 (Compartment 81)

As fairly low levels of K (5.6 $mg.g^{-1}$ DW) had been recorded in an earlier experiment (not reported here) without any distinct effect on seedling growth, we decided to set up another small experiment in view to better define the optimum leaf composition of oak seedlings in natural conditions. This experiment was established in autumn 1987 on a weakly podzolized soil with a coarser texture (table I). Seven treatments were applied: C (control), N_1P Ca, N_1P Ca K_1, N_1P Ca K_2, N_1P Ca K_3, P Ca K_2 and N_2P Ca K_2.

Detailed description of these treatments is given in table II.

There were four replicates. Seedling population from the 1980 mast was very homogeneous. The individual plots were very small (10 x 10 m). Height of 80 dominant seedlings in each plot was measured in autumn of 1987, 1989 and 1992. Statistical tests were performed from the mean heights or height increments of each plot (Snedecor test). Leaf samples were taken in August 1989 and 1991 and analysed by the same methods as in experiment 1.

RESULTS

Experiment 1

Growth

Table III indicates for each treatment the seedling height at the beginning of the experiment, the height increment between autumn 1980 and autumn 1982, and the diameter in autumn 1990. The PKCa treatment did not result in any gain of height or diameter growth, while the NPKCa treatment resulted in a significant improvement of height and diameter growth. The difference is significant for height increment ($P = 0.05$) and diameter growth ($P = 0.01$). The gain was about 10% in height and reached 27% in diameter growth.

Leaf analysis

Results presented in table IV are the means of the two mixed samples which were analysed. Levels of Ca and Mg were normal in the control and in the two treatments. Fertilization mainly improved P concentration, from 1.1 mg.g^{-1} dry weight (DW) in the control up to 1.7 mg.g^{-1} in the PKCa treatment. However, when nitrogen was added, P concentration in leaves decreased slightly. Potassium concentrations seemed low for a broad-leaved species; they were higher after PKCa or NPKCa fertilization than in the control, but as for P concentration, they were lowered by N fertilization.

It is worth noting that N concentration was fairly low, and not higher in the NPKCa treatment than in the PKCa one, except in 1983, 1 year after N application, although growth was improved. Foliar analysis results from experiment 2 (see later) suggested that N fertilization improved N concentration in leaves only for a short period. It could also be seen in experiment 1 that N concentrations in August 1991 had increased up to 25 mg.g^{-1} DW after N fertilizer application in spring 1991.

Experiment 2

Growth (table III)

Results were quite different from those in experiment 1. Height clearly increased with PKCa fertilization and even more with

Table III. Seedling heights, diameters and height increments in experiments 1 and 2.

Treatment	*Experiment 1*					*Experiment 2*				
	Initial height 1980	*Height increment 1980–1982*		*Diameter 1990*		*Initial height 1981*	*Height increment 1981–1983*		*Height 1987*	
	cm	*cm*	*% of control*	*mm*	*% of control*	*cm*	*cm*	*% of control*	*cm*	*% of control*
Control	83.7^a	44.1^a	100	28.9^a	100	33.1^a	27.2^a	100	93.4^a	100
PKCa	83.1^a	41.8^a	95	29.8^a	93	32.9^a	37.4^b	137	119.5^b	130
NPKCa	83.9^a	49.8^b	113	36.7^b	127	33.0^a	55.9^c	205	157.0^c	168

^{abc} Values with the same letter do not differ from each other.

Table IV. Major element concentrations in leaves in experiments 1 and 2.

Experiment, year and treatment		*N mg.g^{-1}*	*P mg.g^{-1}*	*K mg.g^{-1}*	*Ca mg.g^{-1}*	*Mg mg.g^{-1}*	*N/P*	*N/K*	*P/K*
Experiment 1	1983								
Control		21.0	1.2	6.7	7.1	1.7	17.5	3.1	0.18
PKCa		20.0	1.7	7.9	7.3	1.8	11.8	2.5	0.22
NPKCa		22.0	1.5	6.9	7.0	2.0	14.7	3.2	0.22
	1987								
Control		21.5	1.2	7.9	5.3	1.7	17.9	2.7	0.15
PKCa		22.2	1.5	8.1	6.7	1.8	14.8	2.7	0.19
NPKCa		22.1	1.5	8.8	7.1	1.8	14.7	2.5	0.17
	1991								
Control		22.9	1.1	7.5	6.0	2.3	20.8	3.1	0.15
PKCa		23.1	1.9	9.2	9.0	2.1	12.2	2.5	0.20
NPKCa		25.9	1.5	8.1	7.9	2.4	17.2	3.2	0.19
Experiment 2	1983								
Control		21.0	1.0	6.6	5.4	2.0	21.0	3.2	0.15
PKCa		21.0	1.7	9.0	5.8	1.8	12.3	2.3	0.19
NPKCa		25.0	1.6	8.0	5.2	1.4	15.6	3.1	0.20
	1987								
Control		21.0	1.0	8.0	7.7	1.4	21.0	2.6	0.12
PKCa		20.0	1.4	7.8	8.6	1.6	14.2	2.6	0.18
NPKCa		21.0	1.5	7.4	7.9	1.9	14.0	2.8	0.20

NPKCa fertilization. This improvement became effective in 1983, after a very short period of fertilizer action.

The PKCa treatment differed significantly ($P = 0.01$) from the control and the increase in height was about 37%. NPKCa was different from the control and from the PKCa treatment ($P = 0.01$) and the gain in height after 5 years (in 1987) was 68% versus the control and 31% versus the PKCa treatment. In comparison with experiment 1, the 2-year height increment (1981–1983) was smaller in the control, and about equal in both PKCa and NPKCa treatments.

Leaf analysis (table IV)

Phosphorus concentration in leaves of the control plots was very low, in 1983 and 1987, in fact lower than in experiment 1, and was clearly improved by fertilization. In 1983, N concentration reached a high value (25 mg.g^{-1} DW) in the NPKCa treatment, but it must be remembered that N fertilization was applied in the spring of the same year, 4 months before foliage sampling.

In 1987, N concentration had dropped to the same level in the NPKCa treatment as in the control and the PKCa treatment, and a little below the concentration in experiment 1. This again demonstrated that the effect of N spreading on the N concentration in leaves did not last long. The same was found in another experiment not reported here. The potassium concentration seemed low for a broad-leaved species and Mg concentration was relatively poor, clearly below that in experiment 1.

Experiment 3

Growth (table V)

After 4 years, height was slightly but significantly better in all treatments with fertilizers, except N_1PCaK_1, than in the control (*P* = 0.05 in N_1PCa and 0.01 in the other treatments). No fertilization treatment was significantly different from the others, but N_1PCaK_2, N_1PCaK_3, $PCaK_2$ and N_2PCaK_2 differed more from the control than the treatments with lower K fertilization, as well as for height in autumn 1991 as for height increment between 1987 and 1991.

Foliar analysis (table VI)

As in the experiments 1 and 2, P concentration was low in the control and reached about 1.5 $mg.g^{-1}$ in all other treatments. N concentration did not differ between treatments and in particular was not lower in the PKCa treatment (without N fertilization) and not higher in the N_2PCaK_2 treatment (with double N fertlization); K concentration was low in the control and in the N_1PCa treatment (without K addition). K concentration was a little higher in the N_1PCaK_2 and N_1PCaK_3 treatments than in other treatments with single K fertilization.

Table V. Heights and height increments in experiment 3.

Treatment	*Initial height 1987*	*Height 1991*		*Height increment 1987–1991*	
	cm	*cm*	*% of control*	*cm*	*% of control*
Control	33.0[a]	102.6[a]	100	69.6[a]	100
N_1PCa	32.9[a]	118.3[b]	115	85.4[b]	122
N_1PCaK_1	30.3[a]	114.6[a]	112	84.3[b]	121
N_1PCaK_2	31.2[a]	123.9[bb]	121	92.7[bb]	133
N_1PCaK_3	33.7[a]	125.3[bb]	122	92.1[bb]	132
$PCaK_2$	29.5[a]	120.9[bb]	118	91.4[bb]	131
N_2PCaK_2	31.1[a]	120.3[bb]	117	89.7[bb]	129

[ab] Values with one different letter (b) differ from the control at *P* = 0.05; values with two different letters, at *P* = 0.01.

Table VI. Major element concentrations in leaves in experiment 3.

	N $mg.g^{-1}$	*P* $mg.g^{-1}$	*K* $mg.g^{-1}$	*Ca* $mg.g^{-1}$	*Mg* $mg.g^{-1}$	*N/P*	*N/K*	*P/K*
1991								
Control	23.6	1.0	6.8	5.8	2.1	23.6	3.5	0.15
N_1PCa	22.2	1.6	6.3	10.4	2.9	13.9	3.5	0.25
N_1PCaK_1	22.3	1.6	8.2	8.8	2.1	14.2	2.8	0.20
N_1PCaK_2	23.3	1.5	8.8	9.6	2.4	15.5	2.6	0.17
N_1PCaK_3	23.8	1.5	8.6	10.3	2.2	15.9	2.8	0.17
$PCaK_2$	23.4	1.8	8.2	8.5	2.3	13.0	2.75	0.22
N_2PCaK_2	23.8	1.5	8.0	7.9	1.9	15.9	3.0	0.19

DISCUSSION AND CONCLUSION

These experiments must be interpreted, on the one hand, in the light of growth modifications, and, on the other hand, in the light of the leaf composition. Major element concentrations in the leaves of the seedlings in the best treatments of experiment 3, N_1PCaK_2, N_1PCaK_3, N_2PCaK_2 and $PCaK_2$ (table VI) may be considered as near optimum values as these treatments were not very different from the others, but much better than the control, and differed at $P = 0.01$ from the control while N_1PCaK_1 differed at $P = 0.05$ only. These concentrations were not very different from the values adopted by Garbaye and Bonneau (1975) (table VII).

In the control plots of the three experiments, P levels were very low when compared to the above values, particularly in experiments 2 and 3. In both experiments, low P concentrations in controls were linked with strong growth improvement by PKCa fertilization (37% in experiment 2 and 31% in experiment 3).

In experiment 1, although PKCa fertilization did not improve growth, P concentration in leaves was much below the optimum value. N levels were nearer the optimum concentration: 21–22 $mg.g^{-1}$ in the control seedlings in experiments 1 and 2, and 22.6 $mg.g^{-1}$ (equal to optimum) in experiment 3. K concentrations were not always optimum: 6.6–6.7 $mg.g^{-1}$ in the controls in 1983 and 1991 in experiments 1 and 3, a little higher and not far from the optimum in 1987 in experiments 1 and 2. Ca concentrations were always too high to be able to attribute this element with a direct role in the PCaK fertilized plots. Thus, P availability may be thought to be a major growth limiting factor in the soils of the Forêt de Blois.

Table VII. Leaf composition in adequately fertilized young oak trees

	Experiment 3 treatments differing at P = 0.01 from the control ($mg.g^{-1}$)	Garbaye and Bonnau (1975) ($mg.g^{-1}$)
N	23.5	23.0
P	1.5	1.9–2.0
K	8.7	7.5
Ca	10.0	8.0
Mg	2.3	–

Concerning N, the experimental design did not make it possible to evaluate the N effect in the absence of the other elements (the main objective of these experiments was a long-term study of the effect of Ca and P on humus evolution). The effect of N may be judged only after PKCa fertilization. In the control seedling leaves, N concentration was never very low (2.1–2.3) and it never dropped after PKCa fertilization. It also did not increase very much in the NPKCa treatment, except in the summer following N application (1991 in experiment 1, 1983 in experiment 2, table IV). Two interpretations may be made. The first hypothesis concludes that mineral N supply by the soil was good and high enough for sustaining growth improvement after PKCa fertilization without a major decrease of N concentration in the leaves (tables IV and VI). This conclusion is not logical, however, despite the absence of the effect of N in experiment 3, when we consider the very significant growth improvement in the NPKCa treatments of experiments 1 and 2 in comparison with PKCa fertilization: 31% in experiment 2, 20–23% in experiment 1. Thus it may be concluded that, after restoring P (and K) nutrition, N also became a limiting factor.

However, the behaviour of the oak seedlings with respect to N and P levels was very different. Large variations of P concentrations may occur in their leaves (from 1.0 in the control plots up to 1.9) (tables IV and VI), whilst they maintain their N concentration only slightly below the optimal value. It is interesting to consider the effects of the PKCa fertilization in the light of the initial N/P ratio in the leaves and of the available P_2O_5 content in the soil. In experiment 1, with 0.05 to 0.09 $g.kg^{-1}$ P_2O_5 and an N/P of 17 to 20, PKCa fertilization was not effective, whilst it was in experiments 2 and 3 where there were only 0.03 to 0.05 $g.kg^{-1}$ P_2O_5 in the soil and an N/P of ratio 21 to 23 in the leaves.

It was also interesting to note that, after PKCa or NPKCa fertilization, the P level remained stable at 1.5 $mg.g^{-1}$, higher than in the control, whilst an N level higher than in the control was observed only in years when N fertilizer was distributed (1991 in experiment 1, 1983 in experiment 2). Thus, the effect of N on growth seems surprising. It may be hypothesized that, after N enrichment, mainly in the leaves during the first year, added nitrogen was distributed in other tissues (liber, young wood) and was recycled from year to year, thus improving growth although N concentration in the leaves did not reach the optimum level.

From these three experiments, the following conclusions may be drawn.

– P and N nutrition are growth limiting factors in soils such as those of the Forêt de Blois; K is not clearly limiting although the K level in absence of fertilization does not reach the optimum level.

– The following optimum levels of major elements and ratios between elements can be proposed: N: 23 $mg.g^{-1}$ leaf dry matter; P: 1.5 $mg.g^{-1}$; K: 8.5 $mg.g^{-1}$; Ca: 9–10 $mg.g^{-1}$; N/P: 15; N/K: 2.7; K/P: 5.6.

Critical values corresponding to a 20% growth reduction, in comparison with maximum growth, may be proposed: N: 21 $mg.g^{-1}$; P: 1.1 $mg.g^{-1}$; K: lower than 6.3.

Thus oak seedlings are characterized by a much smaller difference between optimum and critical values in foliage content for N than for P or K.

– In soils such as those of the Forêt de Blois, fertilization of oak seedlings from natural regeneration by P, Ca and K may be recommended when the P level in the leaves is less than 1.1, P_2O_5 content (one extraction by 0.004 N H_2SO_4 followed by one extraction by 0.1 N OHNa) in the A_1 horizon lower than or equal to 0.05 $g.kg^{-1}$ and P_2O_5 in mineral horizons lower than or equal to 0.03 $g.kg^{-1}$. N fertilization after PKCa fertilization will give a greater growth improvement when N concentration in the leaves is lower than or equal to 21 $mg.g^{-1}$. When P level in the leaves is higher than 1.2 and N lower than 21 $mg.g^{-1}$ (N/P lower than 17), PKCa fertilization alone will probably not be efficient and complete fertilization NPKCa is recommended.

REFERENCES

Garbaye J, Bonneau M (1975) Premiers résultats d'un essai de fertilisation sur plantation de chêne rouvre *(Quercus sessiliflora). Ann Sci For* 32, 175-183

Garbaye J, Leroy P, Oswald H (1974) Premiers résultats de cinq années de fertilisation de jeunes peuplements de chêne en forêt de Bercé. *Rev For Fr* XXVI, 51-58

Leroy P (1968) Variations saisonnières des teneurs en eau et éléments minéraux des feuilles de chêne *(Quercus pedunculata). Ann Sci For* 25, 83-117

Newnham RM, Carlisle A (1969) The nitrogen and phosphorus nutrition of seedlings of *Quercus robur* L and *Quercus petraea* (Mattuschka) Liebl. *J Ecol* 57, 271-284

Van den Burg J (1974) Application of foliar analysis for young hardwood stands in the Netherlands. *Nederlands Bosbouw Tidjschrift* 46, 225-243

Van den Burg J (1990) Foliar analysis for determination of tree nutrient status. A compilation of literature data. 2. Literature 1985–1989. 'De Dorschkamp' Institute for Forestry and Urban Ecology, Wageningen, the Netherlands, Report 591, 220 p