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Original article

Radial growth of mature pedunculate and sessile oaks in response to drainage, fertilization and weeding on acid pseudogley soils

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Summary — In northeastern France, forest soils on old alluvial terraces are generally unfavourable, strongly acid and often characterized by superficial temporary water tables. In this case, the ground vegetation is dominated by a dense cover of *Carex brizoides* on the moderately hydromorphic soils (Carex site) or *Molinia caerulea* on the strongly hydromorphic soils (Molinia site). Both pedunculate and sessile oaks are present in the Molinia site, and practically only pedunculate oak in the Carex site. The experiment aimed at quantifying the radial growth response of mature oaks to various silvicultural interventions. It included i) ditching in order to drain the soils (in 1974), ii) herbicide application (glyphosate; in 1981), and iii) fertilization (P, K, Ca and Mg in 1982; N in 1982 and 1985). A dendrochronological investigation was performed on 620 adult oaks from 60 to 200 years old, which were subjected to these treatments, alone or in combination. The results refer to basal area increment by comparison with control trees. The effect of drainage depended on the site type, the oak species and the age of the trees. Drainage had practically no effect in the Carex site. In the Molinia site, the effect was positive (+20%) for the young (≤ 110 years old) sessile oaks only. It became even depressive (–15%) for the old (> 110 years old) pedunculate oaks. The effect of weeding differed according to the site type, the age of the trees and the drainage modality. Whatever the drainage modality, the effect was depressive (–13%) for the young trees and nonsignificant for the old ones in the Carex site. There was a positive interaction between weeding and drainage in the Molinia site, in the old trees (+22%) as well as in the young ones (+17%), whereas weeding alone had a negative effect (–5%). The effect of fertilization was strongly beneficial (about +20%) in all cases, without any interaction of site type or drainage. However, the time dynamics of this effect was different according to the age of the trees: i) the mean effect was lower in the young trees (+15%), but it was still high when the trees were cored (1991); ii) it was higher in the old trees (+25%), but tended to vanish about 9 years after fertilizing. For analysing the results related to drainage and weeding, we needed to take into account the competition for the mineral nutrients between trees and weeds, as well as the water table depth in the soil, which depends on the evapotranspiration of the whole vegetation cover including trees and ground layer.

***Quercus robur* / *Quercus petraea* / waterlogging / competition / drainage / weeding / fertilization / radial growth / dendrochronology**

Résumé — Croissance radiale de chênes pédonculés et sessiles adultes après drainage, fertilisation et désherbage sur des sols acides à pseudogley. *La forêt étudiée est située sur des alluvions anciennes de la Meurthe. Les sols y sont souvent défavorables, très acides, souvent caractérisés par des nappes d'eau temporaires superficielles. Le sous-bois est envahi par une végétation herbacée très dense, à base de* Carex brizoides *sur les sols moyennement hydromorphes (station à carex) ou de* Molinia caerulea *sur les sols les plus hydromorphes (station à molinie). Le protocole expérimental comprend i) le creusement d'un réseau de fossés de drainage (1974), ii) un traitement herbicide (glyphosate ; 1981), iii) un apport d'éléments fertilisants (P, K, Ca et Mg en 1982 ; N en 1982 et 1985). Une investigation dendrochronologique a permis de quantifier la réponse de chênes adultes (620 arbres de 60 à 200 ans) à ces divers traitements, seuls ou combinés. L'analyse de l'effet du drainage doit prendre en compte le type de station, l'espèce de chêne et l'âge des arbres. Dans la station à carex, où seul le chêne pédonculé est présent, le drainage est pratiquement sans effet. Dans la station à molinie, l'effet n'est positif (+ 20%) que chez les chênes sessiles jeunes (≤ 110 ans) ; il s'avère même négatif (– 15%) chez les chênes pédonculés âgés (> 110 ans). L'effet du traitement herbicide diffère selon la station, l'âge des arbres et le drainage conjoint ou non du sol. Dans la station à carex, avec ou sans drainage, l'effet est dépressif (- 13%) chez les arbres jeunes, et non significatif chez les arbres vieux. Dans la station à molinie, on observe une interaction positive entre désherbage et drainage, aussi bien chez les arbres vieux (+ 22%) que chez les arbres jeunes (+ 17%), alors que le désherbage seul est dépressif (– 5%). L'effet de la fertilisation est très bénéfique, et comparable dans toutes les situations (+ 20% environ), sans interaction avec la station ou le drainage. La dynamique dans le temps est cependant un peu différente selon l'âge des arbres : i) il est plus faible chez les arbres jeunes (+ 15%) mais se maintenait encore à un niveau élevé au moment du carottage des arbres (1991) ; ii) il est plus important chez les arbres vieux (+ 25%) mais il tend à s'annuler neuf ans après l'apport des fertilisants. L'interprétation des résultats concernant le drainage et le désherbage fait intervenir la compétition pour les éléments minéraux entre arbres et tapis herbacé et le niveau d'engorgement par l'eau des horizons superficiels des sols, qui résulte de l'évapotranspiration de l'ensemble du couvert végétal (arbres + végétation du sous-bois).*

Quercus robur / Quercus petraea / *hydromorphie temporaire / compétition / drainage / désherbage / fertilisation / croissance radiale / dendrochronologie*

INTRODUCTION

Large French forest areas are characterized by acid soils which are subjected to pronounced temporary waterlogging conditions. Most of these forests have been treated for centuries as coppice-with-standards stands, in which oaks (*Quercus robur* L and *Q petraea* [Matt] Liebl) are the predominant species in the standard trees. In many places, the foresters are confronted with crucial problems, especially at the time of the natural regeneration of the trees, which is always sparse and uncertain. The very forest status of the land is even often at stake: the understorey is invaded by a dense cover of few 'social' herbaceous species and the forest slowly turns into a heathland (Aussenac and Becker, 1968; Becker, 1972).

The ecological causes of these natural regeneration problems have been previously studied (Becker and Lévy, 1983). The decisive factor is clearly the high competition the oak seedlings are subjected to from the herbaceous ground vegetation. The potential benefit of the light supplied after a thinning in the stand is lost and even reversed, because, simultaneously, the growth of the competing grasses is highly stimulated. A similar negative result is observed after draining the soil, when the ground vegetation is dominated by the purple moor-grass (*Molinia caerulea* [L] Moench).

There were some studies on the potential interest of various silvicultural operations to improve the growth of trees in somewhat comparable situations. Much of them dealt with soil drainage and fertilization, but few have treated the two aspects at one time. On coniferous seedlings, these treatments may have a separate (Richardson, 1981) or interactive (Kaufmann et al, 1977) positive effect. Results concerning mature broad-leaved species are much rarer. They generally show also, for example, on *Betula pubescens* Ehrh, a separate (Valk, 1982) or interactive (Kollist and Valk, 1982) positive effect of drainage and fertilization. Most other studies dealt with drainage or fertilization separately.

The effect of drainage on the growth of coniferous species is generally favourable in the early stages of the stands (eg, Bialkiewicz, 1976; Wang et al, 1985; Hauser et al, 1993) as well as in mature stands (Pakhuchii, 1978; Dang and Lieffers, 1989; Trettin and Jones, 1989), however sometimes during rainy years only (Vomperskaya, 1980). Less attention has been paid on broad-leaved species, and results are more contrasting, from clear positive effects (Belgrand and Lévy, 1985) to the absence of effect (Kollist, 1975) and even negative effects in young stands (Holstener-Jørgensen and Bryndum, 1983) as well as in older ones (Holstener-Jørgensen, 1968).

The improvement of growth through supplying mineral nutrients to the soil has been often demonstrated, but in site conditions far from those of our study, mainly on coniferous species (eg, Gelpe and Guinaudeau, 1974; Nys, 1981, 1984; Bonneau, 1986; Becker 1992; Brockley, 1992; Lebourgeois et al, 1993). Some authors found a clear interaction with weather conditions and water availability (Spiecker, 1991; Snowdon and Benson, 1992), especially for nitrogen supply (Stegemoeller and Chappell, 1990; Becker, 1992; Benson et al, 1992). Studies dealing with broad-leaved species were much rarer. Most experiments show that fertilization improves growth, for example, in oak (Garbaye et al, 1974) and beech (Toutain et al, 1988) stands.

In comparison, much fewer studies have investigated the competing role of the ground vegetation on tree growth. These studies seem to have been devoted to the young stands exclusively, and show a positive effect of weeding (Frochot, 1984; Balneaves and Henley, 1992), sometimes with an interaction with the hydric status (lack or excess of water) (Lévy et al, 1990; Frochot et al, 1992).

In conclusion, the growth of mature oaks in the unfavourable site conditions just described, and the possibility of improving it through various silvicultural operations, are still poorly known (Becker and Lévy, 1986). Three main ecological factors may play an important role: level and length of the temporary soil waterlogging, chemical soil properties, and competition for water and/or nutrients from the dense herbaceous ground vegetation. The objectives of the present study were i) to quantify the radial growth response of trees to various interventions which were intended to improve each of these factors, that is, draining of the seasonal excess of water through ditching, supply of mineral fertilizers and removal of the herbaceous competition through chemical weeding, and ii) bringing to the fore possible interactions between these treatments.

MATERIALS AND METHODS

Two oak stands were studied. They are located in the state forest of Mondon, southeast of Lunéville (Meurthe-et-Moselle, France; 48°34'N, 6°31'E), on the old alluvial deposits of the Meurthe River. The texture of the soils generally is silty-clayey to sandy-silty-clayey. Elevation is about 250 m asl and rather constant. The climate type is semi-continental; the annual precipitation amounts to 750 mm and is rather well distributed all year long; the annual mean temperature is 9.5 °C (between 0.4 °C in January and 18.8 °C in July).

The 'Molinia' site

This site has a surface area of 2 ha. The stand is a severely degraded coppice-with-standards, in which the coppice is now practically absent and has been replaced by a dense herbaceous layer dominated by the purple moor-grass (*M caerulea* [L] Moench). The standards are not numerous, mainly composed of pedunculate oaks (80%) and sessile oaks (20%), ranging in age between 70 and 180 years. The soil is a secondary pseudogley, with a hydromoder-type humus (pH 4.4), chemically very poor. In winter and spring, during rainy periods, the water table rises close to the surface (0 to –5 cm); in an average year, it is present from the middle of November to the end of May.

The 'Carex' site

This site has a surface area of 2.6 ha. The stand is also an old coppice-with-standards but less degraded than the Molinia site. The standards are almost exclusively pedunculate oaks, ranging in age between 50 and 160 years. The coppice is present but at a very low density. It is mainly composed of hornbeam (*Carpinus betulus* L). The ground vegetation also is very dense, but here it is dominated by a sedge species, *Carex brizoides* L. The soil is not very different from the soil in the Molinia site. It is chemically less poor, and its texture is slightly coarser in the depth, which explains that the water tables are less shallow (–10 to –15 cm) and less lasting.

Treatments

Both experimental areas were divided into two parts in the spring of 1974. One part remained untouched; the other was drained by digging ditches, about 10 to 20 m away from one another. Some measurements indicated that the corresponding lowering of the water tables was about 20 to 30 cm during very rainy periods.

On 18 August 1981, part of the experimental areas, drained and undrained, was chemically weeded. Only one spraying of glyphosate (N-[phosphono-methyl]glycine) was sufficient for totally eliminating both Molinia and Carex layers. The solution used contained 5 L of Roundup® (isopropylamine salt of glyphosate; Monsanto Company) in 1 200 L of water.

Finally, a comprehensive fertilization was carried out in 1982 on various area subsamples. A first supply was made on 26 May in the form of 112 $kg.ha^{-1}$ of 'superphosphate triple', containing 50 kg of P_2O_5; 690 $kg.ha^{-1}$ of 'scories Thomas', containing 110 kg of P_2O_5 and 345 kg of CaO; and 400 $kg.ha^{-1}$ of 'patenkali', containing 120 kg of K_2O and 40 kg of MgO. Nitrogen was supplied later in the year (23 June) to minimize its direct leaching out of the soil: 600 $kg.ha^{-1}$ of 'ammonitrate' containing 204 kg of N. Nitrogen was supplied again in 1985.

Because of practical reasons related to field conditions and to the structure of the stands, it was not possible to obtain a sample which was balanced for all the combinations of the treatments. This was also due to the fact that the experimental design was originally conceived to study the dynamics of the natural oak seedlings (Becker and Lévy, 1983). In particular, fertilization was not crossed with weeding. Moreover, it was not tested on sessile oak, which is not widespread enough in the stands. In this study, replications were not based on sample surfaces. Instead, the age and the size of the trees studied made it possible to consider each tree to be a replication. In total, 618 trees were studied, among which were only six sessile oaks in the Carex site. Table I shows the distribution of the 612 other oak trees in the various treatments and their combinations.

Dendrochronological study

During the winter of 1991/1992, each tree was cored to the pith with a 5-mm Pressler corer, at a height of 2.80 m (to minimize the negative effects on the wood quality of the butt log), from the northern side of the trunk. Throughout the text, age refers to that determined at this height.

The annual ring widths were measured with a binocular microscope fitted with a 'drawing tube' and a digitizing tablet coupled to a computer. The individual ring-width series were synchronized (cross-dating) using a specific computerized graphic program after progressive detecting of so-called pointer years. Neither false nor missing rings were found in both sessile and pedunculate oaks. Then, each ring width was converted into basal area increment (BAI) according to its

Table I. Number of trees studied in the various treatments and their combinations.

	Molinia site								*Carex site*			
	Pedunculate oak				*Sessile oak*				*Pedunculate oak*			
	Undrained		*Drained*		*Undrained*		*Drained*		*Undrained*		*Drained*	
	nW	*W*	*nW*	*W*	*nW*	*W*	*nW*	*W*	*nW*	*W*	*nW*	*W*
Unfertilized	54	16	158	18	6	1	39	8	97	44	90	15
Fertilized	15	–	20	–	–	–	–	–	19	–	15	–

nW: unweeded; W: weeded.

distance from the pith, because BAI is more directly related to the production rate (Federer et al, 1989).

Then, BAIs were standardized in order to filter the residual effect of the cambial age (ie, the age of a tree at the time of annual ring formation) and better observe the own effect of the treatments. The method used for standardizing developed in two stages (Becker 1989; Cook et al, 1990). The first stage consisted in i) calculating the mean BAI of all rings available at each cambial age in the control trees, ii) plotting the resulting curve and iii) fitting a polynomial curve to these averaged data. In the second stage, a radial growth index, expressed in percent, was calculated for each of the rings measured, including those from control and treated trees, by dividing its raw BAI value by the corresponding reference value at the same cambial age given by the polynomial model.

Finally, mean radial growth indices were calculated for each silvicultural treatment and each calendar year, and the corresponding curves were plotted. In order that the specific effects of the treatments may be easier to observe and to quantify, each curve was compensated in such a way that its mean position was similar to that of the corresponding control trees during the 10 years preceding the application of the treatment. The significance of a given treatment was tested for each calendar year with a Student's *t*-test involving the treated trees and the corresponding control trees.

RESULTS

Each of the results presented hereafter refers to the BAI of the trees of a given treatment by comparison with the increment of the corresponding control trees.

The effect of soil drainage

Numerous stratifications were performed on the whole available sample. They showed that it was necessary to take into account the site type, the oak species and the age of the trees for a better understanding of the results related to ditching.

In the Carex site (moderately waterlogged), almost only pedunculate oaks were present. Drainage practically had no significant effect on the radial growth, whatever the age of the trees (fig 1a).

In the Molinia site (strongly waterlogged), the age of the trees is an important parameter. After various tests, trees were divided into 'young' oaks ($\leq$ 110 years) and 'old' oaks (> 110 years). Unfortunately, there were no young sessile oaks available in the undrained parts of the experimental plot.

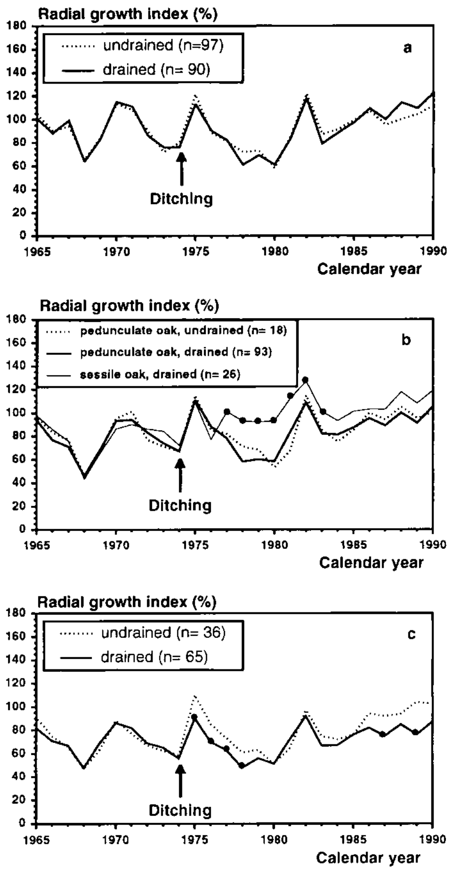


Fig 1. Effect of drainage on oak radial growth without weeding or fertilization. Black dots indicate the significant (at $P = 0.05$) yearly differences between the treated and the control trees. (**a**) Pedunculate oaks in the Carex site (moderately hydromorphic); (**b**) young (≤ 110 years) sessile and pedunculate oaks in the Molinia site (strongly hydromorphic); (**c**) old (> 110 years) pedunculate oaks in the Molinia site.

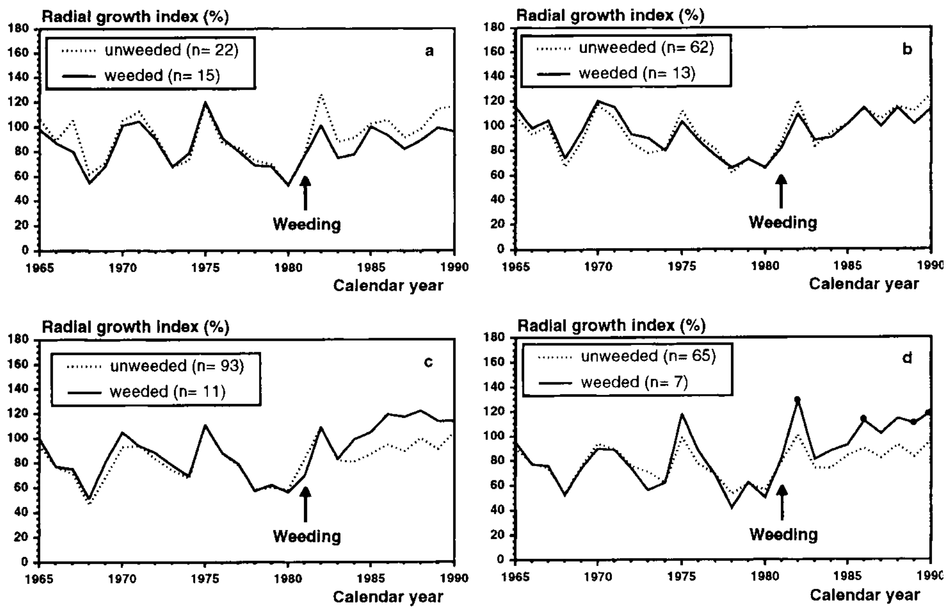
However, the shape of the corresponding growth curve and, above all, the comparison with the growth of the young pedunculate oaks, showed that the young sessile oaks benefited from drainage. The relative increase was about +20% from 1974 to 1991 (fig 1b). The difference in the reaction of the two oak species became suddenly more pronounced after 1976, which was characterized by an exceptionally severe regional drought, and is statistically significant at $P = 0.05$ from 1977 to 1983. On the contrary, the old sessile oaks ($n = 13$) did not significantly react to drainage when compared with the corresponding undrained trees. A rather clear negative effect, significant at $P = 0.05$ in 1975–1978, 1987 and 1989, was even observed in the old pedunculate oaks (fig 1c). The relative radial growth decrease was 12% from 1974 to 1991.

The effect of chemical weeding

To study the effect of weeding, various stratifications showed that it was useful to take into account the site type, the age of the trees and the waterlogging conditions (simultaneous drainage or not). The following results refer to pedunculate oak only.

In the Carex site, there was no interaction with drainage. Weeding seemed to have a steady – although not significant at $P = 0.05$ – negative effect (–13% in the treated trees compared to the control trees) on the growth of the young trees (fig 2a), while it had no significant effect on the growth of the old trees (fig 2b).

In the Molinia site, a strong positive interaction was observed between weeding and drainage, in the young trees as well as in the old trees. In the young trees, although none of the yearly differences is significant at $P = 0.05$, their steadiness since 1983 onwards (+17% in the treated trees; fig 2c) makes the reality of the weeding effect highly probable. In the old trees, the relative growth increase was 22% since 1981 onwards (fig 2d), and four of the yearly differences are significant at $P = 0.05$. On the contrary, although none of the yearly differences is significant at $P = 0.05$, the effect of weeding alone seemed to be rather neg-



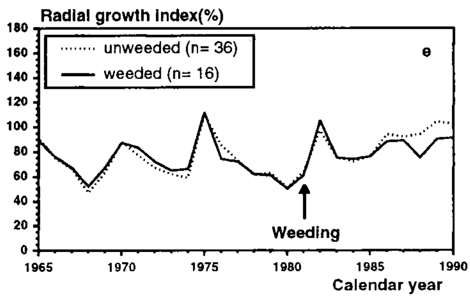


Fig 2. Effect of weeding on pedunculate oak radial growth without fertilization. Black dots indicate the significant (at $P = 0.05$) yearly differences between the treated and the control trees. (**a**) Young trees (≤ 110 years) in the Carex site (moderately hydromorphic); undrained plot. (**b**) Old trees (> 110 years) in the Carex site; plot drained in 1974. (**c**) Young trees in the Molinia site (strongly hydromorphic); plot drained in 1974. (**d**) Old trees in the Molinia site; plot drained in 1974. (**e**) Old trees in the Molinia site; undrained plot.

ative (–5% since 1981 onwards), particularly since 1986 (ie, 5 years after the herbicide spraying) (fig 2e).

The effect of fertilization

For statistical reasons (table I), only pedunculate oak was considered when analysing the results. No interaction was found between fertilization and drainage, nor between fertilization and weeding. The effect of fertilization on radial growth was highly – and significantly at $P = 0.05$ – beneficial in all situations whatever the site type: about +20% in the treated trees compared to the control trees.

However, the time dynamics of this effect was noticeably different according to the age of the trees. The positive effect was lower in the young oak trees (relative growth increase +15% on average from 1982 to 1990), but it still was high when the trees were cored (fig 3a). The yearly differences are significant at $P = 0.05$ from 1986 to 1988. On the contrary, the mean effect was higher in the old oak trees (+25% on average from 1982 to 1990), but it was tending

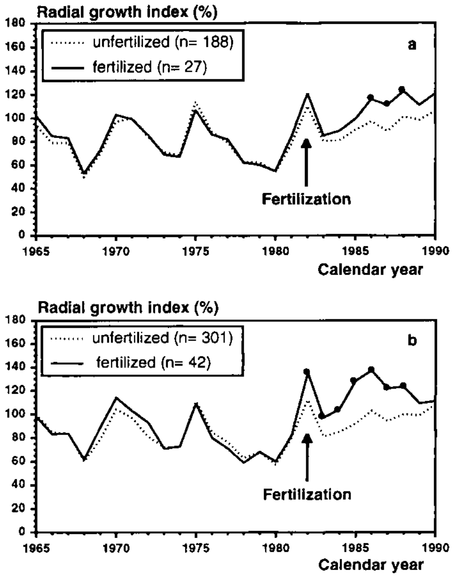


Fig 3. Effect of fertilization on pedunculate oak radial growth whatever the site type and the other experimental treatments. Black dots indicate the significant (at $P = 0.05$) yearly differences between the treated and the control trees. (**a**) Young trees (≤ 110 years); (**b**) old trees (> 110 years).

to vanish 9 years after having supplied the fertilizers (fig 3b). The yearly differences are significant at $P = 0.05$ from 1982 to 1988.

DISCUSSION AND CONCLUSION

The results concerning the effect of fertilization were both clear and simple. As in most of the earlier studies, including those on mature broad-leaved trees (Toutain et al, 1988), especially oak trees (Garbaye et al, 1974), a large and lasting improvement of radial growth occurred after having supplied mineral nutrients on acid and chemically poor soils. In the site conditions of this study, there was no interaction with other treatments. This result differs from that of Kaufmann et al (1977), who found a clear positive interaction between fertilization and drainage, but in young plantations of *Pinus elliottii*. On the other hand, in the mature oak stands we have studied, the duration of the fertilizing effect depended on the age of the trees: the positive effect tended to disappear after about 10 years in the old trees (ie, > 110 years). For both young and old pedunculate oaks, it seems that the renewal of nitrogen supply in 1985 was beneficial to radial growth.

The proper effect of drainage was more complex to analyse. The results available through the literature are also rather variable, even when considering only studies made in mature stands. In numerous studies, the age of the trees seemed an important parameter. While some concluded without reservation that drainage effect was highly positive (Pakhuchii, 1978; Dang and Lieffers, 1989; Trettin and Jones, 1989), other studies showed a depressive effect on growth for several years (Holstener-Jørgensen, 1968) or underlined that drainage was beneficial to the relatively young trees only (Wang et al, 1985). In the case of the temporary waterlogged soils we have studied, drainage alone was clearly beneficial to the rather young (≤ 110 years) sessile oak trees only. Otherwise, digging ditches was a loss of time and money. Drainage tended even to decrease the radial growth of the old pedunculate oak trees.

The most original result of the study concerns the potential role of the herbaceous ground vegetation in the radial growth of mature oak stands. This role was double, and the two aspects had to be dissociated to understand the effect of weeding. The dense *M caerulea* or *C brizoides* layers exert an undoubted competition for the mineral nutrients available in the soils (negative role), but simultaneously they may take an important part in the total evapotranspiration of the forest (Loustau and Cochard, 1991) and therefore in the lowering of the water tables in the soil (positive role). This explains that a depressive effect was observed on the radial growth of oak when weeding was the only silvicultural intervention, because of the aggravation of the temporary waterlogging conditions. On the contrary, when weeding was accompanied by the drainage of the water in excess in the soil, the radial growth of the oak trees was greatly increased (about +20% of basal area increment), at least in the most waterlogged soils such as those in the Molinia site.

The practical conclusions for the silvicultural management of degraded oak forests on acid and temporary waterlogged soils are clear. Any intervention which aims to improve one only of the site factors should be avoided, except possibly the supplying of fertilizers. In particular, drainage alone or weeding alone must be prohibited. On the contrary, a chemical weeding well executed, coupled with the digging of ditches to drain the soil, is highly beneficial to tree radial growth. It already has been shown that this double operation is also the most favourable for the installation and growth of natural oak seedlings (Becker and Lévy, 1983). The productivity of the standing oak trees may be still increased through a complete fertilization.

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