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Field effect of P fertilization on N₂ fixation rate of *Ulex europaeus*

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Abstract – European gorse (*Ulex europaeus* L.) N₂ fixation rate (%Ndfa) was studied in a maritime pine (*Pinus pinaster* Ait.) oligotrophic forest. Fertilization field trials were carried out on 5 sites with various inputs of phosphorus (0–240 kg P₂O₅.ha⁻¹). Seven to ten years after pine planting, gorse were sampled to evaluate the effect of P fertilization on gorse %Ndfa, determined using the ¹⁵N natural abundance method. One of the prerequisites of this method is the existence of a significant difference between the ¹⁵N/¹⁴N ratios in the atmospheric N reference and in the stand soil N references. This prerequisite was satisfied for 80 of 120 cases. The average %Ndfa was high (70 ± 3%) but with high local variability. No significant difference in %Ndfa was detected among P treatments. Nitrogen concentration of gorse was significantly higher in the highest dose treatments compared to the control.

Ulex europaeus / symbiotic N₂ fixation / ¹⁵N natural abundance / P fertilization / *Pinus pinaster*

Résumé – Effet in situ de la fertilisation en phosphore sur le taux de fixation de l'azote atmosphérique d'*Ulex europaeus*. Le taux de fixation de l'azote atmosphérique (%Ndfa) de l'ajonc d'Europe (*Ulex europaeus* L.) a été étudié dans une forêt oligotrophe de pins maritimes. Des essais de fertilisation ont été établis avec plusieurs niveaux d'apport en phosphore (0–240 kg P₂O₅.ha⁻¹). Sept à dix ans après la plantation de pins, les ajoncs ont été échantillonnés afin d'évaluer l'effet de la fertilisation en phosphore sur le %Ndfa, calculé par la méthode de l'abondance naturelle en ¹⁵N. Cette méthode nécessite notamment une différence significative entre les rapports ¹⁵N/¹⁴N de la référence atmosphérique et de la référence du sol des peuplements. Cette condition était satisfaite dans 80 cas sur 120. Le %Ndfa moyen était élevé (70 ± 3 %) mais avec une grande variabilité locale. Aucune différence des %Ndfa n'a été détectée entre les traitements. Les teneurs en azote des ajoncs étaient significativement plus élevées pour les doses maximales que pour les témoins.

Ulex europaeus / fixation symbiotique de l'azote / abondance naturelle en ¹⁵N / fertilisation en phosphore / *Pinus pinaster*

1. INTRODUCTION

Intensively managed forests may suffer in the medium or long-term from nitrogen deficiency [11]. This is particularly true for oligotrophic forests when nitrogen lost by biomass outputs is not offset by N fertilization [16]. This issue has been growing in importance since silvicultural practices have become more and more intensive, notably with rotation lengths getting shorter.

High inputs of nitrogen can be brought naturally into the ecosystem by the presence of N₂-fixing shrubs [25]. P fertilization, used in maritime pine forests due to its positive effect on pine growth [7,24], may increase these natural inputs in two different ways: (i) by increasing the abundance and biomass of N₂-fixing shrubs [3]; and (ii) by increasing the N₂ fixation rate [1]. This second point has been mostly developed in laboratory studies that suggest a P effect on N₂ fixation rate. However, these studies conflict with each others, as such an effect is not always detected. Besides, these results appear signifi-

cant mostly when P concentration is either very low or rather high and thus may not be easily transposable to field conditions (e.g. [1, 12, 17, 19]). They nevertheless show that N₂ fixation is not unresponsive to phosphorus availability.

A previous study tested the field P effect on the fixation rate of leguminous shrubs in a large forest of southwestern France [3]. However, the requested conditions for the used method (¹⁵N natural abundance method) to be properly applied were not met in the fertilized site. It was thus impossible to address the question of the field P effect on fixation rate, even though other P effects on fixing shrubs were quantified. The natural abundance method also revealed to be usable on another sites of the same area.

The objective of this study is to readdress the field P effect on N₂ fixation rate in the same area and on the same specie, but with a strengthened sampling scheme. It tried to use the ¹⁵N natural abundance method on other fertilization trials than Augusto et al. [3]. It also used the other blocks of the previously studied trial as conditions allowing or forbidding the method are very heterogeneous even on short distances.

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Table I. Characteristics of each site. Pines C130: Circumference at 130 cm height. Significant differences are as given by a *t*-test with a 5% error threshold, and confirm the P effect on pine growth [7, 24]. 3 blocks have been sampled at Blagon and 1 for each of the other sites.

Site	Pine density (stems.ha ⁻¹)	Pines age at sampling (year)	P fertilization dose (kg P ₂ O ₅ .ha ⁻¹)	Pines C130 (cm)
Blagon	1530	7	0	24.9 a
			80	29.0 b
			160	30.7 c
			240	30.7 c
Lue	1100	8	0	22.4 a
			40	31.2 b
			80	28.5 b
			120	28.0 b
Caudos	1250	7	0	23.2 a
			40	29.2 b
			80	34.9 c
			120	37.6 c
Clochettes	1666	8	0	34.2 a
			80	38.6 b
Grand Ludee	1250	10	0	31.5 a
			120	31.2 a

2. MATERIALS AND METHODS

2.1. Experimental sites (Tab. I)

The experiment took place in the “Landes” forest of southwestern France (see [3] and [22] for further details). The N₂-fixing species studied was European gorse (*Ulex europaeus* L.), a leguminous perennial evergreen spiny shrub found in 60% of the stands of the forest (French Forest Survey). More details on gorse are given by Richardson & Hill [20] and Clements et al. [8].

Five sites were selected: Lue, Caudos, Clochettes, Grand Ludee, and Blagon, the last being the one used in the previous experiment [3]. All the sites were maritime pines (*Pinus pinaster* Ait.) stands established during triple superphosphate fertilization experiments set up between 1994 and 1997. Two to 4 doses of phosphorus (hereafter named Px with *x* = dose of P as kg P₂O₅.ha⁻¹, P0 being the control) were investigated in each trial (Tab. I). Maximal dose ranged from 80 to 240 kg P₂O₅.ha⁻¹.

2.2. Theory of the ¹⁵N natural abundance method

This method allows estimating the percentage of nitrogen derived from the atmosphere (%Ndfa) in a N₂-fixing plant. It is based on the comparison of the ¹⁵N abundance of a N₂-fixing plant to those of a non fixing plant [15]. The ¹⁵N isotopic enrichment (δ¹⁵N) is calculated as below, defined according to the atmosphere which is considered as the standard:

$$\delta^{15}\text{N} = \frac{[\text{N}^{15}]/[\text{N}^{14}]_{(\text{plant})} - [\text{N}^{15}]/[\text{N}^{14}]_{(\text{atm})}}{[\text{N}^{15}]/[\text{N}^{14}]_{(\text{atm})}} \times 1000.$$

Three δ¹⁵N are used to estimate the %Ndfa: that of the leguminous plant studied (N₂-fixing species, δ¹⁵N_{leg}), that of a reference plant (non N₂-fixing species, δ¹⁵N_{ref}), and that of a leguminous plant with a %Ndfa equal to 100% (same N₂-fixing species, δ¹⁵N_{fix}):

$$\% \text{Ndfa} = \frac{(\delta^{15}\text{N}_{\text{ref}} - \delta^{15}\text{N}_{\text{leg}})}{(\delta^{15}\text{N}_{\text{ref}} - \delta^{15}\text{N}_{\text{fix}})} \times 100.$$

It should be noted that the δ¹⁵N of the bulk soil greatly differs from the pool of nitrogen available to plant nutrition [15, 26]. Thus, using δ¹⁵N_{soil} rather than δ¹⁵N_{ref} would have lead to errors in %Ndfa estimations.

The ¹⁵N natural abundance method needs to satisfy several conditions in order to be applicable: (i) a significant difference between δ¹⁵N_{ref} and δ¹⁵N_{fix} must exist (ii) the reference species absorbs the mineral nitrogen in the same soil volume and during the same periods as the N₂-fixing species. These conditions have been previously tested in the ‘Landes’ forest [3]. It appeared that (i) the significant difference between δ¹⁵N_{ref} and δ¹⁵N_{fix} exists in some sites but not in the northern blocks of Blagon, which forbade the authors to answer the question of the P effect (ii) usable reference species are *Erica scoparia* and *Calluna vulgaris*, the first being the best as its morphology is closer to that of *Ulex europaeus* and (iii) some variability occurred in δ¹⁵N_{ref} at a local scale, so that there could be a significant difference between δ¹⁵N_{ref} and δ¹⁵N_{fix} in other (southern) blocks of Blagon, and/or in other sites.

2.3. δ¹⁵N_{fix} determination

δ¹⁵N_{fix} determination occurred in the same manner than in Augusto et al. [3], but with one more sampling year (2006), resulting in a slightly different mean δ¹⁵N_{fix} value (−0.55‰ with *n* = 14 versus −0.50‰ in [3]).

2.4. Sampling and analyses

2.4.1. N content and fixation rate determination

Lue, Caudos, Clochettes and Grand Ludee trials were sampled in February and March 2005. Blagon was sampled in July 2005. In Blagon, 4 treatments (0, 80, 160 and 240 kg P₂O₅.ha⁻¹) were sampled in the 3 southern blocks (different from those previously sampled by [3]). For each of the 4 other sites, only one block was used per site, with one sampling area in each treatment. The sampling areas were located near the center of the treated plots to avoid edge effects.

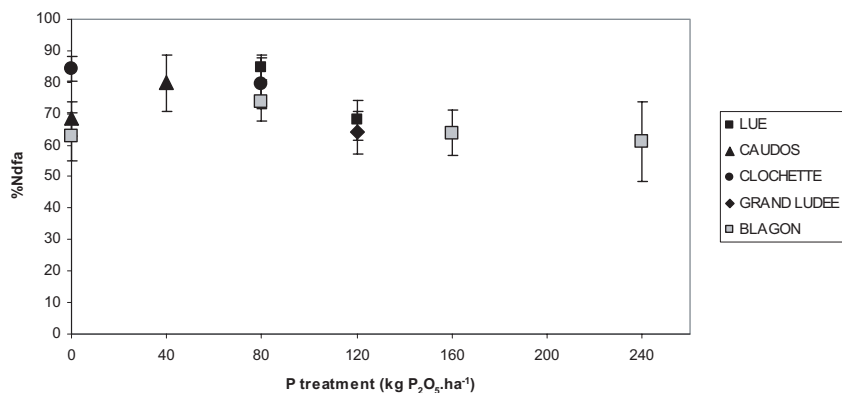


Figure 1. Average N₂ fixation rate (%Ndfa) of *Ulex europaeus* according to sites and P fertilization.

In each sampling area, green twigs from 5 pairs *Ulex europaeus*/reference plant (*Erica scoparia* or *Calluna vulgaris*) were collected. Pairs were selected so that the two plants and their sizes were as close as possible. The distance between the two plants, their respective heights as well as the species of the reference (*Erica scoparia* or *Calluna vulgaris*) were systematically recorded in Blagon. The green twigs were then dried at 65 °C for 48 h, coarsely ground (Willey-ED5 grinder) then finely ground in a ball mill (Retsch PM4 planetary grinder) before N content and δ¹⁵N determination by spectrometry ('sector field' ICP-MS). In the previous study of Blagon, repeats were bulked together before δ¹⁵N determination leading to a unique pair of δ¹⁵N values (δ¹⁵N_{ref} and δ¹⁵N_{leg}) per sampling area. Here, all individual samples were analyzed independently.

2.4.2. Growth determination

Except in Blagon, all European gorse stems in the sampling plots were cut and then brought to the laboratory. Stems were sorted along diameter at 10 cm, and then 10 of them were selected according to a systematic sub-sampling based on the frequency distribution of stem diameters. The 5 remaining biggest stems were then added to the sub-sample. The selected stems were cut at 10 cm shortly after sampling, and the growth rings immediately numerized for measurement with the ImageTool software (UTHSCSA).

2.5. Mathematical and statistical data analysis

According to Watt et al. [25], it is acceptable to calculate %Ndfa when the difference between δ¹⁵N_{fix} and δ¹⁵N_{ref} is 1‰ or higher, provided the soil has been homogenized by ploughing before stand installation, which is the case on all of our sites. We therefore discarded the samples who did not exhibit such a difference. We did the same for negative values of %Ndfa, while %Ndfa values slightly higher than 100 were assumed to be equal to 100.

Statistical analyses were performed either with the STATISTICA software v6.0 (StatSoft Inc., 1984–2001) or with the SAS/STAT software (SAS Institute Inc. 1999). Kruskal-Wallis ANOVA were used to assess differences between treatments, as well as Mann-Whitney U tests whenever ANOVA showed significant differences. Growth rings differences between treatments were tested per year with Bonferroni *t* tests. All significant differences were determined for a 5% error.

3. RESULTS AND DISCUSSION

3.1. Effect of P fertilization on gorse growth and nitrogen concentration

Individual growth of gorse was significantly higher only for the higher doses treatments (P80 and P120) in Caudos. A similar effect had been previously shown in Blagon for the P160 and P240 treatments [3]. It thus seems like gorse growth is positively affected only for very high P doses (P120 being the maximum currently used by local foresters).

The N concentration of gorse increased gradually with P doses (mean [N] across all sites: P0 = 11.5 ± 0.2; P40 = 11.9 ± 0.4; P80 = 12.4 ± 0.3; P120 = 12.6 ± 0.4; P160 = 13.9 ± 0.5; P240 = 14.0 ± 0.6). This result was observed in all sites but it was significant only for the higher doses in Lue (P80 and P120) and Blagon (P160 and P240). Again, an individual response of gorse seems to be more likely to occur for high or very high P doses.

3.2. *Ulex europaeus* fixation rate (Fig. 1; Appendix I)

Augusto et al. [3] showed that most of the conditions required for use of the natural abundance method according to Högberg [15] and Boddey et al. [5] were satisfied in our context, except for the difference between δ¹⁵N_{fix} and δ¹⁵N_{ref} in some cases. The same problem occurred here in a less dramatic manner, as the absolute difference between δ¹⁵N_{fix} and δ¹⁵N_{ref} was low as well as being highly variable. However, following the 1‰ minimum difference preconized by Watt et al. [25] we still retained a sufficient number of %Ndfa values (80 out of 120).

From the 60 %Ndfa values calculated in Blagon, 18 were discarded (P0 = 0; P80 = 9; P160 = 1; P240 = 8). The absolute differences between δ¹⁵N_{fix} and δ¹⁵N_{ref} were on average 1.94 ± 0.19‰ for Blagon. In the control treatment, where no value was discarded, there was no significant difference among blocks. Consequently, values of the three blocks were merged per treatment. No significant difference was then detected between the treatments. Including the discarded values in the data analysis did not change this result. Across all treatments, the average value of nitrogen fixation rate was 63% with a standard error of 4%.

Similarly, 22 %Nd_{fa} values were discarded from the 60 calculated values in the four other sites. The absolute difference between $\delta^{15}\text{N}_{\text{fix}}$ and $\delta^{15}\text{N}_{\text{ref}}$ was on average $1.49 \pm 0.99\%$. We calculated the mean %Nd_{fa} value of a sampling plot only if at least 3 from the 5 %Nd_{fa} values of this plot were satisfying the 1‰ difference criteria. Thus we could not calculate the mean for the following plots: P0 and P40 of Lue, P80 and P120 of Caudos and the P0 of Grand Ludee.

It was assumed that gorse was growing in similar conditions in the five sites and therefore the fixation rates per treatment were globally compared (Fig. 1). Across all sites and treatments, the average nitrogen fixation rate was 70% with a standard error of 3% (standard deviation = 28%). No significant difference was detected among the treatments of the five sites.

3.3. Relevance of the ^{15}N natural abundance method in our context

Some authors such as Högberg [15] preconized a minimum difference of 5‰ between $\delta^{15}\text{N}_{\text{fix}}$ and $\delta^{15}\text{N}_{\text{ref}}$. Our values concerning the fixation rate could therefore be considered as low confidence level results. Despite this limitation, the absence of any effect of in situ P fertilization seems quite robust, as it emerged from 80 individuals and is stable across all sites and treatments. Because of the variability of the rejected values, some treatment means were more reliable than others. In Blagon, almost all the values for the P0 and P160 treatments were retained and their values show reasonable standard errors as well as remarkably close means. Moreover, there was no significant difference between %Nd_{fa} values calculated with a difference of 3‰ or more between $\delta^{15}\text{N}_{\text{fix}}$ and $\delta^{15}\text{N}_{\text{ref}}$ (%Nd_{fa} = $79 \pm 6\%$; $n = 14$) compared to those calculated with less than 3‰ of difference (%Nd_{fa} = $71 \pm 5\%$; $n = 66$). Finally, Danso et al. [9] showed that the reliability of the fixation rate calculation increases with increasing rate, and our %Nd_{fa} values were rather high. Therefore, we assumed that the ^{15}N natural abundance method gave here results with an acceptable level of confidence.

3.4. Nitrogen fixation rate in response to P doses

No response of the N fixation rate to increasing doses of P fertilizer was detected, whatever the site or treatment considered. While this is in contradiction with some laboratory results [1, 12, 17, 19] which mostly showed some effect of phosphorus on nitrogen fixation characteristics (i.e. number and growth of nodules, nodule activity measured by acetylene reduction assays, and fixation rate measured by ^{15}N isotopic dilution), it is not very surprising. As previously stated, these laboratory results generally showed an effect of phosphorus when it was added in high concentrations or when it ended a severe deprivation of this nutrient. These kind of severe conditions were unlikely to happen in situ, as ecosystems are generally naturally buffered by a number of factors (e.g. soil characteristics, leeching, competition...). Even if the Landes soils are quite poor, notably in phosphorus [22], gorse is considered

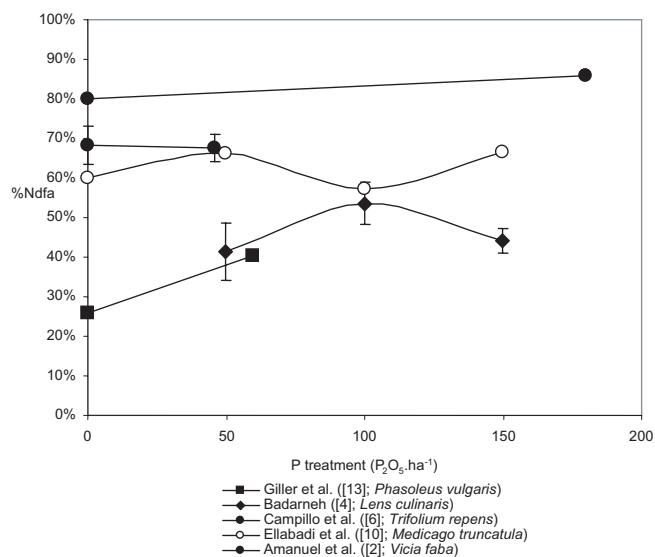


Figure 2. Nitrogen fixation rate as reported by crop studies. Closed symbol: field experiment; open symbol: pot experiment. [4] and [2]: means of 2 and 3 sites, respectively.

to be an oligotrophic species well adapted to these conditions [8, 20].

The N content of gorse is sometimes nevertheless higher for high doses, and this could be interpreted as a physiological response of gorse to high P doses which may be thought not entirely compatible with the absence of effect on fixation rate. We suggest two hypotheses to explain this apparent contradiction (i) The individual growth increase for high doses is responsible for a larger soil exploration as root growth is stimulated as well as aboveground one (root/shoot ratio not being significantly affected by fertilization: control = 0.50 ± 0.13 ; fertilized = 0.57 ± 0.07 ; Cavard and Augusto, unpublished data), increasing both soil N uptake and N fixation flux without modifying the balance between them (ii) Shadowing due to bigger tree canopies in the fertilization treatments [23] overbalance the potential effect on N fixation rate, as Rastetter et al. [18] predicted a decrease in N fixation rate with decreasing light availability.

Whatever the reasons may be, it nevertheless seems that for these conditions and for the P doses likely to be used in the field, gorse N fixation rate do not respond to P fertilization. Even though our results may be considered as frail because of the small differences between $\delta^{15}\text{N}_{\text{fix}}$ and $\delta^{15}\text{N}_{\text{ref}}$, previously published results of in situ P fertilization trials of annual crops showed very similar trends (Fig. 2; see also e.g. [14] or [21]), which strengthen the likeliness of such a conclusion. Of course, P fertilization could nevertheless increase total N₂ fixation by increasing gorse biomass, but our results concerning P effect on gorse individual growth are not very conclusive under 120 kg P₂O₅.ha⁻¹.

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REFERENCES

- [1] Almeida J.P.F., Hartwig U.A., Frehner M., Nösberger J., Lüscher A., Evidence that P deficiency induces N feedback regulation of symbiotic N₂ fixation in white clover (*Trifolium repens* L.), *J. Exp. Bot.* 51 (2000) 1289–1297.
- [2] Amanuel G., Kühne R.F., Tanner D.G., Biological nitrogen fixation in faba bean (*Vicia faba* L.) in the Ethiopian highlands as affected by P fertilization and inoculation, *Biol. Fertil. Soils* 32 (2000) 353–359.
- [3] Augusto L., Crampon N., Saur E., Bakker M.R., Jordan-Meille L., Pellerin S., de Lavaissière C., Trichet P., High rates of N₂-fixation of *Ulex* species in the understory of Maritime pine stands (*Pinus pinaster*) and potential effect of P-fertilisation, *Can. J. For. Res.* 35 (2005) 1183–1192.
- [4] Badarneh D.M.D., Magnitude of nitrogen fixation by lentil at different rates of phosphorus using ¹⁵N technique, *J. Agron. Crop Sci.* 175 (1995) 7–14.
- [5] Boddey R.M., Peoples M.B., Palmer B., Dart P.J., Use of the ¹⁵N natural abundance technique to quantify biological nitrogen fixation by woody perennials, *Nutr. Cycl. Agroecosys.* 57 (2000) 235–270.
- [6] Campillo R., Urquiaga S., Undurraga P., Pino I., Boddey R.M., Strategies to optimise biological nitrogen fixation in legume/grass pastures in the southern region of Chile, *Plant Soil* 273 (2005) 57–67.
- [7] Cheaïb A., Mollier A., Thunot S., Lambrot C., Pellerin S., Loustau D., Interactive effects of phosphorus and light availability on early growth of maritime pine seedlings, *Ann. For. Sci.* 62 (2005) 575–583.
- [8] Clements D.R., Peterson D., Prasad R., The biology of canadian weeds - 112 - *Ulex europaeus* L., *Can. J. Plant. Sci.* 81 (2001) 325–337.
- [9] Danso S.K.A., Hardarson G., Zapata F., Misconceptions and practical problems in the use of ¹⁵N soil enrichment techniques for estimating N₂ fixation, *Plant Soil* 152 (1993) 25–52.
- [10] Elabbadi K., Ismaili M., Materon L.A., Competition between *Medicago truncatula* and wheat for ¹⁵N labeled soil nitrogen and influence of phosphorus, *Soil Biol. Biochem.* 28 (1996) 83–88.
- [11] Fisher R.F., Binkley D., Ecology and management of forest soils, Wiley and sons, New York, 2000.
- [12] Gentili F., Huss-Danell K., Local and systemic effects of phosphorus and nitrogen on nodulation and nodule function in *Alnus incana*, *J. Exp. Bot.* 54 (2003) 2757–2767.
- [13] Giller K.E., Amijee F., Brodrick S.J., Edje O.T., Environmental constraints to nodulation and nitrogen fixation of *Phaseolus vulgaris* L. in Tanzania. II. Response to N and P fertilizers and inoculation with *Rhizobium*, *African Crop Sci. J.* 6 (1998) 171–178.
- [14] Gunawardena S.F.B.N., Danso S.K.A., Zapata F., Phosphorus requirements and nitrogen accumulation by three mungbean (*Vigna radiata* (L.) Welzek) cultivars, *Plant Soil* 147 (1992) 267–274.
- [15] Högberg P., ¹⁵N natural abundance in soil-plant systems, *New Phytol.* 137 (1997) 179–203.
- [16] Laclau J.P., Ranger J., Deleporte P., Nouvellon Y., Saint-André L., Marlet S., Bouillet J.P., Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo. 3. Input-output budgets and consequences for the sustainability of the plantations, *For. Ecol. Manage.* 210 (2005) 375–391.
- [17] O’Toole P., Cahalane D.G., Farrell E.P., Effects of phosphate fertilizer on biomass production and N₂(C₂H₂) fixation by pot-grown *Ulex gallii* Planchon in a forest soil, *Biol. Fertil. Soils* 12 (1991) 177–181.
- [18] Rastetter E.B., Vitousek P.M., Field C., Shaver G.R., Herbert D., Agren G.I., Resource optimization and symbiotic nitrogen fixation, *Ecosystems* 4 (2001) 369–388.
- [19] Ribet J., Drevon J.J., The phosphorus requirement of N₂-fixing and urea-fed *Acacia mangium*, *New Phytol.* 132 (1996) 383–390.
- [20] Richardson R.G., Hill R.L., The biology of Australian weeds. 34. *Ulex europaeus* L., *Plant Protection Quarterly* 13 (1998) 46–58.
- [21] Sanginga N., Early growth and N₂-fixation of leucaena and gliricidia at different levels of phosphorus application, *Fertil. Res.* 31 (1992) 165–173.
- [22] Trichet P., Jolivet C., Arrouays D., Loustau D., Bert D., Ranger J., Le maintien de la fertilité des sols forestiers landais dans le cadre de la sylviculture intensive du pin maritime, *Étude et Gestion des Sols* 6 (1999) 197–214.
- [23] Trichet P., Loustau D., Lambrot C., Linder S., Manipulating nutrient and water availability in a maritime pine plantation: effects on growth, production, and biomass at canopy closure, *Ann. For. Sci.* 64 (2007).
- [24] Warren C.R., McGrath J.F., Adams M.A., Differential effects of N, P and K on photosynthesis and partitioning of N in *Pinus pinaster* needles, *Ann. For. Sci.* 62 (2005) 1–8.
- [25] Watt M.S., Clinton P.W., Whitehead D., Richardson B., Mason E.G., Leckie A.C., Above-ground biomass accumulation and nitrogen fixation of broom (*Cytisus scoparius* L.) growing with juvenile *Pinus radiata* on a dryland site, *For. Ecol. Manage.* 184 (2003) 93–104.
- [26] Zeller B., Brechet C., Maurice J.-P., Le Tacon F., ¹³C and ¹⁵N isotopic fractionation in trees, soils and fungi in a natural forest stand and a Norway spruce plantation, *Ann. For. Sci.* 64 (2007).

Appendix I. Retained $\delta^{15}\text{N}$ values, with a minimum absolute difference of 1‰ between $\delta^{15}\text{N}_{\text{ref}}$ and $\delta^{15}\text{N}_{\text{fix}}$ (-0.55‰).

Site	P fertilization dose (kg $\text{P}_2\text{O}_5\cdot\text{ha}^{-1}$)	$\delta^{15}\text{N}_{\text{leg}}$ (‰)	$\delta^{15}\text{N}_{\text{ref}}$ (‰)	$\delta^{15}\text{N}_{\text{ref}}-\delta^{15}\text{N}_{\text{fix}}$ absolute difference (‰)	%Ndfa
Blagon	0	-1.4	-1.8	1.29	33
		-2.5	-2.7	2.14	10
		-2.5	-4.8	4.25	54
		-0.2	-3.7	3.15	100
		0.0	-3.7	3.11	100
		0.6	-3.3	2.95	100
		-1.0	-3.3	2.22	83
		-1.9	-4.2	2.84	63
		-1.3	-1.5	1.36	20
		-0.8	-4.9	1.71	93
		-1.6	-2.3	2.16	39
		-1.7	-3.1	4.27	56
		-1.3	-4.7	1.97	82
		-2.4	-4.6	2.98	55
		-2.5	-4.6	2.78	53
		80	-1.0	-3.5	2.72
	-1.1		-2.8	3.62	76
	-0.9		-1.3	4.33	49
	-0.8		-2.0	2.04	80
	-1.6		-2.7	1.44	51
	-1.3		-2.7	1.09	64
	160	-0.4	-1.9	2.51	65
		-1.1	-2.3	3.32	70
		-2.2	-2.7	1.72	25
		-1.2	-4.8	2.54	86
		-1.6	-2.5	4.20	46
		-0.5	-2.6	4.07	100
		-1.2	-2.0	4.06	57
		-1.4	-1.6	1.43	26
		-1.1	-3.1	2.16	76
		-1.3	-3.6	2.18	75
		-1.3	-2.3	3.04	58
		-1.3	-3.2	1.75	71
		-0.7	-2.6	2.61	91
		-1.7	-1.9	2.09	17
	240	-0.7	-3.5	1.37	93
-0.7		-3.9	1.42	94	
-1.6		-2.0	2.28	29	
-0.9		-2.8	1.51	82	
-1.7		-2.1	1.43	25	
-0.8		-2.0	1.09	82	
-1.4		-1.6	1.29	23	
0	0.4	-1.8	1.25	100	
	0.6	1.0	1.52	25	
40	1.3	-3.4	2.82	100	
	0.1	-1.7	1.13	100	
80	0.0	-2.9	2.30	100	
	0.8	-1.8	1.26	100	
	-1.0	-2.8	2.24	82	
	-1.3	-2.1	1.50	52	
	-0.7	-2.2	1.61	90	
	-0.1	-1.6	1.05	100	

Appendix I. Continued.

Site	P fertilization dose (kg P ₂ O ₅ .ha ⁻¹)	δ ¹⁵ N _{leg} (‰)	δ ¹⁵ N _{ref} (‰)	δ ¹⁵ N _{ref} -δ ¹⁵ N _{fix} absolute difference (‰)	%Ndfa
Caudos	120	-1.7	-2.0	1.48	20
		0.2	-3.0	2.41	100
		-1.7	-3.1	2.54	56
		-0.9	-1.9	1.34	71
		-0.8	-3.5	2.94	92
	0	0.1	-2.2	1.70	100
		-1.0	-1.8	1.27	61
		-1.1	-2.1	1.56	63
		-0.2	-2.2	1.64	100
		-0.5	0.5	1.04	92
40	-0.6	0.7	1.23	100	
	-1.4	-1.7	1.10	27	
	0	-0.6	-4.0	3.48	98
		-0.6	-3.6	3.08	99
		-1.1	-1.9	1.35	57
-1.3		-2.8	2.28	67	
0.4		-2.7	2.12	100	
Clochettes	80	-1.8	-1.8	1.28	4
		-0.8	-2.3	1.73	87
		-0.5	-2.1	1.56	100
		-0.9	-3.2	2.69	86
		-0.3	-2.6	2.10	100
Grand Ludee	0	-1.0	-3.5	2.96	86
		-1.8	-2.6	2.08	38
		-2.0	-2.7	2.11	32
		-2.6	-4.7	4.20	50
		0.2	-2.2	1.61	100
120	0.9	-3.0	2.47	100	