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Biomass partitioning and leaf area of *Pinus radiata* trees subjected to silvopastoral and conventional forestry in the VI region, Chile

Distribución de biomasa y área foliar en árboles de *Pinus radiata* sometidos a manejo silvopastoral y convencional en la VI región, Chile

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ABSTRACT

The effects of silvicultural regimes on leaf area and biomass distribution were analyzed in 16-year old *Pinus radiata* trees growing in the semiarid zone of Chile. Three stands with different silvopastoral management were compared with a conventionally managed stand. Data were obtained through destructive sampling of 36 trees and analyzed by MANOVA and regression models of ANCOVA. Results show that the management regime affects the leaf area. Specific leaf area was affected by both silvicultural regime and crown position. Total biomass per tree under the silvopastoral regime was 2.1 to 2.5 times larger than in the conventional forestry regime. However, aboveground biomass partitioning was neither affected by the silvicultural regime nor by the schemes of silvopastoral management. The most important allometric change was in fine root biomass, which was greater under the conventional forestry regime than in the silvopastoral one. Fine root biomass increases with a regular distribution of the plants in the field, and decreases with the clumping of trees. Similarly, the fine root biomass decreases with fertilization. Both plantation design and fertilization regimes explain the changes in the fine root biomass to components of the crown. However, crown structure influences the magnitude of these changes.

Key words: leaf area, biomass, silvopastoral management, *Pinus radiata*.

RESUMEN

Se analizaron los efectos del régimen silvícola en el área foliar y distribución de biomasa en árboles de *Pinus radiata* de 16 años, creciendo en la zona semiárida de Chile. Para ello se compararon tres rodales con manejo silvopastoral con uno manejado en forma tradicional. Los datos se obtuvieron mediante muestreo destructivo de 36 árboles y se analizaron mediante MANOVA y regresión en modelos de ANCOVA. Los resultados permiten concluir que el régimen de manejo afectó el área foliar. El área foliar específica fue afectada por el régimen silvícola y su posición en la copa. La biomasa total por árbol con régimen silvopastoral es 2,1 a 2,5 veces mayor que los árboles con régimen solo forestal. Sin embargo, la distribución de la biomasa aérea no fue afectada por el régimen silvícola ni por los diferentes manejos silvopastorales. El cambio alométrico más importante fue en la biomasa de raíces finas, la que fue mayor en el régimen de manejo forestal tradicional que el silvopastoral. La relación significativa entre biomasa de raíces finas y componentes de la copa concuerda con el modelo de balance funcional y aumenta cuando la distribución de las plantas es uniforme. La biomasa de raíces finas decrece con la fertilización. Ambos factores explican los cambios de biomasa de raíces finas a los componentes de la copa. Sin embargo, la magnitud de estos cambios es influenciada por la estructura de copas.

Palabras clave: área foliar, biomasa, silvopastoreo, *Pinus radiata*.

INTRODUCTION

Growth can be defined as the net accumulation of carbon and other organic materials in plants, for which photosynthetic and respiration rates are an indirect measurements (Hari et al. 1991). At the same time, photosynthesis depends on leaf production and carbon assimilation per unit leaf area or mass (Wang & Jarvis 1990). Carbon gain is determined by the local availability of light, water and nutrients[1] (Carlyle 1995).

The environment has also an important effect on the process of intraspecific competition. There is an inverse relationship between the net assimilation rate and leaf area index. Therefore, crown size and structure and initial stand density influence carbon gain and distribution within the plant (Perry 1985, Roberts et al. 1993). Artificial grazing could be used to test the effects of crown structure on leaf area and biomass partitioning (Perry 1984). In a silvopastoral system, forest managers make deliberated changes to reduce the amount of light intercepted by the forest canopy to increase pasture biomass production. Their tools are intensive fertilization together with plantation design, tree density and crown structure (Pyke & Zamora 1982). It can be expected that altering the local availability of resources would increase leaf area (Carlyle 1995). Therefore, carbon partitioning in the silvopastoral system should be different from conventional stands, due to the effect of plantation design on crown structure (Linder & Rock 1985). Considering different management regimes, we also studied how competition can affect leaf area, and individual patterns of biomass partitioning. In this respect, we hypothesized that when conditioning the functional balance, crowns structure may influence carbon allocation of trees (Dewar et al. 1994). Our data are based on four 16-year old stands of planted radiata pine (*Pinus radiata* D. Don).

MATERIAL AND METHODS

Study site and experimental design

A silvopastoral experiment was established by the Corporación Nacional Forestal (Chilean Forest Service), in Tanumé, community of Pichilemu, VI Region, Chile (34º9’-34º15’ S, 72º53’-72º59’ W), at an altitude of 340 m of altitude. The area has a subhumid mediterranean climate, with four to six months of drought annually. The study site has an annual average precipitation of 703 mm, with a minimum average temperature of 8.6 ºC and a maximum average temperature of 15.4 ºC. Data were obtained from meteorological station Tanumé, 2.5 km from the study site, during the period 1983 to 1999. The prevailing topography is hilly, but silvopastoral experiment was established on flat topography. Soils in this area are classified as Alfisol, suborder Xeralfs. Soil series is Curanipe, which is metamorphic in origin, derived from marine terraces, susceptible to mantle erosion and gully formations and has reduced drainage.

The experiment, established in the winter of 1983, consisted of radiata pine planted at two initial densities: 625 and 1000 trees ha^{-1} in 6 ha units. Two years later, pasture was established in combinations with the plantations and they became modules of a silvopastoral system. There were two types of pasture: naturally improved, fertilized every 4 years; and artificial pasture sown and fertilized annually for 12 years (Treatments T1-T3, Table 1). All silvopastoral treatments involved the addition of solid fertilizer providing 209 kg P ha^{-1} and 196 kg N ha^{-1}. The artificial pasture was sown with *Falaris tuberosa* and *Trifolium* sp. Var. *Clare*. In the natural pasture and the improved natural one, *Horedeum* sp., *Plantago lanceolata*, *Trifolium* sp., *Vulpia dertonensis*, *Avena barbata* and *Pasithea coerulea* dominated. Pasture in all silvopastoral treatments was grazed annually by cattle between 1984 and 1993. The 625 trees ha^{-1} (T1, T2, Table 1) consisted of an arrangement of four plant in clusters at a spacing of 2 x 2 m, with 6 x 6 m between clusters. The 1,000 trees ha^{-1} (T3, Table 1) were arrangement in bands, with distances between trees of 2-3 m and between bands of 7 m. In a contiguous area, a plantation was established with an initial density of 1,600 trees ha^{-1} (T4, Table 1) spaced at 2.5 x 2.5 m for the sole purpose of wood production. The silvicultural treatments in all of the stands were thinned in the years 1989, 1991 y 1993 and pruned in 1988, 1990 y 1993. The timing, intensity and residual density were oriented towards optimisation of the silvicultural system and identification of the best combination for tree and pasture growth. In this form, thinning intensity was similar in all treatments (ca. 70 %).

Data sampling

In 44 permanent plots (11 plots per treatment) of 908 m^2, diameter at breast height (dbh) was measured in all trees to obtain diametric ampli-

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[1] CARLYLE C (1995) Managing site resources to maximize the productivity of *Pinus radiata* plantations. Tenth Silvotecna-Expocorma, 27-28 November, Concepción, Chile.

TABLE 1

Treatment assignment according to management regime,initial density and pasture type of 16 year old radiata pine plantations

Asignación de tratamientos según régimen de manejo, densidad inicial y tipo de pradera en pino radiata de 16 años de edad

Management regime	Density (trees ha^{-1})	Type of pasture	Treatment code
	625 (187)[a]	Artificial[a]	T1
Silvopastoral	625 (181)[a]	Naturally improved[a]	T2
	1,000 (185)[a]	Artificial[a]	T3
Forestry	1,600 (489)[a]	Natural[a]	T4

[a]The numbers in parenthesis indicate current density
Los números en paréntesis indican la densidad actual

tudes in each treatment. The trees of each treatment were then divided into three equivalent dbh classes, representing the intermediate, codominant and dominant crown classes (Smith et al. 1997). For each treatment and crown classes, three trees sampled were selected randomly. This gives nine trees per treatment, making a total of 36 trees in the entire sample.

Wood and bark biomass

After felling a tree, total length (including height of stump) and length of live crown were measured, marking its base. Subsequently, disks of 2 to 3 cm of width at stump height (0.30 m), at breast height and every 3.5 m, including a disk at the base of the live crown, were labeled, sealed in plastic bags and stored at 2 ºC for later analysis. In the laboratory, the disks were used to measure diameters and bark width at different heights of the stem for each tree sampled. Total volume was calculated according to the geometric form of the stem portion: stump volume as a cylinder, the section at Dbh as nyloid, the section between Dbh and base of live crown as a paraboloid, and the rest of the sections as a cone (Husch et al. 1982). To determine wood and bark anhydride density, the disks were immersed in water to obtain fresh volume, dried at 100 ºC for 48 h or until a constant weight, and then weighed. The product between the volume and anhydride density gives the dry wood and bark mass of the stem. The sum of all sections of the stem gives the dry mass of the tree.

Crown biomass

To estimate the crown biomass, each tree crown was divided vertically in thirds. Subsequently, all the branches of each section were removed and weighed in the field to determine total fresh weight. A subsample of three branches were selected randomly from each third of the crown to determine dry weight conversions. In nine branches per tree, the twigs were cut with scissors, and needles were separated from twigs and branches. Twigs and needles were weighed separately. These random subsamples of branches, twigs and needles were weighed freshly and then dried at 100 ºC for 24 h or until a constant weight was reached and then weighed. Dry mass of the crown was estimated from the proportions of dry mass of each crown component and the total green mass of each section of the crown measured in the field. A subsample of fresh needles for each third of the sampled tree was stored at 2 ºC, for leaf area measurement. Leaf area was determined with a Li-Cor 3100 measuring device, using a subsample of 12 needles which were subsequently dried at 100º C for 24 h and weighed with a precision of 0.01 g. The sum of three crown sections constitutes the leaf area of the tree (projected leaf area). The specific leaf area was calculated as the proportion of the measured area of the subsample fresh in relation to leaf dry weight.

Root biomass

Four stumps of previously felled trees in each treatment, were randomly selected for root biomass determination, two in the intermediate class and one from each of the other two classes. Areas potentially available for root growth were determined by the procedure described by Santantonio et al. (1977). The soil samples with roots were extracted using a steel tube with a diameter of 10 cm and length of 0.3 m. The samples were taken at 0.3, 0.6 and 0.9 m depths, along four transects to neighboring trees at $^1/_2$ and $^1/_4$ from the stump (Santantonio et al. 1977). In the laboratory, samples were immersed in water and the roots were separated by flotation. Live roots were classified as fine (< 2 mm) and coarse (between 2 and 5 mm), eliminating dead roots. Subsequently, roots were dried at 70ºC and weighed with a precision of 0.01 g. Field work was done between the end of December of 1999 and April of 2000.

Statistical analyses

To test for effect of the treatments on leaf area and biomass partitioning, multivariate analysis of variances (MANOVA) and covariance (ANCOVA) were used. Logarithmic transformation was applied to dbh and biomass data (Neter et al. 1996). The analysis of variance detected significant differences in dbh between treatments, showing an effect of initial density. This indicates the necessity to use dbh as a covariable in the following MANOVA models.

The allometric equations were calculated using regression models with indicator variables, which allows to separate the effect of each treatment and its interaction with dbh. The general allometric equation is:

$$Y = b_o + b_1 \, Log_e(dbh) + b_2 \, Treat_1 + b_3 \, Treat_2 + b_4 \, Treat\ 3 + b_5 \, Treat_1 \, Log_e(dbh) + b_6 \, Treat_2 \, Log_e(dbh) + b_7 \, Treat3\ Log\,(dbh) + e$$

where Y is the biomass component (kg), dbh is the covariable, $b_{o,}\ b_{1...}b_7$ are regressions coefficients. $Treat_1$, $Treat_2$ and $Treat_3$ are dicotomic (0,1) variables used to codify treatment effects. $Treat_1 Logdbh$, $Treat_2$ Logdbh, $Treat_3$ Logdbh are the interaction effects between treatment and dbh, and e is the random error with a supposedly normal distribution N $(0, s_e^2)$.

A non-significant interaction is detected graphically. Parallel mean profiles for the treatments indicate that there is no interaction. In this case, differences in leaf area and biomass between treatments do not depend on tree size. Without interaction terms, the general model is reduced to:

$$Y = b_o + b_1 \, Log_e(dbh) + b_2 \, Treat_1 + b_3 \, Treat_2 + b_4 \, Treat_3 + e$$

In this case, the analyses are given using the reduced model, which allows estimation of the confidence intervals of treatment differences. Let m_i be the population mean for the ith treatment. The confidence intervals for the pairwise diffrences m_I-m_j were calculated using Scheffé's simultaneous estimation method (Neter et al. 1996). The software Statistica (version 1998) was used for all the analyses, especially the modules ANOVA/MANOVA, Multiple Regressions and Visual GLM.

RESULTS

Treatment effects on leaf area

Total leaf area presented significant differences between treatments and was 2.9 to 6.1 times larger in the silvopastoral than in the forestry stand. This difference could be due to planting density, which reflected on tree sizes. Within tree crowns, the upper third did not differ significantly between treatments; however, in the middle and lower thirds significant differences between the forestry and the silvopastoral system were found. Within silvopastoral treatments, there were significant differences in the middle third of the crown, leaf area in T1 and T3 was 1.8 to 2.1 times greater than in T2, respectively (Table 2). The leaf area per tree did not present clear patterns of crown distribution between treatments (Table 2).

Within tree crowns, specific leaf area in silvopastoral treatments was significantly larger than in the forestry regime, except at the crown base (Fig. 1). In the silvopastoral treatment, specific leaf area in T1 was significantly larger (391.4 cm^2g^{-1}), than in T2 and T3, which had averages values of 214.3 and 256.4 cm^2g^{-1}, respectively. This is due to significant differences between the upper third and the base of the crown. However, specific leaf area decreased from top to bottom, except in T3 (Fig. 1).

Biomass partitioning

Total biomass per tree in the silvopastoral treatments was 2.2 to 2.5 times larger than in the forestry regime. Even though there was no significant difference in aboveground biomass between the two management practices, fine and coarse root biomass was significantly lower in T3 that in all the other treatments. Additionally, coarse root biomass was significantly lower in T4 than in T2 and T1 (Table 3). In all treatments more than 95% of the biomass was allocated to aboveground components.

We used ANCOVA models to determine whether biomass components differed between treatments, after adjusting for dbh (covariable). These indicated that needle, twig

TABLE 2

Mean leaf area (LA, in m^2) per tree and per treatment in 16 year-old radiata pine plantations, under four management treatments (T1-T4), see text. Parentheses contain standard deviations. In each line, values with the same superscript do not differ significantly ($P < 0.05$, Tukey test), n = 36

Área foliar media por árbol y tratamientos en plantaciones de pino radiata de 16 años de edad, bajo tratamientos de manejo (T1-T4), vea el texto. Entre paréntesis se indican las desviaciones estándar. En cada fila, los valores de las medias con la misma letra no difieren significativamente ($P < 0,05$; prueba de Tukey), n = 36

Crown position	Treatment							
	T1		T2		T3		T4	
	LA	(%)	LA	(%)	LA	(%)	LA	(%)
Upper tirad	21.82 (5.3)^{a}	16.4	19.84 (5.0)^{a}	27.5	14.20 (4.1)^{a}	9.5	9.4 (2.1)^{a}	38.5
Middle third	60.69 (5,9)^{a}	45.5	12.99 (2,9)^{b}	18.0	102.59 (50,3)^{a}	68.4	11.7 (2.9)^{b}	47.9
Lower third	50.80 (5,5)^{a}	38.1	39.23 (2.9)^{a}	54.5	33.26 (4.4)^{a}	22.1	3.35 (2.9)^{b}	13.6
Total crown	133.3^{a}		72.07^{b}		150.1^{a}		24.6^{c}	

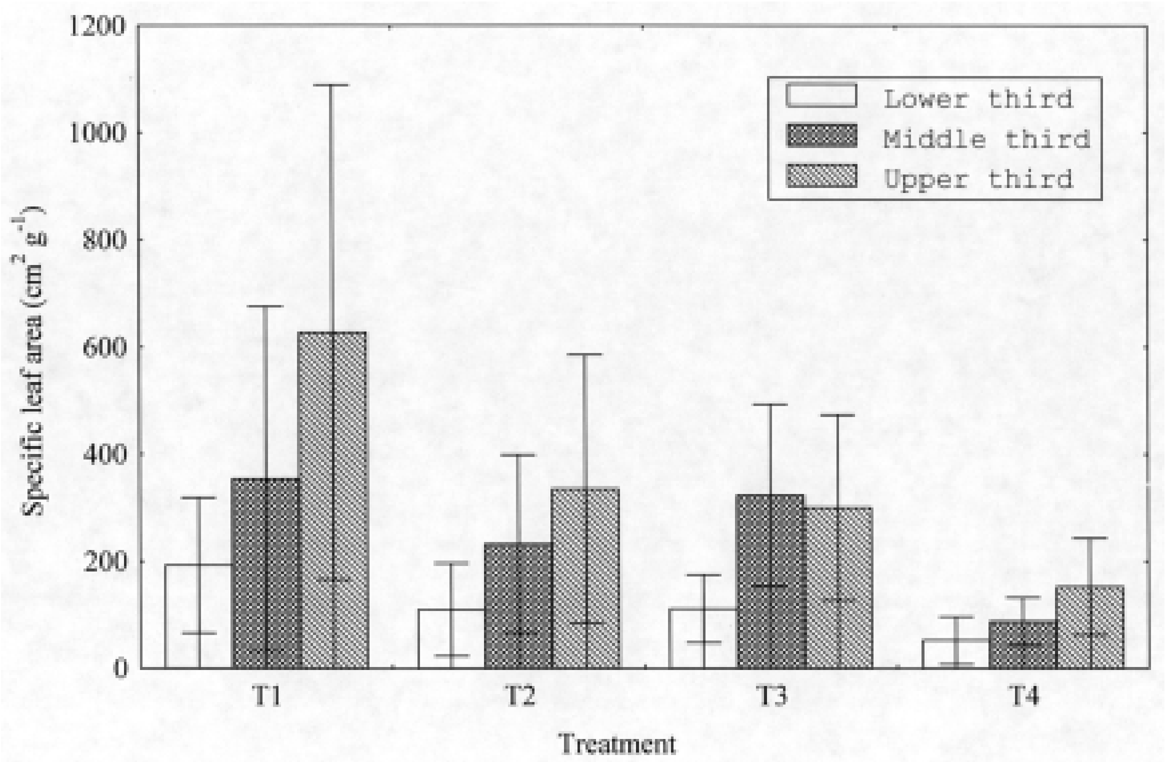


Fig. 1: Mean specific leaf area according to crown position and treatments in 16 year old radiata pine. Columns are the mean values for specific leaf area and the bars indicate standard deviation.

Gráfico de medias del área foliar específica según posición de la copa y tratamientos en pino radiata de 16 años de edad. Las columnas indican la media del área foliar específica y las barras la desviación estándar.

TABLE 3

Mean values of biomass per tree, per component and treatments, in 16 year old radiata pine. Parenthesis indicate standard deviation; (*) indicates significant difference in medium biomass ($P < 0.005$, Tukey test); statistics of MANOVA are Wilk's Lambda = 0.006389, and Rao's R = 4.0731; n = 36

Medias de la biomasa por árbol, componente y tratamientos en rodales de pino radiata de 16 años. Los paréntesis incluyen las desviaciones estándar; (*) indica diferencias significativas en las medias en biomasa ($P < 0,005$; prueba de Tukey); los estadígrafos de la prueba de MANOVA son Wilk's Lambda = 0,006389 y Rao's R = 4,0731; n = 36

Component	Treatments							
	T1		T2		T3		T4	
	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)
Needles	94.43 (70.2)	10.2	82.27 (44.1)	9.8	99.44 (54.9)	10.7	35.66 (28.8)	9.5
Twigs	39.02 (39.6)	4.2	40.83 (25.9)	4.9	76.75 (60.5)	8.2	15.08 (11.1)	4.0
Branches	194.13 (171.1)	21.0	152.17 (94.1)	18.1	170.86 (88.7)	18.3	57.80 (34.2)	15.5
Stemwood	517.05 (399.8)	55.9	473.71 (324.1)	56.3	526.57 (257.1)	56.4	220.35 (129.2)	58.9
Bark	61.25 (55.6)	6.6	69.81 (66.7)	8.3	49.58 (18.9)	5.3	26.23 (13.1)	7.0
Fine roots	14.58 (3.0)	1.6	13.91 (1.5)	1.6	7.41 (1.5)*	0.8	16.18 (2.7)	4.3
Coarse roots	4.53 (2.0)	0.5	8.34 (3.4)	1.0	2.81 (1.0)*	0.3	2.92 (0.9)*	0.8
Total	924.99 (487.4)		841.04 (440.0)		933.42 (365.8)		374.22 (159.3)*	

and bark biomass did not present significant differences between treatments. In all treatments, aboveground biomass of all components presented a high correlation with tree size, because log(dbh) is a very significant component of all the regression models (Fig. 2 to 4, respectively).

Regression analyses showed an inverse relationship between fine root biomass and tree size for all treatments (Fig. 4B). However, trees of all sizes in T3 have significantly less fine root biomass than in all other treatments (Table 3). For coarse roots, a direct relationship with tree size in all treatments was found. However, trees of all treatments have significant differences for coarse roots were found, except between T3 and T4 (Table 3, Fig. 4A).

A regression model for fine root biomass using treatments and crown components as predictor variables was fit (Table 5). It shows a strong correlation with branches, twigs and needles. Actually, the mass of fine roots is almost perfectly predictable ($R^2 = 0.99$) from the crown data (Table 5, Fig. 5).

DISCUSSION

Effect of silvicultural management on leaf area

Since larger leaf areas were found in the silvopastoral managed stands than in the forestry plots and there were significant differences between silvopastoral treatments (T2 respect to T1 and T3), plantation design and pasture fertilization positively influenced leaf area and altered vertical distribution patterns (Table 2). The influence of silvicultural regime and fertilization on leaf area was reported by Gillespie et al. (1994). This result is consistent with Gower et al. (1993), in the sense that resource availability, particularly nitrogen, increases leaf area through various mechanisms such as greater needle size, branch biomass, or larger needle density (Fife & Nambiar 1997). Gillespie et al. (1994) did not find variation in leaf vertical distribution that could have been attributable to silvicultural teatment. Results of this study are in agreement with the hypothesis that silvicul-

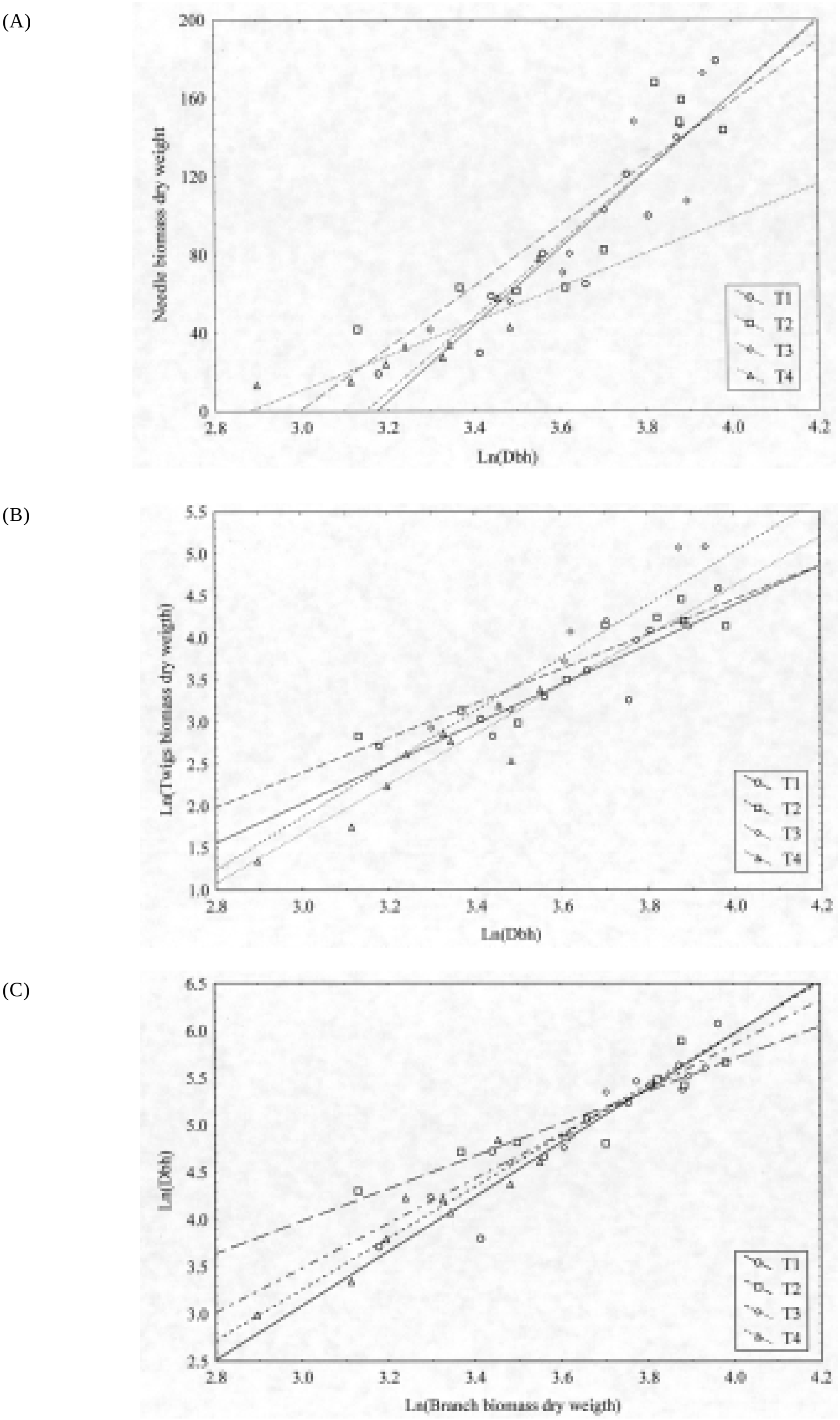
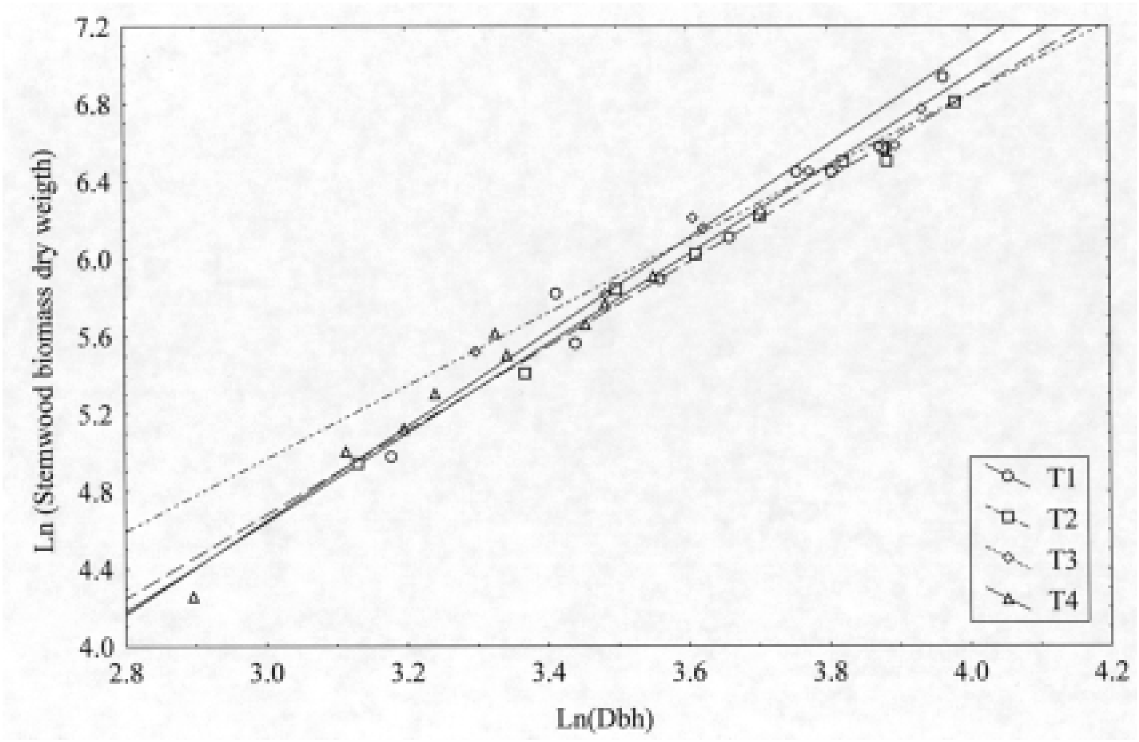


Fig. 2: Allometric relations between dbh and crown biomass components (A, needles; B, twigs; and C, branches) in 16 year old radiata pine. Regression coefficients are shown in Table 4 (Variables were log-transformed).

Relaciones alométricas entre el dap y la biomasa de los componentes de la copa (A, acículas; B, ramillas; y C, ramas) en pino radiata de 16 años. Los coeficientes de las ecuaciones se presentan en la Tabla 4 (Las variables fueron transformadas a logaritmos naturales).

(A)



(B)

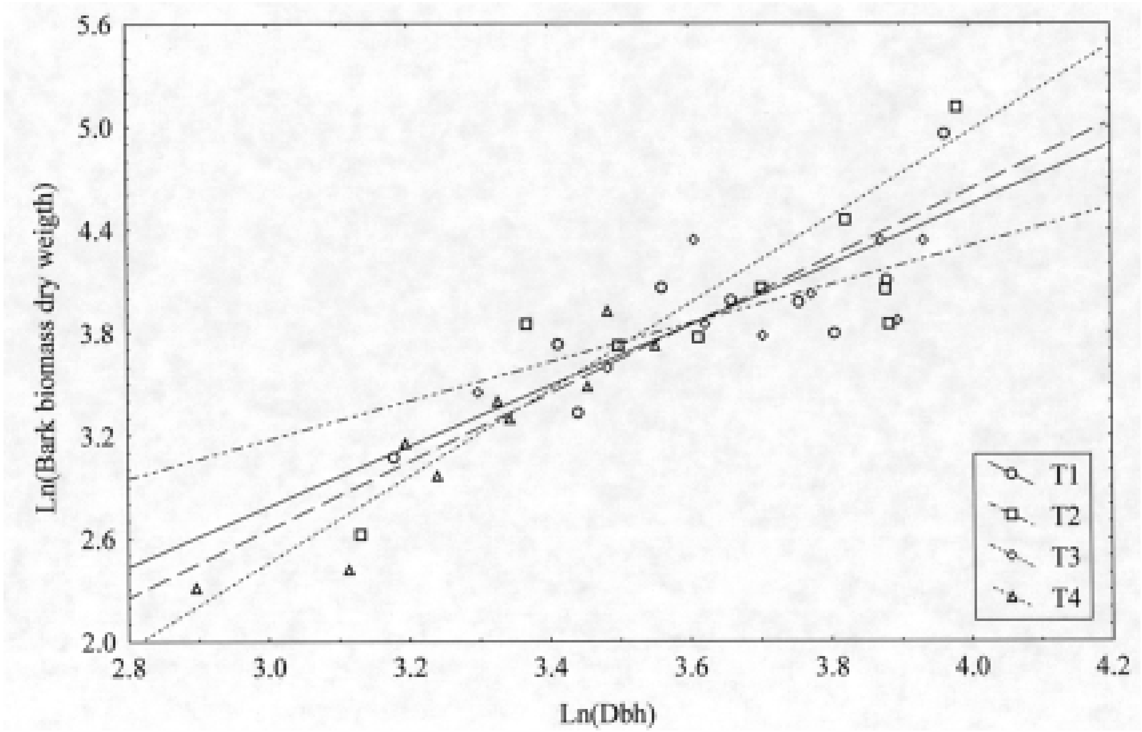
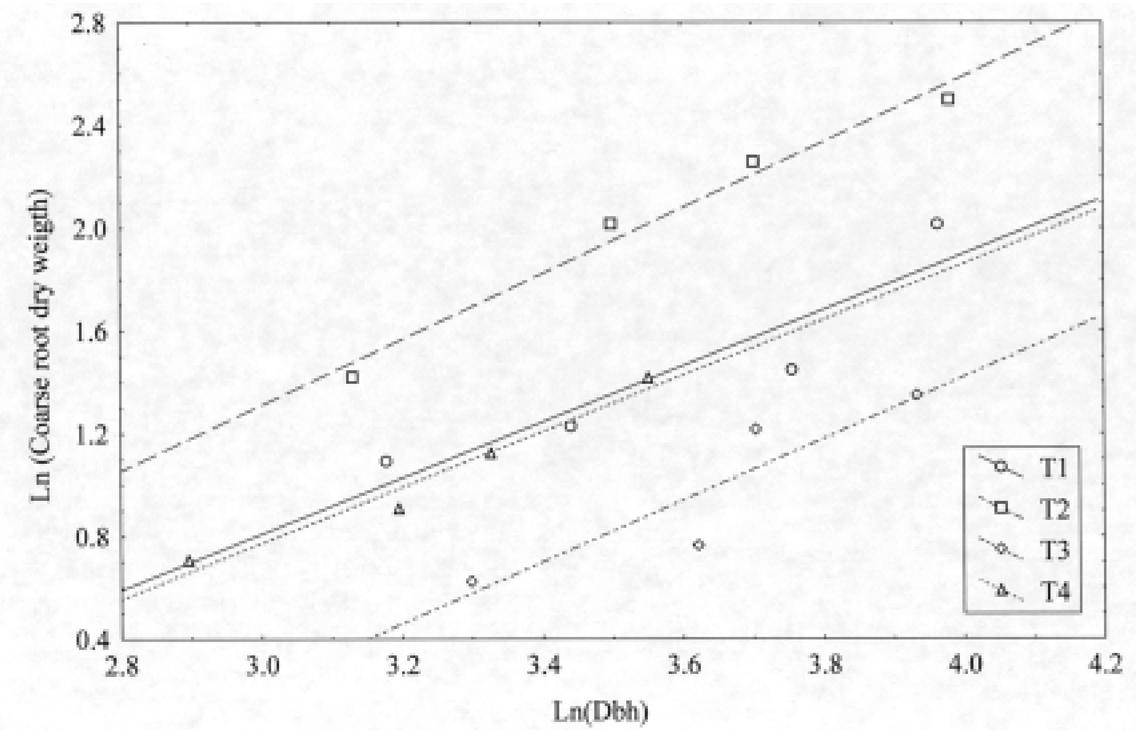


Fig. 3: Allometric relations between dbh and (A) stemwood and (B) bark biomass in 16 year old radiata pine. Regression coefficients are shown in Table 4 (variables were log-transformed).

Gráficos de dispersión para las relaciones alométricas entre el Dap y (A) la biomasa de madera y (B) la corteza en pino radiata de 16 años. Los coeficientes de las ecuaciones se presentan en la Tabla 4 (Las variables fueron transformadas a logaritmos naturales).

(A)



(B)

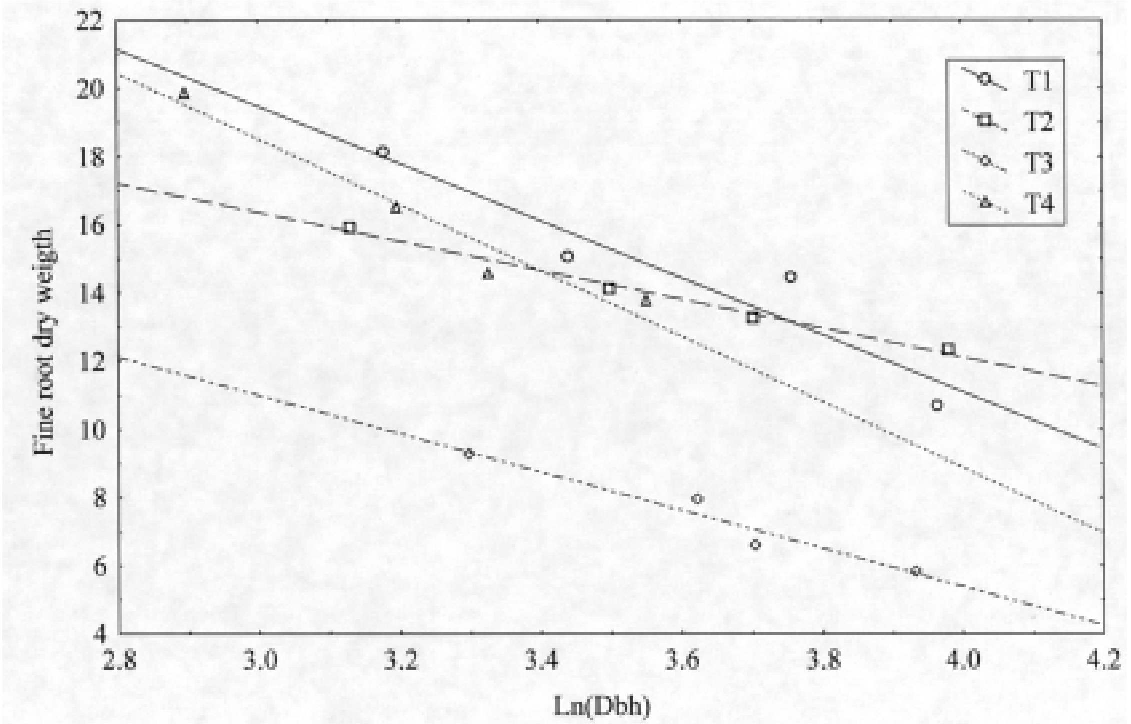


Fig. 4: Allometric relations between dbh and belowground biomass components in 16 year old radiata pine. Regression coefficients are shown in Table 4 (Variables were log-transformed).

Gráficos de dispersión para las relaciones alométricas entre el Dap y la biomasa de raíces en pino radiata de 16 años. Los coeficientes de las ecuaciones se presentan en la Tabla 4 (Las variables fueron transformadas a logaritmos naturales).

TABLE 4

Allometric regression coefficients for different tree components in 16-year old radiata pine plantation

Coeficientes de las ecuaciones alométricas para los distintos componentes del árbol en pino radiata de 16 años de edad

Component	Variation source	b	SSE b	T(11)	p	R^2	SSE
Needles	Intercept	-251.909	116.7204	-2.158	0.0396	0.87	20.433
	Log$_e$Dbh	87.578	35.4220	2.472	0.0197		
	Treatm1	-368.284	156.2631	-2.356	0.0256		
	Treatm2	-217.741	150.5288	-1.446	0.1591		
	Treatm3	-344.001	173.2024	-1.986	0.0568		
	Treat1Dbh	107.812	45.5089	2.369	0.0249		
	Treat2Dbh	69.282	43.9131	1.577	0.1258		
	Treat3Dbh	101.729	49.5516	2.052	0.0495		
Twigs	Intercept	7.1610	1.6827	-4.255	0.0002	0.90	0.295
	Log$_e$Dbh	2.9446	0.5106	5.766	0.0000		
	Treatm1	2.1227	2.2527	0.942	0.3541		
	Treatm2	3.3854	2.1701	1.560	0.1299		
	Treatm3	-0.4288	2.4969	-0.171	0.8648		
	Treat1Dbh	-0.5877	0.6560	-0.895	0.3779		
	Treat2Dbh	-0.8868	0.6330	-1.400	0.1722		
	Treat3Dbh	0.2091	0.7143	0.292	0.7719		
Branches	Intercept	-4.8701	1.2403	-3.926	0.0005	0.92	0.210
	Log$_e$Dbh	2.7111	0.3764	7,202	0.0000		
	Treatm1	-0.6675	1.6605	-0.401	0.6907		
	Treatm2*	3.6932	1.5996	2.308	0.0285		
	Treatm3	1.2628	1.8405	0.686	0.4982		
	Treat1Dbh	0.1649	0.4836	0.341	0.7355		
	Treat2Dbh*	-0.9905	0.4666	-2.122	0.0427		
	Treat3Dbh	-0.3458	0.5265	-0.656	0.5166		
Stemwood	Intercept	-2.6254	0.5052	-5.196	0.0000	0.98	0.08
	Log$_e$Dbh	2.4243	0.1533	15.809	0.0000		
	Treatm1	0.3569	0.6764	0.527	0.6018		
	Treatm2	0.8032	0.6516	1.232	0.2279		
	Treatm3*	1.9613	0.7498	2.615	0.0141		
	Treat1Dbh	-0.1220	0.1970	-0.619	0.5406		
	Treat2Dbh	-0.2574	0.1901	-1.354	0.1865		
	Treat3Dbh*	-0.5470	0.2145	-2.550	0.0165		
Bark	Intercept	-5.0815	1.6656	-3.050	0,0049	0.81	0.292
	Log$_e$Dbh	2.5136	0.5054	4.972	0,0000		
	Treatm1	2.5855	2.2298	1.159	0,2560		
	Treatm2	1.7820	2.1480	0.829	0,4137		
	Treatm3	4.8658	2.4716	1.968	0,0589		
	Treat1Dbh	-0.7530	0.6494	-1.160	0,2557		
	Treat2Dbh	-0.5306	0.6266	-0.846	0,4043		
	Treat3Dbh	-1.3836	0.7071	-1.956	0,0604		
Fine roots	Intercept	38.1569	2.8625	13.329	0.0000	0.95	0.944
	Log$_e$Dbh	-6.7776	0.8707	-7.783	0.0000		
	Treatm1	0.7254	0.7309	0.992	0.3422		
	Treatm2	0.0091	0.7287	0.012	0.9902		
	Treatm3*	-6.0793	0.7517	-8.086	0.0000		
Coarse roots	Intercept	-2.7528	0.3755	-7.329	0.0000	0.96	0.141
	Log$_e$Dbh	1.1690	0.1142	10.233	0.0000		
	Treatm1	0.0078	0.0958	0.081	0.9364		
	Treatm2*	0.6176	0.0958	6.460	0.0000		
	Treatm3*	-0.5146	0.0960	-5.217	0.0002		

(*) Indicates significance of treatment ($P < 0.05$, Tukey test); n = 36
Indica significancia del tratamiento ($P < 0,05$; prueba de Tukey); n = 36

TABLE 5

Allometric relation between crown component and fine roots biomass, in a 16 year old radiata pine

Relación alométrica entre biomasa de los componentes de la copa y raíces finas, en pino radiata de 16 años de edad

Source of variation	Standard b-value	Error of b	t_9	P-value	R^2	SSE
Intercept	30.649	1.49241	20.537	0.00000	0.99	0.427
TREATM1	1.595	0.35633	4.4765	0.00154		
TREATM2	1.179	0.36786	3.2066	0.01071		
TREATM3	-4.731	0.4013	-11.7887	0.00000		
LOGTwigs*	-0.929	0.3298	-2.8171	0.02014		
LOGBranches*	-3.293	0.481633	-6.8376	0.00007		
Needles*	0.0181	0.006299	2.8831	0.01808		

(*) Indicates significance of the crown component in relation to fine root biomass ($P < 0.05$; Tukey test); n = 36
Indica significancia del componente de la copa en relación a la biomasa de raíces finas ($P < 0,05$; prueba de Tukey); n = 36

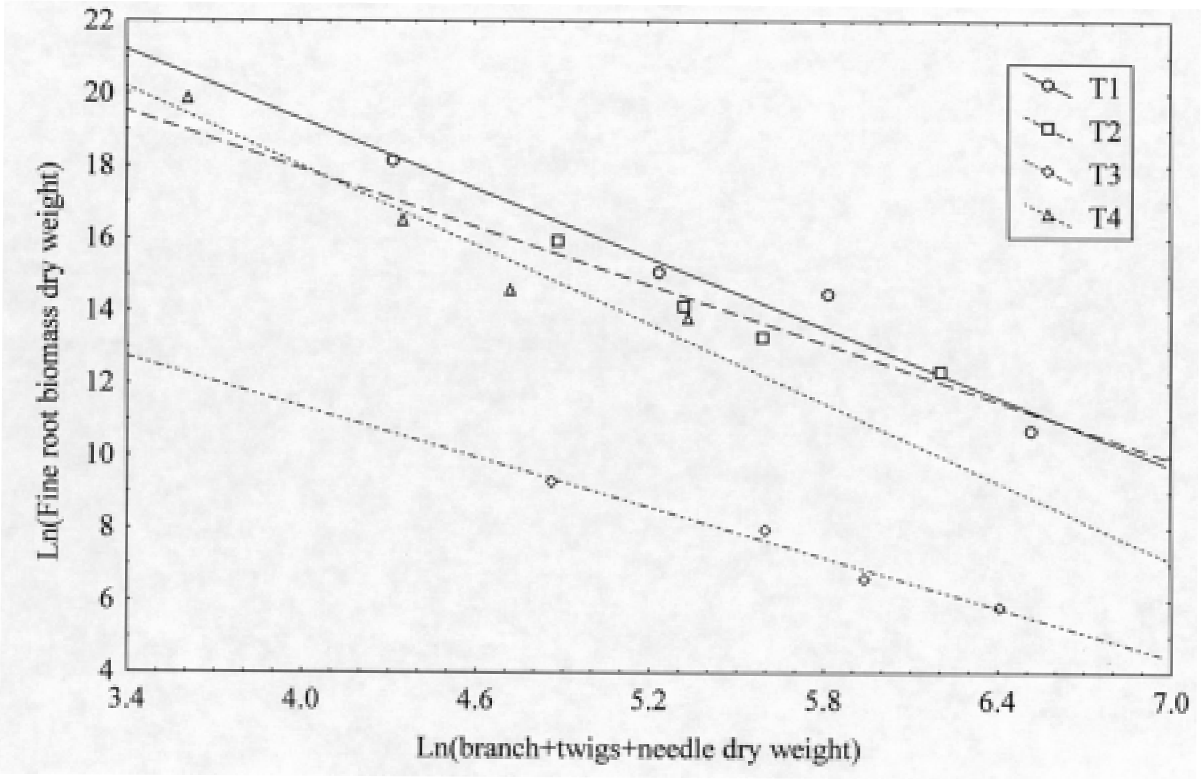


Fig. 5: Relation between crown components (branch + twigs + needles) and fine roots (log-transformed) in 16-year old radiata pine.

Relación entre los componentes de la copa (ramas + ramillas + acículas) y raíces finas (ambas variables transformadas a logaritmo natural) en pino radiata de 16 años de edad.

tural regime changes leaf area as well as vertical leaf distribution patterns. This is due to the enhanced nitrogen availability (Albaugh et al. 1998), initial density and plantation design that modified stand characteristics (Xu & Harrington 1998).

There were differences in specific leaf area between treatments for the upper and middle crown, but not the lower third of the crown (Fig. 1). This is consistent with studies that relate this variability to thinning, fertilization (Beets & Lane 1987) and the different spatial arrangement of needles (Baterlink 1996). These factors allow trees to maximize carbon gain, making a more efficient use of the temporal and long-term variation in site resources (Landsberg & Gower 1997).

Effects of silvicultural management regime in biomass partitioning

The greater leaf area explains the significant differences in total biomass found between the silvopastoral regime and the forestry treatment and between different silvopastoral regimes (Albaugh et al. 1998, Waring & Running 1998). This is explained because the allometric relationships in trees are not affected by practices such as fertilization (Gower et al. 1993), nor by irrigation of radiata pine (Raison et al. 1990, Sands & Mulligan 1990).

Considering that fine roots are responsible for most of the absorption of water and nutrients, their biomass should decrease with fertilization according to the functional balance model (Cannel & Dewar 1994). Results of this study (Table 3) show a higher absolute and relative allocation to fine roots in the forestry regime. This is explained because lower leaf area and the lack of fertilization incremented allocation to fine roots (Linder & Axelsson 1982, Axelsson & Axelsson 1986, Santantonio & Santantonio 1987, Beets & Whitehead 1996). Another possible explanation is the necessity to maintain a high root/shoot ratio in poor soils (Bartelink 1998). In the silvopastoral stands, the significant differences between T3, T1 and T2 are based on the strong relation between foliage biomass and fine root (Fig. 5). Accordingly, plantation design in bands had a larger leaf area which increased carbon allocation to crown components at the expense of fine root biomass (Table 3). The necessity to increase carbon allocation to the crown leads to a reduction of fine root biomass (Linder & Axelsson 1982, Axelsson & Axelsson 1986, King et al. 1999). In the case of T1 and T2 the aggregated plantation design prevented a larger leaf area, increasing allocation of carbon to fine roots, compared to T3.

Fine root biomass decreased with an increase in crown biomass (Fig. 5), tree size (Fig. 4B) and fertilization (Table 3), in all treatments. The inverse relation between fine root biomass and crown biomass and tree size has been reported for *Pinus resinosa* and *Pinus radiata* (Haynes & Gower 1995, Albaugh et al. 1998). This behavior is typical of temperate forest trees (Landsberg & Gower 1997). In the perspective of the functional balance, changes in allometric relations depend on availability of nutrients and water (Fife & Nambiar 1997). However, the magnitude of these changes are controversial. King et al. (1999) suggest a strong regulation of the root/shoot ratio by the moisture stress and probably by ontogenetic controls (Gedroc et al. 1996). On the contrary, Bartelink (1998) indicates strong variability in this allometric relation and reported that up to 80 % of the produced assimilates from photosynthesis are allocated to fine roots in poor soils. This study supports the hypothesis that root/shoot ratios can be greatly altered by crown structure, reducing the fraction allocated to roots, but having almost no effect on the fraction of dry matter allocated to foliage or woody parts (Dewar et al. 1994).

CONCLUSIONS

Leaf area per tree varied greatly due to the silvicultural regime and in response to annual or periodic fertilization of the pasture. Specific leaf area varied with management regimes, silvopastoral schemes and within tree crowns. Total biomass per tree is 2.1 to 2.5 times larger in the silvopastoral regime than in the forestry regime due to final density. However, aboveground biomass partitioning among plant parts was neither affected by the silvicultural regime nor by the schemes of silvopastoral management. The most important allometric changes were in fine root biomass, which was greater under in the forestry regime than in the silvopastoral tratments. Fine root biomass decreases with the level of aggregation of trees and is lower with plantation in bands. In turn, fine root biomass decreases with fertilization. Both plantation design and fertilization explain changes in fine root biomass. Therefore, the significant relation between fine root biomass and crown components is consistent with the functional balance model, and the magnitude of this relation is influenced by crown structure.

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