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Mechanical parameters during static bending of *Pinus radiata* growing in a silvopastoral system I: elasticity and strength

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Abstract The effects of pasture fertilization frequency and two vertical positions in the stem on elasticity and strength parameters during static bending (modulus of elasticity, stress at proportional limit, modulus of rupture) of *Pinus radiata* wood growing in a silvopastoral system were evaluated. Twenty-seven trees were selected randomly from three silvopastoral trials established at Tanumé Experimental Center (34°9′–34°15′ S; 72°53′–72°59′ W). The results indicated that pasture fertilization frequency had no significant effect on the physical and mechanical parameters evaluated. However, the vertical position in the stem did have a significant effect on stress at the proportional limit and on the modulus of rupture due to different average values for the annual ring width and nominal density found in the specimens obtained from logs at two different heights of the stem.

Key words Modulus of elasticity · Modulus of rupture · Silvopastoral system · Fertilization · *Pinus radiata*

Introduction

Silvopastoral systems, in contrast to traditional forestry production, are complex systems, with their management based on multiple uses of the soil.[1] According to Mclaren,[2] Klopfenstein et al.,[3] and Sharrow,[1] these systems as an agroforestry practice are specifically designed and managed for the production of trees, tree products, forage, and livestock on a single site.

In both silvopastoral and forestry systems, the addition of fertilizers has become a common management practice, especially at sites with low nutrient levels. Fertilization improves the growth of trees in *Pinus radiata* stands, which increases biomass production and causes a shift in the annual volume increments and a decrease in wood properties.[4–7] Similarly, Klopfenstein et al.[3] and Sharrow[1,8] pointed out that in silvopastoral systems pasture fertilization increases both forage production and tree growth. The effects of this management practice on wood properties, specifically on parameters of elasticity and strength during static bending, have not been evaluated.

Static bending has been the preferred mechanical property when evaluating wood for structural uses because it integrates other properties, such as compression, tension, and shear.[9,10] Additionally, the effect of wood density and spiral grain on parameters such as the modulus of elasticity (MOE) and the modulus of rupture (MOR) have been increasingly investigated during the last decade.[9,11,12] Researchers have demonstrated that both physical parameters generate an additional source of variation in the behavior of MOE and MOR.

The general objective of the present study was to determine whether pasture fertilization frequency on a silvopastoral system established with *Pinus radiata* had any effect on the mechanical parameters during static bending [i.e., MOE, MOR, and stress at proportional limit (SPL)] at two vertical positions in the stem. The specific objectives were to (1) determine the effect of pasture fertilization frequency and position in the stem on MOE, MOR, and SPL; and (2) analyze the behavior of MOE, MOR, and SPL as a function of nominal wood density (NWD), annual ring width (ARW), and spiral grain (θ).

Materials and methods

The trees used in this study came from the Tanumé Forest Experimental Center located in the VI Region of Chile (34°9′–34°15′ S; 72°53′–72°59′ W). This area has a subhumid, temperate climate, with maritime influence, and 4 dry months. The annual mean rainfall is up to 705 mm; the average annual temperature reaches 11.6°C, varying between 8.6°C and 15.4°C. The prevailing topography is hilly,

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Table 1. Treatment plan according to pasture fertilization frequency

Treatment	Initial density (trees ha^{-1})	Fertilization	
		Frequency	Amount (kg ha^{-1})
None	625 (171.4)	None	0
Every 4 years	625 (184.4)	Every 4 years	76 N–122 P
Annually	625 (192.1)	Annually	109 N–109 P

Final stand densities are in parentheses
N, nitrogen: applied as urea; P, phosphorus: applied as triple superphosphate

but there are also sectors with flat topography. The soil series in the area of the silvopastoral trial is Curanipe, which is metamorphic in origin, derived from marine terraces, and susceptible to mantle erosion and gully formation; it also has reduced drainage.[13]

Treatments in the silvopastoral trial

In 1983 at the Tanumé Forest Experimental Center, under the aegis of CONAF (National Forest Corporation), a silvopastoral trial was established with *Pinus radiata* D. Don to evaluate the technical and economic feasibility of compatible cattle, forage, and forest activities at a single site. The source of planting stock (bareroot seedlings) was seeds collected from an open pollination seed orchard of *Pinus radiata* D. Don.

Three treatments were established with an initial planting density of 625 trees/ha. The planting design or spatial distribution of the trees was four plants at 2 × 2 m in equally spaced clusters 6 m apart. Each treatment covers 6 ha and had different fertilization frequencies (Table 1). The treatments were submitted to pruning (1988, 1990, 1993) and thinning (1989, 1991, 1993); the intensities of these interventions were similar for each of the treatments. Final stand densities are given in Table 1.

Tree sampling and log selection

The stand variables were estimated from six permanent plots established for each treatment. These measurements were recorded annually starting in 1986 for the total height (TH), in 1988 for the diameter at breast height (DBH), and in 1989 for the live crown height (LCH). With this information, the DBH frequency distribution was elaborated for each population. Nine trees were randomly selected from each population, for a total of 27 trees. The average values of the TH, DBH, LCH, and commercial height (CH) (height to minimum usable top diameter of 10 cm) of sampled trees for each treatment are presented in Table 2.

During March 1999, two logs of 1.3 m were obtained from each tree. The first log (P1) was cut at 25% of CH (approximately 4.5 m measured from the base of the tree). The second log (P2) was cut from the zone immediately below the beginning of live crown (approximately 7.2 m). A total of 54 logs were obtained. All logs were processed at the Silvotechnologic Wood Laboratory. A central beam oriented in the north-south direction was obtained from each log. Then, small clear bending specimens were obtained from each beam following the radial direction. A total of 821 specimens (25 × 25 × 410 mm) were obtained. All specimens were dried until 12% moisture content was reached.

Table 2. Average values for trees selected for each treatment

Variable	Fertilization		
	None	Every 4 years	Annually
TH (m)	22.8 ± 1.5	22.7 ± 1.0	23.4 ± 1.8
CH (m)	18.1 ± 1.4	17.5 ± 1.0	18.2 ± 1.9
LCH (m)	7.4 ± 0.6	6.6 ± 0.3	7.5 ± 0.8
DBH (cm)	35.6 ± 4.9	38.7 ± 5.6	37.9 ± 4.5

TH, total height; CH, commercial height; LCH, live crown height; DBH, diameter at breast height
Results are expressed as the average ± SD

Static bending test

Using a universal testing machine with a maximum load capacity of 20 tons, all specimens were tested during static bending in accordance with the method established by the American Society for Testing and Materials D 143–94.[14] The variables determined from the load-defect curves were MOE, MOR, SPL, and Tetmajer's coefficient or the factor of completeness (η), which is a sensitive detector of the defects of wood in bending with values near 0.7 for structural lumber.[15] The physical properties NWD (weight and volume at 12% of moisture content), ARW, and θ were measured for each specimen. All of these parameters were determined following the methodology described by Valenzuela and Nakayama.[9]

Statistical analysis

Considering fertilization (three levels) and the vertical position in the stem (two levels) as fixed effects and trees as random effects, the variables MOE, SPL, MOR and η were analyzed using a nested design (tree nested within fertilization). The experimental unit was the average value of the specimens tested for each of the vertical positions for each tree, obtaining a total of 54 experimental units. The effects of fertilization frequency and the vertical position in the stem were evaluated by analysis of variance (ANOVA). Tukey's test was used for simultaneous comparison of means.

The effects of NWD, ARW, and θ on the behavior of MOE, SPL, and MOR were evaluated by means of multiple regression analysis. Taking into consideration the sign and magnitude of the coefficients associated with each of the physical properties, their effects on the various mechanical parameters could be evaluated.

Results

Effects of treatments on physical and mechanical parameters

The ANOVA showed that the effect of fertilization frequency was not significant for each variable evaluated (MOE, SPL, MOR, η) (Table 3). However, the effect of the vertical position in the stem was significant for SPL and highly significant for MOR (Table 3). The physical parameters NWD, ARW, and θ also were statistically evaluated (Table 4). According to the results (Table 4), the effect of pasture fertilization frequency on the physical parameters was not significant, whereas the effect of the vertical position in the stem was highly significant for NWD and ARW.

Effect of physical properties on MOE, SPL, and MOR

The effect of each of the physical properties on the several mechanical parameters considered was evaluated using multiple regression analysis (Table 5). According to the results (Table 5), NWD had a positive effect on the behavior of the mechanical parameters evaluated (MOR, MOE, SPL), whereas ARW and θ affected them negatively.

Discussion

Silvopastoral systems, in contrast to traditional forestry plantations, are complex systems that are based on the concept of multiple uses of soil. Sciences such as agronomy, ecology, and forestry are integrated in a single site.[1] For this reason, factors such as initial planting density, design, and plantation management in silvopastoral systems differ from those in a traditional condition. Therefore, the analysis and discussion of the results obtained in this study took into consideration that, in general, the information available has been based on studies associated with traditional, not silvopastoral, situations.

Cown and McConchie,[16] Brix and Mitchel,[17] and Cahill and Briggs[18] found that the addition of mineral elements by means of fertilization contributes to an increase in the productivity of a plantation, measured in volume. They also established that wood properties decrease as the growth rate is accelerated, confirming the results obtained by Rudman and McKinell[4] and McKinell and Rudman[5] who found a negative relation between the growth rate and wood properties in *P. radiata.*

Our results (Tables 3, 4, 6), show that for *P. radiata* growing in a silvopastoral system the frequency and amount of fertilizers applied to the pasture during the stands' development did not have a significant effect on the mechanical

Table 3. Analysis of variance for modulus of elasticity, stress at proportional limit, modulus of rupture, and Tetmajer's coefficient

Parameter and source	d.f.	SS	MS	*F*	*P*
MOE					
Fertilization	2	1.63×10^8	8.17×10^7	0.74	0.49
Position	1	1.63×10^7	1.63×10^7	1.22	0.28
Fertilization × position	2	2.40×10^7	1.20×10^7	0.90	0.42
Tree (fertilization)	24	2.64×10^9	1.10×10^8	8.27	0.00
Error	24	3.20×10^8	1.33×10^7		
SPL					
Fertilization	2	5.69×10^3	2.84×10^3	1.07	0.36
Position	1	2.19×10^3	2.19×10^3	4.14	**0.05**
Fertilization × position	2	7.73×10^2	3.86×10^2	0.73	0.49
Tree (fertilization)	24	6.38×10^4	2.66×10^3	5.02	0.00
Error	24	1.27×10^4	5.29×10^2		
MOR					
Fertilization	2	3.52×10^3	1.76×10^3	0.33	0.72
Position	1	2.06×10^4	2.06×10^4	64.24	**0**
Fertilization × position	2	1.69×10^3	8.45×10^2	2.64	0.09
Tree (fertilization)	24	1.28×10^5	5.35×10^3	16.73	0.00
Error	24	7.68×10^3	3.20×10^2		
Tetmajer's coefficient (η)					
Fertilization	2	2.10×10^{-4}	1.10×10^{-4}	0.12	0.89
Position	1	8.20×10^{-4}	8.20×10^{-4}	2.17	0.15
Fertilization × position	2	7.00×10^{-4}	3.50×10^{-4}	0.93	0.41
Tree (fertilization)	24	2.16×10^{-2}	9.00×10^{-4}	2.39	0.02
Error	24	9.03×10^{-3}	3.76×10^{-4}		

MOE, modulus of elasticity; SPL, stress at proportional limit; MOR, modulus of rupture; d.f., degrees of freedom; SS, sum of squares; MS, mean square

Table 4. Analysis of variance for annual ring width, nominal wood density, and spiral grain

Parameter and source	d.f.	SS	MS	*F*	*P*
ARW					
Fertilization	2	7.78	3.89	1.47	0.25
Position	1	23.69	23.69	65.38	**0**
Fertilization × position	2	0.13	0.07	0.18	0.83
Tree (fertilization)	24	63.40	2.64	7.29	0
Error	24	8.69	0.36		
NWD					
Fertilization	2	299.62	149.81	0.16	0.85
Position	1	2652.44	2652.44	19.82	**0**
Fertilization × position	2	385.76	192.88	1.44	0.26
Tree (fertilization)	24	22411.30	933.81	6.98	0
Error	24	3211.32	133.81		
Spiral grain (θ)					
Fertilization	2	3.94	1.97	0.44	0.65
Position	1	0.66	0.66	0.74	0.40
Fertilization × position	2	2.15	1.08	1.20	0.32
Tree (fertilization)	24	107.01	4.46	4.98	0
Error	24	21.51	0.90		

ARW, annual ring width; NWD, nominal wood density

Table 5. Multiple regression analysis for modulus of rupture, modulus of elasticity, and stress at proportional limit

Parameter and source	β (mean ± SEM)	t(841)	*p*	R^2	SEE
MOR					
Intercept	157.60 ± 30.31	5.20	0		
NWD	1.68 ± 0.06	26.80	0	0.64	69
ARW	−7.91 ± 0.76	−10.38	0		
θ	−12.56 ± 1.00	−12.54	0		
MOE					
Intercept	24395.43 ± 5658.40	4.31	0		
NWD	203.65 ± 11.68	17.44	0	0.51	12867
ARW	−1892.12 ± 142.32	−13.30	0		
θ	−1307.63 ± 187.14	−6.99	0		
SPL					
Intercept	125.03 ± 28.93	4.32	0		
NWD	0.95 ± 0.06	15.88	0	0.44	66
ARW	−6.43 ± 0.73	−8.83	0		
θ	−9.19 ± 0.96	−9.61	0		

R^2, coefficient of determination; SEE, standard error of estimate; t(841), t ratio

Table 6. Summary of physical and mechanical parameters determined for each treatment

Parameter	Treatment		
	None	Every 4 years	Annually
MOR (kgf cm^{-2})	612a ± 53	602a ± 50	622a ± 63
MOE (kgf cm^{-2} × 10^3)	69.7a ± 7.7	67.1a ± 6.7	65.5a ± 8.5
SPL (kgf cm^{-2})	339a ± 41	331a ± 35	355a ± 42
η (adimensional)	0.64a ± 0.02	0.64a ± 0.02	0.64a ± 0.03
θ (degrees)	5.8a ± 1.5	6.1a ± 1.9	6.4a ± 1.4
ARW (mm)	14.1a ± 1.4	14.8a ± 1.3	14.9a ± 1.4
NWD (kg m^{-3})	383a ± 18	381a ± 23	387a ± 29

Results are expressed as the average ± SD

Values in the rows with the same letter did not differ significantly ($P < 0.05$)

and physical parameters measured during static bending. According to the hypothesis offered by Daniel et al.,[19] the differentiation and stratification within the stand are the result of competition among trees for growing factors such as light, water, and nutrients. In this way, the lower density of plantation and thinning application in a silvopastoral system contribute to the maintenance of uniform stands.[1] However, there is a possibility that the amount of fertilizer applied was not enough for the soil condition and the stands' densities. This was noted by observing that the mean values for the stand's variables (TH, DBH, CH, LCH) did not differ among treatments (Table 2). We suggest that fertilization prescriptions at any site must be in accordance with the species requirements, stand density, and soil condition because the competition among trees determines the nutrients and water demand of the soil.[19]

In *P. radiata* growing under traditional conditions, fertilization decreases wood density 5%–20% during a period of 3–5 years after fertilizer application. However, our results suggest that such a situation cannot be compared to that of trees growing in a silvopastoral system because the physiologic and ecological aspects related to growth in *P. radiata* differ completely from those of traditional forest plantations. In silvopastoral systems, reduced stand density could determine reduced competition among trees, which in turn could be translated into similar growth among treatments (Table 2). Therefore, the fertilization frequency in these silvopastoral treatments did not contribute to improving the growth of trees or to differentiating the wood properties of *P. radiata* above 25% of the commercial height.

The variation in physical and mechanical properties measured during static bending at different heights on the stem is another important aspect that must be considered. Cown[20] and Tian et al.[21,22] have argued that, independent of the growth condition (natural forest or manmade forest), the wood quality of *P. radiata* decreases as the vertical position in the stem rises. This could be explained by the higher relative proportion of juvenile wood as the distance from the base of the tree increases.[23] Larson[24] and Hejnowics and Tomaszewiski[25] have pointed out that carbohydrate availability and cambium activity exercise an influence on xylem development, generating differences in the morphologic and physical properties of the wood produced. Increased carbohydrate availability and cambium activity would translate into less mechanical strength of the wood and, consequently, a reduced market value. These arguments are in accordance with our findings.

According to Farrar,[26] for coniferous species the highest ARW values and the lowest wood density values are found at the beginning of the live crown. The results obtained in this study (Table 7) confirm that idea. It is also necessary to point out that the increased mean value of ARW and the decreased NWD result in a significant decrease in MOR and SPL. Therefore, it is possible to conclude that logs obtained from approximately 4.5 m (25% of commercial height) have better mechanical properties than those obtained from the zone immediately below the beginning of the live crown (approximately 7.2 m).

Table 7. Summary of physical and mechanical parameters determined for each position

Parameter	Vertical position in the stem	
	P1	P2
MOR (kgf cm^{-2})	632a ± 51	593b ± 53
MOE (kgf cm^{-2} × 10^3)	66.9a ± 8.3	68.0a ± 7.3
SPL (kgf cm^{-2})	348a ± 44	335b ± 36
η (adimensional)	0.63a ± 0.02	0.64a ± 0.02
θ (degrees)	6.2a ± 1.7	6.0a ± 1.5
ARW (mm)	13.9a ± 1.1	15.3b ± 1.4
NWD (kg m^{-3})	391a ± 21	377b ± 24

Results are expressed as the average ± SD

Values in the rows with the same letter did not differ significantly ($P < 0.05$)

P1, approximately 4.5 m; P2, approximately 7.2 m

Cown and Hutchison,[27] Tian et al.,[22] and Zhang[12] have found that wood density is the main property affecting wood strength when it is under stress. However, Tsehaye and Walker[11] and Leban and Haines[28] showed that properties such as θ and ARW were important for elasticity and strength parameters during bending.

According to Valenzuela and Nakayama[9] and Kollman and Cote,[15] η is a sensitive detector of defects in wood during bending, with values near 0.7 for structural lumber and small, clear samples. They pointed out that the η value is negatively affected when spiral grain (a common defect in many coniferous trees) is present. The results obtained in this study (Table 6) confirm those obtained by Valenzuela and Nakayama, who found that when the spiral grain value increases in *P. radiata* the η value decreases.

Our results confirmed that the basic relations among physical properties and mechanical parameters, determined under static bending, persist even when silviculture practices differ. In this context, it is possible that wood density is the main property related to the behavior of the woody material when it is subjected to stress under static bending. It is also important to emphasize the negative effect θ has on the behavior of the mechanical parameters analyzed. Spiral grain is considered a wood defect that is present in most trees, although it is known that it is a normal characteristic of growing and its expression could be explained by genetic factors.[29,30]

Finally, we propose that the use of wood for making various products is related to certain physical and mechanical properties that define their aptitude according to the requirements set for the manufacture and final use of the product.[31,32] Therefore, if wood produced under a silvopastoral system is intended for use in structures, the structural design should consider the mean values for elasticity and strength determined for each treatment and the vertical position in the stem (Tables 6, 7).

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