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Pasture production under different tree species and densities in an Atlantic silvopastoral system

M. J. Rozados-Lorenzo · M. P. González-Hernández · F. J. Silva-Pando

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Abstract We studied the effect of six tree species planted at six different densities on pasture production seven years after establishment. Annual and seasonal pasture production was studied every six months, over three years. Pasture production was lower under conifer trees (*Pseudotsuga menziesii* (Mirb.) Franco, *Pinus pinaster* Aiton, *Pinus radiata* D. Don) than under broadleaved trees (*Betula alba* L., *Quercus rubra* L. and *Castanea sativa* Mill.). Annual pasture production under *Pseudotsuga menziesii* and *Pinus pinaster* decreased progressively starting from 952 trees ha^{-1}, while decline in herbage production under *Pinus radiata* began to occur at 427 trees ha^{-1}. Tree density effect on pasture production was detected at 2,000 trees ha^{-1} for all of the deciduous species studied. This effect on pasture production was more important in the first six months of the year (June sampling), while from June to December herbage production was less affected by tree density. The tree effect became more noticeable over time, with the last sampling showing the inverse relationship between tree density and herbage production most clearly. Seven years after tree establishment, pasture production was quite consistent under tree densities between 190 trees ha^{-1} and 556 trees ha^{-1} and declined remarkably from 556 trees ha^{-1} to 2,500 trees ha^{-1}. The study also indicated that by the sixth growing season, annual pasture production under different tree species is inversely correlated with tree leaf area index.

Keywords Galicia · Herbage production · Leaf area index · NW Spain · Tree canopy · Tree density

Introduction

The use of grazing for vegetation management on forestland has increased in recent years, especially on public lands, where the use of herbicides and fire have been restricted due to environmental concerns. While forest grazing has gained wide acceptance in the Mediterranean countries, a more recent approach has been to introduce trees to non-wooded grazing areas (Dupraz and Newman 1997).

Establishing silvopastoral systems in Europe have been reported to offer benefits to farmers such as grazing for livestock production, diversi-

M. J. Rozados-Lorenzo (✉) · F. J. Silva-Pando
Environmental Information and Research Centre Lourizán, C.I.I.A.-CDS-Medio Ambiente e Desenvolvemento Sostible-Xunta de Galicia, Apdo. 127, CP 36080 Pontevedra, Spain
e-mail: mjrozados.cifal@siam-cma.org

M. P. González-Hernández · F. J. Silva-Pando
Department of Crop Production, Santiago de Compostela University, CP 27002 Lugo, Spain

fication of production, multiple land use, and as a tool for fire prevention (Sibbald 1999). The latter benefit is particularly important in NW Spain where, many hectares of forestland are covered by ligneous and easily inflammable shrubs, such as gorse (*Ulex* spp.), heaths (*Erica* spp., *Calluna vulgaris*) and other legumes, such as *Pterospartum tridentatum.* This type of vegetation has been reported to have low nutritional quality and a high tannin content which often limits digestible protein availability (González-Hernández 2005). Therefore, these areas could benefit from the establishment of agroforestry systems that would enhance productivity, replacing shrubs with herbaceous cover of higher productivity and nutritional value and low flammability. Such systems have been reported to be an alternative approach to preserving rural areas from abandonment and enhancing profits from the land (Rigueiro-Rodríguez et al. 2005).

The optimization of agroforestry systems by choosing the right density and spatial arrangement of trees or species of trees/understory is a complex and long-term process requiring practical and economic feasibility studies before major investments are decided (Newman and Gordon 1997). Also, the point at which trees begin to reduce forage production will depend upon forage species and site characteristics (Sharrow and Fletcher 2003). In an Atlantic area, more benefits could be expected, since warmer temperatures and adequate precipitation, without summer drought, may lead to suitable tree growth and better herbage production than in colder or dryer areas.

There is uncertainty concerning the extent to which herbage yield and quality are affected by tree spacing (Burner and Brauer 2003). Although some studies concerning tree-pasture relationships in temperate climates have been published both in conifer (Sibbald et al. 1994; Fernández et al. 2002; Silva-Pando et al. 2002; Burner and Brauer 2003), and deciduous forests (San Miguel 1994; González-Hernández and Silva-Pando 1996; Dupraz and Newman 1997; González-Hernández et al. 1998; Silva-Pando et al. 1998; Montard et al. 1999; McElwee and Knowles 2000; Teklehaimanot et al. 2002). Armand and Etienne (1996) studied the impact of long-term canopy cover on annual and seasonal production to assess the effect of trees on range management under Mediterranean conditions. However, relatively few studies have compared pasture production under evergreen and deciduous tree species, combining various tree densities and species, in order to assess and optimize agroforestry systems based on specific objectives of management and/or production.

Our research was conducted as a pilot study under field conditions during a seven-year establishment phase of a silvopastoral system in Galicia, NW Spain. The general purpose of the study was to assess approaches to future large-scale field research on tree-pasture production, to respond to the demand of forest owners to increase their livestock and wood production incomes, and to reduce fire risk. The objective of our research was to provide information about seasonal and annual pasture production under different tree species and densities.

Material and methods

The study site is located in Pontecaldelas, Pontevedra, NW Spain (42°22′ N, 8°29′ W, 386 m asl). The climate is temperate and humid with annual rainfall average of 2,740 mm and average maximum and minimum annual temperatures of 18.2°C and 5.9°C, respectively (MeteoGalicia 2004). The area is characterised by a short drought period during the summer.

Tree establishment and measurements

The experiment was established in 1996. Initially, spontaneous vegetation, mainly scrub and grasses, were harrowed and soil mechanically ploughed. Seedlings of *Pseudotsuga menziesii* (Mirb.) Franco, *Pinus pinaster* Aiton, *Pinus radiata* D. Don., *Quercus rubra* L. and *Castanea sativa* Mill., were planted in February the same year, while *Betula alba* L. seedlings were planted in February 1997. Total fenced area was 9,030 m^2 and six 1,170 m^2 plots were established with surrounding buffer strips (Fig. 1). On each plot, 102 one-species seedlings were planted in parallel rows, with one tree species per plot. To avoid border

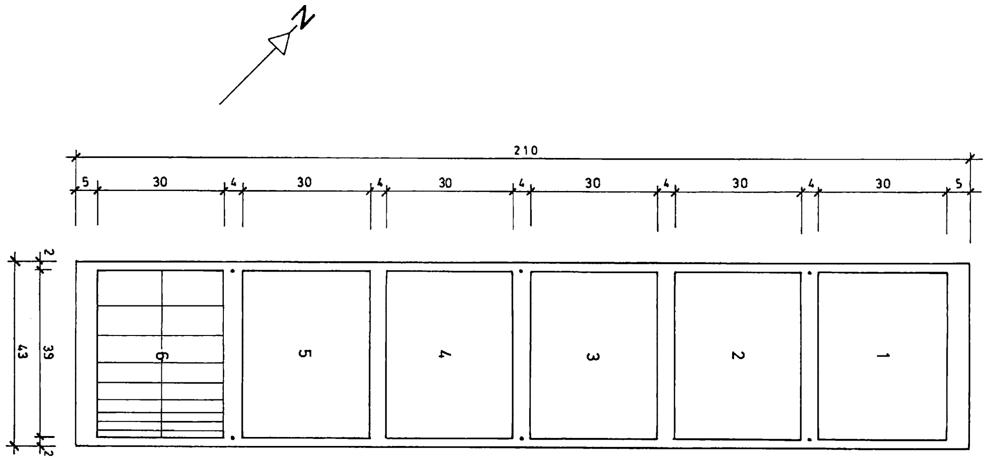


Fig. 1 Experimental layout. 1 = *Pinus pinaster*, 2 = *Quercus rubra*, 3 = *Betula alba*, 4 = *Pinus radiata*, 5 = *Castanea sativa* and 6 = *Pseudotsuga menziesii*. Horizontal lines on plot 6 correspond to tree rows and for the other 5 plots, as well

effects, the first, second and last tree rows, as well as the end trees on each row were not considered. Thus, only 51 trees were sampled per plot. Seedling density and spatial arrangement in the sampling area started from the third row at 2×2 m spacing, and subsequently each row was systematically spaced one metre ahead of the previous row. This resulted in the following spatial arrangement: 2×2, 2×3, 3×4, 4×5, 5×6, 6×7 and 7×8 m. Thus, the final densities were: 2500, 2000, 952, 556, 427, 256 and 190 stems ha^{-1}, respectively. The number of trees within each specific spatial arrangement is shown in Table 1.

Root collar diameter and height were measured for each tree during the dormant season in 2000 and border trees were excluded for mean calculations. In order to reduce tree/tree and tree/pasture competition, and to obtain knot-free logs, lower branches of trees were pruned up to 1–1.5 m in January 2003. The criteria to decide the extent of tree pruning was based on the height of the trees. For each species, the tree mean heights when pruned were: *Pseudotsuga menziesii* 1.7 m, *Pinus pinaster* 5.0 m, *Pinus radiata* 8.3 m, *Quercus rubra* 2.2 m, *Castanea sativa* 2.9 m and *Betula alba* 3.6 m.

Leaf area index was measured using an LAI–2000 (Licor, USA), during a cloudy homogeneous day in August 2002, 30 cm aboveground, between tree rows at 2×2 m spaced. Percentage of canopy cover calculations were made from LAI-2000 data.

Table 1 Experimental plot layout

Subplot size m^2	Number of trees	Tree spacing m × m	Density trees ha^{-1}
157.5	3	7×8	190
195	3	6×7	256
99	5	5×6	427
126	7	4×5	556
94.5	9	3×4	952
65	13	2×3	2,000
52	13	2×2	2,500

Soil characteristics and treatments

The soil where this study was conducted is a sandy brown acidic earth on a granitic substrate. Soil chemical and physical properties (on the top 20 cm) were analyzed before trees and herbage were planted (Table 2). Three samples were selected randomly from each plot and combined into a composite sample. Thus, six samples (one per plot) were analyzed using the methods reported in Table 2. Annually, a first dose of a granular fertilizer was applied at the rate of 5 kg N ha^{-1}, 40 kg Ca ha^{-1}, 1 kg Mg ha^{-1} and 16 kg P ha^{-1} in March, and a second dose was applied in May at the rate of 5 kg N ha^{-1}, 2 kg Ca ha^{-1} and 1 kg Mg ha^{-1}. In 2003, granular fertilizer was replaced by three slow release tablets

Table 2 Chemical and physical soil properties (top 20 cm) before tree planting. Mean ± SD, $n = 6$

Soil properties (top 20 cm)	Mean ± standard deviation	Analytical method
% C	9.92 ± 1.58	Walkley-Black
% Organic matter	17.07 ± 2.69	
% total N	0.602 ± 0.132	Semi-microKjeldahl
C/N ratio	16.73 ± 2.34	
pH	4.59 ± 0.12	1:2.5 H_2O
K exchangeable, mg kg^{-1}	73.67 ± 29.47	Ammonium acetate extraction Atomic emission spectrophotometry
P available, mg kg^{-1}	11.82 ± 3.62	Bray II
Ca exchangeable, mg kg^{-1}	26.67 ± 9.35	Ammonium acetate extraction Atomic absorption spectrophotometry
Mg exchangeable, mg kg^{-1}	22.33 ± 5.85	Ammonium acetate extraction Atomic absorption spectrophotometry
% Sand	81.46 ± 5.62	Robinson pipette
% Silt	10.28 ± 3.51	Robinson pipette
% Clay	8.26 ± 2.19	Robinson pipette

per tree (Medramás® 11% N, 18% P_2O_5, 11% K_2O, 4% MgO), in order to reduce the higher nitrogen doses from the previous fertilization which could negatively affect tree development.

Pasture establishment and production

In 1996, a mixture of *Dactylis glomerata* var. 'Artabro' and *Trifolium repens* var. 'Huia' was sown in early spring. Herbage quadrats were harvested in June and December of 2000, 2001, 2002 and June 2003. Herbage yield was measured by harvesting 4 quadrats of 30 × 30 cm at ground level between two consecutive tree rows. Then, plant material was dried in an air-forced oven at 80°C to constant weight, and pasture production estimated as dry matter. Annual herbage production was calculated using the sum of December and June samplings for each year, and excluded the June 2003 sampling. Pasture of the whole plot was mechanically cut after summer sampling each year.

Statistical analysis

Pasture data were analysed using PROC GLM (SAS Institute 1990) as a repeated measured analysis of variance, with sampling date as a within factor and tree species and densities as between factors. We tested the possibility of grouping conifer (*Pinus radiata*, *Pinus pinaster* and *Pseudotsuga menziesii*) and broadleaved (*Quercus rubra*, *Betula alba* and *Castanea sativa*) tree species for statistical treatment to avoid significant species × density interactions using canopy cover (deciduous and conifers) and density as between factors. In both repeated measures analysis of variance, the probability was adjusted by Huynh-Feldt for within factors to correct, when it is present, the violation of the sphericity assumption by the data. Pre-planned comparisons based on least square means were made to detect changes in production trends for interaction effects. Between and within factors effect may be interpreted with caution to avoid false conclusions in annual pasture production. Height and root collar diameter data were analysed using a two way analysis of variance, with species and density as main factors. Regression techniques were used to correlate LAI values with pasture production.

Results

Tree measurements

Root collar diameter and tree height measured in 2000 are shown in Table 3. Stem diameter sequence across species was *Pinus radiata* > *Pinus pinaster* > *Pseudotsuga menziesii* > *Betula alba* = *Castanea sativa* > *Quercus rubra*. *Sig-*

Table 3 Mean root collar diameter (d) and mean height (h) in year 2000. Border trees in the plots were excluded for mean calculations

Density trees ha^{-1}	*Pseudotsuga menziesii*		*Castanea sativa*		*Pinus radiata*		*Betula alba*		*Quercus rubra*		*Pinus pinaster*	
	d (cm)	h (m)	d (cm)	h (m)	d (cm)	h (m)	d (cm)	h (m)	d (cm)	h (m)	d (cm)	h (m)
190	5.3	2.1	2.9	1.7	15.8	5.3	5.5	2.9	1.6	1.1	13.0	3.9
256	3.4	1.2	4.0	1.8	15.9	5.7	5.7	3.3	1.6	1.3	6.9	2.4
427	5.4	1.6	3.5	1.7	15.9	5.7	5.3	2.8	2.3	1.5	10.6	3.3
556	4.1	1.1	3.7	2.1	17.1	6.2	5.1	2.5	1.9	1.6	11.0	3.7
952	5.5	1.6	3.6	2.1	15.3	6.0	4.0	2.4	2.2	1.8	7.8	2.9
2000	4.6	1.5	3.8	2.0	12.8	6.0	3.3	1.8	1.9	1.5	10.2	3.4
2500	4.0	1.4	4.9	2.4	12.4	6.3	3.1	1.9	1.8	1.3	8.8	3.4

nificantly the highest stem diameters ($P < 0.001$) were found at densities of 190 trees ha^{-1} and the lowest stem diameters at 2,000 and 2,500 trees ha^{-1}. Tree height values were not related to tree density and in decreasing order were Pinus radiata > Pinus pinaster > Betula alba = Castanea sativa > Quercus rubra = Pseudotsuga menziesii, with overall species effect ($P < 0.0001$).

Annual pasture production under different tree species and densities

Statistical analysis of annual herbage production showed significant differences in the two main factors, tree species and density, and their interaction. Pre-planned comparisons broken down by main factors were made on annual herbage

Table 4 Annual pasture production by species and year. Mean ± SD, t ha^{-1}

Density trees ha^{-1}	Year	*Betula alba*	*Castanea sativa*	*Quercus rubra*	*Pinus pinaster*	*Pinus radiata*	*Pseudotsuga menziesii*	*P*
2500	2000	5.54 ± 1.26	6.73 ± 3.52	6.91 ± 2.47	6.27 ± 1.43	5.14 ± 1.26	4.36 ± 1.39	0.7875
	2001	7.81 ± 2.15	5.85 ± 0.39	8.48 ± 1.81	8.02 ± 0.75	3.82 ± 1.02	2.82 ± 0.54	**0.0008**
	2002	5.06 ± 1.01	6.12 ± 1.59	6.26 ± 2.40	3.63 ± 1.15	3.45 ± 0.77	4.57 ± 4.16	0.4951
2000	2000	7.83 ± 1.81	11.36 ± 3.35	7.25 ± 3.02	8.42 ± 1.62	4.83 ± 1.51	6.28 ± 1.99	**0.0400**
	2001	7.00 ± 1.15	7.30 ± 2.26	10.06 ± 3.58	9.77 ± 3.09	5.85 ± 0.71	5.19 ± 2.07	**0.0096**
	2002	9.77 ± 2.58	8.53 ± 1.40	6.14 ± 1.62	6.79 ± 3.17	4.77 ± 1.58	5.63 ± 3.51	0.0613
952	2000	8.26 ± 2.06	10.91 ± 4.53	6.79 ± 1.55	11.13 ± 2.30	8.13 ± 1.11	7.89 ± 3.33	0.1849
	2001	8.87 ± 1.82	7.82 ± 2.02	14.62 ± 5.03	10.89 ± 3.75	6.81 ± 0.46	8.38 ± 2.30	<**0.0001**
	2002	11.18 ± 5.03	8.43 ± 1.94	7.04 ± 2.61	6.85 ± 1.51	3.59 ± 0.86	7.80 ± 2.13	**0.0034**
556	2000	8.35 ± 1.87	9.08 ± 1.17	9.28 ± 3.72	9.11 ± 2.75	8.48 ± 1.33	4.49 ± 1.95	0.1543
	2001	9.43 ± 0.95	7.78 ± 3.27	9.90 ± 2.66	8.92 ± 3.57	7.08 ± 1.52	8.11 ± 0.65	0.4793
	2002	6.79 ± 3.05	9.28 ± 2.61	9.51 ± 6.02	6.20 ± 1.36	6.97 ± 1.69	8.68 ± 3.53	0.2911
427	2000	8.92 ± 2.11	8.26 ± 1.84	9.54 ± 3.52	10.50 ± 1.58	10.88 ± 5.92	9.18 ± 5.46	0.7914
	2001	8.99 ± 2.29	5.91 ± 2.10	9.28 ± 1.18	10.27 ± 1.09	9.24 ± 2.51	8.02 ± 1.55	0.1163
	2002	6.44 ± 1.74	7.43 ± 0.46	7.84 ± 1.75	9.11 ± 1.60	7.42 ± 1.50	6.76 ± 1.46	0.7473
256	2000	10.35 ± 1.33	7.54 ± 1.69	9.13 ± 2.97	10.65 ± 2.28	6.25 ± 4.99	9.40 ± 4.42	0.2217
	2001	7.43 ± 0.77	6.68 ± 2.28	9.87 ± 1.40	16.23 ± 3.86	7.19 ± 2.46	6.58 ± 3.49	<**0.0001**
	2002	7.60 ± 1.00	7.53 ± 2.51	9.60 ± 1.60	5.90 ± 2.03	5.65 ± 2.75	7.65 ± 2.77	0.2872
190	2000	7.76 ± 2.29	8.70 ± 5.33	9.46 ± 3.64	9.32 ± 2.31	6.84 ± 0.76	13.22 ± 1.20	**0.0415**
	2001	8.22 ± 1.49	8.54 ± 2.45	10.71 ± 1.42	10.57 ± 1.64	5.92 ± 2.29	8.92 ± 1.32	**0.0369**
	2002	6.83 ± 1.51	7.01 ± 2.70	6.54 ± 0.85	9.03 ± 1.41	4.42 ± 1.26	14.57 ± 6.25	<**0.000**
P	2000	0.4065	0.2142	0.5666	0.2335	**0.0460**	**0.0002**	
	2001	0.7069	0.5504	**0.0072**	<**0.0001**	**0.0500**	**0.0017**	
	2002	**0.0161**	0.6546	0.2448	**0.0464**	0.1816	<**0.0001**	

Probability values show statistical differences among species for each density and year (right column). Statistical differences among densities for each species and year are also shown (three end rows). Bold text indicate significantly different means at $P \leq 0.05$

production (Table 4). Annual herbage production ranged from 5.18 t to 10.98 t. Significant differences in annual herbage production under the different tree species were only observed at the higher and the lower densities, while no differences were found for intermediate values (427–556 trees ha^{-1}). The most significant effects of tree density on annual pasture production occurred under evergreen species. Significant reductions in pasture production induced by tree density under conifer canopies were observed earlier in *Pinus radiata* (in 2000 and 2001, $P \le 0.05$) than in *Pinus pinaster* (in 2001 and 2002, $P \le 0.05$), while in *Pseudotsuga menziesii* (in 2000, 2001 and 2002, $P \le 0.05$) a tree density effect occurred throughout the three years of the pasture production study (Table 4). In the group of deciduous tree species, annual herbage production was affected by tree density only under *Betula alba* and *Quercus rubra*, in 2002 ($P = 0.0161$) and in 2001 ($P = 0.0072$), respectively. Under both species, pasture production increases by year were detected with decreasing densities down to 952 trees ha^{-1}. Densities of 556–427 trees ha^{-1} resulted in decreases of pasture production, that will be maintained with little changes under the wider densities assayed.

Average annual pasture production throughout the three years of the study decreased significantly ($P < 0.05$) at densities of 2,000 trees ha^{-1} under *Castanea sativa* and *Betula alba* (Fig. 2). Under *Quercus rubra* the significantly lowest values were found at densities of 2,500 trees ha^{-1}. Under conifers, tree density had a highly significant effect on pasture production with identical effect on each species ($P < 0.0001$). Annual pasture production under *Pseudotsuga menziesii* significantly decreased from a tree density of 190–256 trees ha^{-1}, was unaffected at intermediate tree densities, and significantly decreased at tree density of 952 trees ha^{-1}. Annual pasture production under *Pinus pinaster* varied with tree density, but significantly decreased only at densities higher than 952 trees ha^{-1}. Annual herbage production under *Pinus radiata* noticeably decreased at densities narrower than 427 trees ha^{-1} (Fig. 2).

Over all tree densities, the lowest annual pasture production was observed under *Pinus radiata* (Fig. 3). Initially, in year 2000, pasture production was similar for all the species. In 2001, annual herbage production was highest under *Pinus pinaster* and *Quercus rubra.* In the last year, only *Pinus radiata* showed differences from the other species assessed (except *Pinus pinaster*).

When data from the coniferous and deciduous species were compared pasture production under conifers was lower than pasture harvested under deciduous trees throughout the three years (d.f. = 1, $F = 6.38$, $P = 0.0128$). Across both canopy types, density showed a highly significant effect (d.f. = 6, $F = 7.83$, $P < 0.0001$) and the interaction of canopy cover x density effect was avoided (d.f. = 6, $F = 1.86$, $P = 0.0919$). The within-factor, sampling date, was highly significant (d.f. = 2, $F = 10.85$, adjusted $P < 0.0001$). No significant interaction between years and main factors was detected. Pasture production under broadleaved trees was higher than under coniferous species, yearly and overall, but significant differences between the two canopies were detected only in 2001. Under both canopies, density remained a significant effect on pasture production during the three years.

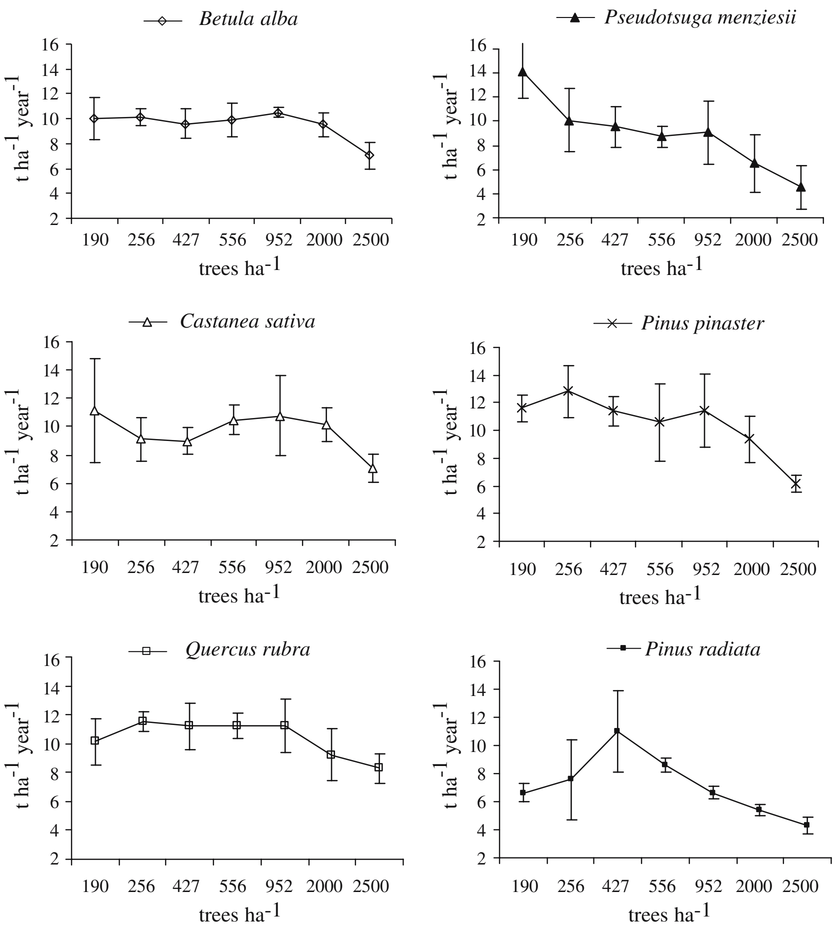
Tree canopy cover percentages at 2,500 trees ha^{-1} under trees with mature leaves were 94% for *Pinus radiata*, 89% for *Pinus pinaster*, 56% for *Pseudotsuga menziesii*, 58% for *Castanea sativa*, 31% for *Betula alba* and 25% for *Quercus rubra.*

The linear regression obtained with annual pasture production and LAI explains most of the variation found (Fig. 4). The fitted line is: Pasture Production = 6.0652–0.8431 LAI, ($r^2 = 0.7243$, $P < 0.0316$), and shows an inverse relationship between the leaf area index and annual pasture production.

Seasonal pasture production under different tree species and densities

Because of the highly significant interactions obtained with the repeated measures analysis of variance on annual production data, simple analysis of variance were made by sampling date. Preplanned comparisons broken down by species or by density allowed the identification of some specifics.

Fig. 2 Variations in average annual pasture production throughout three years for each species stand. Vertical bars are SE of the means, $n = 3$. Probability level associated with differences among least square means for the effect species x density interaction is $P \leq 0.05$



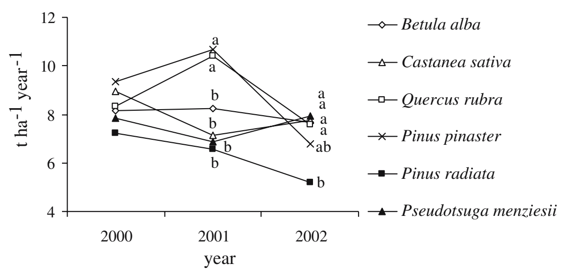


Fig. 3 Mean annual pasture production under different tree species. Different letters for each year indicate significantly different production among species at $P \leq 0.05$

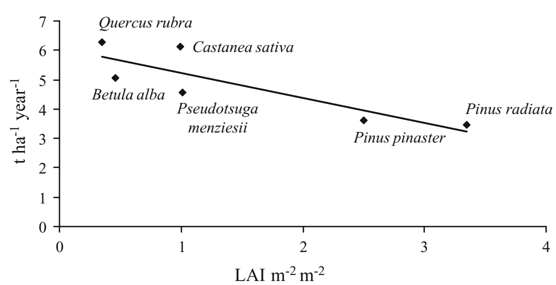


Fig. 4 Relationship between annual pasture production under different tree species and leaf area index planted at 2,500 trees ha^{-1} density

At the lowest density, 190 trees ha^{-1}, yield of pasture harvested in June was affected by tree species, while in December no significant differences among species was found. Pasture production (in the spring and winter samplings) under *Pseudotsuga menziesii* was significantly affected by tree density. Pasture grown under *Betula alba* was, at most dates, independent of tree density, while pasture collected under *Castanea sativa* in spring increased with tree density decrease.

Herbage production obtained in June 2001 and 2003 showed both species and density to have a significant effect without interactions.

Considering each sampling date, similar pasture production was obtained under 556 and 427 trees ha^{-1} density, with no differences between species (Fig. 5). Plots with the highest tree density had the lowest pasture production throughout the study. The effect of tree density on herbage production was higher, or more noticeable, in the June sampling than in the December one. The last sampling, collected in June 2003, showed the highest effect of tree density on pasture production, with the significantly lowest values occurring under 2,500 and 2,000 trees ha^{-1}, and the highest herbage production under 190 trees ha^{-1} (Fig. 5). For previous years, in June 2001 and June 2002, only 2,500 trees ha^{-1} density significantly decreased pasture production.

A logarithmic increment of pasture production in June 2003 was found (pasture production = 2.1175 ln (tree density) + 1.8063, r^2 = 0.9691) from narrower to wider spaced trees, with a noticeable change in the slope at 556 stems ha^{-1}, over all the tree species. Different slope values were obtained breaking the logarithmic trend into two linear trends. From 556 trees ha^{-1} to 2,500 trees ha^{-1}, slope was near –1, thus, pasture production decreased with tree density ($y = -1.1215x + 6.3465$, r^2 = 0.9991). Whereas at 190–556 trees ha^{-1}, slope was about –0.20, thus pasture production was only slightly affected by tree density ($y = -0.178x + 5.8795$, r^2 = 0.9469) (Fig. 6). Pruning on January 2003, could have emphasized these results.

Discussion

Several studies conducted on stands with loblolly pine (*Pinus taeda* L.) planted at different densities showed that tree spacing affected herbage productivity. Burner and Brauer (2003) found this effect at densities below 840 trees ha^{-1} during the fifth to sixth growing season. Brockway et al. (1998) reported that herbage production decreased under 7-year-old loblolly pines planted at 2,315 trees ha^{-1}. However, Pearson et al. (1995b) did not find significant decreases of herbage yield under loblolly pine planted at 4,451 trees ha^{-1} ten years after planting.

Our results showed that under *Pseudotsuga menziesii* and *Pinus pinaster*, annual pasture production decrease started from 952 trees ha^{-1}, while under *Pinus radiata* decreases occurred beginning at 427 trees ha^{-1}. The effect of *Pinus radiata* on annual pasture production could be explained by bigger stem diameters, and the resulting presence of wider crowns intercepting solar radiation. *Pseudotsuga menziesii* had smaller stem diameters, but its branching pattern of larger branches closer to the ground (pasture level), could result in a strong reduction in the amount of solar radiation able to reach soil level.

Fig. 5 Mean pasture production under each tree species on each biannual sampling date by tree density. Different letters within each date indicate significant differences at $P \leq 0.05$

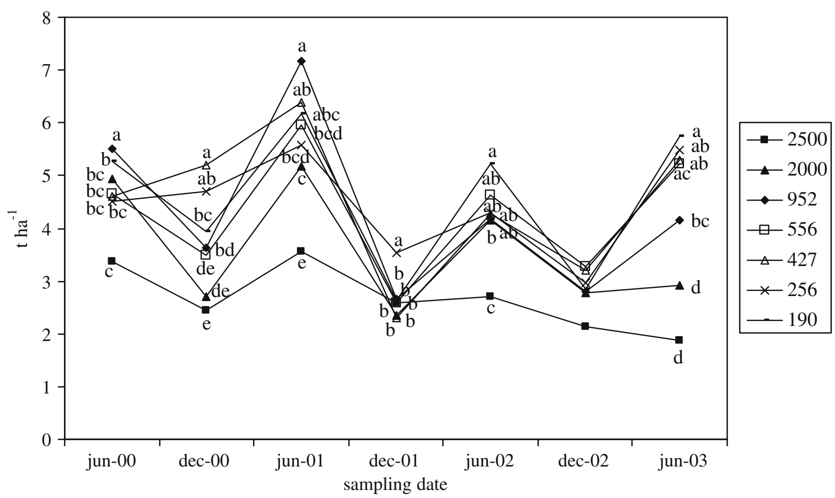
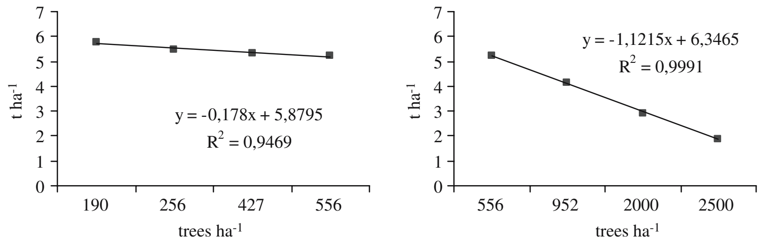


Fig. 6 Trends in pasture production at different tree densities in June 2003



Percival and Knowles (1988) found a very strong relationship between green crown length and the relative herbage yield under *Pinus radiata* Don canopies. Sibbald et al. (1994) reported that the horizontal projection of the crown gives a good prediction of annual herbage yield below *Picea sitchensis* [Bong.] Carr, and indicated that the component of horizontal incident light is very important for herbage growth.

Trees modify the understorey microclimate which in turn alters the seasonal pattern of pasture production (Sibbald 1999). Tree canopy architecture affects production of understorey layers, by producing different microclimatic conditions which influence pasture yield and its seasonal patterns (Silva-Pando et al. 2002). A linear relationship between relative annual pasture production and light transmission under *Pinus pinaster* Ait. and *Pinus sylvestris* L. stands at densities of 833 trees ha^{-1} was observed previously (Silva-Pando et al. 2002). In our study, highly significant interactions of tree species and density with sampling date suggest that microclimatic factors probably explain or justify pasture production. The effect of conifer canopy on annual pasture production led to a decrease of 18% in 2002 pasture production, over production in 2000 while the reduction under the deciduous canopy was 9% over the same period. Climatic parameters most likely are not responsible for this decrease, since 2002 was wetter and warmer than 2000 (2,752 mm total precipitation, 12.5°C mean temperature and 2,714 mm total precipitation, 11.9°C mean temperature, respectively). Herbage production decreased twice as much under conifers compared with the reduction in herbage production under deciduous canopies. This could be explained by the differences in average diameter and height, 9.8 cm and 3.5 m for conifers; versus 3.4 cm and 2.0 m for deciduous trees.

Also, evergreen perennial canopies intercept solar radiation throughout the year, while, in the study area, foliage in deciduous trees is present only from late April to early November. Since in March, higher average temperatures than in April are common, warm temperatures and higher radiation values reaching the soil level (through defoliated trees), can promote increases on pasture production. Furthermore, fast growing conifers produce great quantities of litter year round, and this can negatively affect grass production (Montard et al. 1999).

The leaf area index obtained at *Pseudotsuga menziesii* plots was similar to LAI at *Castanea sativa* plots during summer, but shadow effect in conifers remains over fall and winter, while broadleaved trees are defoliated. This fact, combined with litter decay differences, could explain the lower pasture production under conifer species (about 25% less), compared with broadleaved species with the same leaf area index value. Our results report that at the sixth growing season, annual pasture production under different tree species is inversely correlated with leaf area index. Pearson et al. (1995a) reported 4.9 m row spacing as a reasonable first approximation for agroforestry planning with loblolly pine (*Pinus taeda* L.). Under the same species, Burner and Brauer (2003) found maximum herbage yields at row widths ≥4.9 m and conclude that solar transmission, crude protein and digestibility are relatively high at this spacing. In our study, the density of 556 trees ha^{-1} (equivalent to 4×5 m tree spacing), could be interpreted as a cutpoint; since lower tree densities did not produce an increase on pasture yield, and higher tree densities negatively affects pasture production seven years after planting.

We can conclude that, seven years after planting, 556 stems ha^{-1} (equivalent to 4×5 m tree spacing) and 427 stems ha^{-1} (equivalent to 5×6 m tree spacing) in conifers could be the highest optimum tree density to one while still maintaining consistent pasture production. Furthermore in conifers, it is likely that, thinning should be carried out within the next two years, since fast-growing conifers planted at densities near 500 trees ha^{-1} could seriously limit grass growth. Broadleaved species had no effect on annual pasture production at any of the tree spacing used during the study and more data over time is necessary to obtain pasture production responses to tree density effect.

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