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Comparison between growth performance in two silvopastoral systems comprising trees, short-lived perennial shrub, a forage, and livestock)

Comparação entre o desempenho de crescimento em dois sistemas silvipastoris compostos por árvores, arbusto perene de ciclo curto, uma forrageira e gado

Comparación del rendimiento del crecimiento en dos sistemas silvopastoriles compuestos por árboles, un arbusto de hoja perenne de ciclo corto, un forraje y ganado

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Abstract
We aim to determine the growth performance of two 20-year-old silvopastoral systems comprising two timber trees, a palm tree), a short-lived perennial shrub, a forage and livestock; and to investigate fibre features and certain physical and mechanical properties of two timber trees (*Myracrodruon urundeuva* and *Peltophorum dubium*) in two plantation systems. The first system is called MP with two timber trees and the second one is called MPS with two timbers and a palm tree. The studied systems showed that it was possible to successfully combine fast-growing species, animals, forage and woody tree species, with a production cycle of more than 50 years of different goods and services (e.g., ornamentals, palm hearts, landscaping, fruits, seeds, bee pasture, meat, and wood). The height, diameter and volume for *M. urundeuva* trees in the MP system were greater than in the MPS system, whereas no difference between the systems was observed for *P. dubium*. By comparison, the growth and volume in *P. dubium* were greater than in *M.*

urundeuva. For wood properties, it was shown that both systems can be used successfully, but the MPS system performed better than the MP system, in the aim of wood production of high mechanical strength and calorific value. In addition, the MPS intercropping system can yield more goods and services than the MP system, both systems bring returns with short-term (bean seed, forage, pasture), medium-term (forage, palm products, pasture, wood), and long-term (wood) financial returns.
Keywords: Genetic improvement; Higher heating value; Mean annual increment; Planting systems; Wood properties.

Resumo
Objetivamos determinar o desempenho de dois sistemas silvipastoris com 20 anos de idade compreendendo duas espécies madeireiras, uma palmeira, um arbusto perene de vida curta, uma forrageira e gado; e investigar características das fibras e algumas propriedades físicas, mecânicas e energéticas de *Myracrodruon urundeuva* e *Peltophorum dubium*. O primeiro sistema é denominado MP com duas árvores madeireiras e o segundo é denominado MPS com duas árvores madeireiras e uma palmeira. Os sistemas estudados mostraram que foi possível combinar com sucesso espécies de rápido crescimento, animais, forrageiras e espécies arbóreas lenhosas, com um ciclo de produção de mais de 50 anos de diferentes bens e serviços (por exemplo, ornamentais, palmitos, paisagismo, frutas, sementes, pasto apícola, carne e madeira). A altura, diâmetro e volume das árvores de *M. urundeuva* no sistema MP foram maiores do que no sistema MPS, enquanto nenhuma diferença entre os sistemas foi observada para *P. dubium*. Em comparação, o crescimento e o volume em *P. dubium* foram maiores do que em *M. urundeuva*. Para as propriedades da madeira, foi demonstrado que ambos os sistemas podem ser usados com sucesso, mas o sistema MPS apresentou melhor desempenho do que o sistema MP, no objetivo de produção de madeira de alta resistência mecânica e poder calorífico. Além disso, o sistema consorciado MPS pode render mais bens e serviços do que o sistema MP, ambos os sistemas trazem retornos de curto prazo (semente de feijão, forragem, pasto), médio prazo (forragem, palmeira, pasto, madeira) e retornos financeiros de longo prazo (madeira).
Palavras-chave: Melhoramento genético; Poder calorífico superior; Incremento médio anual; Sistemas de plantio; Propriedades da madeira.

Resumen
Nuestro objetivo fue determinar el desempeño de dos sistemas silvopastoriles de 20 años que comprenden dos árboles maderables, una palma, un arbusto de hoja perenne de vida corta, un forraje y ganado; e investigar las características de la fibra y algunas propiedades físicas, mecánicas y energéticas de *Myracrodruon urundeuva* y *Peltophorum dubium*. Sistema 1 se llama MP con dos árboles maderables y Sistema 2 se llama MPS con dos árboles maderables y una palma. Los sistemas mostraron que era posible combinar con éxito especies de rápido crecimiento, animales, forrajes y especies de árboles leñosos, con un ciclo de producción de más de 50 años de diferentes bienes y servicios (p. ej., ornamentales, palmito, jardinería, frutas, semillas, pasto de abejas, carne y madera). La altura, diámetro y volumen de los árboles de *M. urundeuva* en el sistema MP fueron mayores que en el sistema MPS, mientras que no se observaron diferencias entre los sistemas para *P. dubium*. En comparación, el crecimiento y el volumen en *P. dubium* fueron mayores que en *M. urundeuva*. En cuanto a las propiedades de la madera, se demostró que ambos sistemas se pueden utilizar con éxito, pero el sistema MPS presentó mejor desempeño que el sistema MP, en el objetivo de producir madera con alta resistencia mecánica y poder calorífico. Además, el sistema de consorcio MPS puede generar más bienes y servicios que el sistema MP, ambos sistemas traen retornos a corto plazo (semilla de frijol, forrajes, pastos), medio plazo (forrajes, palma, pastos, madera) y retornos financieros a largo plazo. instrumentos (madera).
Palabras clave: Mejoramiento genético; Mayor poder calorífico; Incremento medio anual; Sistemas de plantación; Propiedades de la madera.

1. Introduction

The proposal for an agroforestry system is only feasible when it meets the needs of rural producer, with regard to optimization in obtaining timber and non-timber products under favorable economic conditions and providing ecological interactions relevant to the environment. These associations between species with short and long cycles are an even greater challenge in tropical regions that practice extensive agriculture, forestry and livestock. Alves et al. (2015) report that in Brazil, the main agroforestry systems involve *Eucalyptus* spp. in association with short-cycle crops such as: rice, soybeans, beans, corn, cassava in the early years and then become a silvopastoral system with the use of pastures. Silva (2013) mentions that zone of greatest concentration and diversity of agroforestry systems in the world is concentrated in tropical areas, and Brazil has been standing out in this area in the last three decades.

There are several types of agroforestry systems combining fast-growing species, timber species, palm trees and livestock, each one with its own particularities (Atangana et al., 2014). Producers should choose a system that is easily implementable at the micro-, meso- and macro-levels, and that is of interest in regard to social development and biodiversity conservation (Huang et al., 2002; Atangana et al., 2014). According to Lana et al. (2016) considered silvopastoral systems to be conservationist systems by combining forestry species with livestock, intercropping trees, and pasture in the same area.

Worldwide, there are many examples of agroforestry systems. Based on the nature of its components, Nair (1985) and Atangana et al. (2014) classified agroforestry systems as agrisilviculture (crops including tree/shrub crops and trees); silvopastoral (pasture/animals + trees); agrisilvopastoral (crops + pasture/animals + trees); and other systems such as entomoforestry, herboforestry, mycoforestry, aquaforestry, and multipurpose tree lots.

Recently, in Europe and North America, various initiatives aimed at increasing hardwood production while maintaining farming activity on rural lands. These have led to the development of hardwood-intercropping systems (Rivest et al., 2010). Cereal (e.g. corn, wheat, barley) and oilseed (e.g. soybean, sunflower) crops are generally used in these intercropping systems. Tree-based intercropping systems are considered to be potentially useful land use systems to mitigate the negative environmental impacts resulting from intensive agriculture (i.e. nutrient leaching and greenhouse gas emissions) (Rivest et al., 2009). Khasanah et al. (2015) studied agroforestry management practices in intercropping systems including *Tectona grandis* and *Zea mays* and found that all simulated intercropping systems produced a higher wood volume than a monoculture. This was explained by the fact that trees benefit from crop fertilization. In Latin America, Rice (2008) report systems with coffee and wood products in Peru and Guatemala, discussing the differences between systems and countries depending on management, tree diversity and relative demand for timber resources.

In Brazil, there are some examples of combined plantations composed of different tree species, or plant species combined with animals. Oliveira et al. (2015) studied the mixed planting species in Cerrado of central Brazil. They concluded that this system is appropriate for the recovery of disturbed areas and may be prescribed to facilitate the recovery of ecological processes in natural reserves, while providing goods and services under sustainable multiple-use landscape management. Pinto & Rodigheri (2001) studied the mixed planting of tree species in southern Brazil and reported positive wood volume, tree survival, height and diameter at breast height (DBH) results of four Brazilian species: *Libidibia ferrea*, *Handroanthus impetiginosus*, *Handroanthus albus* and *Peltophorum dubium*. Souza et al. (2012) also demonstrated a profitable system composed of clones of the natural hybrid of *Eucalyptus urophylla* x *Eucalyptus camaldulensis* and livestock fed with *Urochloa*. Lana et al. (2016) studied the influence of *Zeyheria tuberculosa* (native) and *Eucalyptus grandis* (exotic) trees on soil fertility in a silvopastoral system that had been established for decades in the Brazilian savannah biome and concluded that *E. grandis* plantations accounted for most of the litter composition in this silvopastoral system. Therefore, an efficient silvopastoral management system could be a promising choice for both land use and soil conservation in degraded areas, such as those found in the Brazilian savannah biome.

The establishment of plantations combining various tree species and palms aims to optimize the interaction between the elements in order to obtain an optimal plant mixture. This idea is in part based on the concept of ecological succession (Freitas et al., 2002). Certain studies have previously focused on intercropping systems including tree species from different successional groups, addressing the possibility of introducing fast-growing, short-lived shrub species and animals in silvopastoral agroforestry systems to offer diversified and sustained outputs in space and time (Moraes et al., 2006). Several studies also recommend planting tree species for genetic conservation and wood (Gurgel-Garrido et al., 1997). Using Brazilian native species in reforestation practices enables the maintenance of diversity in pure and mixed plantations, resulting in species conservation. The inclusion of different species in agroforestry systems, such as palm trees, also leads to a short-term return on investment through the harvest of its fruits, seedlings, seeds and palm hearts, which adds value to timber production, particularly in family farms. Certain slow-growing species destined to wood production, such as *Myracrodruon urundeuva*, cannot be used as a short-term economic incentive. Nonetheless, studies on the medicinal properties of other parts of the plant and its seeds increase the value of the species, thereby increasing its price, and expanding the market and its use by farmers. Therefore, the intercropping of different tree species and crops can bring a diversified economic return to the farmer/smallholder who can exploit several products in the same area at different times, while participating in species conservation and benefiting from a decrease in costs related to pests, diseases, and weed control (Freitas et al., 2002).

The objectives of this work were to: i) determine the performance of two 20-year-old silvopastoral systems composed of *Myracrodruon urundeuva* and *Peltophorum dubium* (timber trees), *Syagrus romanzoffiana* (palm tree), *Cajanus cajan* (short-lived perennial shrub), *Urochloa decumbens* (forage) and *Bos taurus indicus* (livestock); ii) investigate fibre characteristics and other physical, mechanical and energetic properties of two woody Brazilian species, *M. urundeuva* and *P. dubium* in two plantation systems, the first one named MP: *M. urundeuva* and *P. dubium* and the second one MPS: *M. urundeuva*, *P. dubium* and *S. romanzoffiana*.

2. Methodology

In our study, we used qualitative and quantitative methods according to Pereira et al. (2018). Specifically, in evaluating systems, we used qualitative analysis to estimate performance and also quantitative to estimate values of each product generated in the systems. Additionally, in methodologies described below there are standardized references for each variable.

2.1 The purpose of this study is to use three native tree species

Trema micranta (pioneer), *Peltophorum dubium* (initial secondary) and *Myracrodruon urundeuva* (late secondary); a palm *Syagrus romanzoffiana*, *Cajanus cajan* (short cycle), *Corymbia citriodora* (exotic) and *Urochloa decumbens* (forage). This system is not yet used on a commercial scale, but it is an alternative for rural producers in areas of legal reserve for continuously supplying timber and non-timber products over time and in the physical space it occupies on rural property. Another relevant factor is that this system has led to the appearance, spontaneously, of several native tree species, *e.g*.: *Andira cuyabensis*, *Andira inemis*, *Astronium fraxinifolium*, *Brosimus gaudichaudil*, *Byrsonima apicata*, *Byrsonima sericea*, *Diospyros tapir*, *Dipteryx alata*, *Jacaranda cuspidifolia*, *Luneta paniculata*, *Mabea fistulifera*, *Myracrodruon urundeuva*, *Qualea grandiflora*, *Qualea parviflora*, *Schefflera macrocarpa*, *Xilopia aromatica*, *Zanthoxilum hassleiranum*. In this step, we only measure the data of *P. dubium*, *M. urundeuva*, *S. romanzoffiana*, *C. cajan*, and *U. decumbens*.

Although monocultures it stands out in State of Mato Grosso do Sul, during 3rd Brazilian Forum on Sustainable Agriculture (2019), the importance of Integration of Livestock and Forestry model (iLPF) was highlighted, developed by Embrapa and adopted by producers in Mato Grosso do Sul, 11.5 million hectares of iLPF in Brazil, 2 million are in Mato Grosso do Sul. According to discussions at meeting, restricted use area in the Pantanal was also established, where producers were encouraged to join the Pantanal Sustainable and Organic Meat program, allowing this producer to have a tax incentive in such a way that he can produce in a sustainable manner and with good profitability and market competitiveness.

2.2 Description of the silvopastoral components

Myracrodruon urundeuva Allemão (Aroeira) is a native, but not endemic species found in Brazil, with a geographical distribution in all regions of Brazil: North, Northeast, Midwest, Southeast, and South of Caatinga, Cerrado, and Mata Atlântica (Santin & Leitão-Filho, 1991; Luz et al., 2019).

Peltophorum dubium (Spreng.) Taub. (Canafístula) is also a native, but not endemic species in Brazil, with a geographical distribution in the Northeast, Midwest, Southeast, and South on Caatinga, Cerrado, Mata Atlântica, and Pantanal (Silva et al., 2017). *P. dubium* wood is not widely used in Brazil, but it could, for example, be used in construction, carpentry, cooperage, railway sleepers or paper production (Lorenzi, 2002; Paula & Alves, 2007).

Syagrus romanzoffiana (Cham.) Glassman (queen palm tree), similar to the other two species, is also a native, but not endemic species in Brazil, with a geographical distribution extending in the Northeast, Midwest, Southeast, and South on Cerrado, Mata Atlântica, and Pampa regions of Brazil (Leitman et al., 2020).

Cajanus cajan (L.) Millsp. (Guandu) is of unknown origin, probably from India or Africa. The species has been cultivated in ancient Egypt, Africa and Asia since prehistoric times, and later introduced to America. It is now acclimatized to several tropical countries (Ripperton & Hosaka, 1942, *apud* FAO, 2016).

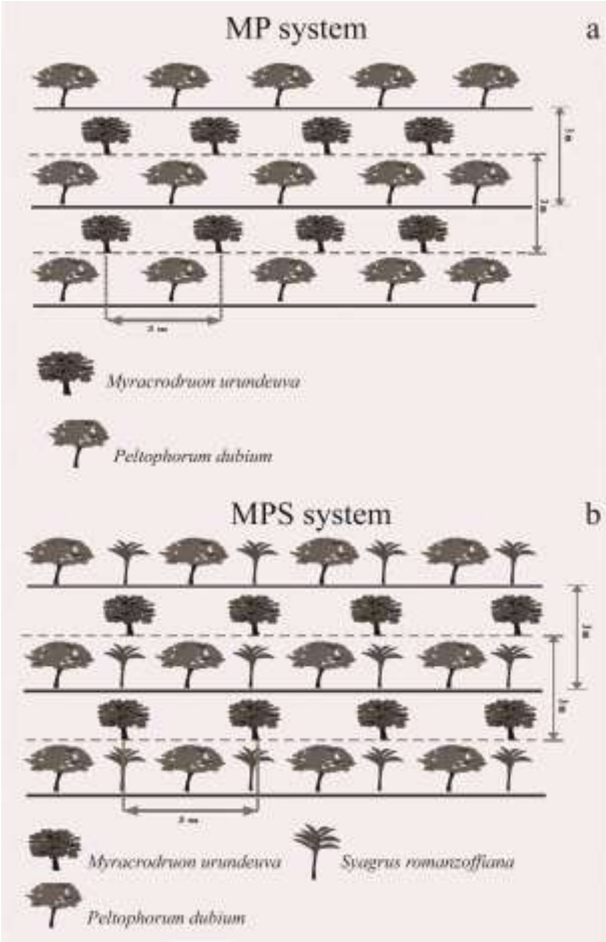
Urochloa spp. P. Beauv. (Braquiária) (syn. *Brachiaria*) occurs in tropical and subtropical regions of Africa, America, Asia and Oceania (Keller-Grein, 1996), with possible origins in central-equatorial Africa (Crispim & Branco, 1991). It has been used in Brazil for forage since the 1950s. According to Alvim et al. (2002), *Urochloa decumbens* (Stapf.) Webster was the most widely used forage species in Brazil. Currently, according to Nogueira (2019) *U. decumbens* has historical importance in development of livestock production system in Brazil, however there are species more suitable for use as forage, *e.g.*, *Urochloa brizantha*, *U. decumbens*, *U. humicola*, *U. ruziziensis*, *Panicum maximum*, and *Andropogon gayanus*.

Bos taurus indicus (Guzerá), originating from India, was the first zebu breed to be introduced into Brazil in the 1870s. Currently, the breed occurs in various regions of the country, e.g., Rio de Janeiro, Minas Gerais, São Paulo, Goiás and especially in northeastern Brazil, due to its high strength to drought (ACGB - Associação dos Criadores de Guzerá do Brasil, 2018).

2.3 Species/provenances, planting area and experimental design

Seeds of *P. dubium* and *S. romanzoffiana* were collected from trees in the municipality of Ilha Solteira, São Paulo State (20°25′S, 51°20′W, elevation 366m) and *M. urundeuva* seeds were collected from trees in Petrolina, Pernambuco State (≈ 09°13′S, 40°29′W), both in Brazil. *C. cajan* seeds (cultivar IAC-Fava Larga) were purchased commercially, while *Urochloa decumbens* plants originated from the soil seed bank. The *Bos taurus indicus* herd came from livestock of the Universidade Estadual Paulista Julio de Mesquita Filho (UNESP) in the municipality of Ilha Solteira, São Paulo State, Brazil. The soil at the planting site is a typical Red-Dystrophic Latosol (Santos et al., 2018). Trees were planted at a spacing of 3 m x 3 m in both plantation systems, MP (*M. urundeuva* and *P. dubium*) and MPS (*M. urundeuva*, *P. dubium* and *S. romanzoffiana*) (Fig. 1). Planting was carried out without chemical fertilization.

Figure 1. Schematic illustration of two plantation systems MP: *Myracrodruon urundeuva* and *Peltophorum dubium* and MPS: *M. urundeuva*, *P. dubium* and *Syagrus romanzoffiana* (adapted from Moraes et al., 2006).

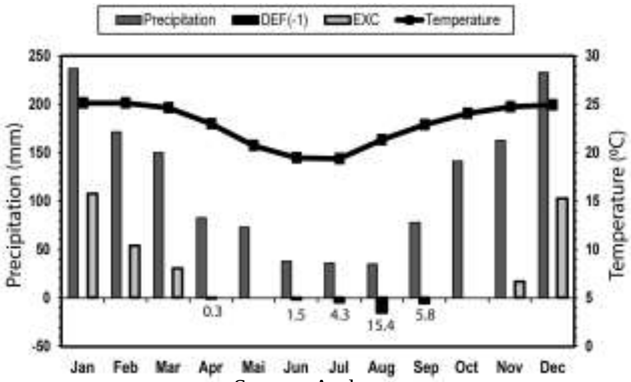


Source: Authors.

The experimental design was a randomized complete block in a split plot scheme, with seven planting systems (in this study two systems were evaluated), three repetitions, 10 progenies and six plants per plot in linear form (Freitas et al., 2002; Moraes et al., 2006). During the first four years of the experiment (1992-1996), *C. cajan* was planted between the two systems along with border trees. The experimental design was established in 1992 in the municipality of Selvíria, Mato Grosso do Sul (20°22′S, 51°25′W, elevation 345 m), climatic type is Aw (UNESP, 2018), tropical wet and dry or savanna climate; with the driest month having precipitation less than 60 mm. According to Flores et al. (2016), the annual average temperature is 23ºC and annual precipitation is 1440 mm. The ombrothermic diagram of Selvíria (Fig. 2) was developed based on data from Flores et al. (2016) on water balance of Thornthwaite and Mather (1955) and prepared using the spreadsheet developed by Rolim et al. (1998).

We emphasize that our study had two periods of data collection: i) Mean annual increment was determined at 25 years of planting (in 2017); ii) The system's performance (relationship among involved species, diameter at breast height, height and volume of trees) and wood properties was assessed at 20 years of planting (in 2012).

Figure 2. Average monthly precipitation, water deficit (DEF^{-1}), water surplus (EXC) in bars, and mean temperature in line (Flores et al., 2016). Water balance of Thornthwaite & Mather (1955) was prepared using the spreadsheet by Rolim et al. (1998).



Source: Authors.

2.4 Mean annual increment

In 2017, we evaluated all planted trees, for a total of 328 *M. urundeuva* trees and 189 *P. dubium* trees. The diameter was measured with a caliper, and the height was measured with a hypsometer Vertex IV. Tree volumes were calculated using the DBH (1.3 m from the ground) and height values. In *P. dubium*, we used the formula proposed by Higuchi (1978) who developed volumetric equations for the commercial volume measurement of four Brazilian native species, included *P. dubium*. The equation used was:

$$Volume = 0.063 + 0.255 \times diameter^2 \times height \ (R^2 = 0.93)$$

In *M. urundeuva*, we used the formula proposed by Cambuim (2017), who studied the same plantation as the one in the present study. The equation used was:

$$Volume = 0.0002 + 0.376 \times diameter^2 \times height \ (R^2 = 0.91)$$

Then, the volume per hectare was calculated according to the spacing (3 m x 3 m), by multiplying the number of plants by the average tree volume, and finally, the volume per hectare per year was calculated by dividing volume per hectare by the age of the plantation (25 years).

2.5 Wood sampling and analysis of Myracrodruon urundeuva and Peltophorum dubium

Before trees were felled, the geographic North was marked on each stem to standardize sampling. In total, 16 *P. dubium* trees and 20 *M. urundeuva* trees were felled (eight and ten in each plantation system, respectively). The 20-year-old trees were felled in 2012, and from each felled tree, we cut 1 m-long logs from the base of the stem and battens near the bark. These samples were used for fibre analysis, and certain physical and mechanical wood properties. The number of samples is in accordance with NBR 7190 (1997) - Annex B - item B.2.b, which specifies that minimum strength characterization of little-known species must be performed with at least 12 specimens. *Peltophorum dubium* and *M. urundeuva* are well-known species with several studies in Brazil, so the sampling is adequate.

2.6 Fibre analyses

Small pieces of wood from each sample were macerated using the modified Franklin's method (Berlyn & Miksche, 1976), stained with aqueous safranin and temporarily mounted in water and glycerine (1:1). Microscopic terminology followed the IAWA list (IAWA, 1989). Anatomical measurements were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus E330 EVOLT) and a computer image analysis software (Image-Pro 6.3).

2.7 Density

Wood density (ρ12%) was determined according to Glass & Zelinka (2010), which consisted of evaluating the mass and volume at 12% moisture content (MC). Specimens of size 2cm x 2cm x 3cm were conditioned at constant temperature (21°C) and 65% MC, respectively and, in these conditions, the mass was determined using an analytical balance and the volume was estimated by means of measurements of their diameters with a caliper.

2.8 Mechanical tests

Mechanical tests evaluated strength in compression parallel to grain ($\sigma c \parallel$) and modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending (three-point test), using a computer-controlled 300 kN eletromechanical testing machine (INSTRON/EMIC). Tests were performed according to Associação Brasileira de Normas Técnicas – ABNT- NBR7190 (1997), Brazilian Standard for the design of wooden structures. Compression tests were performed in 2cm x 2cm x 6cm specimens and bending tests used 2cm x 2cm x 46cm specimens and a span length of 42cm. All results were reported to the EMC (12%), using a conversion coefficient of 3% (of variation per 1% of MC variation) for strength properties and 2% for elastic properties. Wood strength rating was established using the characteristic value of the compression strength parallel to the grain (Eufrade Júnior et al., 2015).

2.9 Higher heating value (HHV)

The samples were fragmented into smaller pieces with a hammer and chisel and milled in a micro mill. Higher heating value was determined after thermal rectification with dry samples. To perform the analysis, the isoperibolic method was used with an IKA C200 calorimeter, according to American Society for Testing and Materials - ASTM D5865-98 (1998).

2.10 Statistical analyses

Descriptive statistical analyses were performed to obtain the means and standard deviations used to test differences between groups. Student's t-test was used to confirm that the number of measurements was sufficient to achieve the desired power for the test (0.75–0.90). Subsequently, from the normal distribution of data, the t-test was used to determine which features varied significantly between the two systems. When data were not normally distributed, a square root transformation was applied. All statistical analyses were performed using the Sigma Plot software - Exact Graphs and Data Analysis - version 12.3 (Systat Software Inc, San Jose, CA, USA).

3. Results

3.1 Growth performance

Information on system's performance was monitored annually by two authors, who planted and monitored the growth through field reports. The results of 20 years of observation (1992-2012) are given in the following lines. During the first four years of evaluation in the presence of *C. cajan* plants, we observed that this pioneer shrub species reached up about 2 m in height, generating shade during the initial growth stages of *M. urundeuva* (secondary succession species), *P. dubium* (pioneer, early secondary) and *S. romanzoffiana* (pioneer). The presence of *C. cajan* resulted in straighter trunks in *M. urundeuva* and *P. dubium* in the agroforestry systems when compared to trunks of trees of these species in natural environments. We suggest that the shading caused by *C. cajan* plants induced competition for light, triggering trees to grow straight, competing for light. In addition, there was a lower number of lateral branches in both arboreal angiosperms, compared to trees growing in natural environments. This is possibly due to the increased investment in vertical growth.

3.2 Mean annual increment

Concerning the growth and volume increase, the species presented different results. The evaluation of the 25-year-old planting systems (1992-2017) showed that *M. urundeuva* had greater DBH, tree height and tree volume in the MP system than in the MPS system. However, we did not observe differences between systems in *P. dubium*. The difference in growth between the two tree species was obvious, with *P. dubium* showing greater tree growth and volume than *M. urundeuva* (Table 1).

Table 1. Silvicultural data and mean annual increment of 25-year-old *Myracrodruon urundeuva* and *Peltophorum dubium* in different planting systems.

	Species/planting systems			
	Myracrodruon urundeuva/MP	*Myracrodruon urundeuva*/MPS	*Peltophorum dubium*/MP	*Peltophorum dubium*/MPS
DBH (cm)	9.7aB	8.7bB	17.4aA	16.3aA
Height (m)	10aB	9bB	12.8aA	12.8aA
Tree volume (m^3)	0.0233aB	0.0189bB	0.341aA	0.318aA
Volume per ha at 25 years ($m^3.ha^{-1}$)	38.12	30.88	378.63	353.67
Mean annual increment ($m^3.ha^{-1}.year^{-1}$)	1.52	1.23	15.14	14.14

DBH = diameter at breast height, 1.3m from the ground; MP = *Myracrodruon urundeuva* and *Peltophorum dubium*; MPS = *Myracrodruon urundeuva*, *Peltophorum dubium* and *Syagrus romanzoffiana.* In the same row, differences in same species between the planting systems is represented by lowercase letters, while the comparison between different species in same planting systems is represented by capital letters. Means with different letters differ statistically at $P<0.05$ according to Student's t-test. Source: Authors.

3.3 Wood anatomy and properties of Myracrodruon urundeuva and Peltophorum dubium

Fibre length of the two species did not vary between the two planting systems. Fibre wall thickness did not vary in *M. urundeuva*, but thicker fibre walls were observed in the MPS system in *P. dubium*. The density and HHV were different between the species in the MPS system, with *M. urundeuva* showing higher values than *P. dubium*. No difference was observed between the systems for *P. dubium*. Most of the mechanical properties assessed showed higher values in the MPS system than in the MP system in both species (Table 2), except for the MOE in *P. dubium*, which did not differ between the systems.

Table 2. Fibre features, physical and mechanical properties, and HHV of *Myracrodruon urundeuva* and *Peltophorum dubium* wood in the different planting systems.

	Planting System	FL (μm)	FWT (μm)	ρ_{12} (kg.m^{-3})	σ_{cl} (MPa)	MOE (MPa)	MOR (MPa)	HHV (kJ.kg^{-1})
M. urundeuva	MP	877a	4.0a	996b	53.2b	9722b	105.5b	19624b
	MPS	859a	4.0a	1033a	62.1a	9990a	110.9a	19798a
P. dubium	MP	945a	3.1b	771a	44.9b	10189a	84.3b	19289a
	MPS	931a	3.4a	768a	50.0a	10248a	95.2a	19286a

MP = *Myracrodruon urundeuva* and *Peltophorum dubium*; MPS = *Myracrodruon urundeuva*, *Peltophorum dubium* and *Syagrus romanzoffiana;* FL = Fibre length; FWT = Fibre wall thickness; ρ_{12} = Density; σ_{cl} = Compression strength parallel to grain; MOE = modulus of elasticity; MOR = Modulus of rupture; HHV = Higher Heating Value. Means followed by different letters (a or b) indicate statistical significance by t-test (p <0.05). Source: Authors.

4. Discussion

4.1 Growth performance

At the age of four, *M. urundeuva* presented average height (2.96 m), average crown diameter (1.86 m), number of branches in relation to main trunk (5.51), trunk diameter at DBH (3.76 cm). *Peltophorum dubium* presented 4.10 m in height, and trunk diameter at DBH 2.82 cm (Freitas, 1999).

We emphasize that all values presented were corrected for 2020 by Índice Geral de Preços – Mercado - IGP-M (General Price Index – Market) in Brazilian currency in the period of each study, and then calculated in dollars for July 2020.

In an economic analysis in same planting of present study, Tarsitano et al. (1994) evaluated variable expenses, e.g., machinery operations, labor, seedlings, pesticides, interest on working capital, depreciation of machinery and equipment. The MP system cost was ≈ US $ 3,240/ha, and the MPS system was ≈ US $ 4,998/ha. Despite the higher value in MPS system, with *S. romanzoffiana*, we understand it as an economically viable alternative due to financial returns in the short and medium terms, as discussed below.

Kunstler et al. (2016) recently published a comprehensive study on how tree characteristics affect the growth of independent neighbouring trees in the ecosystem. These results are important for the timber quality of these species and their end use, since it is possible to obtain straight trunks with higher bifurcations than would normally be found in a natural environment.

Cajanus cajan was sown in the first year of planting, between lines with an average production of 8.25 t.ha^{-1} of dry matter, which were incorporated into the soil at the beginning of flowering. According to Stanton (1966) *apud* FAO (2016), the species is considered as a suitable candidate for fertility restoration and is used in crop rotations due to its nitrogen-fixing ability. Pruning during flowering is recommended, since during this life phase, a lot of the nutrients contained in the plant are transferred to the seed. *Cajanus cajan* plants played an important role in protecting the tree species against herbivory by ants, with preferential foraging on *C. cajan* instead of the trees. When *C. cajan* is attacked, it regenerates faster than the tree species.

After pruning *C. cajan*, *U. decumbens* plants regenerated from the seed bank present in the soil. The crowns of *M. urundeuva*, *P. dubium* and *S. romanzoffiana* provided little shade, especially at four years, which allows a good amount and quality of light to be shone on *U. decumbens* (Rodrigues et al., 2014). Nonetheless, the small amount of shade provided by the trees reduce the risk of overheating and provides resting areas for livestock. Hence, four-year-old trees associated with grass already had a sufficient trunk size and strength to thrive in the presence of livestock. Lemes et al. (2015) report that heifers grazing in shaded area had lower respiratory frequency and rectal temperature than those grazing in unshaded area, result that have influence in thermal comfort of composite beef heifers (*Bos taurus* vs *Bos indicus*) raised in livestock-forest systems in Southeastern Brazil. Therefore, it is important to introduce the animals at the right time and shading interferes with physiology of animals, additionally when the trees are strong enough to endure the potential damage caused by animals. In our systems, twenty-six animals, including one male, grazed in the area between 1997 and 2005. The herd was periodically released in the agroforestry systems for at least 20 days a month. This procedure was adopted to promote pasture rotation. In the field, we noted that pregnancy rates and weight gains were higher when the animals grazed in the planted areas, compared to the rest of the herd, which only grazed *U. decumbens* in other areas of the university. According to Campos & Miranda (2012), the natural shade in pastures ensures comfort for livestock and positively influences milk and meat production. Some of the other advantages include erosion control and soil fertility. The shading of these trees does not influence the growth of *U. decumbens*, which is among the most shade tolerant grasses.

After a few years of planting, *S. romanzoffiana* trees were used for various purposes, e.g. ornamentals, palm hearts from five years old, seedlings for landscaping, wood in rural buildings, sale of fruits and seeds, as well as a bee pasture. Bees were often observed on *S. romanzoffiana* flowers. In general, *S. romanzoffiana* can offer three basic products (honey, palm heart and ornamental tree). Honey can be obtained from flowering, but as no hives were placed, we cannot present an analysis of honey production. Cascaes (2008) studied the pollination of bees of some plant species in the state of Santa Catarina and found that the flowers of *S. romanzoffiana* were one of the plant species most visited by bees. According to EMBRAPA (2010), *S. romanzoffiana* flowers have a great apicultural potential since they produce pollen and nectar. According to Kinupp & Lorenzi (2014), palm hearts, which are large, non-fibrous and without bitterness, can also be used to prepare cream and sweets, and can be consumed sautéed as vegetables or preserved, being superior to *Bactris gasipaes* (pupunha) palm hearts in nutrients. According to information obtained by the authors in local commerce, palm heart unit value is around US$ 3, considering an estimated population of 1,111 plants per ha, it is possible to obtain ≈ US$ 3,300. As an ornamental tree can be used for replanting in squares, avenues, shopping centers. A plant of *S. romanzoffiana* can be sold to ≈ US$ 40. According to EMBRAPA (2010), this palm tree is highly decorative and widely used in landscape projects, mainly in southern Brazil; and it is also a recommended species for planting in mixed species plantations of degraded areas.

Cambuim (2013) presented potential products and monetary income for *U. decumbens* in three aspects: a) hay production and marketing in the first 8 years (there would be no animal grazing in the period). It was considered to make hay bale of 14 kg of hay at the value of $ 1.03/hay bale, $ 0.07/kg. Revenue of $ 0.07x 1207.88 = $ 458.99. We emphasize that when using hay production from dry matter productivity, one can incur, in a bias of underestimation of effective productivity, however, we chose to consider this parameter, because it is productivity effectively practiced in the experimental field in reference. b) commercialization of *U. decumbens* seeds in the first 8 years, considering a productivity of 1500 kg/ha, however in silvopastoral arrangement under study, the forage area was equivalent to 0.7 ha which results in a productivity of 1050 kg/seed/year. The price paid to seed producers in the regional market for processing companies is $ 1.76.kg^{-3} and in consumer market $ 4.11.kg^{-3}. The total resulting revenue is $ 1851.50. c) pasture rental from the 9th year on and lasting for the entire useful life, for pasture rental a stocking of 1 animal unit is considered, generating a revenue of $ 4.41/animal/month. This capacity per unit area is considered low, but it is not far from the standards practiced regionally, in extensive systems (Cambuim, 2013).

The systems were also shown to be sustainable for both studied tree species (*M. urundeuva* and *P. dubium*), because regrowth was observed after tree felling in 2012. In *P. dubium*, we observed many sprouts being produced per stump, so it would be possible to obtain wood at different development stages for different applications with proper management. This type of systems allows the producer to maintain long-lived native tree species while harvesting different products at different times, making it ecologically and economically viable. Paul et al. (2015) reported that tree planting is a sustainable and economically viable form of reforestation in tropical lands, but the widespread adoption, suggesting that intercropping hardwood trees can be an effective tool to improve the financial feasibility of reforestation. It is also very important to carry out management practices in a plantation; otherwise, the mortality rate increases considerably. In other plantation systems located in the same area as the present study, all *Trema micrantha* trees died at four years, and high mortality rates were observed in *Aspidosperma polyneuron* of 12 years, both due to a lack of thinning. The *M. urundeuva*, *P. dubium* and *S. romanzoffiana* plantations were thinned and their survival rate was over 95%. Thus, depending on the successional group of the planted species, thinning should take place at different times, at a younger age in pioneer species and later in non-pioneer species. In addition, we observed that the more homogenous the planting, the greater the need for periodic management.

As a management strategy, we suggest felling *P. dubium* trees at around 18 years of age, while the species still can sprout. When the trees are cut at around 18 years, sprouts of *P. dubium* also find favourable shade conditions for growth and the species has good adaptability when planted in intercropping systems. In a plantation comprising four Brazilian species, Pinto & Rodigheri (2001) reported that *P. dubium* showed the highest survival rates, timber volume and height, and DBH compared to other species. Meanwhile, seeds of *M. urundeuva* trees can be collected until the tree felling period and wood sale. Thus, it is possible to exploit various products in this system (palm hearts, ornamentals, fruits, seeds, bee pasture, and wood).

4.2 Mean annual increment

The differences are expected both for systems and between species, but in the sequence, we will discuss differences between the wood species. The observed trend was expected, since *P. dubium* is an initial secondary pioneer species (Lorenzi, 2002; Carvalho, 2003), while *M. urundeuva* is a late secondary species (Santin & Leitão Filho, 1991). In addition, seeds that gave rise to *M. urundeuva* trees come from Caatinga *stricto sensu* in Petrolina, Pernambuco State, a typically xerophytic vegetation, where an annual rainfall of 386.3 mm was reported in 2005 by Moura (2007). Thus, the growth of *M. urundeuva* trees used in this study may have been influenced by inherited characteristics from mother trees. Seeds of *P. dubium* trees, however, were collected in a region close to the plantation area and therefore, better adapted to local climatic conditions.

Galão (2017) studied 32-year-old *P. dubium* trees planted in the municipality of Luiz Antônio, São Paulo State, Brazil (21º40'S, 47º49'W, elevation 550m), about 500km from the present study area. The author reported mean annual increments of 13.54-13.77 $m^3 . ha^{-1}.year^{-1}$. These values were close to ours, showing the plasticity of the species across edaphoclimatic conditions.

According to Equipe Jornalística da Revista da Madeira (2007), a species is fast growing when productivity is higher than 14 $m^3 . ha^{1} . year^{-1}$, among the 100 Brazilian native species studied, *P. dubium* is among the 32 classified as fast-growing species. *M. urundeuva*, however, has a terribly slow growth and produces high-quality wood suitable for use at 30 to 40 years after being planted. Silva et al. (2017) studied trees of *M. urundeuva* in northeastern Brazil, in the municipality of Uiraúna, in the state of Paraíba (6°33'S, 38°25'W; average annual temperature 23-30°C and rainfall 400-600 mm/year), and although the authors did not mention tree age, they reported a mean tree height of 14.08 m, a mean DBH of 10 cm and a tree volume of 0.025 m^3, the later value being similar to the one observed in the MP system. This result reinforces the demonstration of the slow growth of *M. urundeuva*.

We did not find studies with accurate data and recommendations for cutting *P. dubium* and *M. urundeuva* trees. Therefore, our study becomes essential to monitor, report the growth of these species and to establish the optimal cutting period. It was initially proposed to work in the same way as the species used in reforestation, e.g. Eucalyptus. According to Campbell (1999) the ideal age for cutting can be determined by measuring the current annual increment (CAI), which measures how much the forest has grown in volume in the last year and the mean annual increment (MAI), i.e. mean wood volume increase on one hectare of forest per year since it was planted. Jacobson (2008) report that there are many factors to consider when deciding to timber harvest: sustainability issues, such as ensuring adequate desirable regeneration, and financial and legal considerations, such as timber prices, taxes, boundaries, logging contracts, and liability. Campbell (1999) suggests that trees should be cut when CAI values are equal to those of MAI, in other words, when the plantation reaches the maximum volumetric production of wood per surface area per year. This reasoning serves to support what is most feasible in terms of forest productivity. However, another form of analysis can be used, considering the particularities of Brazilian native species and market requirements, proposing different cutting periods depending on the end use of each species. Cambuim (2013) reported the valuation of timber products to be sold at 50 years of project, wood prices were consulted in regional market (timber companies in the region of Selvíria - MS). Cost / m3 for log splitting paid to ranchers or forest producer net of cutting and loading expenses: \$ 58.78 (considering 50% utilization). Tax on the product sold (17% of fare price for Mato Grosso do Sul: \$ 185.15; Log transportation cost: at \$ 0.59/m^3/km, from the property to the sawmill (20 km was considered); Value charged in Selvíria - MS, (corrected for July 2020) Sales margin of the sawmill: 30% on wood price for resale \$ 587.78 of sawn wood. Obviously, trees can be cut during the 50-year cycle, based on what was proposed by Jacobson (2008).

4.3 Wood anatomy and properties of Myracrodruon urundeuva and Peltophorum dubium

According to NBR 7190 (1997), the strength class of *M. urundeuva* wood differed between the planting systems. In the MP system, *M. urundeuva* fell into strength class C40, while in the MPS system, it fell into strength class C60. The strength class of *P. dubium* wood corresponded to class C40 for both systems, demonstrating the absence of influence of the planting system on the strength class (based on compression strength parallel to grain). However, despite the good mechanical performance, it is necessary to evaluate the wood volume to decide the most appropriate period for cutting. We emphasize that values of physical and mechanical properties were evaluated at the age of 20 years, so an increase of these values is expected, unless they are maintained over the years.

In general, higher mechanical properties were observed in the MPS system, i.e. in the plantation with less spacing between trees. We suggest that in the MPS system, trees grow with greater competition for light due to overlapping crowns, which does not happen to the same extent in the MP system. The same argument can be applied for mineral nutrient competition; the shorter spacing between trees found in the MPS system perhaps led to having more tangled root systems, which then had to be more competitive when seeking soil nutrients than in the MP system. *Eucalyptus* spp. studies show that control of stand density through initial spacing affects tree growth and wood formation. When nutrient and water availability is similar, widely spaced trees will grow faster than crowded trees (Malan, 1995; Florence, 1996). We did not find studies similar to ours with Brazilian native trees, so we discuss based on *Eucalyptus* species. Paula et al. (2013) studied the growth of *Eucalyptus camaldulensis* clone in five spatial arrangements: 3.6m × 2.5m, and 3.3m × 3.3m (monocultural systems), and (2m × 2m) + 10m, (3m × 3m) + 9m, and 9m × 3m (silvopastoral systems). The authors concluded that arrangement did not affect plant height growth up to 50 months, the (2m × 2m) + 10m arrangement in silvopastoral system yielded the highest biomass production with additional benefits of financial returns of pasture compared to monocultural systems while the 9 m × 3 m arrangement showed the best production of trees with wider trunks. In another study of ten production systems over five years, including crop production (soybean/corn), livestock (palisade grass pastures with Nellore steers) and woody component (*Eucalyptus urograndis*) in single and integrated systems, Magalhães et al. (2019) did not find differences in the individual wood volume of *Eucalyptus urograndis* between the production systems.

Our field observations lead us to the conclusion that trees in the MP system grew faster, with a taller and straighter form than the trees of the MPS system. Among all assessed tree species, *P. dubium* showed a faster growth and its canopy cast shade on *S. romanzoffiana* trees. There is not much information about the effect of spacing or of different planting systems on the wood quality of Brazilian native species, because many experimental plantations were established decades ago and only recently have the trees been cut for investigation of their anatomy and mechanical properties, determination of wood quality and recommendations for potential uses. Thus, most of the information available in Brazil is based on commercial forest plantations of exotic tree species, e.g. *Eucalyptus propinqua* (Longui et al., 2014); *E. grandis* (Leonello et al., 2008); *E. citriodora* (now *Corymbia citriodora* - Calonego et al., 2005) and *E. dunnii* (Florsheim et al., 2009).

Despite recent studies that have suggested that xylem anatomical traits are better correlated to tree growth rate than wood density (Fan et al., 2012), the relation between growth rate and wood density is still under debate. While some researchers have found a negative correlation between wood density and growth rate (Scholz et al., 2007; Meinzer et al., 2008), others have found that competitive species (presumably species with high growth rates) have higher wood density (Kunstler et al., 2012). In our results, statistical differences in wood density between the two planting systems were observed exclusively for *M. urundeuva*, with lower densities being found in the MP system, which also had a higher growth rate.

An explanation for higher mechanical property values in MPS system can be related to the higher wood density of *M. urundeuva*. Chave et al. (2009) compiled information on more than 8000 taxa and found that density can be used as an indicator for wood properties, as well as for accounting for ecological information and carbon storage. In *P. dubium*, although wood density did not differ between systems, thicker wall fibres in MPS must have contributed to higher values of compression strength parallel to the grain and modulus of rupture. According to Pratt et al. (2007), thicker walls fibres are correlated with wood density, hence influencing wood properties.

According to Brazilian market, HHV between 16500 - 18000 $kJ.kg^{-1}$ are suitable values for use in bioenergy (Menucelli et al., 2019). The HHV values of the present study were higher, emphasizing that trees were cut at 20-year-old, yet relatively young, wood of both species has energy potential. Thus, in addition to use of *P. dubium* and *M. urundeuva* as lumber, wood residues can be used in production of pellets or briquettes. According to Spirchez et al. (2018), the transformation of wood into pellets or briquettes increases the density of the material, which in turn has increased its energy per unit volume. According to Silva et al. (2007) wood density is indicative of potential energy. The variations in HHV followed the same pattern as density and in fact, density may indicate energy potential.

5. Conclusion

The silvopastoral systems studied proved promising in several aspects, because it was possible to successfully combine fast-growing shrub species (*Cajanus cajan*), resistant grass (*Urochloa decumbens*) eaten by animals (*Bos taurus indicus*) and tree species (*Myracrodruon urundeuva*, *Peltophorum dubium* and *Syagrus romanzoffiana*) which can produce different products on a cycle of more than 50 years, e.g., ornamentals, palm hearts, landscaping, fruits, seeds, bee pasture, and wood with different properties. For *U. decumbens* it is possible to sell hay, seeds and pasture rent.

The system with larger spacing was accompanied by a higher average annual increment only in *M. urundeuva*, and the producer can decide which system to use based on wood quality. As expected, *P. dubium* produces a higher wood volume. Another important result is that both species showed regrowth after cutting, and thus giving rise to a new cycle of exploitation.

For wood quality, we conclude that the two systems can be used successfully, but the MPS system is preferred if the aim is to obtain wood with higher mechanical strength, and bioenergy values for *M. urundeuva*. Additionally, if farmers want to diversify the number of outputs, the MPS system is adequate due to intercropping with *S. romanzoffiana*. Higher strength and higher calorific value wood imply an economic advantage. Both systems bring returns with short-term (bean seed, forage, pasture), medium-term (forage, palm products, pasture, wood), and long-term (wood) financial returns.

In the same study site there are other species, and therefore, other systems to be evaluated in the future by our team. Additionally, we suggest that research with agroforestry systems is needed in several regions and its results can help landowners' decision-making and public policy.

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