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CRESCIMENTO DE ESPÉCIES ARBÓREAS E RESPOSTAS PRODUTIVAS E FISIOLÓGICAS DA CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

Frederico Westphalen, RS

2016

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Dissertação apresentada ao Curso de Pós-Graduação em Agronomia: Agricultura e Ambiente, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Mestre em Agronomia.**

Orientador: Prof. Dr. Braulio Otomar Caron

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Loucura é fazer a mesma coisa e

esperar um resultado diferente.

(*Albert Einstein*)

RESUMO

CRESCIMENTO DE ESPÉCIES ARBÓREAS E RESPOSTAS PRODUTIVAS E FISIOLÓGICAS DA CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

AUTOR: Elvis Felipe Elli
ORIENTADOR: Braulio Otomar Caron

O objetivo do estudo foi avaliar o crescimento de espécies arbóreas e as respostas produtivas e fisiológicas da cana-de-açúcar em sistemas agroflorestais. A pesquisa foi conduzida no período de 2007 a 2014, no município de Frederico Westphalen, Rio Grande do Sul, Brasil, com localização geográfica de 27°22’S, 53°25’W a 480 m de altitude. O delineamento experimental utilizado foi de blocos completos casualizados, com três repetições. Foram utilizadas as seguintes espécies arbóreas: *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden (eucalipto), *Mimosa scabrella* Benth. (bracatinga), *Parapiptadenia rigida* (angico), *Peltophorum dubium* (Spr.) Taubert (canafístula) e *Schizolobium parahybae* (Vell.) Blake (guapuruvu). As espécies foram distribuídas em dois arranjos de sistemas agroflorestais, sistemas faixa e linha. No sistema faixa, as espécies florestais foram distribuídas em faixas separadas por 12m, cada qual composta por três linhas, nas quais as plantas foram espaçadas em 3x3m. A cana-de-açúcar (*Saccharum officinarum* L.) foi distribuída em oito linhas (entre as faixas, no espaço de 12m) e duas linhas na faixa (entre as linhas de árvores). No sistema linha, as espécies florestais foram distribuídas no espaçamento 6x1,5m, ou seja, 6m entre linha e 1,5m entre planta na linha, sendo a cana-de-açúcar distribuída em três linhas (entre as linhas das árvores). Em ambos os sistemas, a cultivar cana-de-açúcar foi a IAC 87-3396, sendo distribuída em espaçamento de 1,20m. Tanto as linhas da cana-de-açúcar quanto as das árvores foram orientadas no sentido Leste-Oeste. As variáveis arbóreas analisadas foram: diâmetro do colo (cm), diâmetro à altura do peito (cm), altura de planta (m) e diâmetro médio da copa (m). As variáveis analisadas na cana-de-açúcar foram: massa de colmo (t ha^{-1}), comprimento de colmo (m), diâmetro do colmo (mm), número de nós, volume de suco (m^3 ha^{-1}), grau Brix, quantidade de sacarose (t ha^{-1}), radiação solar fotossinteticamente ativa incidente (μmol s^{-1} m^{-2}), temperatura da folha (°C), resistência à difusão de vapor (s cm^{-1}) e transpiração (mmol H_2O s^{-1} m^{-2}) das folhas. As variáveis meteorológicas ocorrentes ao longo do estudo foram obtidas por meio da Estação Climatológica do Instituto Nacional de Meteorologia, localizada à 1500 m do local de estudo, nas coordenadas 27°39’S e 53°43’W. O crescimento das espécies arbóreas foi influenciado pelo arranjo de plantas em sistemas agroflorestais. Além disso, os elementos meteorológicos modificaram o crescimento das espécies florestais e devem ser levados em consideração para a realização de um planejamento apropriado e escolha adequada da espécie florestal que compõe o sistema. Dentre as espécies estudadas, o eucalipto apresentou maior crescimento em diâmetro do colo, diâmetro à altura do peito, diâmetro médio da copa e altura total. O sistema faixa proporcionou o aumento do crescimento da maioria das espécies arbóreas (eucalipto, canafístula e angico). Este sistema possibilitou maior entrada de radiação fotossinteticamente ativa em seu interior, resultando em maior produtividade, aumento da resistência a difusão de vapor e redução da transpiração das folhas da cana-de-açúcar.

Palavras-chave: Arranjo de Plantas. Temperatura Mínima. Massa de colmos. Transpiração.

ABSTRACT

GROWTH OF TREE SPECIES AND PRODUCTIVE AND PHYSIOLOGICAL RESPONSES OF SUGARCANE IN AGROFORESTRY SYSTEMS

AUTHOR: Elvis Felipe Elli
ADVISOR: Braulio Otomar Caron

The aim of the study was to evaluate the growth of tree species and productive and physiological responses of sugarcane in agroforestry systems. The research was conducted from 2007 to 2014, in the city of Frederico Westphalen, Rio Grande do Sul, Brazil, with geographic location 27 ° 22'S, 53 ° 25'W and 480 m altitude. The experimental design was a randomized complete block with three replications. The following tree species were used: *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden, *Mimosa scabrella* Benth., *Parapiptadenia rigida*, *Peltophorum dubium* (Spr.) Taubert e *Schizolobium parahybae* (Vell.) Blake. The species were divided into two agroforestry systems arrangements, strip and line systems. In strip system, forest species were divided separate strips by 12m, each composed of three lines, in which the plants were spaced 3x3m. The sugarcane (*Saccharum officinarum* L.) was distributed in eight lines (between the tracks, within 12m) and two lines in range (between the rows of trees). In line system, forest species were distributed in spacing 6x1,5m; i.e., 6m between line and 1.5 m between plants in the line, and the sugarcane distributed in three lines (between the lines of trees). In both systems, the cultivate sugarcane was the IAC 87-3396, which was distributed in spacing 1.20m. Both lines of sugarcane as the trees were oriented east-west direction. The tree variables analyzed were: collar diameter (cm), diameter at breast height (cm), plant height (m) and mean crown diameter (m). The variables analyzed in sugarcane were: stem mass (t ha-1), stem length (m), stem diameter (mm), number of nodes, juice volume (m^3 ha^{-1}), degree Brix, amount of sucrose (t ha^{-1}), photosynthetically active solar radiation (μmol s^{-1} m^{-2}), leaf temperature (° C), resistance to vapor diffusion (s cm^{-1}) and transpiration (s^{-1} H_2O mmol m^{-2}) of leaves. The meteorological variables occurring during the study were obtained through Climatological the National Institute of Meteorology Station, located at 1500 m from the study site, with geographic location 27°39'S and 53°43'W. The growth of tree species was influenced by plant arrangement in agroforestry systems. In addition, meteorological elements changed the growth of forest species and should be taken into account to carry out a proper planning and appropriate choice of tree species that make up the system. Among the species studied, eucalypt showed higher growth in stem diameter, diameter at breast height, mean crown diameter and total height. The strip system provided increased growth of most tree species (eucalyptus, canafístula and bracatinga). This system allowed greater incidence of photosynthetically active radiation under the trees, resulting in increased productivity, increased resistance to vapor diffusion and reduced transpiration from leaves of sugarcane.

Palavras-chave: Arrangement of planting. Minimum temperature. Stem weight. Transpiration.

LISTA DE TABELAS

ARTIGO I

ARTIGO II

ARTIGO III

LISTA DE FIGURAS

ARTIGO I

ARTIGO II

ARTIGO III

ARTIGO IV

SUMÁRIO

1 INTRODUÇÃO

1.1 SISTEMAS AGROFLORESTAIS: CONCEITOS E MODIFICAÇÃO DO MICROCLIMA

Os sistemas agroflorestais (agrossilvipastoris) consistem no uso integrado da terra para fins de produção agrícola, florestal e pecuária. Esta integração pode ocorrer de forma simultânea ou em sequência temporal, de acordo com a finalidade do sistema. A utilização de diferentes espécies no mesmo local de cultivo pressupõe a ocorrência de interações dinâmicas que variam ao longo do tempo, de acordo com o crescimento e as características intrínsecas de cada espécie utilizada.

A evolução da altura e diâmetro da copa das espécies arbóreas ao longo do tempo, pode modificar o microclima do sub-bosque no sistema de cultivo, principalmente, a incidência de radiação solar. O aumento da área foliar das árvores aumenta a interceptação da radiação solar e, consequentemente, reduz a sua disponibilidade para as culturas que estão presentes no interior do dossel vegetativo. A redução da radiação solar condiciona outros elementos meteorológicos, como a temperatura, umidade relativa do ar, velocidade do vento (modificada também devido a barreira física gerada pelo componente arbóreo), umidade e temperatura do solo.

Estas modificações, além de alterar a resposta fisiológica das plantas presentes abaixo do componente arbóreo, pode modificar a atividade biológica do solo. Adicionalmente, podem haver modificações químicas e físicas do solo, devido a deposição de serapilheira, principalmente por espécies caducifólias, e a interceptação radicular das árvores. Devido a grande diversidade existente nas agroflorestas, são necessários estudos demonstrando respostas de planta, e também a recomendação de espécies, tanto arbóreas, quanto agrícolas, que evidenciem resultados positivos, quando inseridas nestes sistemas.

1.2 ARRANJO DAS ESPÉCIES ARBÓREAS EM SISTEMAS AGROFLORESTAIS

Sistemas agroflorestais comumente apresentam arranjos das espécies florestais mais amplos, comparado com plantios arbóreos convencionais. Isto ocorre para possibilitar o crescimento e desenvolvimento das espécies presentes no sub-bosque das mesmas. O arranjo espacial pode modificar a área útil ocupada pela árvore, bem como o período necessário para o fechamento do dossel vegetativo. Tratando-se de sistemas agroflorestais, este fator é de grande relevância devido a interceptação luminosa provocada pela copa das árvores, bem como, pelo nível de competição intra e interespecífica (entre indivíduos da mesma espécie e de espécies diferentes, respectivamente), que ocorre no local de cultivo.

1.3 ELEMENTOS METEOROLÓGICOS SOBRE O CRESCIMENTO ARBÓREO

O crescimento e desenvolvimento vegetal é regulado por uma série de fatores bióticos e abióticos. Dentre os fatores abióticos, destacam-se os elementos meteorológicos, como a radiação solar, temperatura do ar, chuva, vento, umidade relativa do ar. A radiação solar é responsável pelo fornecimento de energia radiante para o processo fotossintético, e consequentemente, produção de matéria seca das plantas.

A temperatura modifica a taxa transpiratória, bem como a atividade metabólica das plantas. Tratando-se de espécies arbóreas e no contexto de sistemas agroflorestais, a temperatura do ar exerce um papel muito importante no que se refere a indução da dormência das plantas. Árvores caducifólias (as quais perdem suas folhas em períodos de baixas temperaturas ou de déficit hídrico) podem auxiliar na ciclagem de nutrientes e aumentar o conteúdo de matéria orgânica do solo por meio da deposição de serapilheira, além de proporcionar a entrada de maior quantidade de radiação solar no interior do dossel vegetativo. A região de estudo caracteriza-se por apresentar temperaturas mínimas extremas inferiores a 0 (zero) °C, bem como a ocorrência de geadas no inverno. Espécies arbóreas suscetíveis a geada, podem apresentar alguns de seus órgãos danificados, tendo o seu crescimento comprometido.

A chuva interfere na disponibilidade hídrica do solo, o que afeta a taxa transpiratória, abertura estomática e fotossíntese. A ausência de estresse hídrico permite o aumento da concentração interna de CO_2 nas folhas devido a maior condutância estomática, aumentando a taxa fotossintética das plantas (LLOYD e FARQUHAR, 2008; SCHIPPERS et al., 2015, VAN DER SLEEN et al., 2015;).

A velocidade do vento modifica a taxa transpiratória das plantas, uma vez que ventos mais fortes renovam com maior rapidez a camada de ar limítrofe da folha, afetando o déficit de pressão de vapor (DPV) entre a folha e o ar, desse modo, intensificando a transpiração. Além deste elemento meteorológico, a umidade relativa do ar também pode modificar as trocas gasosas da planta, uma vez que ela condiciona o DPV do ambiente. Valores baixos de umidade relativa do ar aumentam o DPV do ambiente, favorecendo a perda de água da planta, devido a diferença de potencial hídrico entre a planta e a atmosfera. Este último elemento, pode afetar indiretamente o crescimento vegetal, pelo fato de ser essencial para o crescimento de microorganismos patogênicos, uma vez que estes comumente necessitam de molhamento foliar para poder se locomover e infectar a planta.

A partir da importância dos elementos meteorológicos e suas inter-relações frente ao crescimento vegetal e as repostas de planta, torna-se relevante o estudo da influência dos mesmos sobre as espécies arbóreas, de modo que estas informações possam auxiliar no planejamento, tomada de decisão, realização de tratos culturais, gerando deste modo, resultados produtivos satisfatórios.

1.4 ESPÉCIES ARBÓREAS ESTUDADAS

Para o presente estudo, foram utilizadas cinco espécies florestais: angico-vermelho (*Parapiptadenia rigida* (Benth.) Brenan), bracatinga (*Mimosa scabrella* Benth.), canafístula (*Peltophorum dubium* (Spr.) Taubert), eucalipto (*Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden) e guapuruvu (*Schizolobium parahybae* (Vell.) Blake). As principais características de cada espécie estão descritas a seguir.

Angico-Vermelho: espécie nativa, pertence à família Mimosaceae, planta leguminosa, semi-caducifólia de copa alta e arredondada. Seu fuste pode apresentar até 20 metros de altura e 70 cm de diâmetro à altura do peito (DAP) (CARVALHO, 2003).

Canafístula: espécie nativa, pertence à família Caesalpinaceae, planta leguminosa, caducifólia, com copa ampla, umbeliforme, largamente achatada e arredondada. Seu fuste pode atingir até 20 m de altura e 90 cm de DAP (CARVALHO, 2003).

Eucalipto: originário da Austrália, pertence à família Myrtaceae, perenifólia, com copa muito ampla e densa. Sua altura pode chegar a 60 m e o DAP, até 180 cm. Caracteriza-se por apresentar ampla distribuição edafoclimática (COUTO e MÜLLER, 2008).

Guapuruvu: espécie nativa, pertence a família Caesalpinioideae, planta leguminosa, semi-caducifólia, com copa muito ampla e umbeliforme, sua altura pode chegar a 25 m e o DAP pode alcançar 60 cm (CARVALHO, 2003).

Bracatinga: espécie nativa, pertence à família Mimosaceae, planta leguminosa, perenifólia, com copa alta e arredondada, altura de até 18 m e DAP de até 30 cm (CARVALHO, 2003).

1.5 INSERÇÃO DA CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

A cana-de-açúcar (*Saccharum spp.*) pertence a família Poaceae, sendo originária do Sudeste Asiático e da Índica Ocidental (Aranha e Yahn, 1987). É uma cultura de grande importância socioeconômica no Brasil. A produção nacional estimada para a safra 2016/2017 apresenta um crescimento de 3,8% em relação a 2015/2016, alcançando 691 milhões de toneladas (t) e ocupando uma área de 9,07 milhões de hectares (ha), resultando na produtividade média de 76,15 t ha^{-1} (CONAB, 2016).

Esta cultura apresenta metabolismo C4 e se caracteriza por apresentar elevada taxa fotossintética e alta produtividade biológica, respondendo positivamente a altos níveis de radiação. O estudo da inserção da cana-de-açúcar em sistemas agroflorestais deve ser realizado para que seja possível identificar até que ponto a interceptação de radiação solar pelo componente arbóreo não compromete significativamente a produtividade da cultura presente no sub-bosque.

A região do Médio Alto Uruguai, local onde está instalado o experimento, compõe-se de 30 municípios localizados no Norte do estado do Rio Grande do Sul (RS), em que predominam pequenas e médias propriedades rurais, sendo que a utilização de culturas agrícolas de modo convencional pode, muitas vezes, ser inviável. A instalação de setores produtivos de biocombustíveis e aptidão do cultivo da cana-de-açúcar em algumas regiões do RS despertou o interesse dos agricultores pela cultura.

Além disso, a presença de Cooperativas com projetos destinados à pequenos produtores estimulou o seu cultivo e, paralelamente, gerou a necessidade do desenvolvimento de alternativas para o produtor rural. Estas implicações, aliadas a necessidade da geração de sistemas agrícolas economicamente viáveis e ambientalmente sustentáveis, justificaram a realização do trabalho proposto.

1.8 HIPÓTESES

Espécies arbóreas apresentam diferentes respostas, frente a modificação do arranjo espacial de plantas.

Os elementos meteorológicos, juntamente com a idade das plantas, definem a curva de crescimento em altura das espécies florestais.

A cana-de-açúcar é influenciada pelo sombreamento de espécies arbóreas em sistemas agroflorestais, de modo que sua produtividade é reduzida na medida que aumenta a interceptação de radiação solar global pelo componente arbóreo.

A resposta fisiológica da cana-de-açúcar varia de acordo com o local dentro do sistema agroflorestal, devido ao gradiente de radiação existente pela irregularidade da copa das árvores.

1.9 OBJETIVO GERAL

Avaliar o crescimento de espécies arbóreas e as respostas produtivas e fisiológicas da cana-de-açúcar em sistemas agroflorestais.

1.10 OBJETIVOS ESPECÍFICOS

Avaliar o crescimento das espécies *Schizolobium parahyba* (Vell.) Blake (guapuruvu), *Mimosa scabrella* Benth. (bracatinga), *Peltophorum dubium* (Spr.) Taubert (canafístula), *Parapiptadenia rigida* (Benth.) Brenan (angico-vermelho) e *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden (eucalipto), cultivadas com a cana-de-açúcar (*Saccharum* spp.) em diferentes arranjos de plantas em sistema agroflorestal.

Modificar modelos biológicos já existentes, por meio da adição de variáveis preditoras que levem em consideração o efeito dos elementos meteorológicos no crescimento em altura das árvores.

Avaliar características produtivas, morfológicas e qualitativas da cana-de-açúcar e relacioná-las com a interceptação de radiação solar fotossinteticamente ativa no sub-bosque de cinco espécies arbóreas em dois arranjos de sistemas agroflorestais.

Determinar características fisiológicas e térmicas da cana-de-açúcar, em linhas orientadas ao Norte e Sul, no sub-bosque de canafístula (*Peltophorum dubium* Sprengel) em dois arranjos de plantas em sistema agroflorestal

.

2 ARTIGO I - GROWTH OF TREE SPECIES IN AGROFORESTRY SYSTEMS

Submetido para o periódico: Anais da Academia Brasileira de Ciências
Situação: em avaliação

Front page

Growth of tree species in agroforestry systems

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Key words: array of plants, competition, crown diameter, height.

Running title: Growth of tree species in agroforestry systems

Section: Agrarian Sciences

2.1 ABSTRACT

The proposed hypothesis is that cultivations of tree species will react differently depending on their arrangement. The objective of this study was to evaluate the growth of the tree species guapuruvu (*Schizolobium parahybae* (Vell.) Blake), bracatinga (*Mimosa scabrella* Benth.), canafístula (*Peltophorum dubium* (Spr.) Taubert), angico-vermelho (*Parapiptadenia rigida* (Benth.) Brenan) and eucalypt (*Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden), cultivated with sugarcane (*Saccharum* spp.), in two arrays of planting (strip – 3x3 m + 12 m, and line 6 x 1,5 m) in agroforestry systems. The study was conducted in the city of Frederico Westphalen, RS, in a randomized complete block design with three replications. The root collar diameter, diameter at breast height, plant height and mean diameter of crown were evaluated for four years with an interval of 90 days between assessments. The strip system provides a higher growth rate of angico, canafístula and eucalypt, and the line system favors the growth of guapuruvu. Bracatinga species is not influenced by the studied agroforestry systems. Among the studied species, eucalypt is responsible for the greatest root collar diameter values, diameter at breast height, crown diameter, and plant height.

2.2 INTRODUCTION

Agroforestry systems consist of integrated land use for forestry purposes, crops, and animals. This integration results in numerous socio-economic, environmental and production benefits such as the recovery of degraded areas, reduction of production costs, and an increase input of organic matter which has been shown to improve the chemical, physical and biological properties of the soil (Tracy and Zhang 2008, Neves et al. 2009, Xavier et al. 2014).

The appropriate choice of tree species and planting arrangement used to compose these systems is of great importance in order obtain satisfactory results. The growth and development of different types of plants (ie. crops and tree species) in the same area presupposes the existence of dynamic system interactions and change over time. This is especially true in areas where there is tree component, because the continued growth in height, crown projection, and the index of leaf area; these factors can modify the distribution of existing resources which in turn can cause a constant change in the productivity of species in a system (José et al. 2004).

The study of the vegetative growth of woody plants in mixed systems is important when considering management practices such as the definition of plant spacing and planting arrangements. Meteorological elements directly influence morphological and physiological characteristics of the trees as well as the nutritional factors which can affect the growth of plants in the understory of trees (Paciullo et al. 2011, Mendes et al. 2013, Machado et al. 2014).

The proposed hypothesis is that tree species react differently depending on their arrangement; therefore, we believe that due to these complexities, a unique arrangement is required for optimal growth of different groupings of species. The objective of this work was to evaluate the growth of species *Schizolobium parahybae* (Vell.) Blake (guapuruvu), *Mimosa scabrella* Benth. (bracatinga), *Peltophorum dubium* (Spr.) Taubert (canafístula), *Parapiptadenia rigida* (Benth.) Brenan (angico-vermelho) and *Eucalyptus urophylla* S.T.

Blake x *Eucalyptus grandis* Hill ex Maiden (eucalypt) cultivated with sugarcane (*Saccharum* spp.) in different arrays of planting in agroforestry system.

2.3 MATERIAL AND METHODS

2.3.1 STUDY AREA

The study was conducted in the city of Frederico Westphalen, R.S. geographical location of 27°22’S, 53°25’W at 480 m of altitude. According to the Köppen climate classification, the climate of the region is Cfa, i.e. humid subtropical with average annual temperature of 19.1 °C, varying with maximum 38 °C and minimum of 0 ° C. The soil of the area is classified as typical Entisol Orthents (Cunha 2011). The values of soil chemical characteristics were: pH in water = 5.8; available phosphorus (Mehlich^{-1}) = 2.9 mg dm^{-3}; aluminum = 0.0 cmol$_c$ dm^{-3}; potassium = 82.5 mg dm^{-3}; calcium = 8.7 cmol$_c$ dm^{-3} and magnesium = 2.8 cmol$_c$ dm^{-3}.

2.3.2 DESIGN AND EXPERIMENTAL UNITS

The experimental design was composed of a randomized complete block, and study objects were characterized by a factorial scheme of 2x5x16, i.e., two planting arrays (strip and line), five tree species (angico, bracatinga, canafístula, eucalypt and guapuruvu) were studied. Each species was measured 16 times in total (beginning 159 days after planting, to 1509 days after planting), with an interval of 90 days between assessments and three replications. Ten experimental units were included in each block, and each unit was randomly distributed in the agroforestry system. In these experimental units, 15 trees were included, and the three central trees in each unit were evaluated individually.

To test the proposed hypothesis, this field experiment began in Sep. 2007, through the manual planting of seedlings after subsoiling and harrowing of the area was completed. Fertilization was performed according to the recommendations for each species (CQFS 2004).

Evaluations began on March 21, 2008, 159 days after planting (DAP) in the early autumn season. From this point on, assessments were performed quarterly at the beginning of each season until the summer of 2011, at 1509 DAP, totaling 16 times of measurement.

In the strip system, the forest species were divided into separate strips by 12m. Each strip was composed of three rows in which plants were spaced at 3x3m. Sugarcane (*Saccharum* spp.) was distributed in eight rows (between strips, within 12 m) and two rows between lines of trees. In this system, trees of central lines occupied an area of 9 m^2 while trees of external lines occupied an areas of 22.5 m^2. In the line system, forestry species were distributed with 6x1.5m spacing, or 6 m between rows and 1.5 m between plants in rows, and the crops of sugarcane were distributed in three rows (between the rows of trees). In both systems, the sugarcane was distributed in a spacing of 1.20 m and was an equal distance from the trees in this spacing. Both rows of sugarcane as well as trees were oriented in an East-West direction.

2.3.3 VARIABLES ANALYZED

The root collar diameter (RCD) was sampled immediately above the soil surface and diameter at breast height (DBH) measurements were obtained 1.30 m above the soil. Both variables were determined with the aid of a digital caliper until the values reached 6.00 cm, later a graduated diameter tape in millimeters was used to take measurements. The caliper was used to make two orthogonal measures, the arithmetic means of these measurements was recorded.

For measurement of plant height (H) a graduated diameter tape was used until the values reached 2.00 m. A Vertex Hypsometer III was used make measurements greater than 2.00 m, this device was used to determine the distance from the ground surface to the highest leaf axils. The mean diameter of crown (MDC) was considered to be the distance between the projection lines of the outermost points of the crown; data was obtained by taking two orthogonal measurements with the aid of a graduated tape and later calculating the arithmetic mean.

2.3.4 CHARACTERIZATION OF WEATHER AND DATA ANALYSIS

Maximum and minimum average monthly temperatures as well as monthly precipitation during the years 2008, 2009, 2010 and 2011 is described in Fig. 1. The data was statistically analyzed with the software "*Statistical Analysis System*" (SAS, 2003), and results were obtained through the analysis of variance, F test, and Tukey test ($p > 0.05$). The Bartlett test was used to verify the homogeneity of variances. In the strip system, a test of contrast was conducted between plants of the central and external lines, taking into account that environmental conditions would be different.

Figure 1

2.4 RESULTS

2.4.1 ANALYSIS OF VARIANCE AND CONTRASTS

An analysis of variance revealed a difference in RCD for interaction between agroforestry systems x tree species x DAP, in all variables for tree species x DAP and H, MDC and DBH in the interaction between tree species x agroforestry system. In the strip system, based on the analysis of contrast made between plants of the central and external lines, no differences were observed; therefore a more general analysis which incorporated all trees in each experimental unit was conducted.

2.4.2 INTERACTION OF AGROFORESTRY SYSTEMS X TREE SPECIES X DAP

After 249 DAP species began to show a stratification of RCD means (Table 1), this became more evident at 429 DAP, where eucalypt presented averages greater than all other species in the strip system. In the line system, this trend was observed at 609 DAP, and remained until the last assessment (1509 DAP). Canafístula and guapuruvu presented RCD values greater than bracatinga and angico, this was principally observed in the strip system at 1059 DAP. At 1509 DAP, these two species had the lowest values in the strip system, but this was only observed for angico in the line system.

Table I

Comparing agroforestry systems, the superiority of RCD was observed in the strip system for eucalypt from 429 DAP, a difference that remained until the last evaluation period (Table 1). The evolution of RCD forest species studied over time in both agroforestry systems can be seen in Fig. 2. In strip system (Fig. 2A), one can see that eucalypt species had a more pronounced rate of growth when compared to other species; while in the line system (Fig. 2B) this difference was less evident.

Figure 2

2.4.3 INTERACTION OF TREE SPECIES X DAP

In general, the DBH values were higher for eucalypt, followed by guapuruvu and later by the other three species studied (angico-vermelho, bracatinga and canafístula). Regarding H, eucalypt demonstrated greater values than other species from 339 DAP, this trend continued through the last evaluation (Table 2).

Table II

Higher values were found for the MDC from eucalypt DAP 339, and remained superior until the last evaluation time. With the exception of eucalypt trees, guapuruvu demonstrated higher averages than the other species; however likely due to frost damage, this superiority of guapuruvu MDC was not observed in spring months after the occurrence of winter frosts (Table 3).

Table III

Between winter and spring, the reduction of guapuruvu MDC was 1.06; 1.44; 0.81 and 0.61 m for the years 2008, 2009, 2010 and 2011, respectively. One can identify a stagnant growth of bracatinga, observed in respective MDC values, from the DAP 699. The decline of the MDC, particularly of guapuruvu during periods with the occurrence of frost (vertical arrows in Fig. 3C) resulted in a severe reduction in leaf area. This behavior is best illustrated in Fig. 3.

Figure 3

2.4.4 INTERACTION OF TREE SPECIES X AGROFORESTRY SYSTEM

The strip system demonstrated the highest values of all variables for eucalypt, of DBH and MDC for angico, and only for DBH in canafístula (Table 4). Guapuruvu presented an inverse behavior, that is, it benefited from the line system and had a greater average DBH and H, while bracatinga showed similar characteristics in both systems for all variables.

Table IV

2.5 DISCUSSION

2.5.1 THE SPATIAL ARRANGEMENTS AND COMPETITION BETWEEN PLANTS

The superiority of RCD observed in the strip system for eucalypt from 429 DAP (Table 1 and Fig. 1) may be related to the spacing of each system (3 x 3 + 12 m and 6 x 1.5 m for strip and line, respectively), where reduced spacing between plants in the row system (1.5 m) could have influenced this difference. When compared with other species, eucalypt was seen to require a greater area to fully develop. A study by Stape et al. (2010) supports this result, noting that the proximity of the root system leads to competition for water and nutrients.

Ferreira et al. (2014) analyzed the growth of clones *Eucalyptus urophylla x Eucalyptus grandis*, and found a mean DBH of 13.8 cm four years after planting, using a spacing of 3.0 x 2.5 m. The highest values found in this study were on 1509 DAP (four years after transplantation). This can be explained by different climate conditions between locations and the spatial distribution of species in the field (Nascimento et al. 2012).

Regarding H (Table 2 and Fig. 2), our results supported similar findings by Nascimento et al. (2012), whom also found different H values between tree species; the results of this study in the spacing 3.0 x 2.0 m at 22 months of age are as follows: 2.8 m for the angico-vermelho (*Anadenanthera macrocarpa*); 4.1 m for guapuruvu (*Schizolobium parahybae*); 2.7 m in arroeira (*Schinus terebinthifolius*); 4.1 m in aloe (*Cordia* sp); 1.5 m for inga (*Inga marginata*) and 3.2 m for cotton tree (*Chorisia speciosa*).

Higher values of MDC from eucalypt DAP 339 (Table 3 and Fig. 2) were directly related to the interception of solar radiation and therefore the photosynthetic rate of the species. Findings on the interception of radiation between tree lines, for three tree species (black wattle, bracatinga, eucalypt) were reported by Caron et al. (2012); it was found that 27 % of light was intercepted by black wattle; 56 % by bracatinga, and 74 % by eucalypt trees. Caron et al. (2014) found a value of 85% light interception (between lines of trees) for *Pinus elliottii* with average H and DBH of 25.0 cm and 50.3, respectively, under space of 8x8 m.

2.5.2 RESPONSE OF TREE SPECIES TO FROST AND THE PEST SPECIES *TRIGONA SPINIPIES*

The decline of the MDC due to frost, particularly of guapuruvu (Table 3 and Fig. 2), is likely to have influenced the behavior of other morphological characteristics which were analyzed. This is largely due to a reduction of leaf area which can lead to lower rates of photosynthesis and consequently growth. Souza et al. (2011) found different classifications of frost resistance for the species studied in this experiment; guapuruvu was very sensitive to frost, canafístula showed resistance, while angico, eucalypt and bracatinga were very resistant to frost damage.

Furthermore, Sanquetta et al. (2014) showed that over many years, weather elements (precipitation and maximum mean temperature) can influence the relationship between RCD and DBH, and crown size. Larcher (2000) points out that, at low temperatures, such as in days with frosts, there is a reduction in photosynthetic activity over a period of time due to the freezing of cells.

The stagnant growth of bracatinga (Table 3 and Fig. 2) was mainly due to changing environmental conditions, as well as incidences of the species *Trigona spinipies* (Arapuá bee).

This insect species is known to nest specifically in this bracatinga due to the presence of resinous substances in the bark and stem of the tree which the Arapuá bee prefers to nest in (Piza and Junior, 1991).

According to Caron et al. (2013), the presence of large colonies of Arapuá bees can result in the removal of the bark from bracatinga trees. This removal causes a high release of photosynthates thus creating the appearance of sooty mold which results in a blackish color. As an additional consequence, they can inhibit the flow of sap, and potentially lead to the senescence of branches, reduction crown diameter and photosynthetic rate; this can result in a decreased growth rate for the trees.

2.5.3 THE ARRANGEMENT OF PLANTING AND THE USE OF SOLAR RADIATION

Eucalypt showed the greatest values for all variables in strip system, DBH and MDC for angico, and only for DBH in canafístula (Table 4), these results may be related the better use of solar radiation. The equidistant relationship of trees in the central rows in the strip system (3 x 3m) likely led to a greater use of photosynthetically active solar radiation by the crown, which may have led to increased radiation interception and therefore plant photosynthesis. In addition, the wider spacing of the external rows may have decreased competition for available resources (radiation, water, nutrients) thus justifying the higher values observed in this system for most of the variables reported in this article.

2.5.4 INTRINSIC CHARACTERISTICS OF GROWTH AND ITS IMPLICATION AS TO ARRAYS OF PLANTING

The distinct response from guapuruvu may be related to its dynamic growth and form of branching. The trees angico, bracatinga, canafístula, and eucalypt have sympodial branching, or multiple meristem buds forming consecutively as part of each axis. Unlike the previously mentioned species, guapuruvu presents monopodial branching where growth occurs by one apical bud. In addition, this species (guapuruvu) is characterized by forming dense clusters in large forest clearings (Carvalho 2003); therefore, the reduced spacing between plants in line system (1.5 m between plants) may have benefited the growth of this species in relation to others.

In addition to the findings found by several authors, that a large degree of spacing promotes greater diameter growth of trees (Clark et al. 2008, Harrington et al. 2009), it can be noted that another key factor in the growth of forest species is the arrangement in which trees are planted. The equidistance spacing of trees in center rows, and the larger area of outer rows in strip systems contributed to the greater availability of resources thus allowing enhanced plant growth.

Different behaviors for each evaluation period for each species were identified. This variation clearly demonstrates the dynamics of existing growth, and depends on the endogenous rhythm of growth inherent to each species and their relationship with meteorological elements. In this sense, Machado et al. (2014), working with *Araucaria angustifolia* species, found that the increase in RCD of this species was highly influenced by the intrinsic metabolic activity of these trees.

The differences in the variables (DBH, RCD, MDC and H) between species allow the establishment of morphological characteristics which may be specific to each tree, that is, species which had a higher RCD did not necessarily exhibit a greater DBH, MDC or total H. This is one reason for the analysis of various species and the arrangements and spacing in which they may best be developed.

2.6 CONCLUSIONS

The strip system provides a higher growth of angico, canafístula and eucalypt, while the line system favors the growth of guapuruvu. Bracatinga is not influenced by this studied agroforestry system.

Among the studied species, eucalypt is responsible for the greatest root collar diameter values, diameter at breast height, crown development, and plant height.

2.7 ACKNOWLEDGEMENTS

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2.8 RESUMO

A hipótese proposta é que o crescimento de espécies arbóreas reage diferentemente de acordo com o arranjo das plantas. O objetivo deste trabalho foi avaliar o crescimento das espécies arbóreas guapuruvu (*Schizolobium parahybae*), bracatinga (*Mimosa scabrella*), canafístula (*Peltophorum dubium*), angico-vermelho (*Parapiptadenia rigida*) e eucalipto (*Eucalyptus urophylla* x *Eucalyptus grandis*), cultivadas com cana-de-açúcar (*Saccharum* spp.), em dois arranjos de plantas (faixa – 3x3 m + 12 m e linha – 6 x 1,5 m) em sistemas agroflorestais. O estudo foi realizado no município de Frederico Westphalen, RS, em delineamento experimental de blocos completos casualizados, com três repetições. Avaliou-se o diâmetro do colo, diâmetro à altura do peito, diâmetro médio da copa e altura de planta, durante quatro anos, com intervalo de 90 dias entre as avaliações. O sistema em faixa proporciona maior crescimento do angico, canafístula e eucalipto, já o sistema linha favorece o crescimento do guapuruvu. A bracatinga não é influenciada pelos sistemas agroflorestais estudados. Entre as espécies estudadas, o eucalipto é responsável pelos maiores valores de diâmetro do colo, à altura do peito, da copa e altura de planta.

Palavras-chave: arranjo de plantas, altura, diâmetro da copa, competição.

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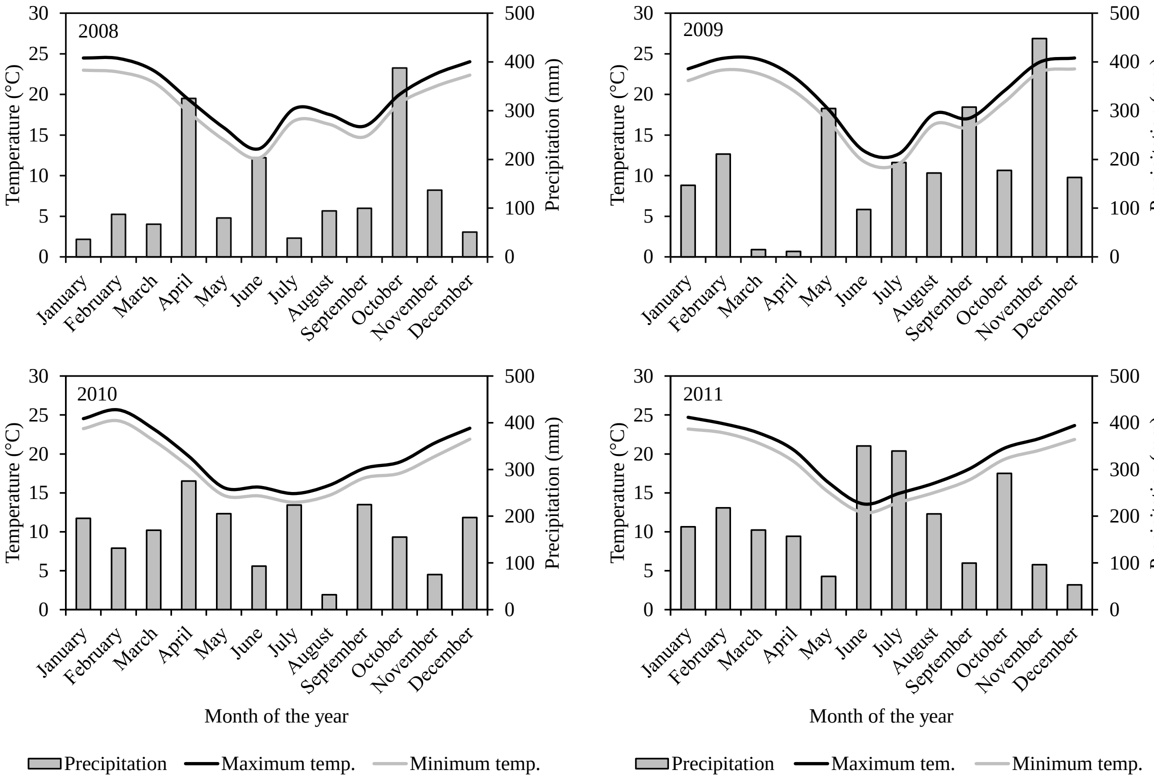

Figure 1 - Average monthly maximum, minimum temperature, and monthly precipitation during the years 2008, 2009, 2010 and 2011, over the entirety of the study which was conducted in the city of Frederico Westphalen.

TABLE I

Root collar diameter of tree species angico (Ang), bracatinga (Brac), canafístula (Can), eucalypt (Euc) and guapuruvu (Guap) in strip and line agroforestry system from 159 to 1509 days after planting (DAP) seedlings in the city of Frederico Westphalen - RS.

DAP	159 (aut*/2008)		249 (win/2008)		339 (spri/2008)		429 (sum/2008)	
System	Strip	Line	Strip	Line	Strip	Line	Strip	Line
Ang	1,06 ^{aA}	0,88 ^{aA}	1,62 ^{bA}	1,33 ^{bA}	2,52 ^{bA}	1,66 ^{cA}	3,05 ^{bA}	2,02 ^{dA}
Brac	1,48 ^{aA}	1,17 ^{aA}	2,94 ^{abA}	2,38 ^{abA}	3,43 ^{bA}	2,83 ^{bcA}	4,27 ^{bA}	3,43 ^{cdA}
Can	1,48 ^{aA}	1,59 ^{aA}	2,63 ^{abA}	2,91 ^{abA}	2,45 ^{bA}	3,60 ^{abA}	3,59 ^{bA}	3,94 ^{bcA}
Euc	1,97 ^{aA}	1,51 ^{aA}	4,04 ^{aA}	3,10 ^{aA}	5,85 ^{aA}	4,51 ^{aA}	7,82 ^{aA}	6,10 ^{aB}
Guap	2,63 ^{aA}	2,31 ^{aA}	4,12 ^{aA}	3,87 ^{aA}	4,23 ^{abA}	3,81 ^{abA}	4,76 ^{bA}	5,38 ^{abA}
DAP	519 (aut/09)		609 (win/09)		699 (spri/09)		789 (sum/09)	
System	Strip	Line	Strip	Line	Strip	Line	Strip	Line
Ang	3,68 ^{cA}	2,49 ^{dA}	3,80 ^{cA}	2,70 ^{cA}	3,85 ^{cA}	3,27 ^{cA}	4,67 ^{cA}	3,84 ^{cA}
Brac	5,11 ^{bcA}	4,06 ^{cdA}	4,86 ^{bcA}	5,12 ^{bA}	5,19 ^{bcA}	5,19 ^{bcA}	5,57 ^{bcA}	5,32 ^{bcA}
Can	4,88 ^{bcA}	5,15 ^{bcA}	5,15 ^{bcA}	5,33 ^{bA}	5,22 ^{bcA}	5,43 ^{bA}	6,09 ^{bcA}	6,16 ^{bA}
Euc	9,68 ^{aA}	7,00 ^{aB}	10,04 ^{aA}	7,71 ^{aB}	12,01 ^{aA}	8,82 ^{aB}	13,66 ^{aA}	10,09 ^{aB}
Guap	5,74 ^{bA}	5,78 ^{abA}	5,85 ^{bA}	5,79 ^{bA}	5,84 ^{bA}	6,57 ^{bA}	7,92 ^{bA}	7,68 ^{bA}
DAP	879 (aut/10)		969 (win/10)		1059 (spri/10)		1149 (sum/10)	
System	Strip	Line	Strip	Line	Strip	Line	Strip	Line
Ang	5,28 ^{dA}	4,72 ^{cA}	5,42 ^{dA}	5,62 ^{cA}	5,87 ^{cA}	5,08 ^{dA}	6,13 ^{cA}	5,51 ^{dA}
Brac	6,12 ^{cdA}	5,57 ^{cA}	6,19 ^{cdA}	7,33 ^{bcA}	6,16 ^{cA}	7,73 ^{cdA}	6,32 ^{cA}	7,74 ^{cdA}
Can	7,72 ^{bcA}	7,67 ^{bA}	7,85 ^{cA}	8,15 ^{bA}	8,70 ^{bA}	8,33 ^{cA}	8,49 ^{bA}	8,50 ^{cA}
Euc	16,71 ^{aA}	11,98 ^{aB}	17,92 ^{aA}	13,03 ^{aB}	19,93 ^{aA}	14,75 ^{aB}	21,69 ^{aA}	15,11 ^{aB}
Guap	9,37 ^{bA}	10,58 ^{aA}	9,77 ^{bA}	10,06 ^{bA}	9,80 ^{bA}	11,01 ^{bA}	9,96 ^{bA}	11,67 ^{bA}
DAP	1239 (aut/11)		1329 (win/11)		1419 (spri/11)		1509 (sum/11)	
System	Strip	Line	Strip	Line	Strip	Line	Strip	Line
Ang	6,91 ^{cA}	5,31 ^{cA}	7,49 ^{cA}	5,86 ^{dA}	7,68 ^{cdA}	6,24 ^{dA}	7,92 ^{cA}	6,44 ^{dA}
Brac	6,43 ^{cA}	7,78 ^{cA}	6,63 ^{cA}	7,62 ^{dA}	6,85 ^{dA}	9,27 ^{cdA}	6,89 ^{cA}	10,01 ^{cA}
Can	9,15 ^{bA}	9,46 ^{bcA}	8,57 ^{cB}	10,28 ^{cA}	9,18 ^{cA}	10,32 ^{cA}	10,80 ^{bA}	11,38 ^{cA}
Euc	22,29 ^{aA}	15,97 ^{aB}	24,26 ^{aA}	17,60 ^{aB}	24,57 ^{aA}	20,00 ^{aB}	25,01 ^{aA}	22,84 ^{aB}
Guap	9,84 ^{bA}	11,96 ^{A}	10,69 ^{bA}	12,24 ^{bA}	11,49 ^{bA}	13,14 ^{bA}	11,73 ^{bA}	13,95 ^{bA}

Root collar diameter is expressed as cm. Means followed by the same letter, lowercase in column compare the species in each system and uppercase in each line compare the systems in each evaluation period, the means do not differ among themselves by Tukey test of probability at 5% of error. * sum: summer; aut: autumn; win: winter; spri: spring.

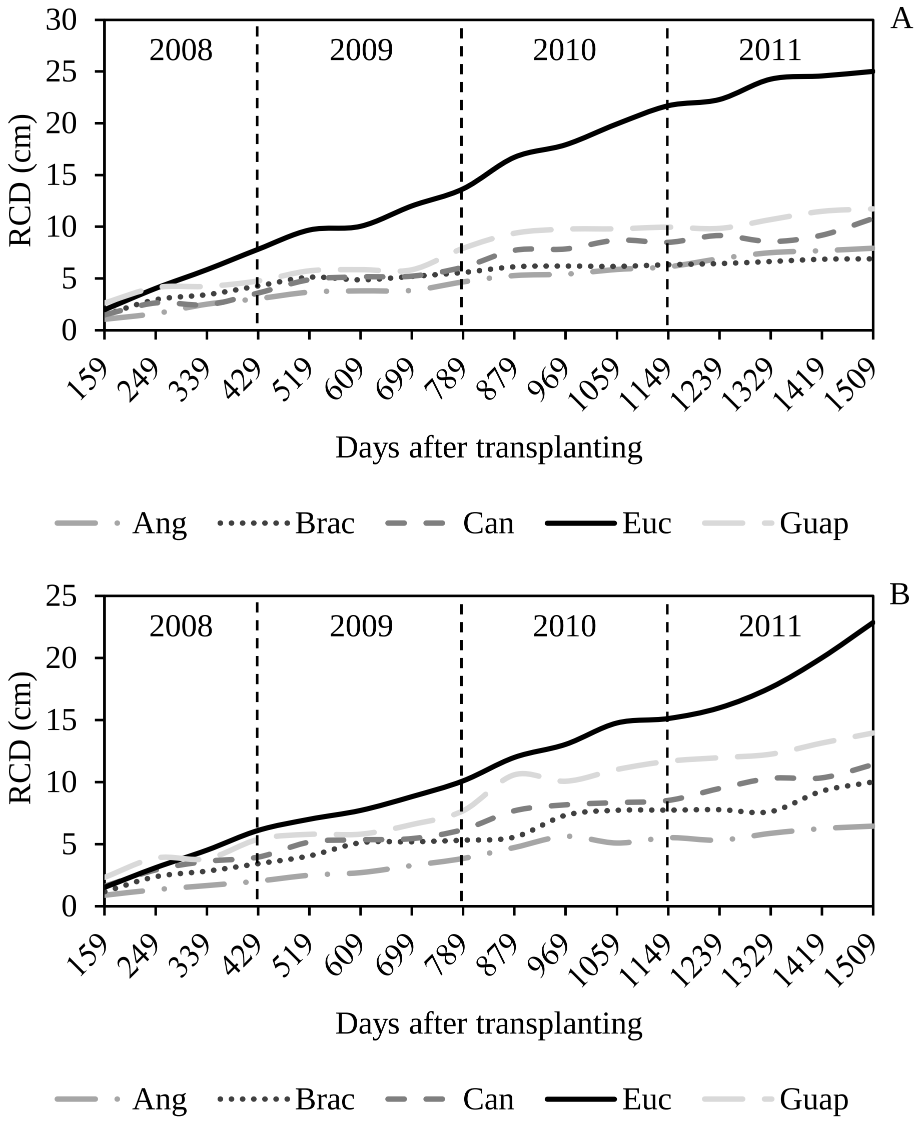

Figure 2 - Growth of root collar diameter (RCD) of tree species angico (Ang), bracatinga (Brac), canafístula (Can), eucalyptus (Euc) and guapuruvu (Guap) in agroforestry systems strip (A) and line (B), from 159 to 1509 days after planting of the seedlings in the city of Frederico Westphalen - RS.

TABLE II

Diameter at breast height (DBH) and height (H) of tree species angico (Ang), bracatinga (Brac), canafístula (Can), eucalypt (EUC) and guapuruvu (Guap), from 159 to 1509 days after planting (DAP) in the city of Frederico Westphalen - RS.

DAP	159 (aut*/2008)		249 (win/2008)		339 (spri/2008)		429 (sum/2008)	
Variable	DBH	H	DBH	H	DBH	H	DBH	H
Ang.	-**	1.02 ^{a}	0.59 ^{b}	1.38 ^{b}	1.30 ^{b}	1.83 ^{bc}	1.45 ^{b}	1.99 ^{bc}
Brac.	-	1.38 ^{a}	1.35 ^{b}	2.19 ^{a}	1.34 ^{b}	2.25 ^{b}	1.96 ^{b}	2.67 ^{b}
Can.	-	0.61 ^{a}	0.37 ^{b}	0.93 ^{b}	0.72 ^{b}	0.93 ^{d}	1.05 ^{b}	1.52 ^{c}
Euc.	-	1.32 ^{a}	1.63 ^{ab}	2.42 ^{a}	2.95 ^{a}	3.33 ^{a}	4.31 ^{a}	4.85 ^{a}
Guap.	-	0.82 ^{a}	3.21 ^{a}	1.21 ^{b}	3.01 ^{a}	1.24 ^{cd}	2.76 ^{ab}	1.50 ^{c}
DAP	519 (aut/09)		609 (win/09)		699 (spri/09)		789 (sum/09)	
Variable	DBH	H	DBH	H	DBH	H	DBH	H
Ang.	1.74 ^{c}	2.43 ^{bc}	1.89 ^{c}	2.80 ^{b}	1.86 ^{c}	2.78 ^{bc}	2.53 ^{c}	3.09 ^{bc}
Brac.	2.43 ^{b}	3.07 ^{b}	2.62 ^{bc}	2.77 ^{b}	2.58 ^{bc}	3.53 ^{b}	2.97 ^{c}	3.83 ^{b}
Can.	1.79 ^{bc}	2.26 ^{bc}	2.14 ^{c}	2.32 ^{b}	2.01 ^{c}	2.44 ^{cd}	2.77 ^{c}	2.79 ^{c}
Euc.	5.97 ^{a}	6.50 ^{a}	6.33 ^{a}	6.60 ^{a}	7.39 ^{a}	7.20 ^{a}	8.90 ^{a}	8.37 ^{a}
Guap.	3.23 ^{b}	1.81 ^{c}	3.77 ^{b}	2.27 ^{b}	3.71 ^{b}	1.82 ^{d}	5.28 ^{b}	2.40 ^{c}
DAP	879 (aut/10)		969 (win/10)		1059 (spri/10)		1149 (sum/10)	
Variable	DBH	H	DBH	H	DBH	H	DBH	H
Ang.	3.06 ^{c}	3.75 ^{b}	3.19 ^{c}	3.84 ^{bc}	3.24 ^{c}	3.77 ^{bc}	3.75 ^{c}	3.74 ^{b}
Brac.	3.46 ^{c}	3.90 ^{b}	4.34 ^{c}	4.64 ^{b}	4.43 ^{c}	4.68 ^{b}	4.46 ^{c}	4.71 ^{b}
Can.	3.88 ^{c}	3.30 ^{b}	3.89 ^{c}	3.47 ^{c}	3.93 ^{c}	3.51 ^{bc}	4.15 ^{c}	4.19 ^{b}
Euc.	10.77 ^{a}	10.47 ^{a}	11.61 ^{a}	10.98 ^{a}	12.53 ^{a}	11.80 ^{a}	13.08 ^{a}	13.14 ^{a}
Guap.	7.09 ^{b}	3.08 ^{b}	6.81 ^{b}	3.04 ^{c}	7.41 ^{b}	2.85 ^{c}	8.10 ^{b}	3.84 ^{b}
DAP	1239 (aut/11)		1329 (win/11)		1419 (spri/11)		1509 (sum/11)	
Variable	DBH	H	DBH	H	DBH	H	DBH	H
Ang.	4.34 ^{c}	3.70 ^{c}	4.46 ^{d}	4.06 ^{bc}	4.50 ^{c}	4.47 ^{b}	5.92 ^{c}	4.93 ^{b}
Brac.	4.47 ^{c}	4.90 ^{b}	5.06 ^{cd}	4.48 ^{b}	5.02 ^{c}	4.86 ^{b}	5.10 ^{cd}	5.12 ^{b}
Can.	4.75 ^{c}	4.55 ^{b}	5.10 ^{c}	4.16 ^{b}	5.16 ^{c}	4.56 ^{b}	6.21 ^{c}	4.74 ^{b}
Euc.	14.34 ^{a}	13.66 ^{a}	15.60 ^{a}	14.24 ^{a}	16.68 ^{a}	15.15 ^{a}	16.76 ^{a}	15.97 ^{a}
Guap.	7.21 ^{b}	3.85 ^{bc}	8.28 ^{b}	3.38 ^{c}	9.30 ^{b}	3.68 ^{b}	9.88 ^{b}	4.23 ^{b}

DBH is expressed as cm; H (heigth) is expressed as m. Means followed by the same letter in the column do not differ among themselves, by Tukey test of probability at 5% of error. * Sum: Summer; aut: autumn; Win: Winter; spri: spring. ** In the first spring season, the plants have not had DBH developed.

TABLE III

Mean diameter of crown of tree species angico (Ang), bracatinga (Brac), canafístula (Can), eucalypt (Euc) and guapuruvu (Guap), from 159 to 1509 days after planting (DAP) of seedlings in city of Frederico Westphalen - RS.

DAP	159 (aut*/2008)	249 (win/2008)	339 (spri/2008)	429 (sum/2008)
Ang.	-**	0.40 ^{c}	0.64 ^{c}	0.67 ^{d}
Brac.	-	1.03 ^{b}	1.15 ^{b}	1.46 ^{c}
Can.	-	1.05 ^{b}	0.79 ^{bc}	1.04 ^{d}
Euc.	-	1.70 ^{a}	2.23 ^{a}	2.35 ^{a}
Guap.	-	1.90 ^{a}	0.84 ^{bc}	1.49 ^{b}
DAP	519 (aut/09)	609 (win/09)	699 (spri/09)	789 (sum/09)
Ang.	0.85 ^{d}	1.15 ^{c}	0.84 ^{c}	0.95 ^{c}
Brac.	1.45 ^{c}	1.62 ^{b}	1.49 ^{b}	1.55 ^{b}
Can.	1.06 ^{d}	1.01 ^{c}	0.44 ^{c}	0.76 ^{c}
Euc.	2.44 ^{a}	2.66 ^{a}	2.36 ^{a}	2.66 ^{a}
Guap.	1.93 ^{b}	1.85 ^{b}	0.41 ^{c}	1.74 ^{b}
DAP	879 (aut/10)	969 (win/10)	1059 (spri/10)	1149 (sum/10)
Ang.	1.39 ^{cd}	1.5 ^{c}	1.82 ^{b}	1.94 ^{c}
Brac.	1.61 ^{c}	1.64 ^{c}	1.66 ^{bc}	1.71 ^{c}
Can.	1.01 ^{d}	1.35 ^{c}	1.40 ^{c}	1.69 ^{c}
Euc.	2.89 ^{a}	3.08 ^{a}	3.21 ^{a}	3.87 ^{a}
Guap.	2.06 ^{b}	2.48 ^{b}	1.67 ^{bc}	2.44 ^{b}
DAP	1239 (aut/11)	1329 (win/11)	1419 (spri/11)	1509 (sum/11)
Ang.	2.07 ^{c}	2.02 ^{c}	2.33 ^{b}	2.50 ^{cd}
Brac.	1.76 ^{c}	1.84 ^{c}	1.92 ^{c}	2.11 ^{d}
Can.	1.81 ^{c}	1.79 ^{c}	2.27 ^{c}	2.43 ^{cd}
Euc.	4.39 ^{a}	4.42 ^{a}	4.49 ^{a}	4.59 ^{a}
Guap.	2.84 ^{b}	2.82 ^{b}	2.21 ^{c}	2.76 ^{c}

Mean diameter of crown is expressed as m. Means followed by the same letter in the column do not differ among themselves, by Tukey test of probability at 5% of error. * Sum: Summer; aut: autumn; Win: Winter; spri: spring. ** In the first spring season, the plants have not had crown developed.

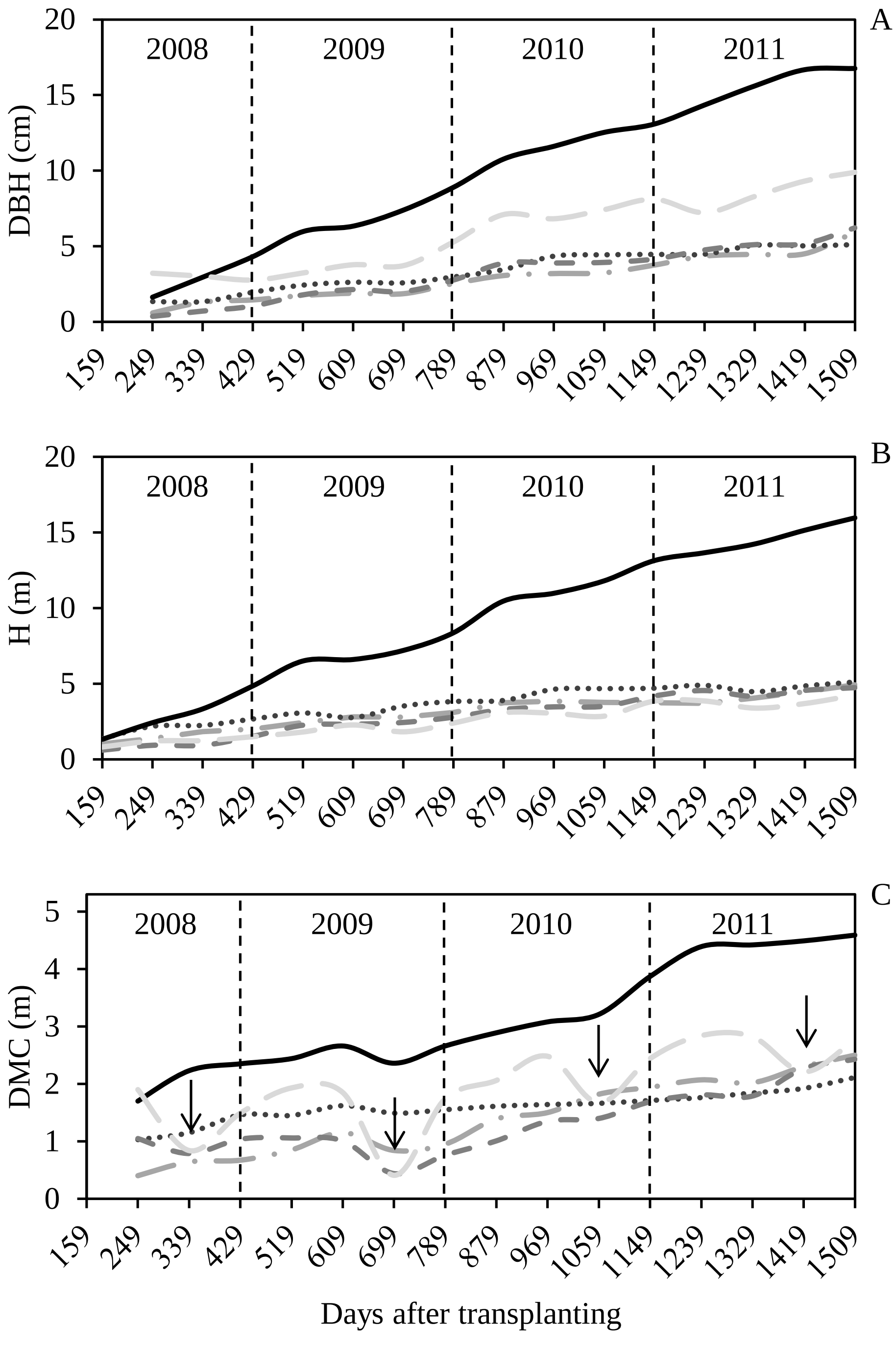

Figure 3 - Growth of diameter at breast height (DBH; A), height (H, B) and diameter mean of crown (MDC, C) of tree species angico (Ang), bracatinga (Brac), canafístula (Can), eucalypt (Euc) and guapuruvu (Guap), from 159 to 1509 days after planting in the city of Frederico Westphalen - RS. Vertical arrows indicate damage related to frost.

TABLE IV

Diameter at breast height (DBH), plant height (H) and mean diameter of crown (MDC) of tree species angico, bracatinga, canafístula, eucalypt and guapuruvu in strip and line agroforestry systems in the city of Frederico Westphalen – RS.

		Species				
Variable	System	Angico	Bracatinga	Canafístula	Eucalipto	Guapuruvu
DBH	Strip	3.26 ^{aD}	2.95 ^{aD}	4.04 ^{aC}	11.16 ^{aA}	5.61 ^{bB}
	Line	2.60 ^{bD}	2.60 ^{aD}	3.39 ^{bC}	8.64 ^{bA}	6.99 ^{aB}
H	Strip	2.85 ^{aB}	3.14 ^{aB}	2.95 ^{aB}	9.30 ^{aA}	2.26 ^{bC}
	Line	2.99 ^{aB}	2.91 ^{aB}	2.92 ^{aB}	8.90 ^{bA}	2.68 ^{aB}
MDC	Strip	1.65 ^{aC}	1.51 ^{aCD}	1.44 ^{aD}	3.35 ^{aA}	1.93 ^{aB}
	Line	1.41 ^{bC}	1.40 ^{aC}	1.35 ^{aC}	2.78 ^{bA}	1.86 ^{aB}

DBH is expressed as cm; H is expressed as m; MDC is expressed as m. Means followed by the same letter, lowercase in column and uppercase in line, do not differ among themselves, by Tukey test of probability at 5% of error.

3 ARTIGO II - METEOROLOGICAL ELEMENTS DEFINING THE HEIGHT GROWTH CURVE OF FOREST SPECIES

Submetido para o periódico: Forest Ecology and Management
Situação: em avaliação

Meteorological elements defining the height growth curve of forest species

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3.1 ABSTRACT

New predictive variables in nonlinear biological models were analyzed which take into account the influence of meteorological elements on the height of tree species. Experiments were conducted from 2007 to 2014, with the species *Eucalyptus urophylla* x *Eucalyptus grandis*, *Parapiptadenia rigida*, *Peltophorum dubium*, *Mimosa scabrella* and *Schizolobium parahybae*. It was seen that growth curve variations over time are determined by the weather conditions. The temperature and rainfall were the most closely correlated weather elements to the height of the trees, and for this reason were added a new parameter to explain the growth curves. The new models provided more accurate estimates of the trees' height regarding the influence of weather conditions.

Keywords: Chapman Richards' model, mean minimum temperature, rainfall.

3.2 Introduction

Tree height is an important variable used for decision making regarding the cultivation and management practices of tree stands, forest planning, forest succession, and estimate of trees volume (Zhang and Liu, 2001). The height of a tree is related to the level of intra-specific interaction, arrangement of planting (Armstrong and McGehee, 1980; Jose et al., 2004), soil characteristics and availability of nutrients (Newman, 1973), as well as the weather conditions of a cultivation area (Fitter, 1987; Lohmus et al., 1989).

Height is commonly used in modeling the growth of trees (David et al., 2015; Diamantopoupou and Ozçelik, 2012; Jiang and Ly, 2010; Perin et al., 2013; Rasche et al., 2012; Uzoh and Oliver, 2006; Zhang et al., 2004). Linear regression models have applications in several areas of research, and are widely used because of their ability to describe the relationship between dependent and independent variables; however, in parameter estimation, there is a unique solution and therefore an analytical method by which to determine the coefficients. We can describe the relationship between variables, using a nonlinear model, based on theoretical knowledge of the condition treated, where often a linear model might not be appropriate. A common example in the biological sciences is the modeling of plant growth, which makes it necessary to fit nonlinear functions to explain growth curve.

Biological growth models commonly present organism size as a dependent variable, and organism age as independent variable, in addition to regression coefficients; in these cases, meteorological elements are not taken into account. In regions where data samples are subjected to harsh winters with absolute minimum temperatures below zero and the occurrence of frosts, tree species sensitive to cold may incur damage on apical buds. Damage due to winter conditions can potentially compromise the growth of the upper third of the trees. These and other variations in the growth curve caused by meteorological variables are not explained by biological models in the literature to date. In addition, the importance of using meteorological elements in forest modeling to explain the arboreal plant responses is evidenced by several authors (Prior and Bowman, 2014; Rais et al., 2014; Subedi and Sharma, 2013; Trouvé et al., 2015).

In this context, we originated the following hypothesis: weather elements, along with the plants age, can be used to define the height growth curve of forest species. In order to test this hypothesis, we endeavored to modify existing biological models, by adding predictive variables that take into account the effect of meteorological elements on the growth in height of trees.

3.3 Material and Methods

3.3.1 Data source

The study was conducted in the city of Frederico Westphalen, Rio Grande do Sul, Brazil, with geographical location of 27°22’S, 53°25’W at 480 m of altitude (Figure 1). The following tree species were used: *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden, *Mimosa scabrella* Benth*.*, *Parapiptadenia rigida*, *Peltophorum dubium* (Spr.) Taubert and *Schizolobium parahybae* (Vell.) Blake.

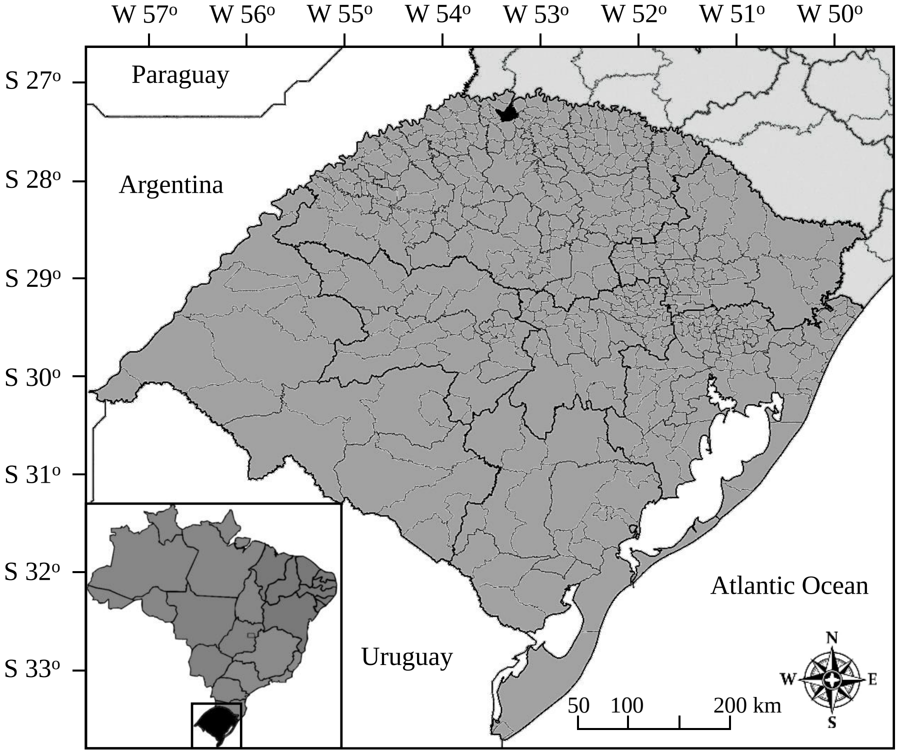

Fig. 1. Geographical location of the Rio Grande do Sul state, highlighted in black on the bottom map, and the city of Frederico Westphalen, highlighted in black on the main map.

The experiment was installed in September 2007, through the manual planting of seedlings, after plowing and harrowing the area. The experimental design was a randomized complete block and the study factors were tree species, ages of trees, and height measurements, with three replicates for each treatment.

The determination of the trees height began in March 2008, at the beginning of the autumn season, by selecting 18 trees of each species for study. From this moment, there were quarterly evaluations at the beginning of each season, until spring 2014, the same selection of trees was always evaluated. For the measurement of plant height, we used a measuring tape until the values reached 2.0 m, and after this height, a Hypsometer Vertex III was used to determine the distance from the ground surface to the top leaf axils.

3.3.2 Height modeling

Seven nonlinear models were tested in order to estimate the tree height as function of time, which was described in Table 1.

Table 1

Height models tested for *Eucalyptus urophylla* x *Eucalyptus grandis*, *Mimosa scabrella, Parapiptadenia rigida*, *Peltophorum dubium* and *Schizolobium parahybae* in Rio Grande do Sul State, Brazil.

Author	Model	Number
Schumacher	$h = \beta_0\, e^{(\beta_1 A^{-1})} + \varepsilon$	(1)
Chapman-Richards	$h = \beta_0(1 - e^{-\beta_1 A})^{\left[(1-\beta_2)^{-1}\right]} + \varepsilon$	(2)
Clutter-Jones	$h = \beta_0(1 + \beta_1 A^{\beta_2})^{\beta_3} + \varepsilon$	(3)
Prodan	$h = \dfrac{A^2}{(\beta_0 + \beta_1 A + \beta_2 A^2)} + \varepsilon$	(4)
Bailey of 4 parameters	$h = \left(1 - e^{\beta_1 A^{\beta_2}}\right)^{\beta_3} + \varepsilon$	(5)
Mitscherlich	$h = \beta_0(1 - \beta_1 e^{-\beta_2 A}) + \varepsilon$	(6)
Gompertz	$h = \beta_0 e^{\left(-\beta_1 e^{(-\beta_2 A)}\right)} + \varepsilon$	(7)

In which: h = height, in m; β_0, β_1, β_2 and β_3 = model parameters; *e* = base of the natural logarithm; A = age, in months; ε = random error;

The evaluation of models was performed using the following criteria: adjusted coefficient of determination ($R^2_{aj.}$), coefficient of variation (CV), in percentage, graphic analysis of residuals (Ri), in percentage, and the Pearson correlation coefficient between estimated and observed values. The statistics were calculated by the expressions highlighted in (8) to (15).

The adjusted coefficient of determination ($R^2_{aj.}$) was expressed as:

$$R^2_{adj.}=1-\frac{(n-1)}{(n-k)}\left(1-R^2\right) \tag{8}$$

In which:

$$R^2=1-\left(\frac{RSS}{TSS}\right) \tag{9}$$

$$R^2=1-\left(\frac{\sum_{i-1}^{n}\left(y_i-\hat{y}_i\right)^2}{\sum_{i-1}^{n}\left(y_i-\bar{y}\right)^2}\right) \tag{10}$$

The coefficient of variation (CV) was determined by the following expression:

$$CV=100\,\bar{y}^{-1}\sqrt{\frac{\sum_{i-1}^{n}\left(y_i-\hat{y}_i\right)^2}{n-k}} \tag{11}$$

The graphical analysis of the residuals (Ri) was obtained by:

$$R_i=100\,y_i^{-1}\left(y_i-\hat{y}_i\right) \tag{12}$$

The Pearson correlation coefficient (r) was expressed by the following:

$$r=\frac{cov\left(y_i;\hat{y}_i\right)^2}{\sqrt{\left(var\,y_i\right)\left(var\,\hat{y}_i\right)}} \tag{13}$$

In which:

$$Cov=\sum_{i=1}^{n}\left(y_i-\bar{y}\right)\left(\hat{y}_i-\bar{y}\right) \tag{14}$$

$$Var_{y_i}=\sqrt{\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2} \tag{15}$$

$$Var_{\hat{y}_i}=\sqrt{\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2} \tag{16}$$

In which:

n = number of observations;

k = number of parameters of the model;

RSS = residual some of square;

TSS = total some of square;

y_i = observed values

$\hat{y}_i$ = estimated values;

$\bar{y}$ = average value;

Cov = covariance between observed and estimated values;

Var = variance of observed and estimated values.

For the estimation of nonlinear regression models, we used the least squares method. For this, we run the “proc nlin” procedure by the Statistical Analysis System software (SAS).

3.3.3 Comparison between model coefficients

Consider that the same model has been selected for more than one studied species. In this case, the model coefficients must be compared in relation their equality. For this, we use the likelihood ratio test with an accuracy given by chi – square (χ^2) statistic (Regazzi and Silva, 2010).

The method uses the addition of two independent variables, D1 and D2, to calculate the maximum likelihood estimates of the parameters under no restrictions in the parametric space (Ω) representing the complete model, and under restriction represented by ω, showing the reduced model. The addition of independent variables is given by:

$$y_{ij} = D_1[A] + D_2[B] + \varepsilon \tag{17}$$

$$D_i = \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \tag{18}$$

In which:

A and B = model coefficients for species A and B, respectively;

1 = if y_{ij} observation belongs to group i;

0 = if y_{ij} observation does not belong to group i;

ε = random error;

The following hypotheses were taken into account for each model coefficient:

$$H_0 = \beta_{0a} = \beta_{0b} = \beta_0 \tag{19}$$

$$H_0 = \beta_{1a} = \beta_{1b} = \beta_1 \tag{20}$$

$$H_0 = \beta_{2a} = \beta_{2b} = \beta_2 \tag{21}$$

$$H_0 = \beta_{na} = \beta_{nb} = \beta_n \tag{22}$$

In which:

β_{na} and β_{nb} = coefficients of complete model;

β_n = coefficients of reduced model.

Consider the following statistic for the maximum likelihood ratio test (L):

$$L=\left(\frac{\hat{\sigma}^2_{\Omega}}{\hat{\sigma}^2_{\omega}}\right)^{N/2} \tag{23}$$

In which:

$\hat{\sigma}^2_{\Omega}$ = estimate the maximum likelihood of $\hat{\sigma}^2$ with no restriction on the parametric space;

$\hat{\sigma}^2_{\omega}$ = estimate the maximum likelihood of $\hat{\sigma}^2$ with restrictions placed on H_0;

N = number of observations.

For large samples of size N, Rao (1973) expresses this test as follows:

$$-2 \ln L = -N \ln\left(\frac{\hat{\sigma}^2_{\Omega}}{\hat{\sigma}^2_{\omega}}\right) \tag{24}$$

From this, consider how the complete model was adjusted under no restrictions in Ω, and the reduced model was adjusted with respect to restrictions defined in H_0. For the H_0 test, the expression may be defined as:

$$\chi^2_{calc.} = -N \ln\left(\frac{\hat{\sigma}^2_{\Omega}}{\hat{\sigma}^2_{\omega}}\right) \tag{25}$$

$$\chi^2_{\mathrm{calc.}} = -N \ln\left(\frac{\mathrm{SSRR}_{\Omega}}{\mathrm{SSRR}_{\omega}}\right) \tag{26}$$

In which:

SSRR_{Ω} = sum of squares residual of the regression of the complete model;

SSRR_{ω} = sum of squares residual of the regression of the reduced model;

The decision rule in order to reject H_0 at significance level (α), if $\chi^2_{calc.} \geq \chi^2_{\alpha}$, took into account the number of degrees of freedom (DF), expressed by:

$$DF = k_{\Omega} - k_{\omega} \tag{27}$$

In which:

k_{Ω} = number of parameters of complete model;

k_{ω} = number of parameters of reduced model;

3.3.4 Including meteorological elements in models

After the selection of models with the best statistical adjustments for each species, we added new predictive variables in to the equations, taking into account weather elements. The first step was to determine which elements were most correlated with the dependent variable, which was the height. This was performed using stepwise Multiple Regression techniques.

The Multiple models determined by the Stepwise method were evaluated for the presence and magnitude of multicollinearity, through the matrix condition number (ratio between the largest and smallest eigenvalues) and the variance inflation factors (VIFs). Factors above 10 indicate a high degree of multicollinearity (Mansfield and Helms, 1982). This is due to a high correlation between independent variables in the model which can compromise estimates, due to increased variance of the coefficients. Therefore, variables that caused high VIFs were excluded. Multicollinearity was considered weak, moderate or severe, when the condition number was <100; of 100-1000 and > 1000; respectively (Montgomery et al., 2012).

The values of the weather elements occurring during the study were obtained through the Climatologic Station of National Institute of Meteorological, located at 1500 m from the study site, at coordinates 27°39’S and 53°43’W. The meteorological variables selected by stepwise method were considered as new explicative variables; nonlinear models selected for each species were adjusted again. New parameters (β_n) were added in the models and the coefficients again were estimated by least squares method.

3.4 Results

3.4.1 Fit statistics

The fit statistics of the models tested for each tree species are shown in Table 2. We selected the following models: Chapman-Richards for *Eucalyptus urophylla* x *Eucalyptus grandis*, *Parapiptadenia rigida* and *Peltophorum dubium*, Clutter-Jones for *Mimosa scabrella* and Gompertz for *Schizolobium parahybae*.

Table 2

Fit statistics and coefficients obtained by adjusting seven nonlinear models to describe the height growth of five tree species.

Model	Coefficients				CV (%)^a	$R^2_{aj.}$
	β_0	β_1	β_2	β_3		
Eucalyptus urophylla x *Eucalyptus grandis*						
Schumacher	28.35	-700			17.40	0.98
Chapman-Richards	26.1731	0.00078	1.3692		16.23	0.98
Clutter-Jones	69.1835	-0.6129	-0.2858	18.5375	25.04	0.95
Prodan	13238.9	50.1822	0.0246		16.24	0.98
Mitscherlich	30.9423	1.0364	0.000489		16.23	0.92
Gompertz	22.2104	3.0673	0.0015		16.57	0.98
Bailey 4P	28.3361	0.00611	0.7443	2.1138	16.25	0.98
Mimosa scabrella						
Schumacher	4.9364	-201.5			24.67	0.95
Chapman-Richards	4.4936	0.00252	1.0117		24.30	0.95
Clutter-Jones	5.3578	-0.0708	-0.6795	502.4	17.78	0.95
Prodan	3044.3	58.5306	0.1833		24.27	0.95
Mitscherlich	4.4816	1.0129	0.00255		24.29	0.73
Gompertz	4.302	2.1256	0.00403		24.60	0.95
Bailey 4P	4.8284	0.1434	0.4536	4.3258	24.34	0.95
Parapiptadenia rigida						
Schumacher	9.9513	-925.4			37.75	0.90
Chapman-Richards	43.7913	0.000053	0.8691		34.42	0.91
Clutter-Jones	533.9	-1.2948	0.0653	2.8678	35.12	0.91
Prodan	-14073.4	302.6	0.00657		33.38	0.92
Mitscherlich	97.2811	0.9925	0.000025		36.63	0.64
Gompertz	192.3	4.931	0.000185		32.56	0.92
Bailey 4P	16.988	0.0652	0.4175	4.4619	36.13	0.91
Peltophorum dubium						
Schumacher	10.4082	-1051.8			26.58	0.95
Chapman-Richards	42.0389	0.000055	0.8688		23.97	0.96
Clutter-Jones	52.7337	-3.858	-0.3189	4.9368	26.79	0.94
Prodan	-10654.3	296.9	0.0164		23.63	0.96
Mitscherlich	121.5000	0.9967	0.000023		23.76	0.81
Gompertz	14.7824	2.701	0.000562		24.11	0.96
Bailey 4P	14.3982	0.0318	0.506	3.4676	24.94	0.95
Schizolobium parahybae						
Schumacher	9.5564	-987			34.21	0.92
Chapman-Richards	30.5062	0.000016	0.5416		37.68	0.90
Clutter-Jones	26.279	-1.1519	-0.0418	0.9824	45.93	0.80
Prodan	-13475	296.4	0.0244		30.08	0.94
Mitscherlich	166.1000	0.997	0.000017		29.90	0.80
Gompertz	10.1216	2.5814	0.000793		30.15	0.94
Bailey 4P	10.2222	0.0001	1.175	0.9438	31.61	0.93

[a] CV = coefficient of variation; R^2_{aj} = adjusted coefficient of determination.

3.4.2 Comparison between model coefficients

The results of the likelihood ratio test performed for the three species for which the same model was selected (Chapman-Richards) are described in Table 3. Based on χ^2 statistic, the H_0 test was significant for combinations *Eucalyptus urophylla* x *Eucalyptus grandis* x *Parapiptadenia rigida* (EU x PR) and *Eucalyptus urophylla* x *Eucalyptus grandis* x *Peltophorum dubium* (EU x PD), demonstrating difference between equations in at least one parameter. Therefore, the common equation which estimates are presented in ω cannot be used. In the combination of PR x DP, the hypothesis of equality of model parameters in the two groups (complete model and reduced model) was not rejected, so the coefficients chosen were those present in ω.

Table 3

Estimating parameters of complete model (Ω) and reduced model (ω) of the combinations between species *Eucalyptus urophylla* x *grandis*, *Parapiptadenia rigida* and *Peltophorum dubium*; sum of squares residual of the regression (SSRR), number of degrees of freedom of the regression residue (DFRR); sampling N; statistical chi-square test: calculated values ($\chi^2_{calc.}$); degrees of freedom (DF) and descriptive test level (P value).

Parameters	Combinations					
	EU (a) x PR (b)		EU (a) x PD (b)		PR (a) x PD (b)	
	Ω	ω	Ω	ω	Ω	Ω
β_{0a}	26.1731		26.1731		43.7913	
β_{1a}	0.00078		0.00078		0.000053	
β_{2a}	1.3692		1.3692		0.8691	
β_{0b}	43.7913		42.0389		42.0389	
β_{1b}	0.000053		0.000055		0.000055	
β_{2b}	0.8691		0.8688		0.8688	
β_0		35.6397		16.2705		42.9151
β_1		0.000176		0.000624		0.000054
β_2		0.847		1.06		0.869
SQRR	1814.9	14865.4	1608.4	17700.1	1003.107	1003.9
DFRR	650	653	738	741	684	687
N	656		744		690	
$\chi^2_{calc.}$	1379.57		1784.35		0.55	
DF (χ^2)	3		3		3	
P ($\chi^2_v > \chi^2_{calc.}$)	1.46×10^{-12}		1.88×10^{-12}		0.91	

3.4.3 Estimating the height of tree species

To evaluate the change in growth specifically, tree height for the species studied, we plotted growth curves by using the models selected and coefficients generated (Figure 2). Comparatively, the *Eucalyptus urophylla* x *Eucalyptus grandis* species showed the best relationship between the observed and estimated values. We can observe that in different points in growth curve, the average of the observed values is distant from the estimated line growth, mainly due to reduction of the trees height after the occurrence of frost. This result is shown easier in other studied species.

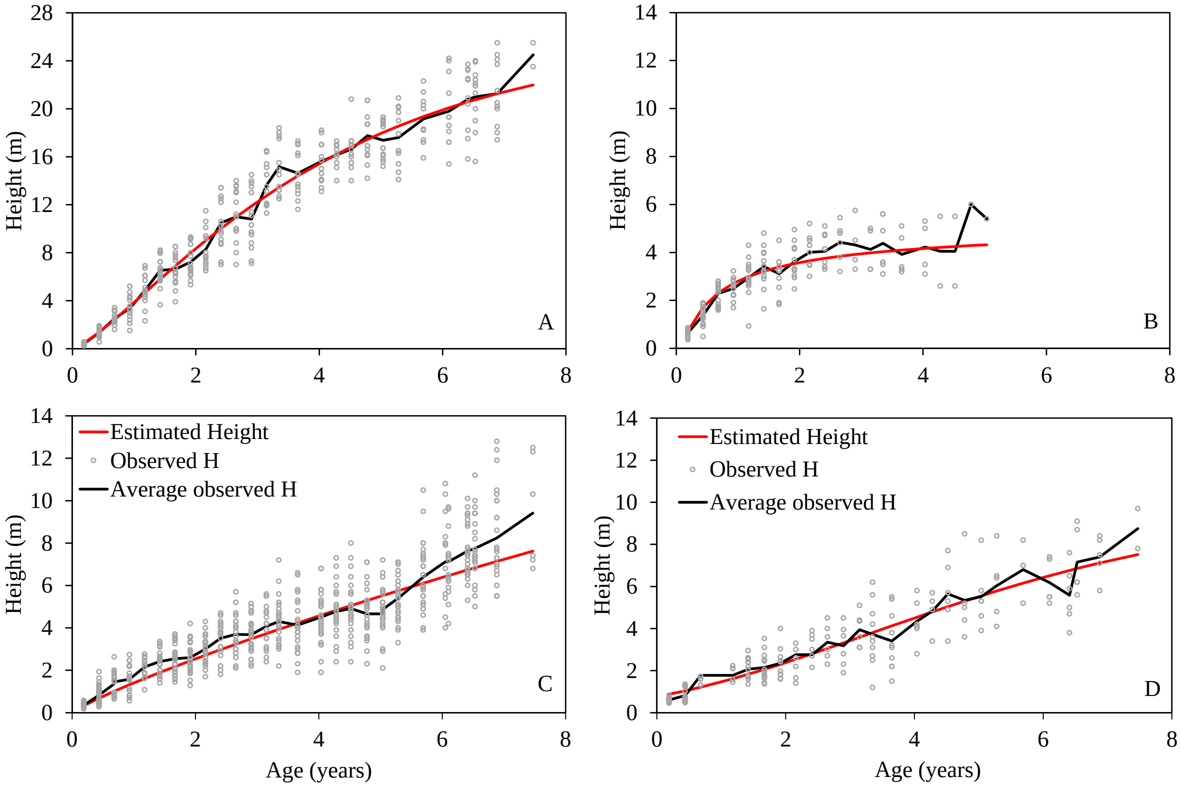

Fig. 2. Observed and estimated height growth values of tree species: *Eucalyptus urophylla* x *Eucalyptus grandis* (A), *Mimosa scabrella* (B), *Parapiptadenia rigida* and *Peltophorum dubium* (C) and *Schizolobium parahybae* (D) according to age.

3.4.4 Meteorological elements selected by Stepwise Multiple Regression

The weather variables, which occurred in the study site, are shown in Table 4 . We observed a wide variation of these elements over the years. We emphasize the irregularity of rainfall and the occurrence of absolute minimum temperature lower than zero. The inclusion of meteorological elements in the models aimed the approximation between observed and estimated mean values, demonstrating that the growth curve of trees does not only occur as a function of age.

Table 4

Mean temperature (Tmea), maximum (Tmax), minimum (Tmin), absolute minimum (Tminabs), absolute maximum (Tmaxabs), accumulated rainfall (Prec), along the seasons and accumulated solar radiation (Asr), from 2008 to 2014, in the city Frederico Westphalen, Rio Grande do Sul, Brazil.

Years	Seasons	Meteorological elements						
		Tmea °C	Tmax °C	Tmin °C	Tmaxabs °C	Tminabs °C	Prec mm	Asr MJ m^{-2}
2008	Summer	23.24	24.04	22.48	34.00	13.40	333.20	2034.08
	Autumn	16.73	17.47	16.00	31.80	-2.10	526.60	3245.71
	Winter	16.15	16.80	15.52	32.70	0.40	316.40	4396.92
	Spring	20.43	21.15	19.76	36.70	4.70	587.00	6309.70
2009	Summer	23.32	24.10	22.57	35.10	12.50	293.20	8311.97
	Autumn	18.12	18.92	17.34	33.80	-0.60	359.00	9620.18
	Winter	15.03	15.65	14.44	31.30	-2.70	671.60	10664.73
	Spring	21.19	21.86	20.56	35.90	5.60	730.00	12389.98
2010	Summer	24.07	24.80	23.39	35.70	13.60	478.80	14306.95
	Autumn	17.10	17.69	16.54	31.50	3.00	706.80	15377.76
	Winter	15.56	16.17	14.95	31.30	-1.80	312.60	16509.36
	Spring	19.68	20.44	18.96	33.10	6.70	589.80	18393.55
2011	Summer	23.39	24.11	22.73	33.36	13.10	464.20	20293.52
	Autumn	17.32	17.99	16.68	31.10	2.40	425.80	21481.79
	Winter	14.97	15.56	14.41	31.70	-2.60	892.80	22505.30
	Spring	20.67	21.47	19.89	34.70	8.50	436.80	24599.31
2012	Summer	24.57	25.47	23.71	37.00	13.30	252.40	26781.67
	Autumn	17.17	17.91	16.46	32.00	-2.20	295.80	28021.24
	Winter	17.16	17.82	16.51	35.70	0.90	328.40	29391.31
	Spring	21.57	22.31	20.85	34.80	2.30	598.00	31482.57
2013	Summer	22.39	23.10	21.71	35.90	11.50	573.60	33479.46
	Autumn	17.12	17.81	16.46	29.90	3.00	435.60	34911.44
	Winter	14.72	15.38	14.08	32.90	-1.80	520.60	36222.07
	Spring	20.78	21.50	20.10	34.10	5.60	510.80	38423.17
2014	Summer	23.89	24.66	23.14	36.70	12.30	556.80	40636.56
	Autumn	17.42	18.03	16.85	32.00	3.00	710.40	41978.62
	Winter	16.46	17.07	15.87	32.60	1.10	707.60	43298.17
	Spring	22.05	22.75	21.39	35.80	9.30	659.80	45403.82

The meteorological variables selected by stepwise method were as follows: Asr, Tmin and Prec for the *Eucalyptus urophylla* x *Eucalyptus grandis*, *Parapiptadenia rigida* e *Peltophorum dubium* species; Asr, Tmin, Prec and Tmea for *Mimosa scabrella*; Asr, Tminabs and Prec for *Schizolobium parahybae*. The very high or perfect correlation between independent variables took the presence of multicollinearity, as also observed by Neter and Wasserman (1974) and Sanquetta et al. (2014).

We identified this effect by high VIFs. In the presence of VIFs above 10, the coefficients associated with these values showed their estimates strongly influenced, negatively, by multicollinearity, as also observed by Mansfield and Helms (1982). In our study, the variables with high VIFs were A and Asr. For this reason, there was the exclusion of variable Asr. After that, the VIFs were adequate (≤ 10) and multicollinearity was considered weak in all carried selection methods.

3.4.5 The new models developed

After the inclusion of weather variables and the new fit of the nonlinear models, the parameters were tested for their significance by using t-tests. The models developed after this procedure and the species used in each model are shown in Table 5.

Table 5

Biological models modified after the inclusion of predictive variables that take into account the influence of meteorological elements on the height growth of tree species.

Species	Model	Number
E. urophylla x *grandis*	$h = \left(Prec^{\beta_0}\right)\left(Tmin^{\beta_1}\right)\beta_2(1- e^{-\beta_3 A})^{\left[(1-\beta_4)^{-1}\right]} + \varepsilon$	(28)
M. scabrella	$h = \left(Prec^{\beta_0}\right)\left(Tmin^{\beta_1}\right)\beta_2\ (1+\beta_3 A^{\beta_4})^{\beta_5} + \varepsilon$	(29)
P. rigida and P. dubium	$h = \left(Prec^{\beta_0}\right)\beta_1(1- e^{-\beta_2 A})^{\left[(1-\beta_3)^{-1}\right]} + \varepsilon$	(30)
S. parahybae	$h = \left(Prec^{\beta_0}\right)\left(Tminabs^{\beta_1}\right)\beta_2 e^{\left(-\beta_3\, e^{(-\beta_4 A)}\right)} + \varepsilon$	(31)

In which: h = height, in m; Prec = precipitation, in mm; Tmin = minimum temperature, in °C; Tminabs = absolute minimum temperature, in °C; β_0, β_1, β_2,β_3,β_4, and β_5 = model parameters; *e* = base of the natural logarithm; A = age, in months; ε = random error;

The new adjusted coefficients for each model are described in table 6.

Table 6

Fit statistics and coefficients obtained by adjusting four nonlinear models based on meteorological elements and the age, to describe the height growth of tree species: *Eucalyptus urophylla* x *Eucalyptus grandis* (A), *Mimosa scabrella* (C), *Parapiptadenia rigida* and *Peltophorum dubium* (B), and *Schizolobium parahybae* (D).

Species	Model	Coefficients						CV (%)[a]	$R^2_{aj.}$
		β_0	β_1	β_2	β_3	β_4	β_5		
A	(28)	0.0109	0.1028	17.8813	0.0008	1.3824		16.61	0.98
C	(29)	0.0431	0.0871	7.1046	-1.663	-0.1112	0.7324	25.74	0.95
B	(30)	0.2192	10.5684	0.000023	0.6399			31.17	0.93
D	(31)	-0.0424	1.0002	15.0384	2.579	-0.0007		31.60	0.94

In which: CV = coefficient of variation; R^2_{aj} = adjusted coefficient of determination.

From the new predictive variables generated, we visualized the evolution of the height of tree species along the time, under the influence of meteorological elements, as shown in Figure 3. The relationship and the Pearson correlation coefficient (r) between observed and estimated values are presented in figure 4.

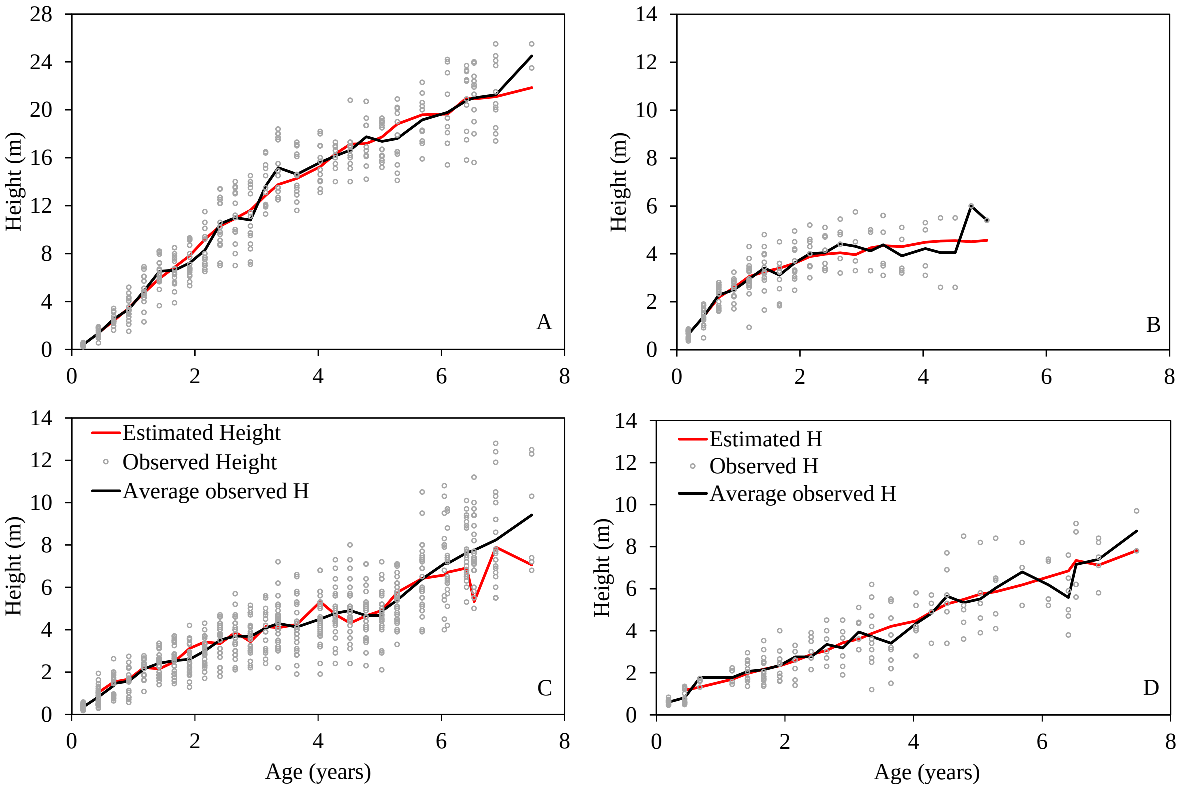

Fig. 3. Observed and estimated values of the height growth of tree species: *Eucalyptus urophylla* x *Eucalyptus grandis* (A), *Mimosa scabrella* (B), *Parapiptadenia rigida* and *Peltophorum dubium* (C), and *Schizolobium parahybae* (D), according to age and meteorological variables.

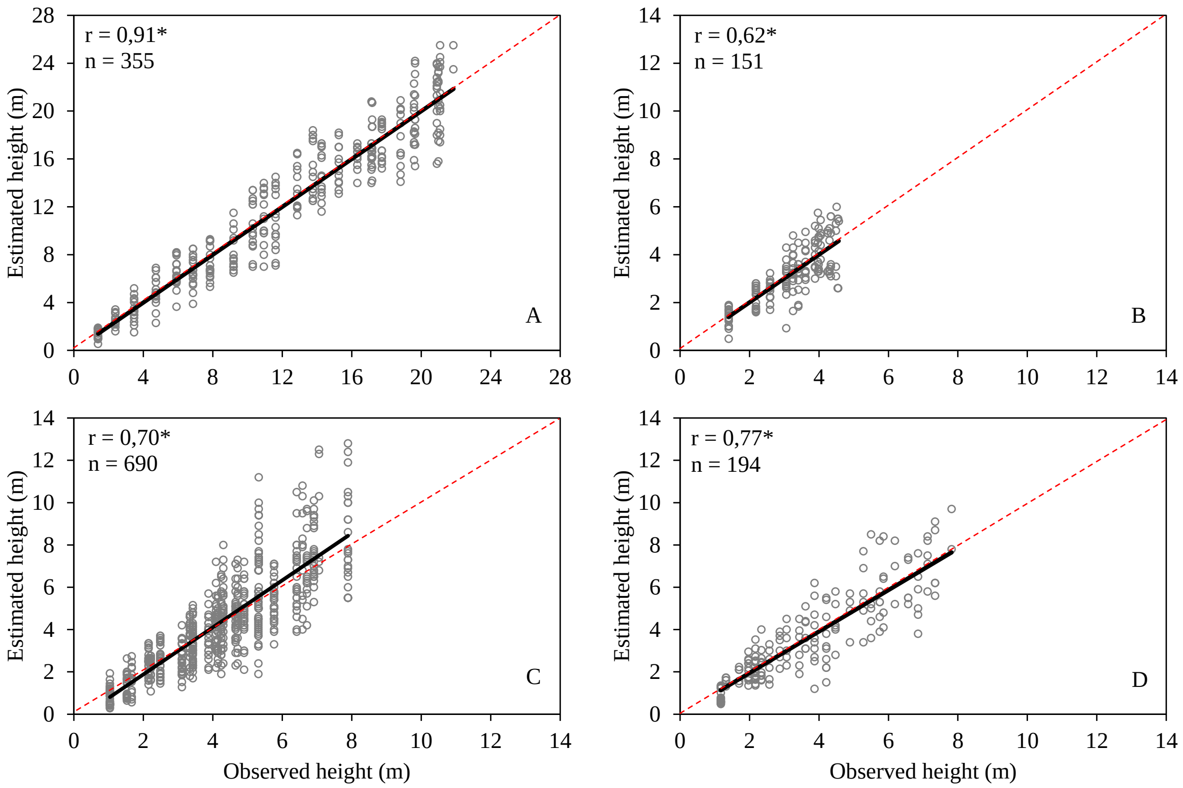

Fig. 4. Relationship between estimated and observed height of tree species: *Eucalyptus urophylla* x *Eucalyptus grandis* (A), *Mimosa scabrella* (B), *Parapiptadenia rigida* and *Peltophorum dubium* (C) and *Schizolobium parahybae* (D).

3.5 Discussion

The models selected to estimate the height growth of tree species were appropriate, and fit statistics showed satisfactory results. The Chapman-Richards model presented the best fit, as also observed by other authors (Rohner et al., 2013; David et al., 2014). Zeide (1993); one can justify the good fits this model due to its capacity to quantify ecological processes underlying the growth function.

After the development of biological models that take into account weather variables, we find an approximation of the estimated values to the observed values, compared to curves adjusted based on traditional nonlinear models (Figure 3). The adjusted determination coefficient values of the models were satisfactory and the coefficient of variation was acceptable (Table 6). In addition, a good consistency in the models can be viewed by the significance of the Pearson correlation coefficient (r) between observed and estimated values for all species (Figure 4).

We can observe that in all modified models, the selected weather variables were the minimum temperature and precipitation, and were therefore the factors that most influenced the tree growth. We can view the modification in the growth curve in Figure 5. In many points of the curve, variations are observed in plant height (Figure 5B) which are not identified in traditional nonlinear models (5A).

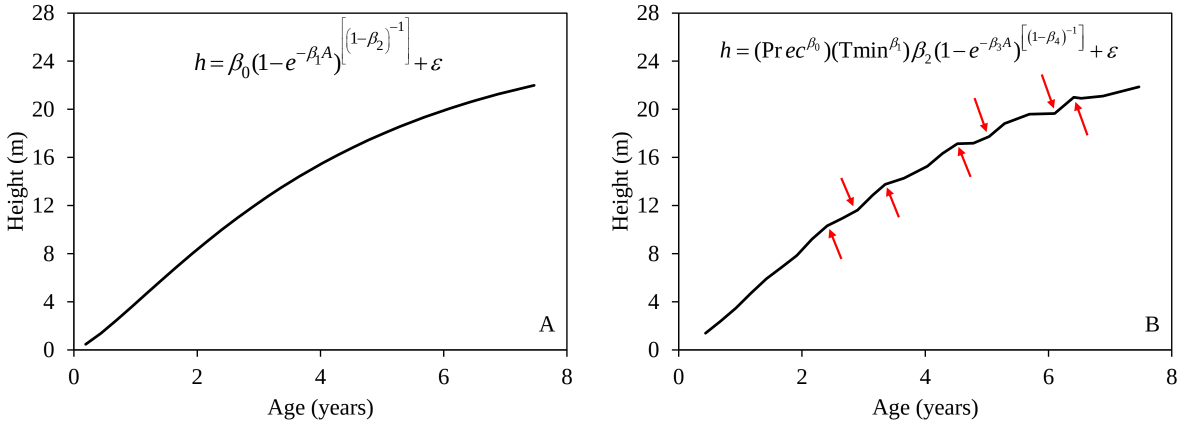

Fig. 5. Comparison between the height growth curves of *Eucalyptus urophylla* x *Eucalyptus grandis* determined by the Chapman Richards model (A) and a model that takes into account the age of the trees, rainfall and minimum temperature as curve estimators (B).

The damage of low temperatures on the trees may vary depending on sensitivity level of the species, plant age, type of plant structure or organ, intensity of minimum temperature and the occurrence and frequency of frost. This damage may occur as a reduction in the growth rate of plants or biomass loss of the stem apex and leaves. Hendrickson et al. (2004) found that minimum temperatures from 1 to 3 °C reduce 34-63% the growth rate of *Vitis vinifera*. Gatti et al. (2008) showed that low temperatures affect the photosynthetic rate of *Euterpe edulis*.

Wang et al. (2011) found that the occurrence of frost caused 31.3% defoliation of exposed shoots of *Kandelia ovata*. Augspurger (2011) found that there was a death of branches which reduced the canopy percentage, contributed to early senescence, and reduced growth and led to the death of *Aesculus glabra* yolks. Additionally, research shows that the occurrence of frost affects plant organs, (Luken, 1990) and their growth (Strain, 1966), survival (Mooney, 1977), reproduction (Inouye, 2008) and demographic distribution (Inouye, 2000).

The senescence of leaves and stems occurs due to the freezing of the extracellular solution. From this, an imbalance occurs between the chemical potential of intra and extra-cellular water, generating the process of water transfer until an equilibrium is again achieved. However, hydric transfer causes cellular dehydration, decreased cell turgor, solute accumulation and rupture of the plasma membrane (Heber and Santarius, 1973).

We performed a simulation to demonstrate the influence of different levels of minimum temperature occurring in winter and different annual rainfall regimes, on the height growth of forest species (Figure 6).

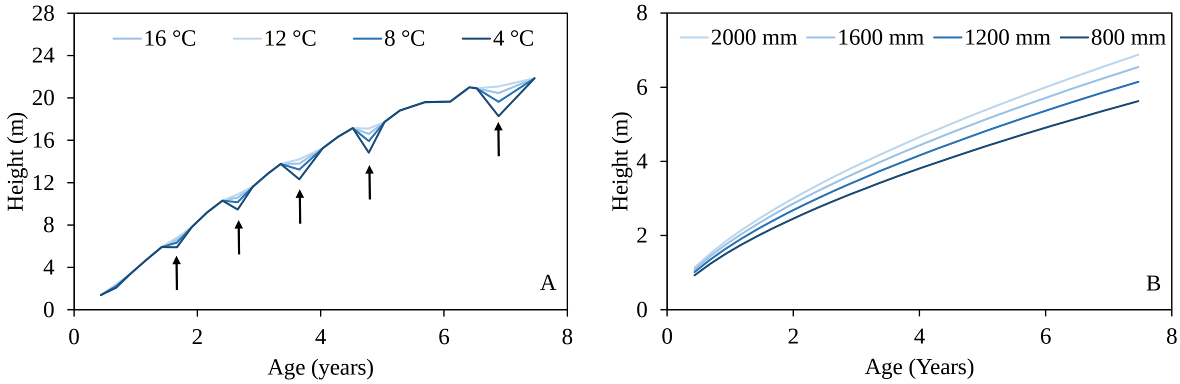

Fig. 6. Simulating height growth of *Eucalyptus urophylla x Eucalyptus grandis* at different levels of minimum temperature (A), using the model $h = \left(Prec^{\beta_0}\right)\left(Tmin^{\beta_1}\right)\beta_2\left(1-e^{-\beta_3 A}\right)^{\left[(1-\beta_4)^{-1}\right]} + \varepsilon$; *Parapiptadenia rigida* and *Peltophorum dubium* (B) at different annual rainfall regimes (B) through the model $h = \left(Prec^{\beta_0}\right)\beta_1\left(1-e^{-\beta_2 A}\right)^{\left[(1-\beta_3)^{-1}\right]} + \varepsilon$. Black arrows represent the damage due to frosts in winter.

In the case of rainfall, the simulation reveals that higher rainfall regimes provide positive results in the growth of tree species. The results are consistent with Sanquetta et al. (2015), which verify that the growth of *Acacia mearnsii* depends of available water content in the soil.

Morales et al. (2004) found high correlation between precipitation and the growth of the species *Juglans australis*, *Alnus acuminata*, *Prosopis ferox* and *Polylepis tarapacana*. Dünisch et al. (2003) and Grogan and Schultz (2012) showed this same result with the *Swietenia macrophylla* species. Allen and Albaugh (1999) reported that low water availability and extreme temperatures negatively affect the leaf area and the interception and use of solar radiation in *Pinus taeda*, influencing their overall growth.

The water availability in the soil directly affects the transpiration rate, stomatal conductance, and photosynthesis (Schippers et al., 2015), because the opening and closing of stomata are controlled by soil water potential. The absence of water stress allows increased internal CO_2 concentration in the leaves due to greater stomatal conductance, increasing the photosynthetic rate (Lloyd and Farquhar, 2008; van der Sleen et al., 2014). This information shows consistency with the results of this work and with the meteorological variables selected in the proposed models.

3.6 Conclusions

The Chapman Richards, Clutter-Jones and Gompertz models were more flexible in representing the growth of the species: *Eucalyptus urophylla* x *Eucalyptus grandis, Parapiptadenia rigida*, *Peltophorum dubium*, *Mimosa scabrella* e *Schizolobium parahybae*.

The new models demonstrate that the growth curve of tree species is influenced by meteorological elements, especially the minimum temperature and rainfall, proving the hypothesis established in this study.

With the obtained models, in which the estimators are dependent on some meteorological elements, along with the age of plants, it is possible to perform the growth simulations of tree species, ahead of changing weather conditions; these determinations can be very important for the achievement of adequate management of forests.

3.7 Acknowledgements

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Supplementary material: residual analysis.

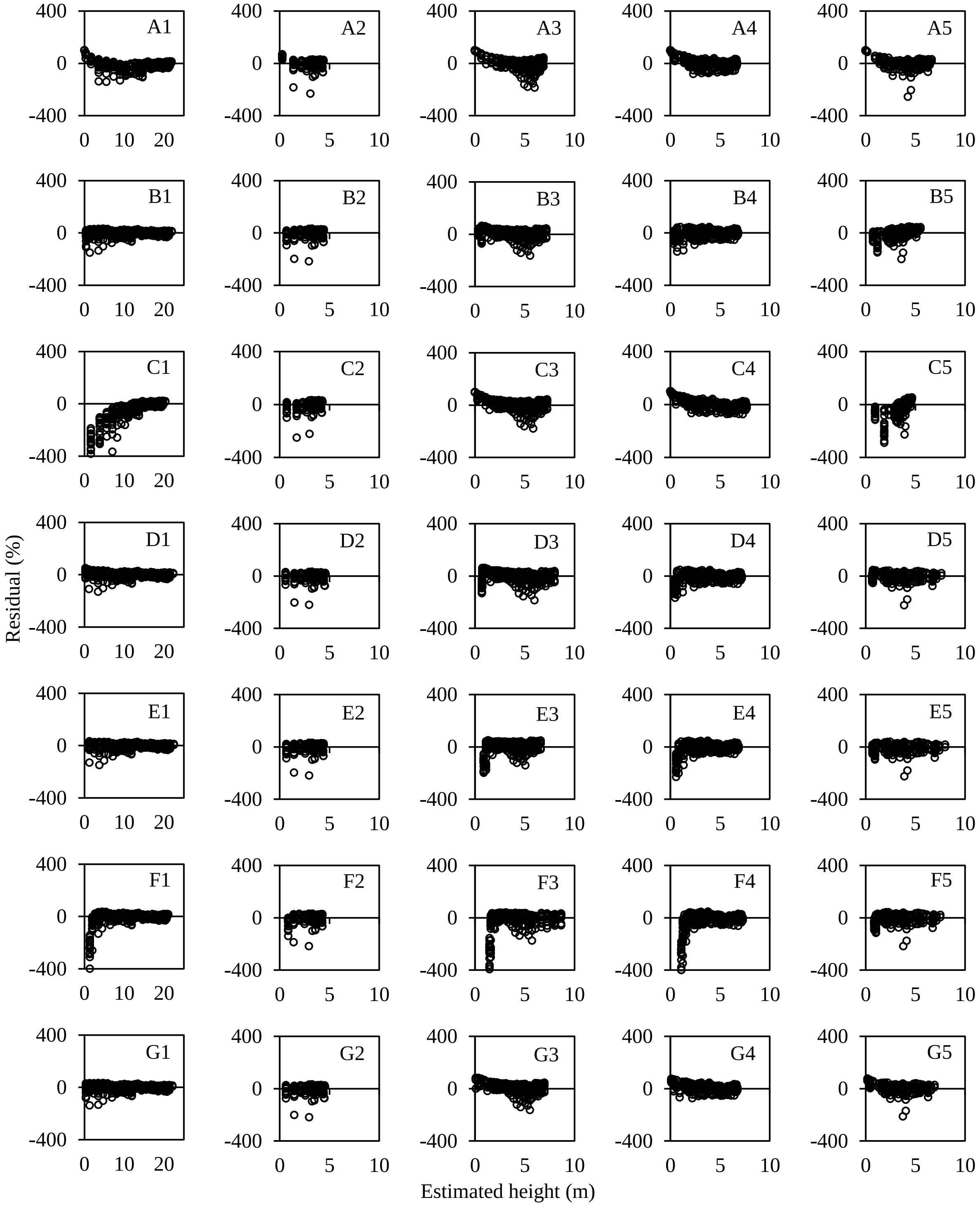

Fig. 7. Residual distribution (%) obtained by fitting of the models: Schumacher (A) Chapman-Richards (B), Clutter-Jones (C), Prodan (D), Mitscherlich (E), Gompertz (F), and Bailey of 4 parameters (G) in order to describe the height growth of species *Eucalyptus urophylla* x *Eucalyptus grandis* (1), *Parapiptadenia rigida* (2), *Peltophorum dubium* (3), *Mimosa scabrella* (4) and *Schizolobium parahybae* (5) dependent upon the age of the plants.

Supplementary material: residual analysis.

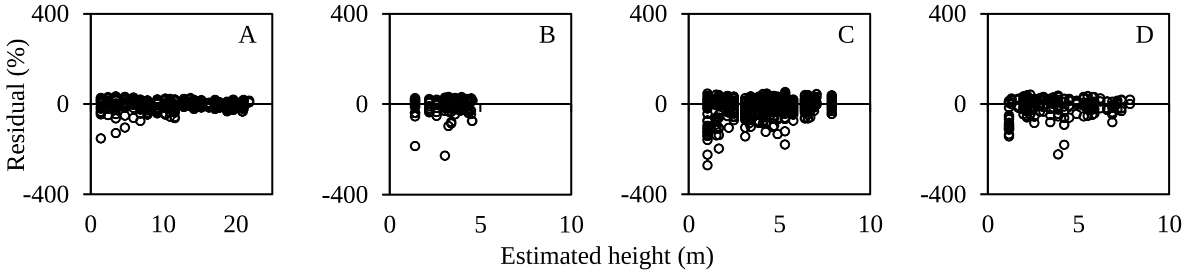

Fig. 8. Residual distribution (%) obtained by the fitting of models: $h = (Prec^{\beta_0})(Tmin^{\beta_1})\beta_2(1 - e^{-\beta_3 A})^{[(1-\beta_4)^{-1}]} + \varepsilon$ for *Eucalyptus urophylla* x *Eucalyptus grandis* (A); $h = (Prec^{\beta_0})(Tmin^{\beta_1})\beta_2\,(1+\beta_3 A^{\beta_4})^{\beta_5} + \varepsilon$ for *Mimosa scabrella* (B); $h = (Prec^{\beta_0})\beta_1(1 - e^{-\beta_2 A})^{[(1-\beta_3)^{-1}]} + \varepsilon$ for *Parapiptadenia rigida* and *Peltophorum dubium* (C); $h = (Prec^{\beta_0})(Tminabs^{\beta_1})\beta_2 e^{(-\beta_3\, e^{(-\beta_4 A)})} + \varepsilon$ for *Schizolobium parahybae* (D) in order to describe the height growth depending on the age of plants and meteorological elements.

4 ARTIGO III - PRODUCTIVE, MORPHOLOGICAL AND QUALITATIVE CHARACTERISTICS OF SUGARCANE IN THE UNDERSTORY TREE SPECIES IN AGROFORESTRY SYSTEMS

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Productive, morphological and qualitative characteristics of sugarcane in the understory tree species in agroforestry systems

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4.1 ABSTRACT

This study aimed to evaluate productive, morphological and qualitative characteristics of sugarcane in the understory tree species in two agroforestry systems. The study was conducted in the city of Frederico Westphalen, RS, in a randomized complete block design, characterized by a factorial arrangement of 2x5x3, i.e. two agroforestry systems (strip and line), five tree species (angico bracatinga, canafístula, eucalypt and guapuruvu) and three years of sugarcane cultivation (2009, 2010 and 2011), with three replications. The weight, length and stem diameter, number of nodes, Brix degree, juice volume, amount of sucrose, and how these factors related to the interception of photosynthetically active solar radiation by the tree components in each system were evaluated. The interception of photosynthetically active solar radiation by tree components is smaller in the strip system, but increased over the years of sugarcane cultivation. Among the tree species, eucalypt is responsible for the greatest values of interception. When grown in the understory of angico, bracatinga and canafístula, sugarcane presents greater length, diameter and stem weight, juice volume and amount of sucrose, mainly from the second cultivation year than when under the other tree species. The cultivation of sugarcane in the strip system resulted in an increased of stem weight and juice volume from the second year of cultivation.

Key words: *Saccharum officinarum* L.; solar radiation; shading; stem weight.

4.2 INTRODUCTION

One of the biggest challenges of agriculture in Brazil is managing the balance between crop production and environmental preservation. In order to achieve this balance, it is necessary to meet the demand for food and energy without compromising existing agro-ecosystems (Godfray et al., 2010). Agroforestry systems deserve highlight in this scenario and are a promising strategy, which can be used in order to achieve these objectives. These systems may consist of integrated use of land for forestry purposes, crops, and livestock. This integration has brought numerous socio-economic, environmental and production benefits, such as the recovery of degraded areas, reducing production costs, and an increased input of organic matter, which has been to seen to improve chemical, physical, and biological properties of soil (Tracy; Zhang, 2008; Neves et al., 2009; Salton et al., 2013).

The insertion of sugarcane (*Saccharum officinarum* L.) in agroforestry systems can be an interesting alternative, due to its socio-economic importance in Brazil; in addition, the monoculture system is predominant for this culture and because of this predominance, it is becoming increasingly important to consider alternative production systems, which aim to preserve natural resources. These systems can provide an alternative to the cultivation of sugarcane in areas unsuited to mechanized harvesting, and considering ecological, agronomic and socioeconomic aspects such methods may be more ideal for family farmers who may have small area of cultivation as an alternative source of income.

The growth and development of different species in the same area, such as in agroforestry presupposes the existence of dynamic interactions and change over time especially in areas which include trees; given their continued growth in height, crown projection, and the leaf area index, which can modify the distribution of existing resources. These tree interactions can be a source of a constant change in the productivity of both species system (José; Gillespie; Pallardy, 2004).

Solar radiation, which is to be intercepted by the canopy of the arboreal components of these agroforestry systems can be absorbed, transmitted, and reflected in varying proportions depending on the angle of incident sunlight and structural features of plants. The spatial arrangements of plants can include the arrangement of the leaves, leaf insertion angle, leaf area index, and various optical properties of vegetation. The radiation transmitted by the canopy is only available to plants beneath the canopy, and can be propagated in a direct or diffuse way. The interactions of the transmitted solar radiation influence the internal microclimate of intersystem vegetation, which can have an affect the on the morphological, physiological and nutritional aspects of this species in the understory, thereby affecting growth (Paciullo et al., 2011; Mendes et al., 2013).

The study aimed to evaluate productive, morphological, and qualitative characteristics of sugarcane and relate them to the interception of photosynthetically active solar radiation in the understory of five tree species in two arrays of planting in agroforestry systems.

4.3 MATERIALS AND METHODS

The study was conducted in the experimental area belonging to the Agroclimatology Laboratory, linked to the Federal University of Santa Maria campus in the city of Frederico Westphalen, Rio Grande do Sul State, Brazil, with geographical location at 27°22’S, 53°25’W at 480m of altitude. According to the Köppen climate classification, the climate is Cfa, i.e. humid subtropical with average annual temperature of 19.1 °C, varying with maximum 38 °C and minimum of 0 °C. The soil of the area is classified as typical Entisol Orthents (Cunha, 2011). The values of soil chemical properties were: pH in water = 5.8; available phosphorus (Mehlich^{-l}) = 2.9 mg dm^{-3}; aluminum = 0.0 cmol$_c$ dm^{-3}; potassium = 82.5 mg dm^{-3}; calcium = 8.7 cmol$_c$ dm^{-3} and magnesium = 2.8 cmol$_c$ dm^{-3}. Fertilization was performed according to the recommendations made by the CQFS (CQFS, 2004).

The experimental design was a randomized complete block design, characterized by a factorial arrangement of 2x5x3, i.e. two agroforestry systems, strip and line, five tree species, angico (*Parapiptadenia rigida* (Benth.), bracatinga (*Mimosa scabrella* Benth.), canafístula (*Peltophorum dubium* (Spr.) Taubert), eucalypt (*Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden) and guapuruvu (*Schizolobium parahybae* (Vell.) Blake) and three years of sugarcane cultivation. The first evaluation of sugarcane occurred in 2009, the second in 2010, and a third in 2011, cultivar IAC 87-3396. In each repetition, ten experimental units were randomly assigned to the combination between agroforestry system and tree species.

Forest species were planted in the field in September and the sugarcane in November 2007; the process occurred through the manual planting of seedlings and cuttings, after plowing and harrowing. In the strip system (SS), the forest species were divided into separate strips by 12m, each was composed of three lines, in which the plants were spaced at 3x3m. The sugarcane was distributed in six lines (between strips, 12m in space) and two lines in strips (between lines of trees). In the line system (LS), forestry species were distributed at 6x1.5m spacing, or 6m between lines and 1.5 m between plants in the line, and the sugarcane distributed in three lines (among lines of trees).

In both systems, the sugarcane had 1.20 m spacing and a density of 18 buds per meter, with both trees and sugarcane oriented in lines towards the East and West. After planting sugarcane, plots were delineated to have two meters in length, and were distributed at different points in the understory of each experimental unit. These plot areas were chosen with the intention to represent existing microclimate conditions in the areas under the canopy of each tree species and agroforestry system. For subsequent analysis of the data, average values of the lines in each system were calculated in order to comply with objectives of the study, which is the recommendation of the best system and species in different years of assessment. The arrangement of trees, sugarcane and plot of evaluation are shown in Figure 1.

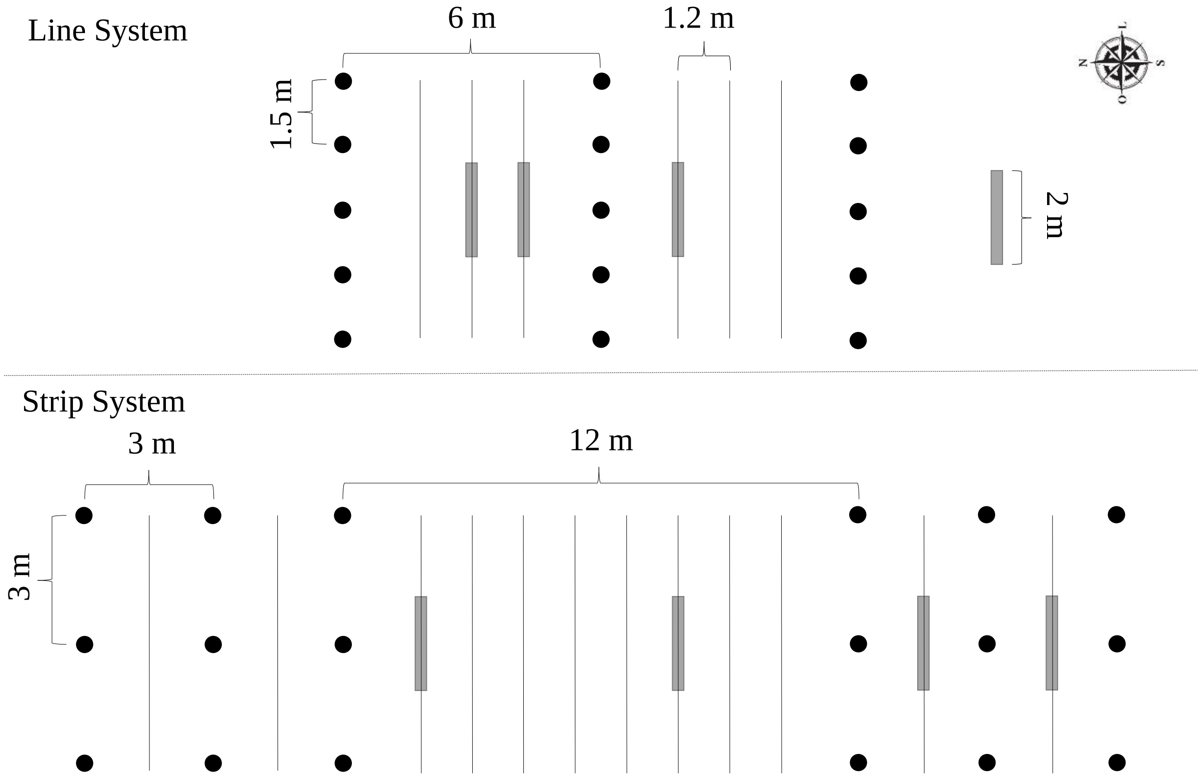

Figure 1. A sketch of an experimental unit of line and strip systems. Black circles represent the trees; continuous lines indicate where the sugarcane was planted, and the rectangles in gray represent the annual evaluation plots of sugarcane.

The samples were collected in June 2009 (about one and half years after planting), 2010 and 2011, constituting the three years of sugarcane. In each marked line, we collected two medium stalks which were taken to the laboratory for evaluation. For the existing population in the experimental units, values were extrapolated for one hectare (ha).

The stalk weight (SW, t ha^{-1}) was obtained with the aid of a digital scale and stalk length (SL, m) by means of a measuring tape, the length being considered from the basal portion to the intersection of the youngest leaf sheath. The stalk diameter (SD, mm) was determined by measuring three points in the same basal medium and higher, and then the arithmetic means were obtained. The number of nodes (NN) was obtained by the total count of nodes in each stem of evaluation.

The juice volume (JV, m^3 ha^{-1}), was obtained from milling the stalk, and was measured with the aid of a graduated cylinder with a capacity of 1 L. By JV, samples were taken to determine the Brix degree by means of an automatic digital refractometer Acetec RDA 8600. The sucrose concentration (SC, g L^{-1}) was determined using the equation proposed by Torres Neto et al. (2006):

$$SC = \text{Brix degree} \times 10.13 + 1.445 \qquad (1)$$

Wherein: SC = sucrose concentration (g L^{-1});

The sucrose quantity (S, t ha^{-1}) was determined from the values of SC and JV, by the following expression:

$$S = SC \times JV / 1000 \qquad (2)$$

Wherein: S = sucrose quantity (t ha^{-1}); SC = sucrose concentration (g L^{-1}); JV = juice volume (m^3 ha^{-1}).

Photosynthetically active radiation (PAR) was obtained at harvest over the three years of evaluation, with the aid of a quantum sensor LI-190-1, with spectral strip of 400-700 nm, coupled to a porometer dynamic balance LICOR-LI1600 model. From this, the interception of photosynthetically active radiation was determined (IPAR) by canopy tree species, according to the equation proposed:

$$\% \, IPAR = [100 - (Rn \times 100/Rt)] \qquad (3)$$

Wherein: Rn = photosynthetically active radiation inside the canopy of the tree species; R_t = photosynthetically active radiation inside the canopy of the tree species;

The height values (H), diameter at breast height (DBH) and average crown diameter (MDC) of forest species at harvest of each year of sugarcane cultivation were collected for characterization purposes of the conditions existing in the experimental area (Table 1). They were obtained with the aid of a Hypsometer Vertex III, tape measure and graduated tape, respectively.

Table 1. Height (H), diameter at breast height (DBH) and mean diameter of crown (MDC) of forest species at harvest of each year of sugarcane cultivation, in agroforestry systems strip and line.

Variable	Species	Years					
		2009		2010		2011	
		Strip	Line	Strip	Line	Strip	Line
H (m)	Angico	2.42	2.19	3.56	4.01	3.58	3.56
	Bracatinga	3.24	3.00	4.04	4.06	3.78	5.60
	Canafístula	2.40	2.27	3.60	3.14	4.29	4.82
	Eucalypt	6.82	6.24	10.90	10.14	15.34	14.06
	Guapuruvu	1.75	1.96	2.62	4.03	3.18	4.58
DBH (cm)	Angico	1.61	1.54	2.80	3.21	3.71	4.58
	Bracatinga	2.53	2.41	4.14	3.30	3.43	4.57
	Canafístula	2.05	1.94	4.35	3.82	4.71	4.88
	Eucalypt	6.83	5.20	12.35	9.31	16.64	12.16
	Guapuruvu	3.00	3.94	6.37	8.91	6.15	8.42
MDC (m)	Angico	0.99	0.65	1.5	1.25	2.34	1.74
	Bracatinga	1.56	1.36	1.58	1.95	1.62	1.98
	Canafístula	1.10	1.00	1.35	1.22	1.86	1.75
	Eucalypt	2.79	2.11	3.08	2.74	4.67	4.16
	Guapuruvu	1.98	1.90	2.48	1.64	2.74	2.95

The values of meteorological elements during the experiment were obtained from the Climatological Station INMET (National Institute of Meteorology) linked to Agroclimatology Laboratory (UFSM), which is located about 1500 m from the study site at coordinates 27 ° 39'S and 53 ° 43'W. The data was statistically analyzed with the software “*Statistical Analysis System*” (SAS, 2003), and results were obtained through the analysis of variance, F test, and Tukey test ($p > 0.05$). The Bartlett test was used to verify the homogeneity of variances.

4.4 RESULTS AND DISCUSSION

Average monthly minimum and maximum temperature, monthly accumulation of precipitation and solar radiation during the conduct of study are shown in Figure 2. The annual average minimum and maximum temperatures were 18.5 and 19.9 in 2008; 18.7 and 20.1 in 2009; 18.4 and 19.8 in 2010; 18.4and 19.8 °C in 2011. The cumulative annual rainfall for these respective years was 1606.20; 2246.60; 1978.40 and 2229.40 mm. The accumulated global radiation flux averaged 513.4; 501.1; 504.9; 516.2 MJ m^{-2} $month^{-1}$ in 2008, 2009, 2010 and 2011, respectively. These values varied in the same order, from 265.6 to 806.6; 302.7 to 722.1; 275.92 to 717.9 and 258.9 to 808.5 MJ m^{-2} $month^{-1}$.

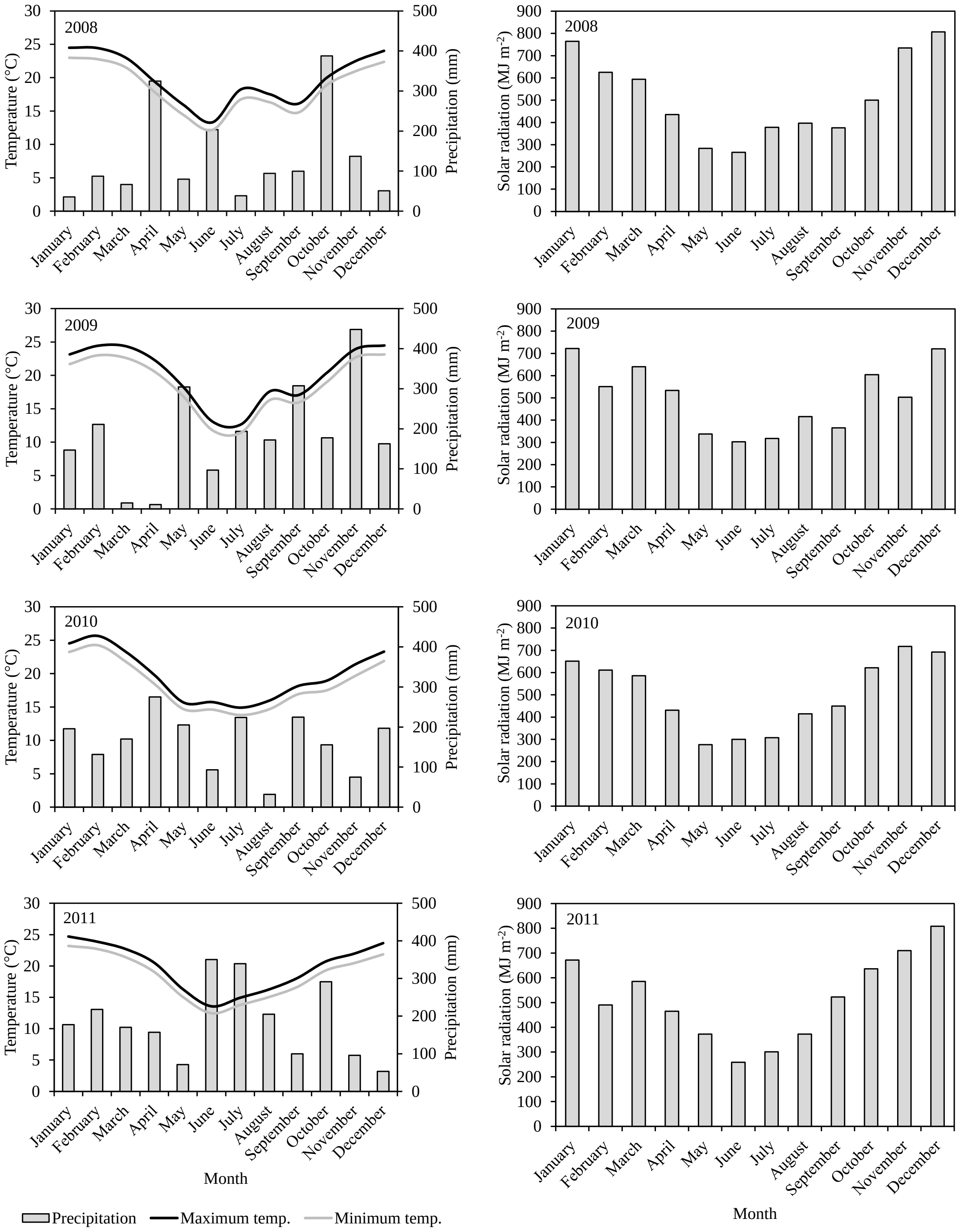

Figure 2. Average monthly maximum, minimum temperature; precipitation and cumulative monthly global solar radiation during the years 2008, 2009, 2010 and 2011 in the city of Frederico Westphalen, Rio Grande do Sul State, Brazil, for the entirety of the study.

The analysis of variance revealed differences in the IPAR, SL, SD, SW, JV and S for interactions between tree species x year of sugarcane cultivation and IPAR, SW and JV for agroforestry system x year of sugarcane cultivation. All tree species showed an increase of IPAR over the growing year of sugarcane (Table 2), except bracatinga, where values between 2010 and 2011 showed no difference.

Table 2. Interception of photosynthetically active radiation (IPAR), stem length (SL), stem diameter (SD), stem weight (SW), juice volume (JV) and amount of sucrose (S) of sugarcane grown in the understory of various tree species from 2009 to 2011, in the city of Frederico Westphalen, Rio Grande do Sul State, Brazil,

Variable	Species	Years of sugarcane cultivation		
		2009	2010	2011
IPAR (%)	Angico	27.02 ^{dC}	40.46 ^{cB}	46.43 ^{eA}
	Bracatinga	46.67 ^{cB}	56.41 ^{bA}	58.74 ^{dA}
	Canafístula	50.98 ^{bC}	68.81 ^{aB}	73.3 ^{bA}
	Eucalypt	56.41 ^{aC}	65.06 ^{aB}	89.74 ^{aA}
	Guapuruvú	47.78 ^{bcC}	55.23 ^{bB}	67.66 ^{cA}
SL (m)	Angico	1.51 ^{aA}	1.74 ^{aA}	1.52 ^{bA}
	Bracatinga	1.22 ^{bB}	1.78 ^{aA}	1.81 ^{aA}
	Canafístula	1.19 ^{bB}	1.63 ^{aA}	1.56 ^{abA}
	Eucalypt	1.24 ^{bA}	1.25 ^{bA}	1.20 ^{cA}
	Guapuruvú	1.27 ^{bB}	1.64 ^{aA}	1.30 ^{bcB}
SD (mm)	Angico	21.97 ^{aA}	20.95 ^{abA}	20.68 ^{bA}
	Bracatinga	19.37 ^{bB}	23.35 ^{aA}	23.31 ^{aA}
	Canafístula	19.44 ^{bA}	20.34 ^{bA}	21.14 ^{abA}
	Eucalypt	19.80 ^{bA}	17.09 ^{cB}	18.55 ^{cAB}
	Guapuruvú	20.53 ^{abA}	19.41 ^{bcAB}	18.19 ^{cB}
SW (t ha^{-1})	Angico	61.89 ^{aA}	53.08 ^{aA}	41.56 ^{abB}
	Bracatinga	26.56 ^{cB}	50.44 ^{aA}	50.52 ^{aA}
	Canafístula	30.44 ^{bcA}	36.19 ^{bA}	35.26 ^{bA}
	Eucalypt	30.48 ^{bcA}	14.81 ^{cB}	15.20 ^{cB}
	Guapuruvú	36.42 ^{bA}	36.25 ^{bA}	18.04 ^{cB}
JV (m^{3} ha^{-1})	Angico	30.11 ^{aA}	25.77 ^{aA}	19.68 ^{abB}
	Bracatinga	15.34 ^{bB}	24.97 ^{aA}	25.10 ^{aA}
	Canafístula	16.59 ^{bA}	16.60 ^{bA}	17.06 ^{bA}
	Eucalypt	17.45 ^{bA}	5.94 ^{cB}	6.80 ^{cB}
	Guapuruvú	18.74 ^{bA}	17.11 ^{bA}	7.37 ^{cB}
S (t ha^{-1})	Angico	5.05 ^{aA}	4.88 ^{aA}	3.79 ^{abA}
	Bracatinga	2.32 ^{bB}	4.75 ^{abA}	4.94 ^{aA}
	Canafístula	2.76 ^{bA}	3.28 ^{bA}	3.24 ^{bA}
	Eucalypt	2.39 ^{bA}	1.09 ^{cA}	1.27 ^{cA}
	Guapuruvú	2.86 ^{bAB}	3.46 ^{abA}	1.26 ^{cB}

Means followed by the same letter, lowercase in column compare the species in each year and uppercase letters in each line compare the years for each species, the means do not differ among themselves by Tukey test of probability at 5% of error.

Comparing all of the species, eucalypt was responsible for the higher values in 2009 and 2011, and did not differ from canafístula in 2010. Angico had the lowest percentage of IPAR in the first two years (2008 and 2009). Bracatinga had the lowest percentages if IPAR in the third year. These variations are related to an increase of the MDC of tree species (Table 1) which increased leaf area and intercept a larger quantity of solar radiation. Similarly, for bracatinga, this small variation in IPAR was influenced by reduced growth in MDC from 2010 to 2011.

The IPAR values are similar to those found by Caron et al. (2012) in between planting lines of from 42.3% in black wattle, 83.2% in bracatinga and 89.1% in eucalypt trees with one year old. In the case of agroforestry systems, the amount of radiation intercepted by the tree component can be considered a determining factor of their deployment in the understory since the radiation transmitted inside the canopy of tree plants should be sufficient for your growth and development. The evaluation of dynamic radiation of forestry species and systems is not a widespread practice in scientific circles yet. Another study was carried out by Pezzopane et al. (2015) and Bosi et al. (2014) reported on high relation between levels of incident solar radiation, and its effect on microclimate, growth characteristics of plants and soil moisture in areas with high rations

During crop cycles, there is an increase in the overall radiation interception, followed by an increase in leaf area index (LAI), but only up to a certain value when full canopy closure is reached, due to leaf self-shadowing (Posada et al., 2012). At this point, the issue of new leaves does not result in an increased amount of light interception. In the case of this study, it can be noted that, maximum IPAR may not be present for up to four years after planting since there was an increase of this variable every year, without stabilization trend (Table 2).

The response of plants to shade varies depending on the species, and the degree of shading. According to Varella et al. (2010), percentages of transmission below 50% can harm the growth and development of fodder of temperate climate. Bosi et al. (2014) found that silvopastoral systems with native trees, indicated shading greater than 39% which affected the productivity of the species *Urochloa decumbens*. Baruch and Guenni (2007) stated that shading levels above 35-40% can affect the growth of most tropical grasses.

The SL of sugarcane when grown in the understory of angico, canafístula and eucalypt remained stable over the cultivation years (Table 2). Under bracatinga, higher means were found in the past two years. The angico understory showed higher SL values in the first year, probably due to reduced IPAR (27.0%) compared to other species. In the second year, this difference was not observed; instead, in the third year only lower averages were observed in the cultivations located in the understory of eucalypt and guapuruvu. According to Abreu et al. (2007) values were found of 1.80; 1.70; 1.88; 1.92; 1.87 e 1.85 m for the cultivations IAC 86-2210, IAC 86-2480, IAC 93-6006, SP 81-3250, IAC 87-3396, RB 72-454, respectively, in the city of Barbacena / Minas Gerais, 15 months after planting.

Similarly, one can observe a reduction in SD from 2010 for the understory of Eucalypt and guapuruvu, and similar medians for angico and canafístula, respectively between the years (Table 2). In this context, Guiselini et al. (2013) analyzed the acclimation of sugarcane seedlings in greenhouse under two types of shading screens, found a limitation of SL and SD of the sugarcane when grown in an environment with less availability of solar radiation. This feature was not observed in bracatinga understory, where levels were higher in the last two years.

Cultivations grown under eucalypt negatively affected SW in the second year of cultivation, as compared with the first, where SW was not effected as strongly (Table 2). In addition, for in bracatinga understory, even with increasing solar radiation over the years and an increase in tree components’ crown diameter, SW increased in the second and third cultivation year (Table 1). Abreu et al. (2013), working with five varieties of sugarcane, found the following SW averages: 89 t ha^{-1} in first year, 75 t ha^{-1} in second year and 88 t ha^{-1} in the third year in Tabuleiros Costeiros / Alagoas. Neto et al. (2006) found mean values of 64.5 t ha^{-1} for cultivating SP79-1011 in first year in the city of Capim/Paraíba. The values recorded in the aforementioned article are higher than those found in this study; however, this may be due to the variety used, the site of cultivation, weather conditions occurring in each cultivation cycle and, in this case, the amount of radiation available for the sugarcane cultures.

This last factor can be observed in this study, where the SW of sugarcane when cultivated under the eucalypt in the third cultivation year (15.2 t ha^{-1}) was decreased by 63.4% when compared to the angico (41.6 t ha^{-1}) and 69.9% as bracatinga (50.5 t ha^{-1}); whereas IPAR values in this cultivation year were 89.7% for eucalypt, 46.4% and 58.7% for the angico and bracatinga, respectively. This reduction in the SW of sugarcane may due to the fact that morphophysiological adjustments, as to shade tolerance strategy, were not able to compensate the radiation reduction in Eucalypt understory conditions (Paciullo et al., 2011). By comparing the species, it can be seen that SW values were higher in the cultures under angico in the first cultivation year. In the second and third years, this characteristic was observed to be greater for both angico and bracatinga (Table 2).

The JV of sugarcane grown under the angico and guapuruvu remained stable until the second cultivation year (2010), and were subsequently decreasing (Table 2). This decrease was also observed in the second year for eucalypt; however, an opposite behavior was seen in the understory of bracatinga whose JV values increased from the second year and remained similar in the third year. In the analysis between species found higher means in cultivation under angico in the first year and, under angico and bracatinga in the second and third year. In third year, intermediate values were observed under canafístula and lower under the eucalypt and guapuruvu.

The average S showed no difference over the cultivation years in the understory of tree species angico, eucalypt and canafístula (Table 2). This result indicates greater stability in the metabolic activity of sugarcane when subjected to shading. In this regard, Caron et al. (2014) found that the production of *Ilex paraguariensis* (leaves + branches) is higher in unshaded cultivations when compared to shaded cultivations. Taking into account the content of some nutrients (calcium, magnesium and phosphorus) in these plant, minor variations were observed in low light conditions (85% shading) for different times of the year which may indicate a more constant level of metabolic activity of the studied plants, and be considered an important factor in the final product quality.

The S of sugarcane in the understory of bracatinga was higher in the last two years, since when grown under guapuruvu, the highest averages were found in the second year, even with the IPAR of 55.2%. In the third year, the S values declined, since the IPAR increased to almost 70%. It can be seen that both the highest values of treatment with guapuruvu were seen in the second year, and for bracatinga in the last two years, the radiation interception remained in the range of 55-60%. In this respect, Paciullo et al. (2011) found that the shading caused a positive effect on crude protein species *Urochloa decumbens* grown in the understory of *Acacia mangium*, *Acacia angustissima*, *Mimosa artemisiana* and *Eucalyptus grandis.*

Another important aspect to be emphasized is that the lower amounts of solar radiation inside the canopy, due to the interception of it through the canopy, may have been offset by the increase of diffuse radiation in this environment. This fraction of the radiation has the characteristic of being multidirectional and better penetrate inside the canopy (Buriol et al., 1995), promoting more efficient use of solar radiation. However, this increase in efficiency can often not compensate for the reduction in photosynthetic rate, since there is a smaller amount of solar radiation available under the tree species.

IPAR between systems demonstrated the difference of this the first year (Table 3), but this difference did not affect the SW and JV. This variation was observed in the last two years (2010 and 2011), where the strip system was responsible for the greatest values of both productive variables of sugarcane. This system provided higher SW in the second year of cultivation, where the IPAR was 48.9%. Except in this case, the SW and JV did not show difference between the first two years, while the third was reduced.

Table 3. Photosynthetically active radiation interception (IPAR), stem weight (SW) and juice volume (JV) of sugarcane in agroforestry systems of strip and line for three years three years of sugarcane cultivation (2009, 2010 and 2011) in the city of Frederico Westphalen, Rio Grande do Sul State, Brazil.

Variable	System	Years of sugarcane cultivation		
		2009	2010	2011
IPAR (%)	Strip	40.78 ^{bC}	48.86 ^{bB}	59.980 ^{bA}
	Line	50.78 ^{aC}	65.53 ^{aB}	74.37 ^{aA}
SW (t ha^{-1})	Strip	39.304 ^{aB}	48.891 ^{aA}	40.180 ^{aB}
	Line	35.014 ^{aA}	27.414 ^{bAB}	24.054 ^{bB}
JV (m^3 ha^{-1})	Strip	20.888 ^{aAB}	24.071 ^{aA}	19.439 ^{aB}
	Line	18.340 ^{aA}	12.082 ^{bAB}	10.969 ^{bB}

Means followed by the same letter, lowercase in column compare the system in each year and uppercase in each line compare the years in each system, the means do not differ among themselves by Tukey test of probability at 5% of error.

In the strip system, likely due to the spacing of 3 m between lines and between plants, and 12 m between trees strips, there was lower IPAR compared to the line system in which the plants were spaced every 1.5 m and the spacing between lines of trees was 6 m. Consequently, the smaller IPAR in strip system led to greater transmissivity of solar radiation into the canopy, which was crucial to the larger SW and MS values. In addition, the greater proximity to the root systems of trees in the line system may have intensified the competition in the system. Whereas, IRFA values were already higher in the first year, it is assumed that this system demonstrated a closing between lines faster than the strip system, which can be justified by its closer spacing.

This may also have not been sufficient to influence the MC and VS sugarcane in his first crop, however, demonstrated influence on subsequent years.

From the results obtained, it can be observed that the productive, morphological and qualitative characteristics, with the passing of sugarcane cultivation years, presented numerous variations, which are strongly influenced by tree species and agroforestry arrangement. The fact of the characteristics, especially productive characteristics (SW, JV, S), are relatively minor compared to other studies, this does not prevent successful cultivation of sugarcane in these systems. The study sought to provide new sustainable alternatives for farmers, in order to increase the diversification of the rural property and maintain the preservation of existing agro-ecosystems.

4.5 CONCLUSIONS

The interception of photosynthetically active solar radiation by tree components is lower in the strip system, and increases over the years of sugarcane cultivation. Among the tree species, eucalypt is responsible for the highest values of interception.

When grown in the understory of angico, bracatinga and canafístula, sugarcane presents greater length, diameter and stem weight, juice volume and amount of sucrose, mainly from the second cultivation year than when under the other tree species.

The cultivation of sugarcane in the strip system resulted in an increased of stem weight and juice volume, from the second year of cultivation.

4.6 CONFLICT OF INTEREST

The authors have not declared any conflict of interest.

4.7 ACKNOWLEDGEMENTS

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5 ARTIGO IV - ECOFISIOLOGIA DA CANA-DE-AÇÚCAR NO SUB-BOSQUE DE CANAFÍSTULA EM ARRANJOS DE SISTEMA AGROFLORESTAL

Submetido para o periódico: Comunicata Scientiae

Situação: aceito

Ecofisiologia da cana-de-açúcar no sub-bosque de canafístula em arranjos de sistema agroflorestal

5.1 Resumo

O objetivo deste trabalho foi avaliar aspectos fisiológicos e térmicos da cana-de-açúcar, em linhas orientadas ao Norte e Sul, no sub-bosque de canafístula em dois arranjos de plantas em sistema agroflorestal. O delineamento experimental utilizado foi de blocos completos casualizados, em esquema fatorial 2x2x6, ou seja, dois sistemas agroflorestais (faixa e linha), duas linhas de avaliação (Norte e Sul) e seis horários do dia (9, 10, 12, 14, 15 e 16 h), com três repetições. As características avaliadas foram: radiação fotossinteticamente ativa (RFA) incidente, temperatura da folha (TF), resistência à difusão de vapor (RS) e transpiração (E), com uso de um porômetro digital LI-1600 LI-COR. A análise de variância revelou diferença na interação Sistema agroflorestal x Linha de avaliação x Hora do dia, para todas as variáveis analisadas. As características fisiológicas e térmicas da cana-de-açúcar são influenciadas pelo arranjo de plantas do sistema agroflorestal e pelo local de avaliação dentro do sistema. O sistema faixa, de modo geral, apresenta maior quantidade de RFA disponível em seu sub-bosque, o que reflete em aumento dos valores de RS e redução da E da cana-de-açúcar. A linha Sul apresenta maior E da cana-de-açúcar pela manhã no sistema faixa e menor a tarde no sistema linha, devido aos maiores valores de TF.

Palavras-chave: Radiação fotossinteticamente ativa, sombreamento, transpiração.

Ecophysiology of sugarcane in the understory of *Peltophorum dubium Spr.* in agroforestry systems arrangements

5.2 Abstract

The objective of this study was to evaluate physiological and thermal aspects of sugarcane, in lines oriented North and South, in canafistula understory under two arrangements of plants in agroforestry system. The experimental design was a randomized complete block in a factorial 2x2x6, ie, two agroforestry systems (strip and line), two evaluation lines (North and South) and six times of day (9, 10, 12, 14 ,15 and 16 h) with three replications. The characteristics evaluated were: photosynthetically active radiation (RFA) incident, leaf temperature (TF), resistance to vapor diffusion (RS) and transpiration (E), using a digital porometer LI-1600 LI-COR. Analysis of variance revealed differences in interaction Agroforestry system x evaluation line x Time of day, for all variables. The physiological and thermal characteristics of sugarcane are influenced by plant arrangement agroforestry system and the evaluation local within the system. The strip system generally has a higher amount of RFA available in its understory, which reflects in increased RS values and reduced E of sugarcane. The South line has higher E of sugarcane in the morning in strip system and lower in the late in line system, due to higher TF values.

Keywords: Photosynthetically active radiation, shading, transpiration.

5.3 Introdução

Os sistemas agroflorestais consistem no uso integrado da terra para fins de produção florestal, agrícola e animal. Esta integração vem trazendo inúmeros benefícios, como a recuperação de áreas degradadas, redução dos custos de produção, maior aporte de matéria orgânica, o que acarreta a melhoria dos atributos químicos, físicos e biológicos do solo (Tracy & Zhang, 2008; Neves et al., 2009; Salton et al., 2013; Xavier et al., 2014).

A cana-de-açúcar (*Saccharum officinarum* L.) apresenta expressiva importância socioeconômica no Brasil, sendo que o sistema de monocultivo é predominante para a cultura. A sua inserção em sistemas agroflorestais é uma alternativa interessante, pelo fato dos mesmos serem considerados uma forma de produção alternativa, visando a preservação dos recursos naturais e o uso eficiente da terra.

O crescimento e desenvolvimento de diferentes espécies em uma mesma área, provocam interações dinâmicas na comunidade de plantas, que se alteram com o tempo. Em áreas onde há o componente arbóreo, ocorre crescimento contínuo em altura, projeção de copa e índice de área foliar (IAF), que modificam a distribuição dos recursos existentes no sistema (Müller et al., 2014).

A radiação solar, ao ser interceptada pelo dossel arbóreo, pode ser absorvida, transmitida ou refletida, dependendo do ângulo de incidência dos raios solares, ângulo de inserção foliar e IAF. A fração transmitida através da copa, disponível às plantas no interior do dossel, pode apresentar forma direta ou difusa, a qual condiciona o microclima interno do sistema, podendo afetar as características fisiológicas das espécies presentes no sub-bosque (Mendes et al., 2013).

A radiação solar pode variar em diferentes pontos dentro de um sistema agroflorestal (Paciullo et al., 2011), dependendo da área de sombra proporcionada pela copa, bem como da orientação e espaçamento entre as árvores. Estas características arbóreas podem interferir na velocidade e na direção do vento, modificando a renovação do ar na camada limítrofe da folha, a qual afeta o déficit de pressão de vapor (DPV) entre a folha e o ar (Taiz & Zeiger, 2013).

A modificação do DPV pode afetar a taxa transpiratória e a resistência à difusão de vapor, as quais caracterizam o estado hídrico da planta. Estas variáveis apresentam diferenças de acordo com a espécie, idade da planta, condições de solo, meteorológicas e hídricas. Temperaturas mais elevadas, proporcionadas pelo aumento da incidência de radiação solar, podem aumentar a transpiração das plantas. Entretanto, ocorre até o momento em que o potencial hídrico da folha reduza, induzindo o fechamento estomático (Melo et al., 2010).

O objetivo deste trabalho foi determinar características fisiológicas e térmicas da cana-de-açúcar, em linhas orientadas ao Norte e Sul, no sub-bosque de canafístula (*Peltophorum dubium* Sprengel) em dois arranjos de plantas em sistema agroflorestal.

5.4 Material e métodos

O estudo foi realizado em Frederico Westphalen – RS, com localização geográfica de 27°22'S, 53°25'W, a 480 m de altitude. Segundo a classificação climática de Köppen, o clima da região é Cfa, ou seja, subtropical úmido com temperatura média anual de 19,1°C, variando com máximas de 38°C e mínimas de 0°C.

O solo da área experimental é classificado como NEOSSOLO LITÓLICO Eutrófico típico pouco profundo (Cunha, 2011). Os valores das características químicas do solo foram: pH em água = 5,8; fósforo disponível (Mehlich^{-I}) = 2,9 mg dm^{-3}; alumínio = 0,0 cmol$_C$ dm^{-3}; potássio = 82,5 mg dm^{-3}; cálcio = 8,7 cmol$_C$ dm^{-3} e magnésio = 2,8 cmol$_C$ dm^{-3}. A adubação foi realizada conforme as recomendações para a cultura da cana-de-açúcar (Comissão de Química e Fertilidade do Solo, 2004).

O delineamento experimental utilizado foi de blocos completos casualizados, caracterizado por um esquema fatorial de 2x2x6, ou seja, dois sistemas agroflorestais (faixa e linha), duas linhas de avaliação (Norte e Sul) e seis horários do dia (9, 10, 12, 14, 15 e 16 h), com três repetições.

O plantio da canafístula foi realizado em setembro de 2007 e a cana-de-açúcar (cultivar IAC87-3396) foi implantada em novembro de 2007, através do plantio manual das mudas e dos toletes, após a aração e gradagem da área. No sistema faixa (SF), a canafístula foi distribuída em faixas separadas por 12m, cada qual composta por três linhas, nas quais as plantas foram espaçadas em 3x3m. A cana-de-açúcar foi distribuída em oito linhas (entre as faixas, no espaço de 12m) e uma linha na faixa (entre as linhas de árvores).

No sistema linha (SL), o canafístula foi distribuída no espaçamento 6x1,5m, ou seja, 6m entre linha e 1,5m entre planta na linha, sendo a cana-de-açúcar distribuída em três linhas (entre as linhas das árvores). Em ambos os sistemas, a cana-de-açúcar apresentava espaçamento de 1,20m e a densidade utilizada foi de 18 gemas por metro, sendo que, tanto as linhas da cana-de-açúcar quanto as das árvores foram orientadas no sentido Leste-Oeste. A disposição das árvores, da cana-de-açúcar e as linhas de avaliação estão demonstrados na figura 1.

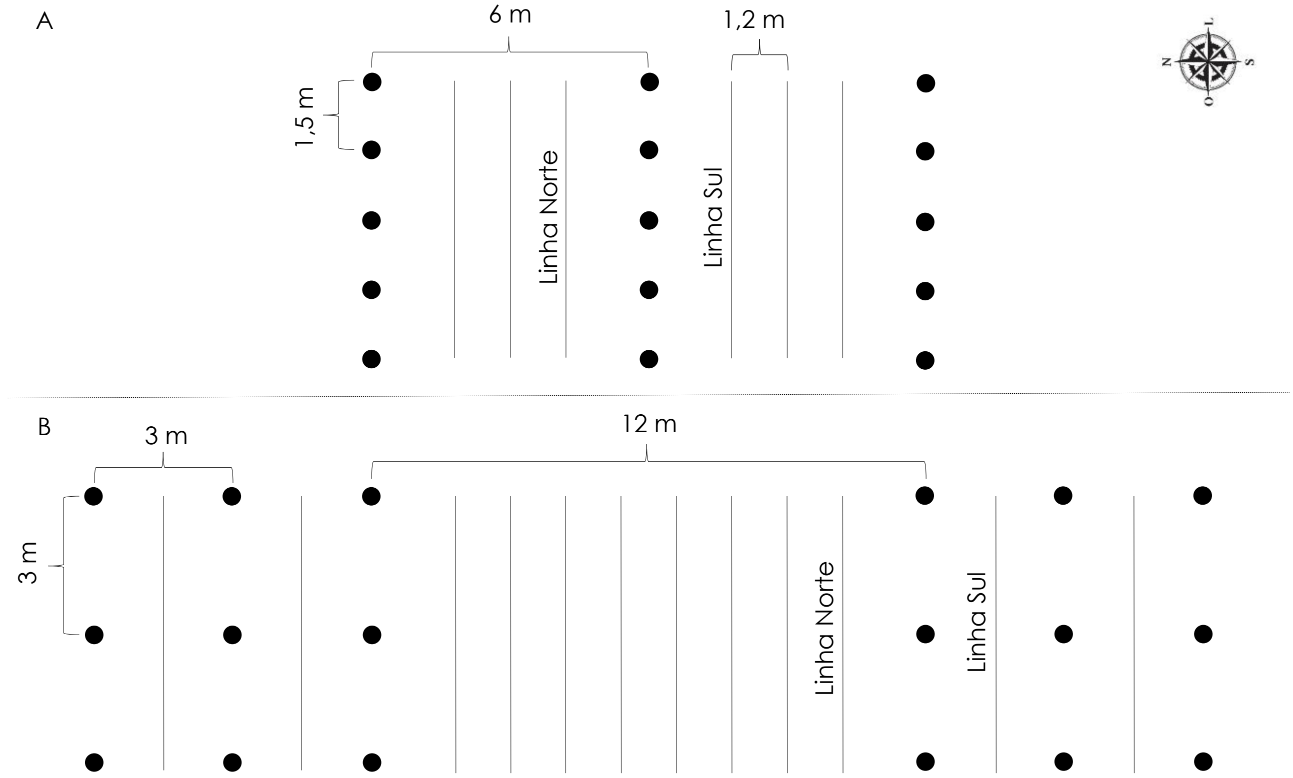

Figura 1. Croqui de uma unidade experimental dos sistemas Linha (A) e faixa (B). Círculos em cor preta representam as árvores de canafístula. Linhas contínuas indicam a cana-de-açúcar.

As características avaliadas foram: radiação fotossinteticamente ativa (RFA, μmol s^{-1} m^{-2}) incidente, temperatura da folha (TF, °C), resistência à difusão de vapor (RS, s cm^{-1}) e transpiração (E, mmol H_2O s^{-1} m^{-2}) ao longo de um dia, com uso de um porômetro digital LI-1600 LI-COR. As avaliações foram realizadas na última folha totalmente expandida da cana-de-açúcar presente no centro das linhas avaliadas uma a norte e outra a sul, em cada unidade experimental.

No momento da avaliação, as árvores de canafístula apresentavam diâmetro à altura do peito (DAP) médio de 2,05 e 1,94 cm, altura média de 2,40 e 2,16 m e diâmetro médio da copa de 1,10 e 1,00 m, nos sistemas faixa e linha, respectivamente. Até o momento da avaliação, não foram realizadas práticas culturais no que se refere à condução da copa e ao desbaste das árvores.

As avaliações foram realizadas no dia 10/02/2009, aos 17 meses após o plantio, considerado dia típico em agroclimatologia. Esse dia foi escolhido por apresentar a abóboda celeste em condições de nebulosidade zero, permitindo assim, a obtenção dos máximos efeitos dos elementos meteorológicos sobre o ambiente de cultivo e, consequentemente, sobre as características analisadas. Este método foi utilizado por Caron et al. (2014a) em mudas de pata-de-vaca (*Bauhinia forficata* Link). Realizou-se balanço hídrico da área experimental, utilizando-se capacidade de água disponível no solo (CAD) de 100 mm, para verificar se houve deficiência hídrica durante o período de avaliação.

Os dados foram submetidos à análise de variância, por meio do programa computacional *Statistical Analysis System Learning Edition* 8.0 (SAS, 2003). Os parâmetros que demonstraram diferenças significativas através do teste F a nível de 5% de probabilidade de erro, foram comparados pelo teste de Tukey para os fatores sistema agroflorestal e linha de avaliação. Utilizou-se o teste de Bartlett para verificar a homogeneidade da variância.

5.5 Resultados e Discussão

De acordo o com balanço hídrico realizado para a área experimental, não observou-se deficiência hídrica durante o período de avaliação. A análise de variância revelou diferença na interação Hora do dia x Sistema agroflorestal x Linha de avaliação para todas as variáveis analisadas (RFA, TF, RS, E).

No primeiro e último horário de avaliação (9 e 16h, respectivamente), a RFA foi superior na linha Sul nos sistemas faixa e linha. Nos outros horários não foi observada esta mesma resposta, onde a linha Norte apresentou os maiores valores, às 14h no sistema faixa e, às 10, 14 e 15h no sistema linha. Na comparação entre sistemas, o faixa, de modo geral, apresentou os maiores valores de RFA incidente na linha Sul, característica que variou de acordo com o horário na linha Norte (Figura 2).

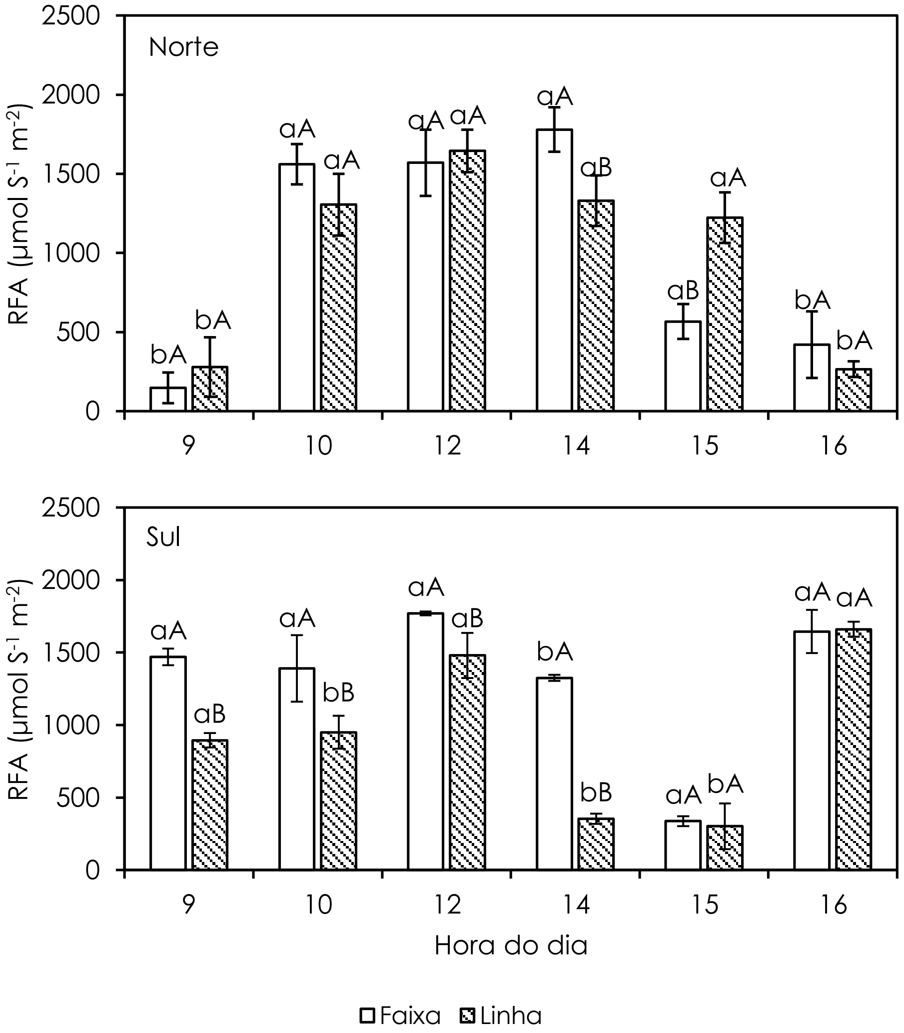

Figura 2. Radiação fotossinteticamente ativa (RFA) incidente na cana-de-açúcar no sub-bosque de canafístula em diferentes arranjos (faixa e linha) de sistema agroflorestal, nas linhas Norte e Sul, ao longo de um dia típico (10/02/2009) no município de Frederico Westphalen – RS.

*Médias seguidas pela mesma letra, maiúscula comparando os sistemas agroflorestais Faixa e linha e minúscula comparando as linhas Norte e Sul, não diferem entre sí, pelo teste de Tukey a 5% de probabilidade de erro ($p<0,05$).

A dinâmica da RFA do sub-bosque de sistemas florestais ainda é pouco difundida em estudos científicos. As variações observadas estão relacionadas ao componente arbóreo do sistema (canafístula), principalmente o arranjo e as características morfológicas das plantas. A maior RFA incidente no sistema faixa ocorreu devido ao maior espaçamento entre árvores e entre as faixas (3 x 3 m entre árvores e 12 m entre as faixas), comparado ao sistema linha.

Os maiores espaçamentos resultaram em menor quantidade de RFA interceptada pelo componente arbóreo, principalmente pela copa das árvores. A interceptação de RFA em espécies florestais foi relatada por Caron et al. (2012a), os quais encontraram os seguintes valores nas entre-linhas de plantio: 27,3% em acácia negra (*Acacia mearnsii* De Wild); 56,3% em bracatinga (*Mimosa scabrella* Benth) e 73,8% nas árvores de eucalipto (*Eucalyptus grandis* W. Hill ex Maiden), independente dos espaçamentos testados (2,0 x 1,0; 2,0 x 1,5; 3,0 x 1,0 e 3,0 m x 1,5 m), todas as espécies com 1 ano de idade. Caron et al., (2014b) observaram valores de 85% para Pinus (*Pinus elliotti* Engelm.) com 34 anos de idade, altura média de 25,0 m e DAP de 50,3 cm, sob espaçamento de 8x8 m.

De acordo com Caron et al., (2014a), estudando a variação da RFA no interior de ambiente protegido em um dia típico de verão, os valores desta variável aumentam até as 12h e depois decrescem. Nos sistemas agroflorestais, em alguns horários de alta incidência de radiação solar ao longo do dia, a radiação é atenuada, como pode ser observado principalmente as 15h na linha Sul, nos sistemas faixa e linha (Figura 2).

Esta variação ocorre devido à interação com o componente arbóreo. A canafístula apresenta ramificação dicotômica (ocorrência de brotação múltipla, provocando bifurcações no fuste da árvore), copa ampla, umbeliforme, largamente achatada e arredondada (Carvalho, 2003).

O diâmetro médio da copa foi semelhante nos arranjos faixa e linha (1,10 e 1,00 m, respectivamente). Apesar do tamanho da copa ser reduzido em ambos os sistemas, estas características provavelmente foram responsáveis pela atenuação da radiação solar. O aumento da radiação solar após às 15h ocorreu devido à modificação da inclinação solar ao longo do dia, pelo aumento do ângulo zenital (formado entre o zênite local e a inclinação dos raios solares), uma vez que a projeção da copa demonstrou menor influência. Interessante ressaltar que a redução da RFA incidente na cana-de-açúcar não provocou o estiolamento das plantas.

A redução da quantidade de RFA incidente no sub-bosque dos sistemas agroflorestais acarretou modificações nas características térmicas e fisiológicas da cana-de-açúcar. A diferença da TF entre os sistemas faixa e linha foram pouco evidentes, entretanto a variação entre as linhas Norte e Sul foram expressivas. No sistema faixa, a linha Norte apresentou menor TF nos primeiros horários da manhã (9 e 10h) e maior TF no último horário de avaliação (16h) (Figura 3).

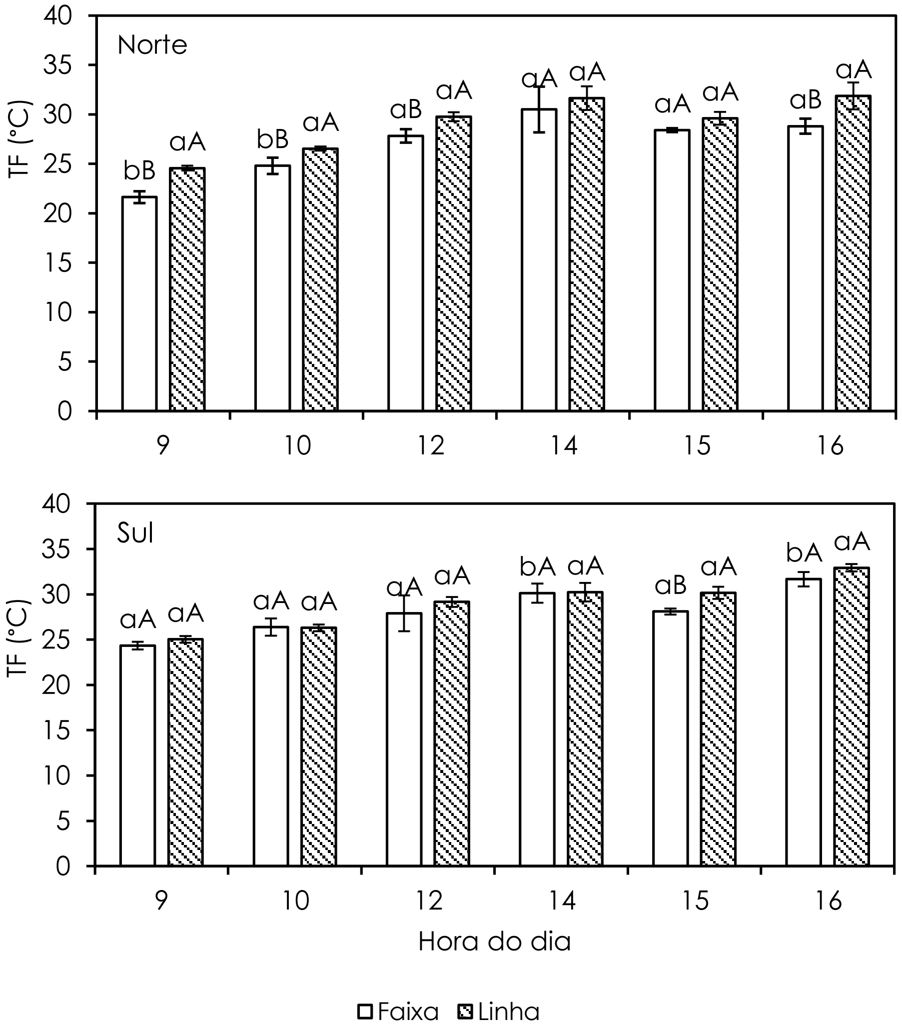

Figura 3. Temperatura da folha (TF) da cana-de-açúcar no sub-bosque de canafístula em diferentes arranjos (faixa e linha) de sistema agroflorestal, nas linhas Norte e Sul, ao longo de um dia típico (10/02/2009) no município de Frederico Westphalen – RS.

*Médias seguidas pela mesma letra, maiúscula comparando os sistemas agroflorestais Faixa e linha e minúscula comparando as linhas Norte e Sul, não diferem entre sí, pelo teste de Tukey a 5% de probabilidade de erro (p<0,05).

No sistema linha não foram observadas variações da TF entre as linhas de avaliação (Figura 3). Este resultado pode estar atrelado a menor incidência de RFA e menor variação destes valores ao longo do dia, uma vez que as árvores neste sistema estão mais próximas e interceptam uma maior quantidade de radiação solar. Resultados semelhantes foram encontrados por Caron et al. (2012b), ao constatar que uma maior densidade de plantas permite o fechamento mais rápido do dossel vegetativo, e consequentemente maior interceptação de RFA.

A RS no sistema faixa foi maior na linha Norte nos dois primeiros horários de avaliação. A linha Sul foi responsável pelos maiores valores às 16h. Na comparação entre sistemas, de modo geral, a RS foi superior no sistema faixa, exceto no primeiro horário de avaliação (Figura 4).

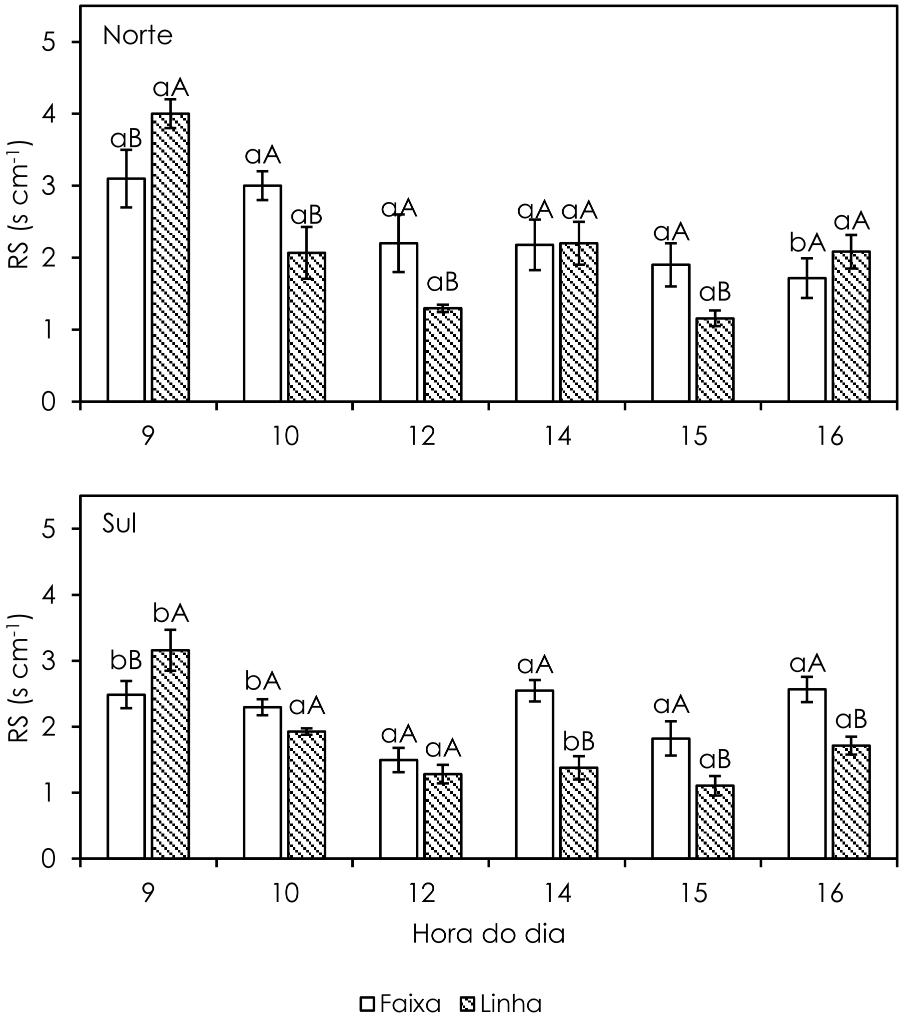

Figura 4. Resistência à difusão de vapor (RS) das folhas de cana-de-açúcar no sub-bosque de canafístula em diferentes arranjos (faixa e linha) de sistema agroflorestal, nas linhas Norte e Sul, ao longo de um dia típico (10/02/2009) no município de Frederico Westphalen – RS.

*Médias seguidas pela mesma letra, maiúscula comparando os sistemas agroflorestais Faixa e linha e minúscula comparando as linhas Norte e Sul, não diferem entre sí, pelo teste de Tukey a 5% de probabilidade de erro (p<0,05).

Esse resultado está atrelado à maior incidência de radiação no interior deste sistema. Caron et al. (2014a) constataram que, à medida em que a RFA aumenta, a RS também aumenta. Tal variação ocorre pelo fato das plantas de cana-de-açúcar realizarem o fechamento parcial dos estômatos em condições de alta incidência de RFA para evitar perdas excessivas de água por transpiração (Ding et al., 2006).

Entretanto, esse comportamento pode depender do tipo de metabolismo da espécie estudada e da intensidade de RFA. A cana-de-açúcar apresenta metabolismo C4, tendo alta eficiência fotossintética e ponto de saturação luminosa elevado (Barbieri, 1981). De acordo com Gazolla-Neto et al. (2013), altos valores de radiação solar, dependendo da espécie, podem prejudicar a eficiência quântica da fotossíntese, provocando a danificação do aparato fotossintético.

Em sistemas agroflorestais, a RFA se altera frequentemente no interior do dossel vegetativo, uma vez que o componente arbóreo é irregular e mesmo sofre influência da ação dos ventos. Tais fatores acarretam a modificação da projeção de sombra das árvores, além da modificação do ângulo solar ao longo do dia.

A redução da RS devido à maior abertura estomática influenciou a ocorrência de um aumento da taxa transpiratória (E) da planta, a qual, de modo geral, foi maior no sistema linha (Figura 5).

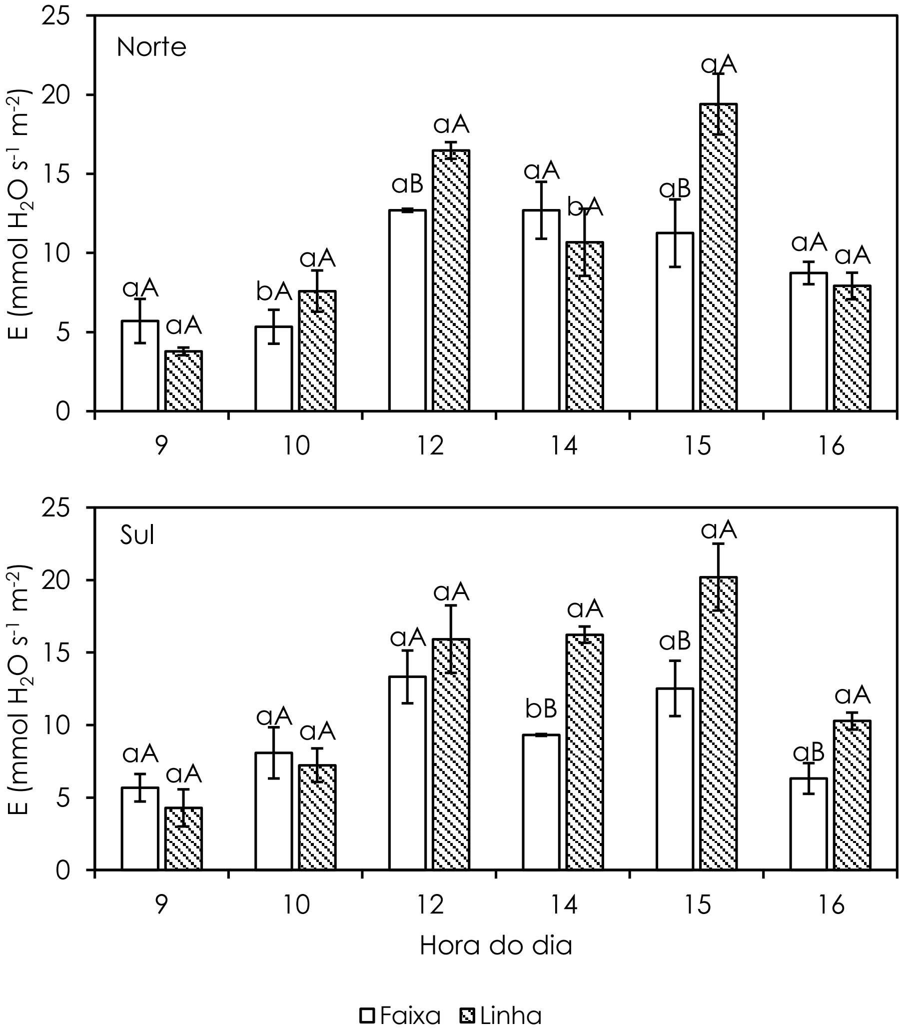

Figura 5. Transpiração (E) das folhas da cana-de-açúcar no sub-bosque de canafístula em diferentes arranjos (faixa e linha) de sistema agroflorestal, nas linhas Norte e Sul, ao longo de um dia típico (10/02/2009) no município de Frederico Westphalen – RS.

*Médias seguidas pela mesma letra, maiúscula comparando os sistemas agroflorestais Faixa e linha e minúscula comparando as linhas Norte e Sul, não diferem entre sí, pelo teste de Tukey a 5% de probabilidade de erro ($p<0,05$).

Os resultados estão de acordo com aqueles encontrados por Elli et al. (2013) e Caron et al. (2014a), ao constatarem que na medida em que RS diminui, a E aumenta, principalmente em condições de baixa intensidade luminosa. Os valores transpiratórios mais elevados em ambientes sombreados podem estar associados à menor variação da umidade relativa do ar, característica comum a ambientes mantidos nessas condições (Souza et al., 2011). Neste contexto, Casaroli et al.

(2010) relatam que a taxa de transpiração das folhas é diretamente influenciada pelo saldo de radiação, condutância estomática, e do déficit de saturação de vapor no ar.

Na comparação entre as linhas, às 10h foram observados valores de E superiores na linha Sul, para o sistema faixa e às 14h na linha Norte, para o sistema linha (Figura 5). A maior E nestes horários, diferentemente da variação entre os sistemas, foi motivada pelo aumento da RFA (Figura 2). Apesar dos valores de E serem maiores em ambientes sombreados, a RFA apresenta expressiva importância neste contexto. Entretanto, a resposta da RFA na transpiração pode não ser instantânea, uma vez que a quantidade de energia necessária para separar as moléculas de água da fase líquida e movê-las para a fase sólida (calor latente de vaporização da água), a 25°, é de 44 kJ mol^{-1} (Taiz & Zeiger, 2013).

Isso demonstra que, para ocorrer a transpiração de água pelas folhas, é necessário o acúmulo de uma determinada quantidade de energia, provinda da radiação solar. Além disso, a maior incidência de RFA não reflete diretamente no aumento instantâneo da temperatura do ar (calor sensível), sendo que é outra variável que pode modificar a temperatura da folha e consequentemente a E.

Indiretamente, a modificação das características fisiológicas podem influenciar o crescimento, desenvolvimento e produtividade vegetal. Taiz & Zeiger (2013) destacam que o fechamento estomático, que ocorre principalmente nas horas mais quentes do dia, prejudica a atividade fotossintética pelo fato de impedir a entrada de CO_2, reduzindo a taxa de crescimento das culturas.

O conhecimento da dinâmica dos elementos meteorológicos existentes no interior de sistemas agroflorestais, bem como da resposta fisiológicas das plantas presentes no sub-bosque, podem ser úteis para a escolha de um correto planejamento, bem como dos tratos culturais e do espaçamento a ser utilizado para o componente arbóreo do sistema. Novas pesquisas devem ser realizadas com outras espécies, tanto arbóreas, quanto anuais, para maiores esclarecimentos e a inserção de novas alternativas neste ramo de estudo.

5.6 Conclusões

As características fisiológicas e térmicas da cana-de-açúcar são influenciadas pelo arranjo de árvores do sistema agroflorestal e pelo local de avaliação dentro do sistema.

O sistema faixa, de modo geral, apresenta maior quantidade de radiação fotossinteticamente ativa disponível em seu sub-bosque, o que reflete em aumento dos valores de resistência à difusão de vapor e redução da transpiração da cana-de-açúcar.

A linha Sul apresenta maior transpiração da cana-de-açúcar pela manhã no sistema faixa e menor à tarde, no sistema linha, devido aos maiores valores de temperatura da folha.

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6 DISCUSSÃO GERAL

O arranjo espacial das espécies arbóreas em sistemas agroflorestais foi um fator primordial, tanto para as espécies florestais, quanto para as culturas presentes nos seus sub-bosques. Arranjos mais adensados proporcionaram o rápido fechamento do dossel arbóreo, disponibilizando menor quantidade de radiação solar para a cana-de-açúcar. O eucalipto apresentou maior crescimento comparado as outras espécies arbóreas, entretanto, no segundo ano após o plantio, interceptou em torno de 65% da radiação solar. O sistema faixa proporcionou o maior crescimento individual das árvores, exceto o guapuruvu, e possibilitou a incidência de maiores níveis de radiação solar para o sub-bosque arbóreo.

O crescimento das espécies arbóreas, além do arranjo de plantio, foi influenciado pelas condições meteorológicas do local de cultivo. A ocorrência de geada causou a necrose do ápice de árvores mais susceptíveis, como o guapuruvu, reduzindo a altura das plantas. Além da ocorrência de geadas (efeito de temperaturas mínimas extremas), a precipitação demonstrou significativa influência sobre o crescimento arbóreo, sendo que altos níveis pluviométricos proporcionaram efeitos positivos sobre o crescimento.

Modificações na altura e diâmetro médio da copa das árvores resultaram em mudanças na morfologia, produtividade e fisiologia da cana-de-açúcar. Quando conduzida sob espécies como o eucalipto e guapuruvu, reduziram até 50% da massa de colmos (t ha^{-1}), do primeiro para o terceiro ano de cultivo. Estas espécies apresentaram maior diâmetro médio da copa, comparado às demais espécies estudadas e consequentemente, maior interceptação de radiação solar. Tratando-se dos arranjos de plantio estudados, o sistema faixa proporcionou maior produtividade de colmos da cana-de-açúcar (30% maior que o sistema linha). O cultivo das árvores em faixas e a presença de um maior espaçamento entre as faixas possibilitou maior disponibilidade de radiação solar no interior do dossel vegetativo. O plantio de árvores em linhas individuais e a redução do espaçamento entre as linhas (sistema linha) causou o rápido fechamento do dossel vegetativo, diminuição da RFA no sub-bosque e redução significativa da produtividade da cana-de-açúcar.

As respostas da cultura frente ao sombreamento podem ser explicadas pela modificação da fisiologia das plantas. A presença do componente arbóreo modificou a incidência de radiação solar ao longo do dia, entre os arranjos das plantas estudados e em diferentes locais dentro de cada arranjo. A maior RFA no sistema faixa, de modo geral, aumentou a resistência estomática da cana-de-açúcar, como uma estratégia das plantas para evitar perdas excessivas de água. Entretanto, a maior RFA possibilitou a maior taxa fotossintética da cultura, resultando em maior produtividade. Os sistemas agroflorestais, por serem altamente dinâmicos, não modificam apenas a radiação solar em seu interior, mas a umidade relativa do ar, umidade e temperatura do solo, teor de matéria orgânica do solo. Portanto, a fisiologia da cana-de-açúcar pode ser responsiva a modificação de diversos fatores. Estudos mais aprofundados devem ser realizados para a compreensão mais detalhada da resposta fisiológica da cana-de-açúcar e a sua implicação sob a dinâmica dos sistemas agroflorestais.

O próximo passo deste estudo é realização detalhada da análise econômica dos diferentes componentes destes sistemas consorciados. Apesar da produtividade da cana-de-açúcar ser reduzida, devido a interferência das espécies arbóreas, deve-se levar em consideração o retorno econômico das árvores, bem como a inserção de outras espécies sequenciais após o cultivo da cana-de-açúca, que possam ser aclimatadas ao sombreamento e proporcionar resultados satisfatórios. Deve-se ressaltar que, além do retorno econômico, a inserção destes sistemas é uma alternativa sustentável para o uso da terra e, da mesma forma, que os mesmos podem suprir, ou complementar, a necessidade de pequenos produtores rurais.

7 CONCLUSÃO GERAL

O crescimento das espécies arbóreas foi influenciado pelo arranjo de plantas em sistemas agroflorestais. Os elementos meteorológicos modificaram o crescimento das espécies florestais e devem ser levados em consideração para a realização de um planejamento apropriado e escolha adequada da espécie florestal que compõe o sistema.

Dentre as espécies estudadas, o eucalipto apresentou maior crescimento em diâmetro do colo, diâmetro à altura do peito, diâmetro médio da copa e altura total. O sistema faixa proporcionou o aumento do crescimento da maioria das espécies arbóreas (eucalipto, canafístula e angico). Este sistema possibilitou maior entrada de radiação fotossinteticamente ativa em seu interior, resultando em maior produtividade, aumento da resistência a difusão de vapor e redução da transpiração das folhas da cana-de-açúcar.

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