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Felipe Schwerz

INTERAÇÕES DINÂMICAS NO CRESCIMENTO DE TUNGUE E CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

Frederico Westphalen, RS

2017

Felipe Schwerz

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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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A Deus, pelo dom da vida, aos meus pais Jorge Leonel Schwerz e Noeli Teresinha Schwerz, meu irmão Luciano Schwerz, por serem meu espelho e inspiração diária, dedico-lhes este trabalho.

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(Michel Eyquem de Montaigne)

RESUMO

INTERAÇÕES DINÂMICAS NO CRESCIMENTO DE TUNGUE E CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

AUTOR: Felipe Schwerz
ORIENTADOR: Braulio Otomar Caron

O objetivo do estudo foi avaliar a influência das variáveis meteorológicas no crescimento do Tungue e suas implicações sobre o crescimento e produtividade da cana-de-açúcar em sistemas agroflorestais. A pesquisa foi conduzida no período de 2011 a 2016, 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. Foi utilizada a espécie florestal Tungue (*Aleurites fordii*) e a cana-de-açúcar (*Saccharum officinarum* L.) para compor os sistemas agroflorestais. As árvores foram distribuídas em dois arranjos de sistemas agroflorestais, denominados I e II. No sistema I, as árvores foram distribuídas em fileiras espaçadas a 12m e a cana-de-açúcar foi distribuída em oito linhas, disposta em intervalos correspondentes entre as fileiras das árvores. No sistema II, as árvores foram cultivadas em fileiras espaçadas a 6m e a cana-de-açúcar foi distribuída em quatro linhas dispostas em correspondência com intervalos entre as fileiras das árvores. Para o sistema de monocultura com cana-de-açúcar, as plantas foram distribuídas em seis linhas com 12 metros de comprimento. Em ambos os sistemas, a cultivar de cana-de-açúcar utilizada foi a IAC 87-3396, sendo distribuída em espaçamento entre linhas de 1,20m. Tanto as linhas de cana-de-açúcar quanto as das árvores foram orientadas no sentido Leste-Oeste. As variáveis de crescimento do Tungue analisadas foram: diâmetro do colo (cm), diâmetro à altura do peito (cm), altura de planta (m) e diâmetro médio da copa (m). As variáveis produtivas analisadas na cana-de-açúcar foram: massa de colmo (Mg ha^{-1}), comprimento de colmo (m), diâmetro do colmo (mm), número de nós, número de colmos, volume de suco (m^{3} ha^{-1}), conteúdo de sacarose (g L^{-1}) e quantidade de sacarose (Mg ha^{-1}). As variáveis de crescimento avaliadas foram: Índice de área foliar (m^{2} m^{-2}), taxa de crescimento absoluto (g dia^{-1}), taxa de assimilação líquida (g m^{-2} dia^{-1}), eficiência do uso da radiação (g MJ^{-1}), partição da matéria seca (g), matéria seca total (g m^{-2}), altura de planta (m), número de perfilho, coeficiente de extinção de luz e % de interceptação da radiação solar. As variáveis meteorológicas ocorrentes ao longo do estudo foram obtidas por meio da Estação Climatológica do Instituto Nacional de Meteorologia, localizada à 200 m do local de estudo, nas coordenadas 27°39'S e 53°43'W. As interações dinâmicas existentes entre as árvores de Tungue e as variáveis meteorológicas foram determinantes para o crescimento e produtividade da cana-de-açúcar cultivada no sub-bosque. Para a produção de cana-de-açúcar, deve-se priorizar o uso de um sistema agroflorestal com arranjos de 12x12m, pois promove maiores rendimentos de cana-de-açúcar quando comparados com um sistema agroflorestal de 6x6m, uma vez que a qualidade da cana-de-açúcar não foi afetada pelos sistemas de cultivo. No futuro, a partir do momento em que as árvores de Tungue apresentarem retorno produtivo, uma nova análise conjunta dos dados deve ser realizada a fim de verificar a recomendação sugerida na presente pesquisa.

Palavras-chave: Taxas de crescimento. Componentes de rendimento. Preservação ambiental. Variáveis meteorológicas.

ABSTRACT

DYNAMIC INTERACTIONS ON THE GROWTH OF TUNGUE AND SUGARCANE IN AGROFORESTRY SYSTEMS

AUTHOR: Felipe Schwerz
ADVISOR: Braulio Otomar Caron

The aim of the study was to evaluate the influence of meteorological variables on the growth of Tungue and its implications on the growth and productivity of sugarcane in agroforestry systems. The research was conducted from 2011 to 2016, 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 species Tungue (*Aleurites fordii*) and Sugarcane (*Saccharum officinarum* L.) were used to compose the agroforestry systems. The trees were distributed in two arrangements of agroforestry systems, designated I and II. In the system I, trees were distributed in rows spaced at 12m; the sugarcane was distributed in eight rows, arranged in corresponding intervals between tree rows. In the system II, trees were grown in rows spaced at 6m; the sugarcane was distributed in four rows arranged in correspondence with intervals between tree rows. For the monocrop system with sugarcane, the plants were distributed in six rows with 12 meters length. 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: stem diameter (cm), diameter at breast height (cm), plant height (m) and crown diameter (m). The productive variables analyzed in sugarcane were: stalk weight (Mg ha^{-1}), stalk length (m), stalk diameter (mm), number of nodes, number of stalks, juice volume (m^3 ha^{-1}), sucrose content (g L^{-1}) and sucrose quantity (Mg ha^{-1}). Sugarcane growth variables evaluated: leaf area index (m^2 m^{-2}), absolute growth rate (g day^{-1}), net assimilation rate (g m^{-2} day^{-1}), radiation use efficiency (g MJ^{-1}), biomass partitioning (g), total dry matter (g m^{-2}), plant height (m), number of tillers, extinction coefficient and % of intercepted global radiation. The meteorological variables occurring during the study were obtained through Climatological the National Institute of Meteorology Station, located at 200 m from the study site, with geographic location 27°39'S and 53°43'W. The dynamic interactions between Tungue trees and meteorological variables were determinant for the growth and productivity responses of sugarcane cultivated in the understory. For the sugarcane production, the use of an intercropping system with 12x12m arrangements should be prioritized, because it promotes greater sugarcane yields when compared to a 6x6m intercropping system, since the quality of the sugarcane was not affected by the cultivation systems. In the future, from the moment that *Aleurites fordii* trees show a productive return, a new joint analysis of the data should be made in order to verify the suggested recommendation of the present research.

Keywords: Growth rates. Productive components. Environmental preservation. Meteorological variables.

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1 INTRODUÇÃO

1.1 SISTEMAS AGROFLORESTAIS: ABORDAGEM GERAL E APLICABILIDADE

Os sistemas agroflorestais 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 utilização de sistemas agroflorestais têm chamado a atenção de agricultores devido a importância dos sistemas na melhoria das condições de manejo de áreas agrícolas, condições de fertilidade do solo, exploração de diferentes camadas do solo por meio de diversos sistemas radiculares, melhoria da absorção de água e nutrientes, ciclagem de nutrientes, ou seja, revertendo em melhor uso da terra, buscando-se não somente o aumento da produtividade biológica, mas também aspectos ambientais e socioeconômicos.

Adicionalmente, esse sistema integrado do uso da terra pode contribuir para a variabilidade econômica dos produtores rurais, em função da melhoria da qualidade de vida das comunidades por meio da diversificação da produção, bem como ampliando alternativas alimentares de subsistência. Segundo Vivan e Fioriani (2006), os sistemas agroflorestais têm sido cada vez mais importantes no Brasil como estratégia-piloto de desenvolvimento sustentável em ecossistemas ameaçados.

Neste mesmo contexto, de acordo com a Lei n° 12.651, de 25 de maio de 2012, que institui o novo Código Florestal (BRASIL, 2012), pequenas propriedades rurais podem utilizar plantios de sistemas agroflorestais em suas áreas de preservação permanente (APP) e reservas legais (RL), desde que esses sistemas sejam submetidos ao plano de manejo sustentável. Tal fato pode alavancar a aceitação e implantação de sistemas agroflorestais pelos produtores. Assim, tornam-se indispensáveis pesquisas direcionadas e específicas a respeito da resposta das plantas cultivadas nestes sistemas e as interações existentes a fim de gerar informações aos produtores rurais.

Diante do cenário mundial de energia renováveis, o Brasil tem se destacado como ator principal no setor de agroenergia. Produzido a partir de fontes naturais renováveis, o biodiesel e o álcool vem, cada vez mais, sendo utilizado como fonte alternativa de combustível. Dentre as espécies exploradas para esse fim, o Tungue (*Aleurites fordii*) tem despontado como alternativa para produção de biodiesel, e a cana-de-açúcar para a produção de álcool. Neste sentido, o uso destas espécies em sistemas consorciados deve ser avaliado. Devido à grande diversidade de interações existentes nos sistemas agroflorestais e a falta de estudos envolvendo tais sistemas, são necessários estudos demonstrando as respostas das plantas, e também a recomendação de espécies, que evidenciem resultados positivos, quando inseridas nestes sistemas.

1.2 ARRANJO DAS ÁRVORES 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, esse fator é de grande relevância devido a interceptação da radiação solar 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.

No planejamento de um sistema agroflorestal, a escolha do arranjo de árvores é essencial para o sucesso do sistema de produção. Os arranjos arbóreos devem considerar o uso da árvore, o crescimento futuro da árvore e as necessidades de recursos das árvores e culturas a serem cultivadas em um sistema consorciado (ROZADOS-LORENZO et al., 2007, PRASAD et al., 2010). Em arranjos arbóreos reduzidos, as árvores interferem nas plantas cultivadas no sub-bosque devido à maior interceptação da radiação solar pela copa das árvores, bem como pelo aumento da competição por água e nutrientes. A competição é um dos principais fatores que têm impactado negativamente no rendimento dos sistemas em consórcio (LI et al., 2011).

Em contrapartida, arranjos de árvores mais espaçados estimulam uma associação favorável entre as espécies (PRASAD et al., 2010). Neste sentido, a produção dos componentes da árvore e das culturas deve ser considerada como um todo, a fim de definir o arranjo de árvores mais adequado e proporcionar maiores rendimentos das culturas cultivadas no sub-bosque, bem como promover maiores taxas de crescimento da espécie florestal.

Para determinar a sustentabilidade de um sistema agroflorestal, é essencial a compreensão dos fatores ambientais e das interações das plantas (ONG et al., 2000). As interações árvore-cultura podem ser reguladas efetivamente e a competição entre espécies pode ser minimizada empregando-se arranjos de árvores eficientes e selecionando-se espécies compatíveis (ONG e KHO, 2015). Em sistemas agroflorestais é importante considerar as características e os benefícios das duas espécies consorciadas. Neste sentido, as árvores de Tungue são uma alternativa para compor os sistemas agroflorestais devido às características de crescimento da espécie (espécie caducifólia), as quais possibilitam o cultivo de culturas em seu sub-bosque. No entanto, torna-se necessário identificar a resposta das árvores quando submetidas a diferentes arranjos espaciais, e além disso, definir práticas de manejo como por exemplo o arranjo de plantas apropriado para o seu cultivo, uma vez que na literatura atual não existem informações referentes ao arranjo de árvores apropriado para o cultivo do Tungue.

1.3 INSERÇÃO DA ESPÉCIE TUNGUE EM SISTEMA AGROFLORESTAL

Espécies florestais com grande potencial energético estão começando a destacar-se no cenário de produção de energia nacional. Dentre as espécies, o Tungue, considerado de grande importância como fonte produtora de óleo e devido suas características de crescimento que possibilita o cultivo de espécies em seu sub-bosque, pode ser considerada como alternativa viável para compor os sistemas agroflorestais.

As árvores de Tungue (*Aleurites fordii*) pertencente à família Euphorbiaceae, tem como centro de origem a China. Espécie caducifólia, que de acordo com (SHOCKEY et al., 2016) apresenta as seguintes características: altura de 3 a 9 metros, ramos robustos e glabros, folhas glabras, frutos são do tipo drupóide, carnoso, globoso e com alto teor de óleo (pode chegar a 65% do peso total do fruto). As propriedades químicas únicas do óleo de sementes de Tungue tornam um dos óleos de secagem industrial mais conhecidos. Estudos realizados com a espécie levaram à identificação de vários constituintes químicos, incluindo cumarinas, ésteres diterpênicos, óleos, esteróis e taninos (POTTER, 1959, CHEN et al., 2010). Além disso, o óleo de Tungue é atualmente usado em resinas, tintas, impressão de alta qualidade, plastificantes, em certos tipos de medicamentos e reagentes químicos (PARK et al., 2008, SHANG et al., 2010, PEI et al., 2012), bem como para a produção de biodiesel (SHOCKEY et al., 2016). Do total produzido, a China ainda representa, pelo menos, 70% da produção mundial de óleo de Tungue, no entanto, ao longo do tempo a produção tem alcançado vários outros países tais como o Paraguai, Argentina e Brasil (SHOCKEY et al., 2016).

No Brasil, o Tungue foi introduzido no final de década de 40, a partir desta data houve um crescente incentivo por parte da indústria de tintas, resultando em fomento da cultura na década de 60. Dentre os estados do Brasil, o Rio Grande do Sul foi o que apresentou melhor adaptação para a cultura, sendo que os maiores plantios concentravam-se nas regiões das

Missões e Serra Gaúcha (ÁVILA, 2010). O sistema de cultivo do Tungue no Rio Grande do Sul em sua maioria ocorre de forma extensiva, onde as plantas estão distribuídas em meio a pastagens e culturas anuais. A colheita é realizada à medida que os frutos caem no chão, sendo que de modo geral são necessárias duas ou mais operações de colheita, pois a maturação do Tungue não é uniforme (ÁVILA, 2010).

O Tungue propicia retorno econômico num período mínimo de 5 a 7 anos, alcançando sua máxima produção em 10 a 12 anos (DUKE, 1983, SHOCKEY et al., 2016). Este fator tem sido um empecilho para a viabilidade do cultivo desta espécie na região, onde as exigências de fluxo financeiro em curto prazo e contínuo são necessárias nas pequenas e médias propriedades. No entanto, a utilização desta espécie em proporções pequenas na propriedade e em sistema de consórcio pode vir a torná-la viável, principalmente quando as culturas em consórcio proporcionam retorno em curto prazo, como por exemplo com o uso da cana-de-açúcar. Dessa maneira, espera-se que a cana-de-açúcar venha gerar renda inicial aos agricultores e posteriormente o Tungue.

Os resultados de pesquisa com a espécie Tungue ainda são incipientes no país, principalmente em relação ao crescimento e adaptação as condições meteorológicas, a qual é essencial para o sucesso no estabelecimento da espécie. Nesse sentido, o estudo da inserção do Tungue em sistemas agroflorestais, bem como a análise da influência das variáveis meteorológicas sobre o seu crescimento são fundamentais a fim de potencializar a sua implantação nos sistemas produtivos.

1.4 USO DA CANA-DE-AÇÚCAR EM SISTEMAS AGROFLORESTAIS

O Brasil é um dos principais países produtores de cana-de-açúcar no mundo, com estimativas para 2017/2018 de 8,84 milhões de hectares plantados, que fornecem 647 milhões de toneladas de cana-de-açúcar, resultando em um rendimento médio de 73 toneladas ha^{-1} (CONAB, 2017). O monocultivo de cana-de-açúcar (*Sacharum officinarum* L.) tem resultado em um grande impacto socioeconômico e ambiental no Brasil. Neste sentido, os sistemas agroflorestais têm sido considerados como uma alternativa para a produção sustentável em ecossistemas ameaçados. Apesar do potencial dos sistemas agroflorestais já descritos anteriormente, poucos trabalhos estão sendo desenvolvidos com a cana-de-açúcar a fim de avaliar o crescimento da planta, produtividade e a dinâmica dos recursos disponíveis nestes sistemas.

A cana-de-açúcar apresenta metabolismo C4 e se caracteriza por apresentar elevada taxa fotossintética e alta produtividade biológica, respondendo positivamente a altos níveis de radiação solar. 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, no caso deste estudo pela espécie Tungue, não compromete significativamente as características produtivas e qualitativas 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, em que predominam pequenas e médias propriedades rurais. Após a vinda de empresas do setor de biocombustível para a região, bem como a aptidão do cultivo pelo zoneamento agroclimático, a cana-de-açúcar tem despertado interesse por muitos agricultores, sendo uma alternativa interessante para compor os sistemas agroflorestais, principalmente após o estabelecimento de parcerias entre as Cooperativas e os proprietários rurais para o cultivo de cana-de-cana de açúcar em sua propriedade para suprir a demanda das indústrias instaladas na região. O objetivo da cultura é posteriormente a industrialização de etanol em micro usinas distribuídas pela região.

Para tanto, um dos principais atributos para o bom desenvolvimento e consequentemente rendimento da cana-de-açúcar são as condições meteorológicas em que são cultivadas. O desenvolvimento da cultura é dividido em dois estágios: crescimento vegetativo, em que as condições de alta umidade e alta disponibilidade de radiação solar favorecem seu crescimento; e sua maturação: nesse período as plantas necessitam de temperaturas mais amenas e baixa quantidade de água disponível, favorecendo o acúmulo de sacarose. Nesse sentido, torna-se importante avaliar a resposta da cana-de-açúcar as diferentes condições meteorológicas, bem como sua adaptação aos sistemas agroflorestais. Estas implicações, aliadas a necessidade da geração de sistemas agrícolas economicamente viáveis e ambientalmente sustentáveis, justificam a realização do presente trabalho.

1.5 IMPORTÂNCIA DAS VARIÁVEIS METEOROLÓGICAS NOS SISTEMAS AGROFLORESTAIS

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. O crescimento das plantas ocorre em função da matéria seca acumulada através da fotossíntese. A produção de fitomassa em plantas depende da quantidade de radiação fotossinteticamente ativa absorvida pelas folhas, e a eficiência pela qual as folhas podem converter e assimilar a radiação solar através da fotossíntese.

Em sistemas agroflorestais, devido ao crescimento contínuo em altura e diâmetro da copa da espécie arbórea ao longo do tempo, ocorre uma modificação no microclima do sub-bosque do sistema de cultivo, principalmente, nos balanços energético e hídrico. 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 sub-bosque. A redução da radiação solar condiciona outros elementos meteorológicos, como a temperatura e umidade relativa do ar, velocidade do vento, umidade e temperatura do solo.

Entre as variáveis meteorológicas, a radiação solar e a temperatura do ar são as principais condicionantes do crescimento e desenvolvimento das plantas em sistemas agroflorestais (ELLI et al., 2016, ELLI et al., 2017). 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 caducifólias e no contexto de sistemas agroflorestais, a temperatura do ar exerce um papel muito importante no que se refere a senescência e queda das folhas em períodos de baixas temperaturas ou de déficit hídrico, as quais podem proporcionar a entrada de maior quantidade de radiação solar no interior do sub-bosque dos sistemas agroflorestais em determinados períodos de tempo. Além disso, a região de estudo caracteriza-se por apresentar temperaturas mínimas extremas inferiores a 0 (zero) °C, bem como a ocorrência de geadas no inverno. Tal fato pode afetar o crescimento das espécies cultivadas nos sistemas agroflorestais.

Os estudos em agrometeorologia têm centrado seus esforços na determinação dos valores dos elementos meteorológicos na quantificação a nível ambiental. Entretanto, torna-se necessário relacionar esses valores com os valores máximos admitidos pelos vegetais em seus ambientes a fim de potencializar a máxima expressão genética resultando em maior produtividade. Os valores extremos de temperatura (máximas e mínimas), por exemplo, podem limitar o crescimento e desenvolvimento das culturas influenciando, por exemplo, na divisão celular, na translocação de nutrientes e na absorção de água. A quantidade de radiação solar pode se tornar fator limitante no que diz respeito à eficiência da planta em produzir fotoassimilados, bem como pode alterar a quantidade e qualidade da biomassa a ser produzida e consequentemente consumida.

Não menos importante, as variáveis meteorológicas chuva, vento e umidade relativa do ar também podem influenciar a respostas das plantas cultivadas nos sistemas agroflorestais. 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 (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. 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.

A partir da importância das variáveis meteorológicas e suas inter-relações frente ao crescimento vegetal e as repostas de planta, torna-se relevante o estudo da influência das variáveis meteorológicas no crescimento e produtividade das espécies em sistemas agroflorestais, de modo que essas informações possam auxiliar no planejamento, tomada de decisão, realização de tratos culturais, gerando deste modo, resultados produtivos satisfatórios.

1.6 HIPÓTESES

As variáveis meteorológicas determinam o crescimento de Tungue de forma diferenciada para cada estação do ano devido principalmente à variação das temperaturas do ar e quantidade de radiação solar incidente.

O crescimento e a eficiência do uso da radiação solar pela cana-de-açúcar é influenciado pelo sombreamento da copa das árvores de Tungue, principalmente nas primeiras linhas de cultivo em função da maior competição pelos recursos disponíveis (radiação solar, água e nutrientes).

A cana-de-açúcar cultivada em sistemas agroflorestais apresenta produtividade e qualidade de suco igual ou superior à da cana-de-açúcar produzida em sistemas de monocultura, uma vez que as alterações no microclima dos sistemas agroflorestais podem não ser suficientes para alterar o rendimento e qualidade da cana-da-açúcar.

1.7 OBJETIVO GERAL

Avaliar a influência das variáveis meteorológicas no crescimento do Tungue e suas implicações sobre o crescimento e produtividade da cana-de-açúcar em sistemas agroflorestais.

1.8 OBJETIVOS ESPECÍFICOS

Determinar as correlações canônicas entre as variáveis meteorológicas e variáveis de crescimento do Tungue, durante quatro estações do ano em cinco anos de cultivo em dois sistemas agroflorestais.

Avaliar as taxas de crescimento, eficiência do uso da radiação e produtividade da cana-de-açúcar cultivada no sub-bosque do Tungue, em dois sistemas agroflorestais e um sistema de monocultura.

Avaliar os componentes de rendimento e qualidade da cana-de-açúcar em cinco ciclos de cultivo, no sub-bosque do Tungue em dois sistemas agroflorestais e um sistema de monocultura.

2 ARTIGO I - MULTIVARIATE ANALYSIS BETWEEN METEOROLOGICAL CONDITIONS AND GROWTH VARIABLES FOR *ALEURITES FORDII* IN AGROFORESTRY SYSTEMS

Submetido para o periódico: Journal of Forestry Research
Situação: em avaliação

Multivariate analysis between meteorological conditions and growth variables for *Aleurites fordii* in agroforestry systems

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2.1 Abstract

Knowledge of relationships between tree growth variables and meteorological variables would permit understand the dynamic interactions which exist in agroforestry systems; this is necessary when considering possible crop management systems with an emphasis on a system's successful establishment. The goals of this study was to evaluate correlations between meteorological variables and *Aleurites fordii* growth variables during four seasons of the year in five cultivation years and in two agroforestry systems in Frederico Westphalen-RS, Brazil. A field experiment was conducted from September 2011 to June 2016. The information generated in this study can aid in the planning of new agroforestry systems. The groups of meteorological variables and *Aleurites fordii* growth variables are not interdependent, especially regarding the secondary growth observed in the variables diameter at breast height and stem diameter; these showed high magnitudes when correlated with the meteorological variables. The seasons of the year influenced *Aleurites fordii* growth in a differentiated way. The summer season was responsible for the greatest tree growth. The incident solar radiation and the minimum air temperature were the main meteorological variables that affected tree growth.

Keywords: intercrop systems, meteorological variables, canonical correlations, season.

2.2 Introduction

Tung trees (*Aleurites fordii*) are a good candidate for composing agroforestry systems because of the species' growth characteristics which can lead to improved cultivation of crops grown in its understory. The unique chemical properties of Tung seed oil make it one of the best known industrial 'drying oils'. Phytochemical research into *Aleurites fordii* has led to the identification of various compounds including coumarins, diterpenoid esters, oils, sterols, and tannins as chemical constituents (Chen et al. 2010). In addition, Tung oil is currently used in paints, high quality printing, plasticisers, in certain types of medicines and as chemical reagents (Park et al. 2008; Pei et al. 2012) and biodiesel production (Chen et al. 2010).

To determine the sustainability of an agroforestry system, an understanding of environmental factors and plant interactions is essential (Berlyn and Cho 2000; Ong et al. 2000). Tree–crop interfaces can be regulated effectively, and interspecies competition can be minimized by employing efficient tree spacing (Ghezehei et al. 2016) and selecting compatible species (Ong 2014; Bayala and Wallace 2015; Black et al. 2015; Ong and Kho 2015). It is important to analyze the effect of *Aleurites fordii* as an alternative for the composition of the agroforestry systems, because it may lead to better crop growth rates and overall systemic viability.

In planning agroforestry systems, the choice of tree arrangement is essential to the success of a production system. Tree arrangements should consider tree use, future tree growth, and the resource requirements of both the trees and crops to be used in the intercropped system (Binkley et al. 2004; Rozados-Lorenzo et al. 2007; Prasad et al. 2010). It is therefore, that the production of tree components and crops should be considered as a whole, in order to define the most ideal tree arrangement.

In agroforestry systems, dynamic in solar radiation can lead to changes in other meteorological variables such as air temperature, air humidity, and soil temperature and humidity. These changes can determine the response of the plants grown in agroforestry systems. Monteith et al. (1991) highlight the existence of dynamic interactions in agroforestry systems, where competition for limited resources is inevitable, both above and below ground. In this context, understanding the effects of climate variability on tree growth is essential for many reasons including, vulnerability assessments, predictive modeling and adaptive agroforestry management (Spittlehouse 2005; Griesbauer and Green 2012), but tree species have growth–climate relationships that vary over time and across spatial scales (Benavides et al. 2013).

Correlations between meteorological variables and forest species growth are highly complex, due to the meteorological conditions which can positively and/or negatively affect tree growth at different intensities depending on the season of the year. To better understand these correlations, new studies with the use of multivariate statistical models are necessary; these analyses can simultaneously consider variables from distinct groups. One way to evaluate the correlation and contribution of the meteorological variables on the growth of forest species is through canonical correlation analysis.

Canonical correlation analysis (CCA) was proposed by Hotelling (1936) and developed to determine the relationship between two sets of variables obtained by transforming the vectors x and y into two vectors z and w in lower dimensions whose association has been greatly strengthened. CCA has been widely used in the many research fields such as computer vision (Kim et al. 2007; Yamamura et al. 2016), medical science (Soneson et al. 2015; Fox and Hammond 2017), agriculture (Qiu et al. 2016; Carvalho et al. 2016) and forestry (Ashiq and Anand 2016; Resende et al. 2016). To the authors' knowledge, this study is the first to investigate the relationship between meteorological variables and growth variables using CCA to analyze agroforestry systems.

In addressing this lack of information, the following hypotheses were created: (1) meteorological variables determine Tung growth in a differentiated way for each season of the year; (2) the tree arrangements affect Tung growth due to the changes in micrometeorological conditions; and (3) canonical correlations are a reliable method for analyzing the influence of meteorological variables on Tung growth. The goals of this study was to evaluate correlations between meteorological variables and *Aleurites fordii* growth variables during four seasons of the year in five cultivation years and in two agroforestry systems in Frederico Westphalen-RS, Brazil.

2.3 Materials and Methods

2.3.1 Study area

The field experiment was conducted from November 2011 to June 2016 in the city of Frederico Westphalen – Rio Grande do Sul, Brazil, at the coordinates 27º23'48 " S, 53º25'45 " and an altitude of 490m (Fig. 1). According to Köppen climate classification, the climate is Cfa, i.e., humid subtropical with mean annual temperatures of 19.1°C and varying maximum and minimum temperatures of 38ºC and 0°C, respectively (Alvares et al. 2013).

The soil of the experimental area was classified as typical Entisol Orthents. Fertilization was performed using 150 grams of formulated fertilizer for each seedling at the time of transplantation. The experiment was established in September 2011. Tree species were planted in an experimental field in September and the sugarcane in November of 2011. The seedlings and cuttings were manually planted after ploughing and harrowing the area. The tree and sugarcane were oriented in lines towards the East and West.

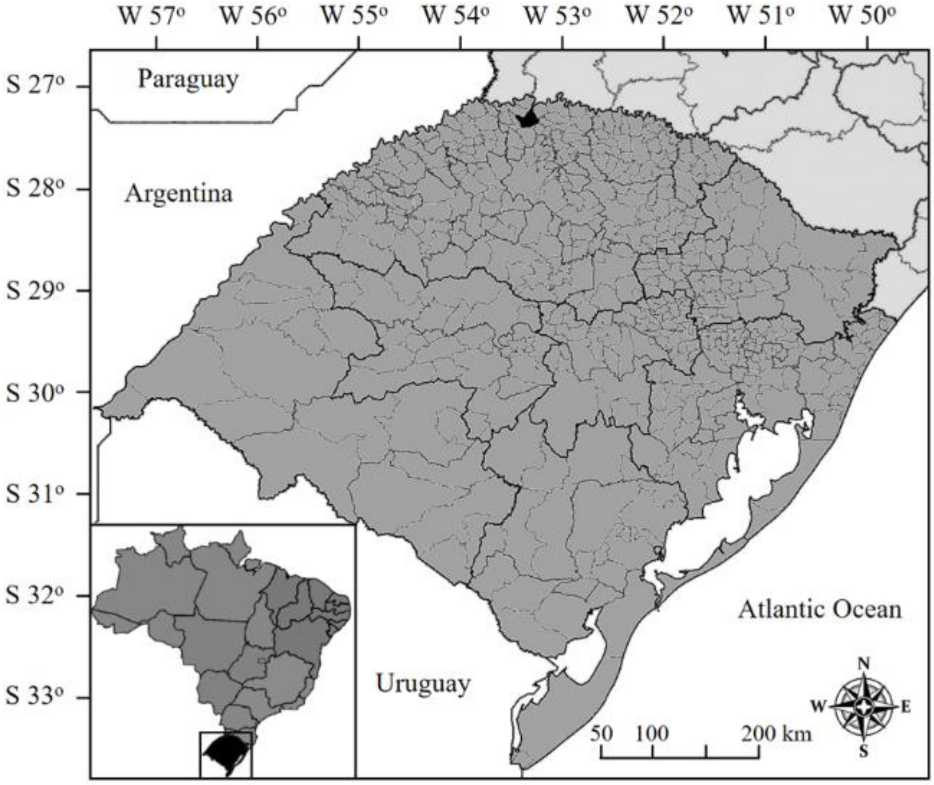

Fig 1. Geographical location of the experiment. The state of Rio Grande do Sul is highlighted in black on the bottom map, while the city of Frederico Westphalen is highlighted in black on the main map.

2.3.2 Experimental design

The experimental design was a randomized complete block, characterized by a factorial arrangement of 2x4x5, i.e., two agroforestry systems, intercrop system I (12 x 12m) and intercrop system II (6 x 6m), four seasons of the year (autumn, winter, spring and summer) during five evaluation years (2012 to 2016) and three replications. A total of 15 trees were allocated for each experimental unit. Three trees were evaluated in each block, and each evaluated tree was considered a repetition within the block.

The tree species Tung (*Aleurites fordii*), of the Euphorbiaceae family, an exotic deciduous species, was used to compose the agroforestry system. It was chosen due to its adaptability to environmental conditions, the high oil yield of its fruits, and due to its potential for worldwide cultivation. The productive evaluations (oil yield) were not performed due to the period of cultivation; the minimum period necessary for fruit production is five years with the peak production at ten years (Duke 1983; Zhan et al. 2012).

The arrangement of Tung tree and sugarcane plants are shown in Fig. 2. In the intercrop I system, trees were distributed in rows spaced at 12m; the sugarcane was distributed in eight rows and arranged in corresponding intervals between tree rows, totaling 16 rows throughout the system. In the intercrop II system, trees were grown in rows spaced at 6m; the sugarcane was distributed in four rows arranged in correspondence with intervals between tree rows. In both systems, the sugarcane had a spacing of 1.20m and an initial density of 16 buds per meter.

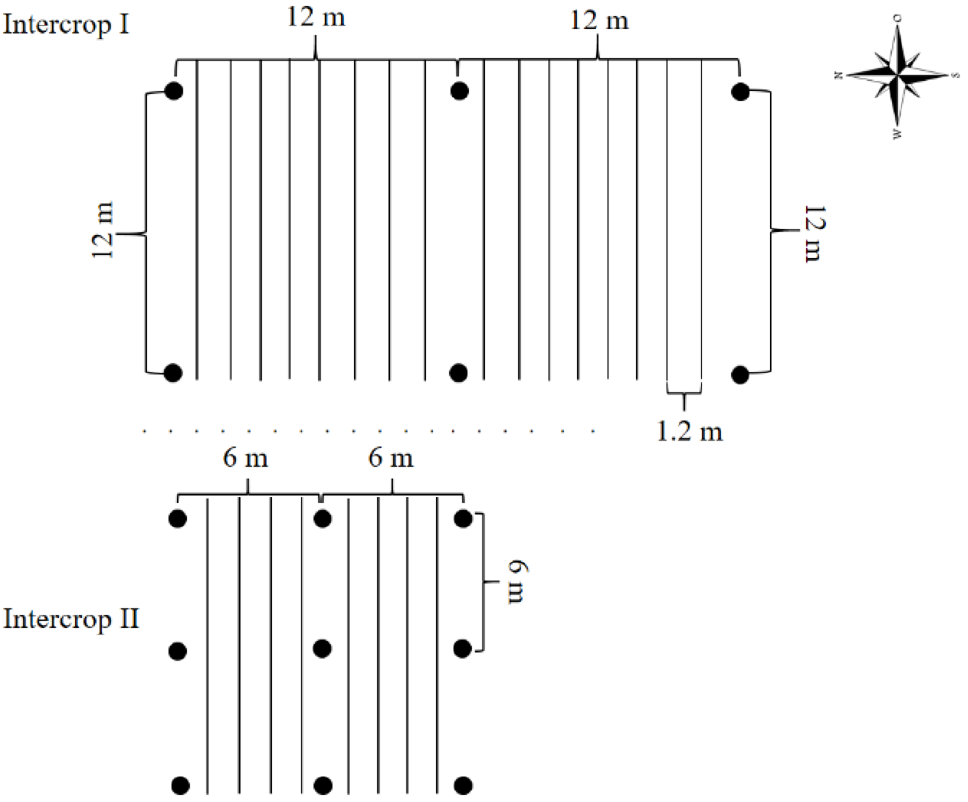

Fig 2. A sketch of the agroforestry system experimental units: intercrop I: 12 × 12m, and intercrop II: 6 × 6m. Black circles represent trees and continuous rows indicate sugarcane plants. Frederico Westphalen - RS, Brazil.

After the transplanting of the seedlings to the field, quarterly evaluations were conducted from March 17, 2012, which corresponds to 176 days after transplanting the seedlings (DAT). The evaluations were conducted until June 21, 2016, resulting in 1736 DAT throughout 18 total evaluation periods. The evaluations were carried out on the days that marked the half of each season studied, not necessarily on the same day in the different evaluation years. We considered the respective dates as the beginning of each season of the year: autumn 03/20, winter 06/21, spring 09/22 and summer 12/21.

2.3.3 Tree growth variables evaluated

The determination of height values (H), stem diameter (SD), diameter at breast height (DBH) and crown diameter (CD) of Tung trees were evaluated during each season of the year and the average values for each agroforestry system was used to compose the group 1. Tree height was measured from ground level to the top leaf axils using a measuring tape until the trees reached 2.0 m, thereafter a Vertex III Hypsometer was used. The stem diameter at ground level was measured using a tape measure at 5 cm above ground level, and the diameter at breast height was evaluated using a measure tape at a height of 130 cm. For crown diameter, evaluations were performed using a metric tape and taking vertical and horizontal measurements.

2.3.4 Meteorological variables analyzed

The values of meteorological variables during the experiment were obtained from a Climatological Station of the National Institute of Meteorology (INMET) linked to the Agroclimatology Laboratory (UFSM) located about 200m from the study site at coordinates 27° 39'S and 53° 43'W. Meteorological values were computed for each season of the year. The sum of the values for incident solar radiation and rainfall were recorded, while values for the air temperature (maximum, minimum and average) were computed using the average values for each season of the year. In this way, it was possible to characterize each season of the year during the evaluation years. The determination of the canonical correlation was based on the season of the year, due to the importance of the variability of meteorological conditions for each season.

The meteorological variables used to compose group 2 in the canonical analysis were as follows: incident solar radiation (RAD, MJ m^{-2}), rainfall (RAIN, mm), minimum air temperature (TMIN, °C), maximum air temperature (TMAX, °C) and average air temperature (TAVE, °C). These variables were chosen because they were selected in the Stepwise procedure. We used the Stepwise regression modeling procedure ($p \leq 0.15$), using SAS 9.0 software (SAS Institute 2002). The meteorological variables were considered independent input variables in the models and the tree growth variables were considered as dependent variables.

2.3.5 Multivariate analysis of variance and canonical correlations

Multivariate analysis of variance (MANOVA) was used to test whether the vectors of means for the two groups were sampled from the same sampling distribution. The MANOVA was used for two main reasons: firstly, because there are several correlated dependent variables and the researchers wanted a single, overall statistical test for this set of variables instead of performing multiple univariate tests, and secondly, was to explore how independent variables influence some patterning of response on the dependent variables. Once the statistics of Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace and Roy's Greatest Root are obtained, they are translated into F statistics in order to test the null hypothesis. More information about the statistical tests may be seen in Morrison (2005).

The goal of the canonical correlation was to describe the relationships between the two sets of variables, and to find their canonical weights (coefficients). The reason for using canonical correlations is that, in an agroforestry system, due the continuous tree growth which is influenced by meteorological conditions, some variables may be associated with one another and can be considered as independent variables (predictors) while others (predicted) are dependent upon previous variables. With respect to other statistical approaches for the study of multiple correlations, such as multiple linear regression (Apitz et al. 2009) which computes coefficients for individual trace elements depending on the major ones, CCA has the advantage of providing simultaneous estimates of coefficients for the multiple combinations of trace elements and multiple combinations of major elements with the best possible correlation.

An important property of canonical correlations is that they are invariant with respect to affine transformations of the variables: CCA finds the coordinate system that is optimal for correlation analysis, and the eigenvectors define this coordinate system. For more information on this technique, see (Sherry and Henson 2005; Wilks 2011).

Tree growth variables and meteorological variables were used to calculate the canonical correlation. Canonical correlation analysis was used to identify and quantify the relationship between two sets of traits by using the PROC CANCORR procedure (SAS Institute 2002). Canonical correlation analysis is based on correlations between a linear combination of a set of variables (Xp) and a linear combination of another set of variables (Wq). Linear combinations of variables are very useful for making comparisons and predictions (Johnson and Wichern 1986). Thus, linear combinations for sets of variables can be defined as follows:

$$U_i = a_{i1}X_1 + a_{i2}X_2 + ... + a_{ip}X_p \tag{1}$$

$$V_i = b_{i1}W_1 + b_{i2}W_2 + ... + a_{iq}W_q \tag{2}$$

Where a_{ip} and b_{iq} are canonical coefficients and U_i and V_i are the ith pair of canonical variates, Ui and Vi form the first pair of canonical variates which is associated to the first canonical correlation.

The total number of pairs of canonical variates was defined by the minimum value between Xp and Xq. For this study, the number of canonical pairs were four. Two sets of traits were established: group 1 contained predicted variables (SD, H, DBH and CD) and group 2 contained predictors variables related to meteorological variables (RAD, RAIN, TMIN, TMAX and TAVE). The verification of the significance between the groups of variables was evaluated based on the statistic chi-square test.

Additional analyses were made in order to evaluate the treatment effects and possible interactions between agroforestry systems, seasons and cultivation years. Tree growth variables were statistically analyzed with the software SAS 9.0 (SAS Institute 2002). Data were initially examined for homogeneity of variance among years for tree values, and then subjected to analysis of variance. The Tukey test ($p> 0.05$) was used to compare the difference between the treatments.

2.4 Results and Discussion

The air temperature during the years of the experiment ranged from -2.6 ºC to 37.0 ºC, with an average temperature of 18.8 ºC. The flux of global solar radiation was 17.35 MJ m^{-2} day^{-1} on average, with a variation of 0.49 to 38.46 MJ m^{-2} day^{-1}. The rainfall accumulated during the experimental period (January 2011 to December 2016) was 12,329.3 mm (Fig. 3). In general, solar radiation had the highest values in the first and last month of the year (summer season) and diminished values during June and July (winter season).

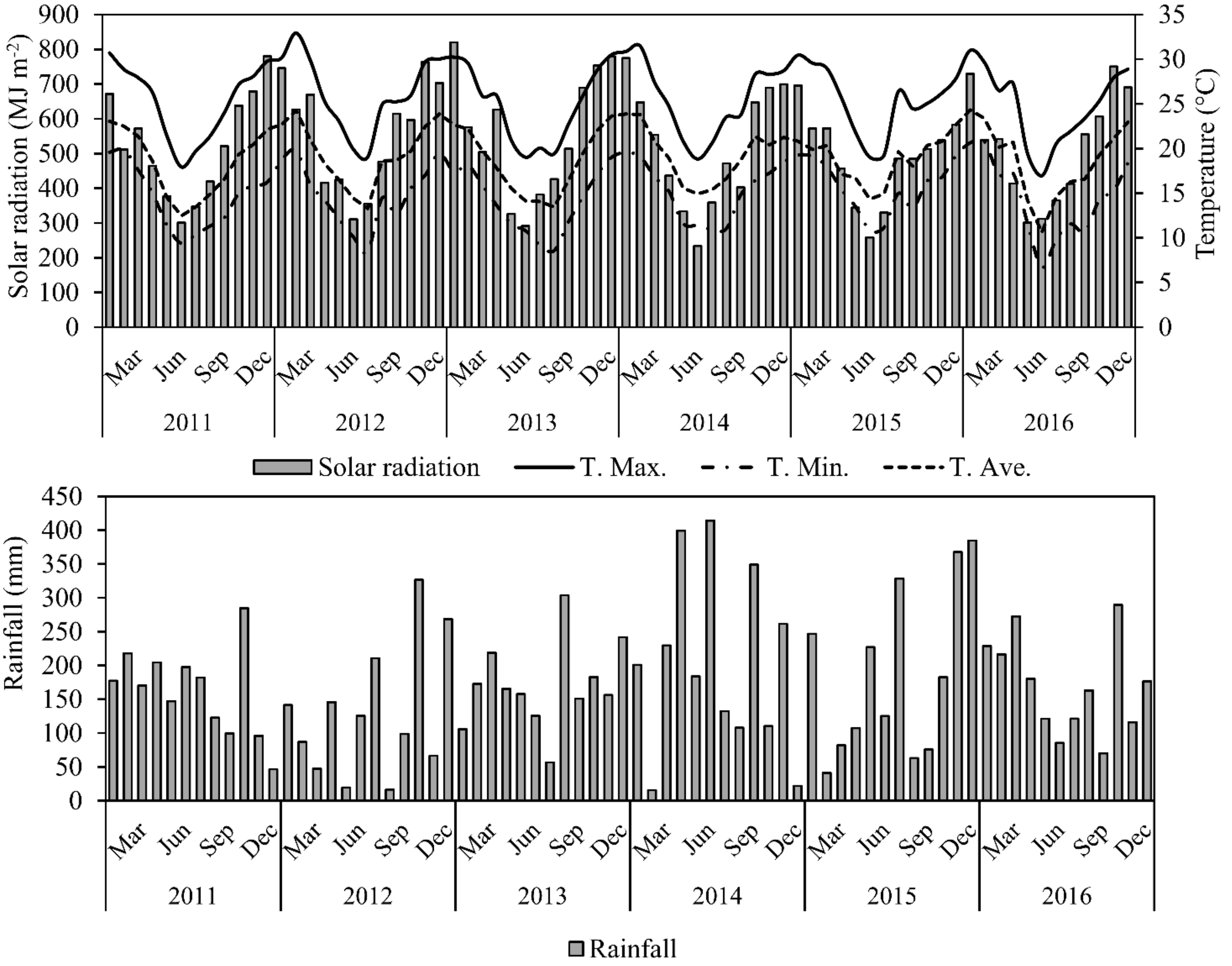

Fig 3. Average monthly values for minimum, maximum and average temperature (T.Max, T.Min and T.Ave), accumulated incident solar radiation, and accumulated rainfall during the experimental period. Frederico Westphalen - RS, Brazil.

Tung trees require specific climatic conditions. Tung trees require average air temperatures of 18.7-26.2°C, hot summers with abundant moisture, with usually at least 1,120 mm of rainfall evenly distributed throughout the year (Duke 1983). The trees require 350-400 hours in winter with temperatures at 7.2°C or lower; without this cold requirement, trees tend to produce suckers from the main branches. Trees are also susceptible to cold damage when in active growth (Duke 1983).

According to variance analysis, we observed interactions between evaluation years and agroforestry systems for all growth variables analyzed; for the seasons of the year, interactions were not observed, because of this, the main effect was analyzed. Tung trees cultivated in the intercrop II system showed greater tree growth when compared to the intercrop I system (Fig. 4). In general, all growth variables analyzed showed greater values for the intercrop II system.

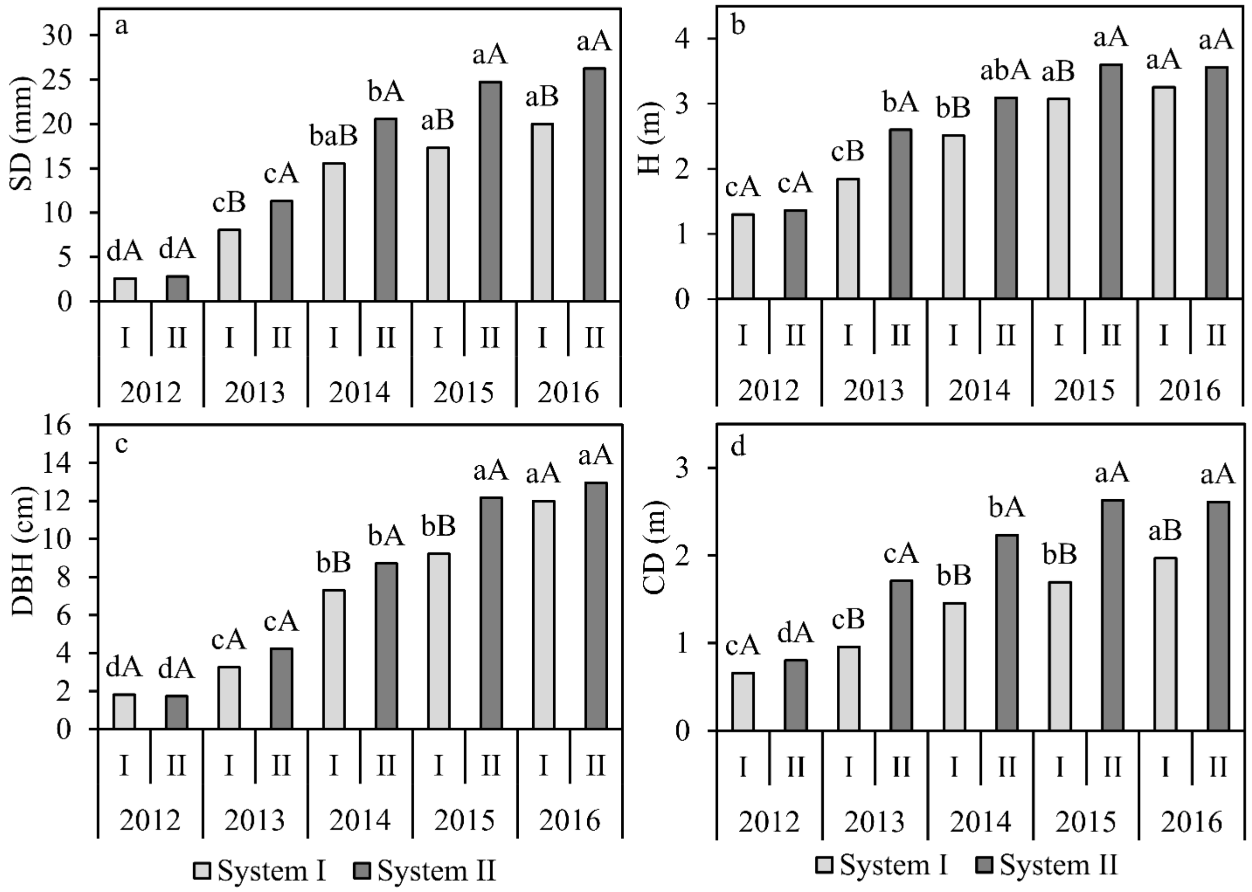

Fig 4. Stem diameter (SD), height (H), diameter at breast height (DBH) and crown diameter (CD) of *Aleurites fordii* in two agroforestry systems (System I: 12 x 12m and System II: 6 x 6m) during the experimental period. Means followed by the same letter do not differ among themselves. Uppercase letter compare the agroforestry systems for each year and lowercase letters compare the evaluation years for each agroforestry system by Tukey test ($p<0.05$).

For the first and last evaluation year, no significant differences for the variables height and diameter at breast height between the agroforestry systems were observed (Fig. 4b, c). This response can be explained by initial periods of tree growth, as competition for resources was reduced due to the smaller height and canopy of the trees. According to the continuous tree growth (height, diameter and canopy closure) the intraspecific competition was greater; this resulted in a greater tree growth in the agroforestry system II which was not expected due to the greater competition among trees grown in reduced tree arrangements.

The greater degree of competition seen in the intercrop II system led to greater tree growth, a development which can be associated with a strategy of the trees to acquire more resources (solar radiation, water, nutrients) through greater plasticity of the tree canopy (Schröter et al. 2012; Longuetaud et al. 2013; Van de Peer et al. 2017). The results observed in the present study are consistent with those described by Binkley (2004) and Fernández and Gyenge (2009), whom reported that as long as enough resources are available (i.e. canopy closure is not reached) all trees of a stand will be equally efficient; however, when inter-tree competition begins, tree growth is determined by a tree's ability to acquire and utilize resources (solar radiation, water, nutrients).

Regarding the seasons of the year, the summer season was responsible for the greatest increase in tree growth variables (Fig. 5) while for the autumn, winter and spring seasons, significant difference for the tree growth variables were not observed. A difference of 20.6% between the summer season when compared to the other three seasons (autumn, winter, spring) was observed for the four growth variables (SD, DBH, H, CD).

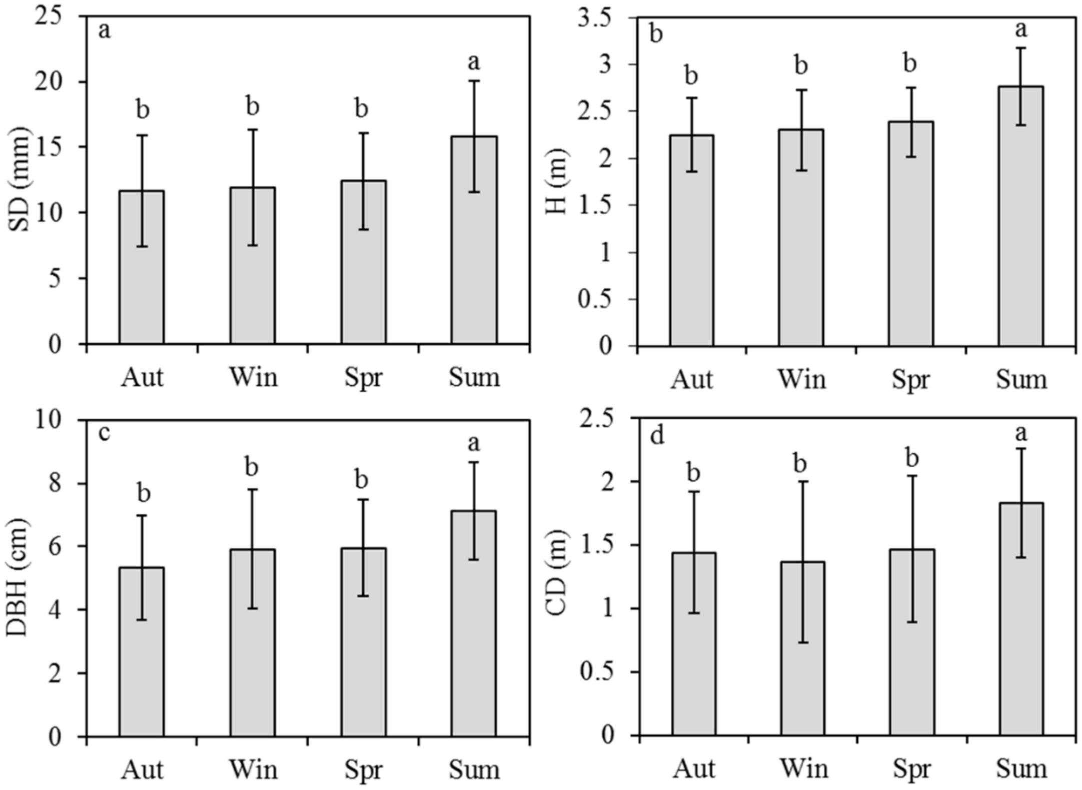

Fig 5. Stem diameter (SD), height (H), diameter at breast height (DBH) and crown diameter (CD) of *Aleurites fordii* in each season of the year. Each bar represents average values ± SE. Means followed by the same lowercase letter do not differ among themselves by Tukey test ($p<0.05$).

Tung growth is determined by the season of the year. In summer season, the tree growth is favored. A higher rate of incident solar radiation and the occurrence of higher temperatures benefits the photosynthetic rate of the trees and results in an increase in the production of photoassimilates which contribute to overall tree growth. On other hand, in the autumn, winter and spring seasons the growth of Tung trees was determined by variations in meteorological conditions. For each season of the year, determined meteorological variables influenced the tree growth variables; this was confirmed in the present study through the canonical correlations between meteorological variables and tree growth variables.

According to multivariate analysis, a significant effect in the four seasons of the year and in two agroforestry systems was observed (Table 1). The null hypothesis for all statistical tests Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace and Roy's Greatest Root were rejected. These statistical tests show that the data set represented in group 1 (tree growth variables) and group 2 (meteorological variables) were sampled from the same sample distribution.

Table 1. Multivariate analysis of variance for each season of the year and agroforestry systems. Frederico Westphalen - RS, Brazil.

Statistic	Autumn				Winter			
	System I		System II		System I		System II	
	Value	F Value	Value	F Value	Value	F Value	Value	F Value
Wilks' Lambda	0.16	2.87*	0.13	3.60**	0.19	2.54*	0.10	4.21**
Pillai's Trace	1.09	1.98*	1.06	2.08*	1.02	1.79*	1.13	2.26*
Hotelling-Lawley Trace	3.77	4.04*	5.09	6.08**	3.34	3.57*	6.45	7.70**
Roy's Greatest Root	3.36	17.63*	4.82	27.70*	3.03	15.93**	6.13	35.26**
Statistic	Spring				Summer			
	System I		System II		System I		System II	
	Value	F Value	Value	F Value	Value	F Value	Value	F Value
Wilks' Lambda	0.20	2.65*	0.10	4.52**	0.10	4.78**	0.06	8.21**
Pillai's Trace	1.08	2.27*	1.20	2.81*	1.26	3.28*	1.34	4.46**
Hotelling-Lawley Trace	2.78	3.08*	5.94	7.07**	5.13	6.53**	8.70	13.96**
Roy's Greatest Root	2.26	9.05*	5.49	23.32**	4.39	19.77**	7.94	43.65**

* and **: Significant by F test at 5% and 1% respectively.

The canonical correlation analysis and pair canonical significance for each season of the year and agroforestry systems are shown in Table 2. The canonical correlation analysis revealed that the groups of variables are not interdependent and demonstrates that multivariate relationships occurred between the two groups studied.

One canonical pair between characteristics from group 1 and 2 were significant for the autumn, winter and spring seasons for the agroforestry systems (Table 2). For the summer season, two significant canonical pairs were observed for the agroforestry systems (Table 2). The high magnitude of the canonical correlation coefficients indicate high dependence between the two groups of characters studied and reveals an association between these variates.

Table 2. Canonical correlation analysis for each season of the year and agroforestry systems. Frederico Westphalen - RS, Brazil.

Autumn									
System I					System II				
DF	CCA	Eigen.	Prop.	Cum.	DF	CCA	Eigen.	Prop.	Cum.
16	0.85*	3.36	0.89	0.89	16	0.89*	4.82	0.94	0.95
9	0.38^{ns}	0.34	0.09	0.98	9	0.15^{ns}	0.18	0.03	0.98
4	0.14^{ns}	0.07	0.02	0.99	4	-	0.09	0.02	0.99
1	-	0.01	0.001	1.00	1	-	0.01	0.001	1.00
Winter									
System I					System II				
DF	CCA	Eigen.	Prop.	Cum.	DF	CCA	Eigen.	Prop.	Cum.
16	0.84*	3.03	0.91	0.89	16	0.91*	6.13	0.95	0.95
9	0.08^{ns}	0.18	0.05	0.98	9	0.18^{ns}	0.20	0.03	0.98
4	.	0.11	0.03	0.99	4	.	0.11	0.02	1.00
1	.	0.01	0.003	1.00	1	.	-	-	1.00
Spring									
System I					System II				
DF	CCA	Eigen.	Prop.	Cum.	DF	CCA	Eigen.	Prop.	Cum.
16	0.79*	2.26	0.81	0.81	16	0.90*	5.49	0.92	0.92
9	0.44^{ns}	0.41	0.15	0.96	9	0.41^{ns}	0.37	0.06	0.99
4	0.31^{ns}	0.11	0.04	1.00	4	0.26^{ns}	0.09	0.01	1.00
1	.	-	-	1.00	1	-	-	-	1.00
Summer									
System I					System II				
DF	CCA	Eigen.	Prop.	Cum.	DF	CCA	Eigen.	Prop.	Cum.
16	0.88*	4.39	0.85	0.86	16	0.93*	7.94	0.91	0.91
9	0.59*	0.70	0.13	0.99	9	0.61*	0.74	0.08	0.99
4	0.09^{ns}	0.04	0.01	1.00	4	0.08^{ns}	0.03	0.003	1.00
1	-	-	-	1.00	1	-	-	-	1.00

DF: degree of freedom; CCA: Canonical correlation adjusted; Eigen: Eigenvalue; Prop: Proportion; Cum: Cumulative; * Significant by chi-square test at 5%; ns: Not significant

One canonical pair was significant for the autumn season. We observed a correlation coefficient (r=0.85 and r=0.89) between groups 1 and 2 for systems I and II, respectively (Table 2). The diameter at breast height, stem diameter and the total height (group 1) were directly related to the minimum air temperature (group 2) (Table 3).

Table 3. Canonical pairs estimated for Tung growth variables (group I) and meteorological variables (group II) in the seasons of the year (autumn and winter) in two agroforestry systems. Frederico Westphalen - RS, Brazil.

	Autumn							
Variables	System I				System II			
	Group I				Group I			
	1°*	2°	3°	4°	1°*	2°	3°	4°
SD	0.838	-0.546	0.007	0.007	0.877	-0.348	0.261	0.204
H	0.822	-0.178	0.285	0.460	0.628	0.027	0.357	0.691
DBH	0.986	-0.053	0.155	-0.040	0.942	0.104	0.292	0.131
CD	0.615	-0.425	0.625	-0.223	0.449	-0.113	0.775	0.431
	Group II				Group II			
	1°*	2°	3°	4°	1°*	2°	3°	4°
RAD	-0.609	0.727	-0.155	-0.277	-0.495	0.439	-0.325	-0.676
RAIN	-0.293	0.461	-0.813	0.204	-0.080	0.152	-0.970	0.170
TMIN	0.790	0.597	0.113	0.077	0.817	0.576	-0.008	-0.027
TMAX	-0.336	0.928	0.157	-0.022	-0.068	0.943	0.048	-0.322
TAVE	-0.132	0.701	-0.580	0.394	0.078	0.568	-0.783	0.242
	Winter							
Variables	System I				System II			
	Group I				Group I			
	1°*	2°	3°	4°	1°*	2°	3°	4°
SD	0.883	-0.098	0.459	0.012	0.864	0.289	0.296	0.287
H	0.790	0.390	0.309	-0.358	0.647	-0.071	0.739	0.172
DBH	0.939	0.235	0.158	0.195	0.947	-0.089	0.142	0.275
CD	0.581	0.495	0.612	0.207	0.512	-0.103	0.569	0.635
	Group II				Group II			
	1°*	2°	3°	4°	1°*	2°	3°	4°
RAD	0.855	-0.106	0.341	0.376	0.794	0.402	0.293	0.351
RAIN	-0.450	-0.661	0.470	0.584	-0.306	0.938	0.150	0.069
TMIN	0.031	0.153	0.746	0.647	0.058	0.532	0.584	0.611
TMAX	0.532	0.100	0.494	0.681	0.411	0.534	0.418	0.609
TAVE	-0.352	-0.033	0.620	0.701	-0.334	0.635	0.446	0.535

* Canonical pair significant by chi-square test at 5%

Worldwide tree growth is considered to be strongly influenced by air temperature (Körner 2003, Bhattacharyya et al. 2006) and a positive growth response to an increase in low temperature had been seen by Atkin and Tjoelker (2003) and Zanon and Finger (2010). The growth-temperature relationship is not a fixed constant (Dang et al., 2009; Gruber et al., 2009), because it may vary according to the season of the year and a species' sensitivity to the impacts of increasing and/or decreasing air temperature.

Regarding the tree species in the context of agroforestry systems, air temperature has a very important role in inducing plant dormancy. Deciduous trees (which lose their leaves in periods of low temperatures or water deficit) have a dormancy period when subjected to a certain duration of cold hours, which for the *Aleurites fordii* species is 350-400 hours with air temperatures of 7.2°C or lower (Duke 1983). The region of this study is characterized by an extreme minimum temperature below 0 (zero) °C, as well as the occurrence of frost. Accordingly, although the Tung trees are cold-adapted, significant damage in the apical buds was observed, which affected the growth of the upper third of the tree (Fig. 6).

Fig 6. Sugarcane shading on Tung trees (A); apical buds without damage (B1 and B2), and apical buds with damage due to the frost occurrence (C1 and C2). The scales refer to the length of the arrows.

The date/season of frost occurrence and the intensity of the minimum temperature and the occurrence and frequency of frost explain the damage observed in the trees. In this study we observed the occurrence of frost in the autumn season, specifically on the 7th and 8th of June 2012 and 11th and 12th of June 2016, with minimum air temperature values of -2.2°C, -1.2°C, -2.3°C and -1.9°C respectively. The occurrence of frost in the autumn season is detrimental because the branches and leaves are in full activity during this season. The occurrence of frost in these periods results in a reduction of cell division/expansion, the process of leaf senescence generally then follows shortly after, which then affects tree growth.

The observed results corroborated with those obtained by other authors. Hendrickson et al. (2004) found that minimum temperatures from 1°C to 3°C reduce the growth rate of *Vitis vinifera* by 34-63%. 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 resulted in 31.3% defoliation of exposed shoots of *Kandelia ovata*. Augspurger (2011) found that the death of branches reduced the overall canopy percentage, contributed to early senescence and reduced growth, and led to the death of *Aesculus glabra* yolks.

Our study demonstrated that the increase of minimum temperatures in the autumn season, might benefit the growth of Tung in agroforestry systems (Table 3), and thus methods of preventing the occurrence of low temperatures may yield significant results. In this context, we recommend the development of clones resistant to the occurrence of low air temperature (and frost), through new studies involving genetic improvement.

One canonical pair was significant for the winter season. We observed a correlation coefficient (r=0.84 and r=0.91) between groups 1 and 2 for the systems I and II, respectively (Table 2). The diameter at breast height, stem diameter and the total height (group 1) were directly related to incident solar radiation (group 2) (Table 3).

The occurrence of low air temperatures in winter is directly related to the period of dormancy for trees. Full winter dormancy is characterized by the suspension of growth processes (elongation and diametric growth), a reduction in metabolic activity, the enhancement of frost and desiccation resistance, and changes in cellular and cytoplasmic structures (Havranek and Tranquillini 1995). After the period of tree dormancy, a period of cellular reorganization occurs, and consequently new buds are formed.

Greater incident solar radiation and air temperature can stimulate the formation of new buds and consequently optimize the leaf area of the trees. This may benefit photosynthetic processes, and result in a greater accumulation of biomass and greater growth of Tung trees. These affirmations explain the correlation between solar radiation and growth variables in the winter season. Similar results were found by Havranek and Tranquillini (1995), whom reported that the occurrence of greater solar radiation and warmer days in the winter season resulted in a reorganization of cell structures, and chloroplasts which became enriched in thylakoid membranes (Senser and Beck, 1979) and an anticipated return of photosynthetic processes.

Regarding the spring season, the associations established through the first canonical pair presented correlations (r = 0.79 and r = 0.90) for the systems I and II, respectively. The diameter at breast height and stem diameter (group 1) were highly related to greater amounts of incident solar radiation and with an increase of minimum and average air temperatures (group 2) (Table 4).

Table 4. Canonical pairs estimated for Tung growth variables (group I) and meteorological variables (group II) in the seasons of the year (spring and summer) in two agroforestry systems. Frederico Westphalen - RS, Brazil.

	Spring							
Variables	System I				System II			
	Group I				Group I			
	1°*	2°	3°	4°	1°*	2°	3°	4°
SD	0.902	0.023	-0.420	0.096	0.809	0.554	0.024	-0.195
H	0.626	-0.378	-0.443	0.520	-0.575	0.402	0.711	-0.044
DBH	0.933	-0.206	-0.090	0.281	0.951	0.238	0.154	0.123
CD	0.694	0.130	-0.205	0.678	-0.667	0.611	0.287	0.315
	Group II				Group II			
	1°*	2°	3°	4°	1°*	2°	3°	4°
RAD	0.854	0.131	-0.504	-	0.877	-0.276	0.394	-
RAIN	0.423	0.861	-0.283	-	0.330	0.918	-0.219	-
TMIN	0.717	-0.015	0.697	-	0.792	0.302	-0.530	-
TMAX	0.499	0.382	0.778	-	-0.487	0.507	-0.711	-
TAVE	0.739	0.084	0.765	-	0.722	0.343	-0.601	-
	Summer							
Variables	System I				System II			
	Group I				Group I			
	1°*	2°*	3°	4°	1°*	2°*	3°	4°
SD	0.837	0.419	0.208	0.285	0.895	-0.588	0.332	0.080
H	0.643	-0.846	-0.171	0.742	0.694	-0.830	0.416	0.582
DBH	0.926	-0.523	0.097	0.290	0.938	-0.720	0.326	0.013
CD	0.335	-0.030	0.812	0.477	0.410	0.155	0.862	0.254
	Group II				Group II			
	1°*	2°*	3°	4°	1°*	2°*	3°	4°
RAD	-0.817	0.574	0.046	-	-0.726	0.646	-0.051	-
RAIN	0.834	-0.589	-0.750	-	0.769	-0.654	-0.653	-
TMIN	0.649	0.558	-0.517	-	0.570	0.363	-0.511	-
TMAX	-0.643	0.764	-0.057	-	-0.566	0.808	-0.161	-
TAVE	-0.353	0.297	-0.887	-	-0.231	0.191	-0.954	-

* Canonical pair significant by chi-square test at 5%

Storage material accumulated during autumn appear to be marginally affected by winter respiration and are thought to be mainly used for new spring growth (Kimura 1969). Budbreak and new leaf growth in spring are not dependent on reserve materials but are exclusively supplied by recent photosynthates from the previous year's leaves (Hansen and Beck 1994). Any restriction of carbohydrate production during the spring before budbreak could result in the inhibition of new leaf emissions and consequently affect tree growth.

Greater incident solar radiation and air temperature in the spring season can benefit the photosynthetic rate of Tung trees. This can be explained by the greater leaf area of the buds which optimize the interception of solar radiation. The buds exhibit a high rate of photosynthetic activity per unit leaf area, and in this context, greater photoassimilate production favors primary growth and especially the secondary growth of the trees. This relationship can be seen by the high correlations between the growth variables diameter at breast height and stem diameter, and meteorological variables (Table 4). According to Boardman (1977), Chaves et al. (2005) and Li et al. (2016), photosynthetic activity determines plant growth through an increase or decrease in the production of photoassimilates as a function of meteorological conditions.

Two canonical pairs were significant for the summer season (Table 2). We observed a correlation coefficient (r=0.88 and r=0.93) between groups 1 and 2 for the first canonical pair and (r=0.59 and r=0.61) for the second canonical pair for systems I and II, respectively (Table 2). Regarding the first canonical pair (Table 4), we observe that the diameter at breast height and stem diameter (group 1) were directly related to rainfall and inversely influenced by incident solar radiation (group 2).

All plants depend on the availability of water, nutrients and solar radiation, resources which are essential for growth (Toledo et al. 2011). In temperate climactic regions (conditions of this study), variability in the distribution of rainfall and the occurrence of great amounts of incident solar radiation, especially in the months of January to March (summer season), is a common occurrence. Accordingly, tree growth is dependent upon the availability and the efficient use of available natural resources in each season of the year. In general, tree growth increases with rainfall (Murphy and Lugo 1986; Morales et al. 2004; Dauber et al. 2005) and decreases in periods of drought (Nath et al. 2006; Lola da Costa et al. 2010).

An inverse response from what was observed in the winter season was verified for the summer season where the occurrence of high amount of solar radiation negatively influenced the growth of Tung trees (Table 4). The negative effect of excessive solar radiation is related to the increase of the transpiratory rate of the plant, and results in stomatal closure and reduction of photosynthesis.

Another point to be observed is related to the capacity of the carotenoids in dissipating energy as heat through the formation of toxic byproducts which affect the photosynthetic apparatus through the degradation of the membrane due to luminous saturation (Taiz and Zeiger, 2013).

Regarding the second canonical pair, an inverse correlation between height and crown diameter with maximum air temperature was observed. The occurrence of high air temperatures significantly affect the apical meristem of the Tung trees causing a reduction in the process of cell division and, in some cases, the death of cells (Taiz and Zeiger, 2013). The effects of high air temperature can be associated with a reduction in water availability.

The occurrence of high air temperature associated with periods of low rainfall may limit the growth of a plant. Sands and Mulligan (1990), Landsberg (2003) and Elli et al. (2017) reported that water availability and air temperature are the most common limiting factors for trees growth due to their effect on stomatal closure and opening which regulates the absorption of nutrients from the soil, as well as the chemical and biochemical reactions of photosynthesis.

A similar response for the two agroforestry systems (system I and system II) in the four seasons of the year (Table 3 and 4) were observed. These results suggest that the spacing between trees did not affect the correlation between tree growth and the meteorological variables. The differences between tree responses due to the competition for available resources was not great enough to alter the canonical correlation in the different agroforestry systems. This is not to say that tree growth was similar in both agroforestry systems, but rather that the trees grown in the system II were more efficient in acquiring and utilizing available resources.

In this study, the meteorological variables showed a strong influence on the variables of diameter at breast height and stem diameter with magnitudes above 0.90 in most cases, independent of the season of the year and the agroforestry systems. This result indicates that the meteorological variables directly influenced the secondary growth of the Tung trees, which occurred due to an increase in thickness and activity of the phellogen. In order to quantify the effect of the meteorological variables on tree growth, a Stepwise regression modeling procedure was performed.

The equation generated by stepwise procedure showed more than one meteorological variable selected to compose the model (Table 5 and 6). It is possible to affirm that the Tung growth is affected not only by isolated meteorological variables, but also by a set of variables which combined can affect Tung growth in agroforestry systems differently in each different seasons of the year.

Table 5. Stepwise multiple regression between Tung growth variables and meteorological variables during the seasons of the year (autumn and winter) in two agroforestry systems. Frederico Westphalen - RS, Brazil.

Season	System	Regression equation	Confidence interval	R^2	% Contribution
Autumn	System I	SD = 73.29 + 7.02(TMIN) - 6.48(TMAX)	(16.2≤TMIN≥16.9)* (27.1≤TMAX≥27.9)	0.61	TMIN=42% TMAX=19%
		H = 331.78 + 91.08(TMIN) - 58.15(TMAX)	(16.2≤TMIN≥16.9) (27.1≤TMAX≥27.9)	0.53	TMIN=28% TMAX=25%
		DBH = -0.12 + 5.11(TMIN) - 2.87(TMAX)	(16.2≤TMIN≥16.9) (27.1≤TMAX≥27.9)	0.74	TMIN=45% TMAX=29%
		CD = -234.17 - 0.03(RAD) + 25.98(TMIN)	(17.3≤RAD≥18.5) (16.2≤TMIN≥16.9)	0.33	RAD=25% TMIN=8%
	System II	SD = 104.47 + 10.96(TMIN) - 9.90(TMAX) + 43.12(RAIN)	(16.2≤TMIN≥16.9) (27.1≤TMAX≥27.9) (4.0≤RAIN≥6.5)	0.77	TMIN=33% TMAX=29% RAIN=15%
		H = 538.64 + 80.83(TMIN) - 57.86(TMAX)	(16.2≤TMIN≥16.9) (27.1≤TMAX≥27.9)	0.32	TMIN=22% TMAX=10%
		DBH = 21.94 + 6.67(TMIN) - 3.77(TMAX) - 1.09(TAVE)	(16.2≤TMIN≥16.9) (27.1≤TMAX≥27.9) (19.7≤TAVE≥20.5)	0.74	TMIN=52% TMAX=19% TAVE=3%
Winter	System I	SD = -9.27 - 0.05(RAD) + 4.39(TAVE)	(10.2≤RAD≥11.1) (14.3≤TAVE≥15.0)	0.58	RAD=36% TAVE=22%
		H = 223.98 - 0.40(RAD) + 36.24(TMIN)	(10.2≤RAD≥11.1) (16.2≤TMIN≥16.9)	0.50	RAD=34% TMIN=16%
		DBH = -4.33 - 0.03(RAD) + 2.52(TAVE)	(10.2≤RAD≥11.1) (19.7≤TAVE≥20.5)	0.67	RAD=46% TAVE=21%
		CD = 27.80 - 0.24(RAD) + 30.17(TMIN)	(10.2≤RAD≥11.1) (16.2≤TMIN≥16.9)	0.32	RAD= 14% TMIN=18%
	System II	SD = -25.43 - 0.07(RAD) + 7.10(TAVE)	(10.2≤RAD≥11.1) (19.7≤TAVE≥20.5)	0.66	RAD=31% TAVE=35%
		H = 146.03 - 0.43(RAD) + 49.68(TMIN)	(10.2≤RAD≥11.1) (16.2≤TMIN≥16.9)	0.39	RAD=17% TMIN=22%
		DBH = 4.99 - 0.03(RAD) + 2.68(TMIN)	(10.2≤RAD≥11.1) (16.2≤TMIN≥16.9)	0.77	RAD=49% TMIN=28%

*Confidence interval (95%); R^2: Determination coefficient.

Table 6. Stepwise multiple regression between Tung growth variables and meteorological variables during the seasons of the year (spring and summer) in two agroforestry systems. Frederico Westphalen - RS, Brazil.

Season	System	Regression equation	Confidence interval	R^2	% Contribution
Spring	System I	SD = 518.23 - 0.29(RAD) - 76.76(TMIN) + 55.95(TAVE)	(17.0≤RAD≥18.6)* (13.5≤TMIN≥14.4) (18.2≤TAVE≥19.1)	0.58	RAD=33% TMIN=17% TAVE=8%
		H = 3699.58 - 1.12(RAD) - 116.60(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.33	RAD=16% TMIN=17%
		DBH = 167.06 - 0.05(RAD) - 5.02(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.59	RAD=44% TMIN= 15%
	System II	SD = 423.25 - 0.14(RAD) - 12.62(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.61	RAD=53% TMIN=8%
		H = 5106.99 - 1.54(RAD) - 164.11(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.34	RAD=20% TMIN=14%
		DBH = 267.25 - 0.08(RAD) - 8.41(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.78	RAD=61% TMIN=17%
		CD = 4380.85 - 1.41(RAD) - 134.14(TMIN)	(17.0≤RAD≥18.6) (13.5≤TMIN≥14.4)	0.44	RAD=35% TMIN=9%
Summer	System I	SD = -120.49 + 11.10(TMIN) - 3.27(TAVE)	(18.5≤TMIN≥18.9) (22.1≤TAVE≥22.9)	0.64	TMIN=38% TAVE=26%
		H = 712.07 - 0.21(RAD) + 47.52(RAIN)	(22.4≤RAD≥23.9) (5.1≤RAIN≥8.4)	0.46	RAD=26% RAIN=20%
		DBH = -327.95 - 0.11(RAD) - 8.58(TMIN) + 24.72(TMAX)	(22.4≤RAD≥23.9) (18.5≤TMIN≥18.9) (29.3≤TMAX≥30.0)	0.72	RAD=58% TMIN=10% TMAX=4%
	System II	SD = -184.79 + 16.51(TMIN) - 4.70(TAVE)	(18.5≤TMIN≥18.9) (22.1≤TAVE≥22.9)	0.75	TMIN=48% TAVE=27%
		H = -1046.59 + 117.31(TMIN) - 37.32(TAVE) + 31.34(RAIN)	(18.5≤TMIN≥18.9) (22.1≤TAVE≥22.9) (5.1≤RAIN≥8.4)	0.63	TMIN=24% TAVE=21% RAIN=18%
		DBH = -533.18 - 0.16(RAD) - 12.63(TMIN) + 38.07(TMAX)	(22.4≤RAD≥23.9) (29.3≤TMAX≥30.0) (18.5≤TMIN≥18.9)	0.79	RAD=53% TMAX=21% TMIN=5%

*Confidence interval (95%); R^2: Determination coefficient.

For the autumn season, the meteorological variable that presented the greatest contribution to the models was minimum air temperature, while for the winter and spring seasons the greatest contribution to the models was incident solar radiation. In addition, for the summer season, two variables (minimum air temperature and incident solar radiation) showed greater contributions to the equations (Table 5 and 6). Regarding the influence of the meteorological variables on Tung growth, it was possible to conclude that the incident solar radiation and minimum air temperature were the meteorological variables that provided the greatest influence on the Tung growth in agroforestry systems in the different seasons of the year. These affirmations are confirmed by the high correlation, both positive and negative, for these variables in the canonical correlation analysis (Table 3 and 4).

The use of canonical correlation analysis aided in the understanding of the dynamics of the meteorological conditions in the different seasons of the year on the growth of the Tung trees cultivated in agroforestry systems. With our findings, we can recommend some management practices in order to promote the growth of the forest species, and in addition, to help facilitate the cultivation of crops in its understory. According Monteith et al. (1991), the principles of complementarity in resource utilization hold good for agroforestry systems, and should form the guidelines for the development of new agroforestry systems.

In the summer season, the occurrence of high temperatures associated with periods of low water availability (due to the reduction of rainfall) negatively affected the Tung growth variables. For this reason, we recommend the use of irrigation as a way to mitigate these damages. In the winter season, the increase in the availability of solar radiation benefits the growth of Tung trees. In this study, consortium with the sugarcane crops in the initial periods after the establishment of the agroforestry systems, provided shading on the Tung trees, which affected its growth (Fig. 6). Due to this interaction, we recommend the use of wider spacings in order to avoid the competition between the forest species and crops, especially in the initial periods after the establishment of the agroforestry systems.

The information generated in this study can aid in the planning of new agroforestry systems. This is especially relevant in the context of Brazilian law No. 12,651, May 25, 2012, which established a new Forest Code that allows farmers to plant agroforestry systems in areas of permanent preservation (APP) and legal reserves (RL), provided that those systems are subject to a sustainable management plan.

2.5 Conclusions

The groups of meteorological variables and *Aleurites fordii* growth variables are not interdependent, especially regarding the secondary growth observed in the variables diameter at breast height and stem diameter; these showed high magnitudes when correlated with the meteorological variables, and support the first hypothesis.

The seasons of the year influenced *Aleurites fordii* growth in a differentiated way. The summer season was responsible for the greatest tree growth, supporting the second hypothesis. The incident solar radiation and the minimum air temperature were the main meteorological variables that affected tree growth. The Tung trees showed greater growth when cultivated in the intercrop II system due to the greater ability to acquire and utilize the available resources.

Canonical correlation analysis enabled researchers to generate important information for the forest sector (e.g. recommendations for species management), by examining the influence of meteorological variables on tree growth; affirmations were supported by high degrees of significance for the groups of variables analyzed, and this confirms the third hypothesis.

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3 ARTIGO II - PLANT GROWTH, RADIATION USE EFFICIENCY AND YIELD OF SUGARCANE CULTIVATED IN AGROFORESTRY SYSTEMS: AN ALTERNATIVE FOR THREATENED ECOSYSTEMS

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Situação: em avaliação

Front page

Plant growth, radiation use efficiency and yield of sugarcane cultivated in agroforestry systems: An alternative for threatened ecosystems

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Key words: biomass partitioning, crop systems, growth rates, *Sacharum officinarum* L., yield traits.

Running title: An approach about sugarcane in agroforestry systems

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3.1 ABSTRACT

Sugarcane (*Sacharum officinarum* L.) monocropping has had a great socio-economic and environmental impact in Brazil, and agroforestry systems have been considered as an alternative for more sustainable production; however, there is a lack of field research under such conditions. The aim of this study was to evaluate the growth rates, radiation use efficiency and yield traits in sugarcane cultivated in the understory of *Aleurites fordii*, in two agroforestry arrangements and monocropping systems. A field experiment was conducted from July 2015 to June 2016 in the city of Frederico Westphalen – Rio Grande do Sul, Brazil. The radiation use efficiency, assimilate partitioning, leaf area index, absolute growth rate, net assimilation rate, number of tillers, plant height, % of intercepted solar radiation, extinction coefficient, and yield in each system were evaluated. In agroforestry systems, the dynamic interactions between multiple plant species change with the time, and can result in unique microclimates. The use of agroforestry systems in 12 x 12m arrangements should be prioritized because it enables greater yields and radiation availability in the understory. This 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 agroecosystems.

3.2 INTRODUCTION

One of the greatest national and global challenges is to generate a 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 agroecosystems (Godfray et al. 2010). Agroforestry systems deserve to be highlighted in this scenario and are a promising strategy in order to achieve these objectives. These systems consist of integrated land uses, for example, land used for forestry purposes, crop production, and/or raising livestock. Such systems provide clear agro-ecological advantages over systems in which only one crop species is grown (Brooker et al. 2014). Advantages include higher production per unit of land (Zhang et al. 2007; Li et al. 2013), greater resource-use efficiencies of water and nutrients (Vandermeer 1989; 2011), greater carbon sequestration in the soil (Makumba et al. 2006; Cong et al. 2014), and an increased input of organic matter, which has been shown to improve chemical, physical and biological properties of soil (Tracy and Zhang 2008; Salton et al. 2013).

Intercropping is a dominant strategy of agriculture in many parts of the world, i.e. sub-Saharan Africa and large parts of Latin America, and provides an estimated 20% of the world’s food supply (Altieri 2009; Chappell et al. 2013). Despite the great potential of intercropping, little research has been carried out to determine the traits of cultivated species which drive the positive effects of intercropping systems.

Brazil is one of the major sugarcane producing countries in the world, with estimates for 2015/2016 of 8.97 million hectares in planted area, which yields 685 million tn of sugarcane, with an average yield of 76 tn ha^{-1} (Conab 2016). Sugarcane (*Sacharum officinarum* L.) monocropping has had a great socio-economic and environmental impact in Brazil, and agroforestry systems (AFs) have been considered as an alternative for the sustainable production in threatened ecosystems. Despite the potential for AFs previously described, little research has been carried out to assess plant growth, yield traits, and the dynamics of resources available in these systems.

The dynamic interactions between plants in agroforestry systems is especially relevant in areas in which plants grow beneath trees, given that a tree's height, crown projection, and leaf area index can influence the distribution of existing resources such as solar radiation (Muller et al. 2014, Elli et al. 2016). The amount of solar radiation transmitted through the canopy can be presented in direct or diffuse forms, which is a determining factor in the internal microclimate of a system (Pezzopane et al. 2015). Direct and diffuse radiation can affect radiation use efficiency and light extinction coefficients (Campbell and Norman 1998), which in turn may modify the growth rate (Pinto et al., 2005), assimilation and partitioning of photoassimilates produced by species in the understory (Mendes et al. 2013). In the case of sugarcane, the response due to reduced radiation available within the canopy can be optimized. Sugarcane, a C4 metabolism plant, has a high solar radiation demand, in order to meet the photosynthetic rates of plants.

Biomass production in plants depends upon the quantity of absorbed photosynthetically active radiation (PARa) by leaves, and the efficiency by which leaves convert and assimilate the radiant light through photosynthesis. Thus, the intercepted photosynthetically active radiation (PARi) that is converted into biomass reveals the efficiency of the use of radiation (εb) by a species (Monteith 1977; Van Heerden et al. 2010). While photosynthesis is the basis for the production of biomass, little attention has been given to the radiation use efficiency in order to improve sugarcane yields (Zhu et al. 2010; Flood et al. 2011). Solar radiation intercepted by the plant canopy is the most important component for growth analysis, but to estimate this radiation, it is necessary to know the LAI and the extinction coefficient.

Solar radiation can change at different points in the understory of agroforestry systems (Paciullo et al. 2011), depending on the area of shade provided by the canopy, and the orientation and spacing of the trees. Thus, new projects should be developed in order to evaluate the growth, yield and radiation use efficiency of sugarcane cultivated in different agroforestry arrangements, as well as in different positions within each system. There is a lack of published results for field experiments under such conditions.

To address this lack of information, the following hypothesis was created: Sugarcane cultivated in agroforestry systems presents a sugarcane yield, radiation use efficiency and plant growth equal or greater to that of sugarcane produced in monocropping systems, and thus can be recommended to farmers as a sustainable alternative of production in threatened ecosystems. The aim of this study was to evaluate the growth rates, radiation use efficiency, and yield traits of sugarcane cultivated in the *Aleurites fordii* understory, in two agroforestry arrangements and a monocropping system.

3.3 MATERIAL AND METHODS

3.3.1 STUDY AREA AND EXPERIMENTAL DESIGN

A field experiment was conducted from July 2015 to June 2016 in the city of Frederico Westphalen – Rio Grande do Sul, Brazil, at the coordinates 27º23'48" S, 53º25'45" W and an altitude of 490 m. According to Köppen’s climate classification (Alvares et al. 2013), the climate is Cfa, i.e., humid subtropical with a mean annual temperature of 19.1°C, and varying maximum and minimum temperatures of 38ºC and 0°C, respectively. The experiment was performed in ratoon sugarcane (1st cut performed on 07/26/2012), and the analyses were conducted in the 4th cut, crop cycle 2015/2016.

The soil of the experimental area was classified as typical Entisol Orthents. Fertilization was carried out in response to a soil analysis following the recommendations for sugarcane crops (CCSF, 2004).

The experimental design was a randomized complete block, characterized by a factorial arrangement of 3x3x9, with three cropping systems, two agroforestry systems (12 x 12m and 6 x 6m) and an isolated system with sugarcane; three positions in line of the agroforestry systems (Line 1, Line 2 and Line 3); and eight months of plant collection, with three repetitions. The first evaluation of sugarcane occurred in September 2015 and the last in May 2016. The sugarcane utilized was developed by the Agronomic Institute of Campinas (IAC), cultivar IAC 87-3396, which is characterized by a high yield, sucrose content, and excellent adaptation to soils with lower fertility.

In the 12 x 12 system, forest species were distributed in lines spaced at 12m. The sugarcane was distributed in eight lines arranged in correspondence to each interval between the lines of forest species, totaling 16 lines throughout the system. In the 6 x 6 system, the forest species was planted in lines spaced at 6m. The sugarcane was distributed in four lines in each interval corresponding with lines of *Aleurites fordii* plants. A total of 15 trees were allocated to each experimental unit.

The forest species were planted in the experimental field in September, while the sugarcane was planted in November 2011. After plowing and harrowing seedlings were manually planted. In both systems, the sugarcane had a spacing of 1.20m and a density of 16 buds per meter, with both tree and sugarcane lines oriented from East to West. After planting the sugarcane, plots were delineated by stakes set two meters apart, and were distributed at different points in the understory of each experimental unit. In the 12 x 12 system lines L1, L2 and L3 of the evaluation were positioned at a distance of 1.2m, 3.6m and 4.8m from the *Aleurites fordii* species, respectively. Differently, in the 6 x 6 system lines L1, L2 and L3 were positioned at 1.2m, 2.4m and 1.2m, respectively. These plot areas were chosen with the objective of representing microclimate conditions in areas under the canopy of each agroforestry system. For subsequent analyses of the data, average values of the lines in each system were calculated in order to comply with the objectives of this study. The arrangement of tree, sugarcane, and plot of evaluation are shown in Fig. 1.

Figure 1

Forest species Tung (*Aleurites fordii*), of the Euphorbiaceae family, an exotic species with deciduous characteristics, was used to establish the agroforestry system. It was chosen because of its adaptability to environmental conditions and high oil content in its fruits, which make it a viable option for the composition of agroforestry systems. Table I describes the allometric characteristics of *Aleurites fordii* plants.

Table I

3.3.2 PLANT GROWTH EVALUATIONS

The sugarcane was cut on July 2, 2015; evaluations started 84 days after cutting (DAC), due to the slow initial growth of shoots, evaluations were performed every 30 days, with the last at 332 DAC, amounting to 9 months of plant collection. In each evaluation period, a total of 48 plants were collected, and two representative plants per evaluation plot were analyzed, resulting in a total of 432 evaluated plants. On the day of collection, tiller numbers were counted and plant height was measured with a metric tape measure.

In the laboratory, plant sectioning was performed, as well as the preparation of leaf discs to determine the leaf area and dry matter partitioning. The total dry matter (TDM) of the plants was determined as the sum of the components: leaf, pseudoculm+senescent, and stalk. Each component was gathered and placed in labeled, individual paper sacks. The sacks were then sent into a forced circulation oven at 60°C until a consistent mass was obtained. The samples were later weighed on a precision balance in order to obtain the dry mass of each component, which together resulted in the TDM.

Leaf area (LA) was calculated according to the equation:

$$\text{LA} = (\text{n}^{\text{o}}\ \text{discs}*\text{punch disc area})*\frac{(\text{DM leaves+discs})}{\text{DM discs}}$$

Where, n° discs = number of discs by sample; punch area = punch disc area in mm^2; DM leaves = total dry matter of the leaves, in grams; and DM discs = dry matter of the disc, in grams. The leaf area index (LAI) from the total leaf area of each plant and the soil area (SA) occupied by plants was determined according to the equation: LAI = LA/SA.

Based on the results of dry matter and leaf area, the growth analysis of the variables was conducted: total dry matter (TDM, g m^{-2}), absolute growth rate (AGR, g day^{-1}); net assimilation rate (NAR, g m^{-2} day^{-1}) according to the methodology described in the literature (Thornley 1976; Marafon et al. 2012).

3.3.3 EXTINCTION COEFFICIENT AND LIGHT INTERCEPTION

Solar radiation at each evaluation period was measured using a portable sensor pyranometer (LICOR PY32164) coupled to a Datalogger (LICOR 1400). The values of incident global solar radiation were obtained from the meteorological station of the National Meteorology Institute, situated roughly 200m from the experiment. The values of active photosynthetically radiation were estimated to be 45% of global solar radiation. This fraction follows the average values found by Assis and Mendez (1989). The estimation of accumulated photosynthetically active radiation was based on the methods by Monteith (1977) and Varlet-Grancher et al. (1989).

The extinction coefficient (k) was calculated using the following equation:

$$k = -\frac{\ln\left(\frac{Rn}{Rt}\right)}{LAI}$$

Where k = extinction coefficient; Rn = solar radiation measured under the plant canopy (MJ m^{-2}); Rt = radiation above the plant canopy (MJ m^{-2}); LAI = leaf area index.

The values for intercepted global radiation (IGR) were measured monthly, where the incident radiation was measured above and under the plant canopy with a portable pyranometer, which recorded measurements in the period from 10 to 12h. The values of intercepted global radiation were obtained according to the following equation:

$$\% \text{ Intercepted} = [100 - (Rn \times 100 / Rt)]$$

Where: Rn = incident radiation under the canopy; Rt = incident radiation above the canopy.

3.3.4 RADIATION USE EFFICIENCY

Production of dry matter was based on the model proposed by Monteith (1977), whereby the dry matter production was calculated from intercepted photosynthetically active radiation (PARi) multiplied by the use efficiency. The εb was calculated by the relation between the average production of accumulated TDM and the PARi involved in the production of biomass according to following expression:

$$TDM = \varepsilon b * PARi$$

Where TDM = total dry matter produced (g m^{-2}); PARi = intercepted photosynthetically active solar radiation (MJ m^{-2}); and εb = radiation use efficiency of dry matter produced (g MJ^{-1}). The value of the radiation use efficiency given by the angular coefficient represents the amount of accumulated biomass for each unit of intercepted energy.

Values for intercepted photosynthetically active radiation were based on the model proposed by Varlet-Grancher et al. (1989):

$$PARi = 0.95 * (PARinc) * (1- e^{(-k * LAI)})$$

Where: PARi = intercepted photosynthetically active radiation (MJ m^{-2}); PARinc = incident irradiant photosynthetically active radiation (MJ m^{-2}); k = extinction coefficient, which was set to 0.20 for all systems, as this was the average value obtained in this study; LAI = leaf area index.

3.3.5 YIELD TRAITS AND STATISTICAL ANALYSIS

The yield traits were evaluated at 350 DAP, by collecting and weighing the sugarcane stalk samples from each plot, and each of the twelve different positions in each system, in order to obtain greater homogeneity of the samples. The yield was determined based on the variables stalk weight and juice volume. The stalk weight (SW, t ha^{-1}) was obtained with the aid of a digital scale. The juice volume (JV, m^3 ha^{-1}), was obtained from milling the stalk and measuring the obtained juice with the aid of a graduated cylinder with a capacity of 1 L.

The data was statistically analyzed with the software “Statistical Analysis System” (SAS, 2003). The results were obtained through the analysis of variance. According to the F test, significant differences were found at 5% probability among the cropping systems. We reject the null hypothesis H0. The Dunnet test ($p> 0.05$) was used to compare the 12 x 12 and 6 x 6 intercropping systems with the control (monocropping system) and the Tukey test ($p> 0.05$) to compare the difference between intercropping systems 12 x 12 and 6 x 6. In addition, a regression analysis for the variable of intercepted global radiation was performed.

3.4 RESULTS

3.4.1 METEOROLOGICAL CONDITIONS

The air temperature during the sugarcane crop cycle ranged from 6.3ºC to 31.0ºC, with an average temperature of 19.2ºC; the flux of global solar radiation was 15.89 MJ m^{-2} dia^{-1} on average, with a variation of 1.98 to 33.03 MJ m^{-2} dia^{-1}; the rainfall accumulated during the crop cycle was 2587.5mm (Fig. 2).

Figure 2

3.4.2 RADIATION USE EFFICIENCY AND LIGHT INTERCEPTION

Growth of TDM presented a positive linear relationship with PARia during the crop cycle and presented high correlation coefficients (Fig. 3A). We observed variations in the radiation use efficiency of the conversion into biomass, in different cropping systems and evaluation lines within the agroforestry systems.

Figure 3

Of the crop systems, the greatest radiation use efficiency of sugarcane was obtained by the isolated system (2.28 g MJ^{-1}). In relation to the evaluation lines, we observed that for the 12 x 12 system, line 3 showed a greater efficiency, 2.03 g MJ^{-1}, when compared to the lines L1 and L2, which showed values of 1.89 and 1.85 g MJ^{-1}, respectively, revealing a 9% difference for plants located in the center of the plot. For the 6 x 6 system, we observed a greater radiation use efficiency in line 2, which demonstrated 1.96 g MJ^{-1}, i.e., 10 and 6% higher than the values in line 1 (1.77 g MJ^{-1}) and line 3 (1.84 g MJ^{-1}) of the evaluation, respectively (Fig. 3A).

The intercepted global radiation showed a quadratic response for the different cropping systems and evaluation lines (Fig. 3B). The greatest amount of intercepted global radiation was observed for the isolated system of sugarcane, which intercepted 89.3% of incident radiation at 237 DAC. In the agroforestry systems, we found different response values for each evaluation line. In the 12 x 12 system, we observed a reduction of 16.5 and 12.5% in the interception of radiation with the sugarcane lines nearest to the forest species (L1 and L2), when compared to L3, which intercepted 85.4% of the radiation at 265 DAC. Furthermore, the 6 x 6 system showed a similar response, where lines L1 and L3 presented lower values of 13 and 8.5% in the interception of radiation compared to the L2 evaluation line, which showed 82.3% interception of the incident solar radiation at 265 DAC (Fig. 3B).

3.4.3 LIGHT EXTINCTION COEFFICIENT

The k values were similar in the different cropping systems (Table II). In the initial stages of plant growth, k values were 0.15 on average. Due to the plant growth, through the elevated LAI and dry matter accumulation (Fig. 4), the extinction coefficient showed increased values, with a maximum value of 0.32 at 237 DAC. Considering the crop cycle and generalizing the crop systems, the average light extinction coefficient for the sugarcane crop was 0.20.

Table II

3.4.4 LEAF AREA INDEX AND DRY MATTER PRODUCTION

The highest values of LAI were observed in the stage of stalk growth, a period between 237-265 DAC. The isolated system had the highest LAI, 7.1; additionally, the intercropping system provided changes in values of LAI in accordance to the line position. The 12 x 12 system showed the highest value in line 3, with a value of 6.2, which is 15.6 and 12.5% higher than in lines 1 and 2, respectively. In the 6 x 6 system, the highest LAI was found in line 2, with values around 6.4; these values were 14.5 and 11.6% higher than those obtained by lines 1 and 3, respectively (Fig. 4A).

Figure 4

Dry matter accumulated during the cycle of sugarcane presented a positive linear relation, with an observed stabilization for 300 DAC. This period marks the beginning of the maturation of stalks, which can be noted by the reductions in growth rates and an increase in sucrose content of stalks (Fig. 4B). The greatest values for total accumulated dry matter were observed in the isolated system, which increased a total of 592.7 g plant^{-1}. For the intercropping systems, a similar response in accumulated dry matter was obtained from the different evaluation positions in the understory. While the 12 x 12 system had a total of 504.8 g plant^{-1} on average, the accumulation total of dry matter of the 6 x 6 system was found to be 469.3 g plant^{-1} (Fig. 4B).

3.4.5 GROWTH RATES

The absolute growth rate and net assimilation rate throughout the crop cycle are showed in Fig. 5. The response curves demonstrated similar behavior for the analyzed variables. We were able to observe two peaks during the crop cycle; the first occurred at 200 DAC and the second at 300 DAC, with a subsequent decrease in growth rates in accordance with the senescence of the leaves and stalk maturation. In addition, a similar response in the different crop systems and lines of evaluation was verified. Overall, the largest absolute growth rate and net assimilation rates were observed at 206 DAC, this stage corresponds with intense stalk growth.

Figure 5

The number of tillers in sugarcane reduces in accordance to the DAC, stabilizing at 265 DAC (Fig. 6A). Overall, a similar response between the crop systems and lines of evaluation throughout the crop cycle were observed. In the initial growth stages, a period of intense tillering, we observed an average of 10 tillers m^{-2}. In the stage of maturation, we found values between 4 to 5 tillers m^{-2}, a reduction of more than 50% in the number of tillers. In relation to plant height (Fig. 6B), we observed a linear response in accordance to the DAC, with stabilization in height from 300 DAC onwards. Overall, the plants presented values of approximately 265 cm.

Figure 6

3.4.6 BIOMASS PARTITIONING

The pattern of dry matter accumulation in the leaves, pseudoculm+senescent and stalks of sugarcane was similar for the different cropping systems (Fig. 7). In the initial stages of plant growth, up to 115 DAC, the leaves and pseudoculm+senescent were responsible for 100% of total dry matter accumulation, 50% for each compartment on average; the dry matter of the stalks was computed from 115 DAC onwards. At 206 DAC, the plants showed stabilization in the partition of assimilates up to the harvest; where the leaves (20%) pseudoculm+senescent (5%) and stalk (75%) were responsible for the total dry matter accumulated by the sugarcane crop.

Figure 7

3.4.7 YIELD TRAITS

According to the variance analysis, we observed a significant difference for the variables stalk weight and juice volume in the different cropping systems (Fig. 8). The stalk weight and juice volume in sugarcane grown in the isolated system were higher than those observed in the agroforestry systems (Fig. 8). We observed a reduction of 17.5 and 32.7% of stalk weight for the 12 x 12 and 6 x 6 systems, respectively, when compared to the isolated system by the Dunnet test ($p<0.05$). Additionally, between the crop systems, the stalk yield was 18.4% greater in the 12 x 12 system than in the 6 x 6 according to the Tukey test ($p<0.05$).

Figure 8

Regarding the juice volume produced, a similar response to the stalk weight was observed, confirming the correlation between these variables, where the isolated system also showed a higher juice volume. We also observed a reduction of 16.6 and 35.3% by juice volume produced in the 12 x 12 and 6 x 6 systems, respectively. In addition, between agroforestry systems, the juice volume of the 12 x 12 system was 22.5% higher than in the 6 x 6 system. With this, we can infer that the 12 x 12 system showed greater stalk yields and volume of produced juice, compared to the 6 x 6 system.

3.5 DISCUSSION

The meteorological conditions during the growing cycle were favorable for sugarcane, especially with respect to the air temperature and water availability. Sugarcane needs 1500 to 2500mm of water evenly distributed over the growing season (FAO 2013).

Within the agroforestry system the positioning of sugarcane lines is very important, and therefore should be considered in studies with intercropping systems; the canopy of forest species can result in changes to microclimates. In this case, the canopy provided a reduction in LAI (Fig. 4A) and consequently in intercepted radiation (Fig. 3B) in the lines of sugarcane near the tree species, resulting in an overall lower radiation use efficiency by plants. The growth and development of different species in the same area causes dynamic interactions in species planted near one another, which changes with the time. These interactions modify the distribution of existing resources in the system (Muller et al. 2014), with the solar radiation changing first.

The results observed are consistent with those of Marchiori et al. 2014, who reported that excessive shading might affect certain growth traits causing decreases in tillering and in photosynthetically active leaf area, as well as in the interception of solar radiation, producing thinner, elongated stalks. In addition, excessive shading during extended periods may affect the photosynthetic apparatus as a result of decreases in chlorophyll content (Chl), in nitrogen content, and in the Chl a/b ratio (Pearcy, 1998; Dinç et al. 2012).

The values of radiation use efficiency obtained in this study are similar to what has been observed by other authors. De silva and De costa (2012) found values of RUE which vary from 1.63 to 2.09 g MJ^{-1} and 0.71 to 1.03 g MJ^{-1} under irrigated and rain-fed conditions in Sri Lanka. Anderson et al. (2015), analyzing the RUE in two crop sites in Hawaii, USA, found average values of 1.24 ± 0.22 g MJ^{-1} during the period of growth for locations of low altitude and 1.15 ± 0 15 g MJ^{-1} for location of high altitude. The maximum RUE for sugarcane can vary between 1.7 g MJ^{-1} (Robertson et al. 1996) to 2.0 g MJ^{-1} (Muchow et al. 1997).

In the national and international literature, RUE values for sugarcane grown in agroforestry systems have not been determined. Comparing the RUE values obtained from the monocropping system with those obtained in the intercropping systems in this study, even under the influence of the tree species, the sugarcane in the understory of agroforestry system showed high values for RUE and can therefore be recommended for cultivation in alternative production systems, such as agroforestry systems.

The lowest amount of radiation intercepted by the sugarcane in the 12 x 12 system, in the first and second lines of evaluation, as well as in the first and third lines in the 6 x 6 system, are associated with the effects of the canopy of the species *Aleurites fordii*, which shaded the sugarcane plants. Due to sugarcane's high photosynthetic rate (C4 species), it needs a large amount of solar radiation to meet its photosynthetic demand. Plants submitted to different levels of shading (for example, in proximity of the evaluation line to the tree species) demonstrate changes in photosynthetic rate, and consequently, the production of assimilates, which influences the radiation use efficiency of plants.

The observed results are similar to those of Hardy et al. (2004), who reported that the amount of radiation intercepted by the forestry species and consequently the radiation that reaches the ground level is determined by canopy characteristics, such as the average crown diameter and the size of the existing gaps in the canopy, which can all be affected modified by plant arrangement. Naturally, the probability of photosynthetically active radiation reaching the ground is inversely proportional to the degree in which it is intercepted by the canopy structure.

Péllico Netto et al. (2015), evaluating the dynamics of solar radiation in the understory of *Acacia mearnsii,* concluded that in the center of the plot, i.e. between rows of trees, more than 70% of the radiation reaches the ground level. However, under the canopy, the values were reduced significantly, to only 20%, thereby diminishing the availability of radiation for understory crops. This confirmed the influence of the canopy trees on the interception of incident radiation. Our findings are in line with a study carried out by Pezzopane et al. (2015) and Bosi et al. (2014) who reported the strong relation between levels of incident solar radiation, and its effect on microclimate, growth characteristics of plants, and soil moisture.

The growth of sugarcane was correlated to an increase in k values (Table II), coinciding with an increase in LAI. This result provides an increase in radiation interception up to a determined value, when the plants reach a critical IAF and begin self-shading, resulting in an increased extinction coefficient. It can be inferred that independent of the cropping system, the k values depend primarily on the LAI, which determines the amount of solar radiation available in the understory of sugarcane. According to Behling et al. (2015), this condition is understandable since light attenuation of the plant canopy is determined by leaf density (which can be expressed by LAI) and also by the geometric characteristics of the leaves and the tree canopy, as well as the optical properties of the leaves. Thornley (1976) reported that the value of k might vary with leaf traits, sun angle, spacing, and latitude.

High values of LAI (> 6) resulted in the average k value of 0.20, for the conditions as observed in this study. Similar values were obtained by De Silva and De costa (2012), who found values near to 0.27 in irrigated sugarcane in Sri Lanka., although other authors found values higher than those obtained in this study. Muchow et al. (1994; 1997) reported k values near to 0.40 for irrigated sugarcane in Australia and Hawaii. Meki et al. (2015) found a value of k equal to 0.53 for sugarcane in Hawaii. This is similar to a value obtained by Inman-Bamber et al. (2011) in a study conducted in Australia with a value of 0.58. It can be highlighted that in both national and international literature, k values were not determined for sugarcane grown in agroforestry systems.

The greatest values of LAI were found in periods of intense vegetative growth (237 to 265 DAC), with values near to 7. In accordance with the results of Inman-Bamber (1994), for the cultivation of sugarcane, the critical value of LAI to intercept 95% of the radiation is near 4, thus average values obtained in this study are above the critical value of LAI.

According to Pinto et al. (2005), the main limiting factor in agroforestry systems is the availability of solar radiation, which together with the competition for water and nutrients limits the growth of sugarcane near the forest species. In new research conducted with agroforestry systems, the effect of a reduction in radiation availability must be considered due the influence in the growth and development of the species in intercropping systems.

The changes in the microclimatic conditions in different cropping environments resulted in variations of the absolute growth rate and net assimilation rate of plants (Fig. 5). The reduction in growth rates is explained by the effect of self-shading due to an increase in the LAI (Fig. 4A), as well as in the ripening stage due to leaf senescence as a result of reduced air temperature. In accordance with the results of Cardozo and Sentelhas (2013), in the south of Brazil, the lowest air temperature in the months of autumn-winter, combined with the occurrence of moderate water deficit, are the main factors responsible for the reduction of growth rates, except, at the beginning stage of maturation where it results in a high increase in sucrose content.

The reduction in the number of tillers up to DAC 237 is due to the effect of intraspecific competition among plants, especially in the initial stages of growth, i.e., the stage of high tillering. The competition occurs mainly for solar radiation, since this is the limiting factor in the agroforestry system. In addition, we recorded low levels of cumulative rainfall in August and September, periods that corresponded to approximately 50 and 80 DAC and the tiller emission stage, which affected the tillering of sugarcane.

The tillering pattern found in this study is similar to that described by Bezuidenhout et al. (2003), but with a lower tiller density than what was reported in that study: peak tillering at 12 to 14 tiller m^{-2}. After the senescence stage, tiller density stabilized at 7 tiller m^{-2} regardless of water source (rain or irrigation) or planting site. This implies that tillering rate and survival of tillers is related to the quantity and quality of the solar radiation intercepted by plants (Inman-Bamber 1994; Bezuidenhout et al. 2003).

Regarding the partitioning of assimilates, the biomass accumulated in the leaves decreased gradually throughout the crop cycle, especially in the maturation stage due to the senescence of lower leaves. Another important aspect to be emphasized is the exportation of sucrose and starch from leaves to other compartments. In our study, the total dry matter in the stalk in the sugarcane plants resulted in an average accumulation of 75% (Fig. 7).

The metabolism and partitioning of sucrose is essential for all stages of the sugarcane crop cycle, and requires hydrolysis to use it as a source of energy (Leite et al. 2009). In leaves (the source), the synthesis of carbohydrates is realized, which are translocated to the stalks (sink) in the form of sucrose, in order to meet plant maintenance and growth metabolism demands (Taiz and Zeiger 2013). These processes are accompanied by constant changes in source-sink relations (Roitsch and González 2004), which was confirmed in this study through the partitioning of dry matter by the sugarcane (Fig. 7).

The observed results are similar to those of Marin et al. (2011), who, evaluating the partition of biomass throughout the sugarcane cycle, found higher initial biomass accumulated in the leaves and in stalks starting from 129 DAP. This is equivalent to 9% of TDM with increasing values, reaching 70% at 330 DAP. In a study conducted in southern Brazil, Simoes et al. (2005) found ratios of around 80% of dry matter accumulated in stalks at 400 DAP. Muchow et al. (1994) found the stalk biomass values change from 60% to 80% for DAP 300 to 450 DAP, in Australia.

The greatest stalk yield and juice volume observed for the monocropping system is explained by the favorable meteorological conditions during the crop cycle (Fig. 2). The average stalk yield of 61.8 t ha^{-1} is consistent with the values found in the literature. In the study conducted by Liu et al. (2016), who evaluated the yield of sugarcane in China, observed an average yield of 56.1 and 79.9 t ha^{-1} for Kaiyuan and Yuanjiang, respectively. Abreu et al. (2013), studying five cultivars of sugarcane, found the following average yields: 89 t ha^{-1} in the first year of cultivation, 75 t ha^{-1} in the second year and 88 t ha^{-1} in the third year of cultivation in the state of Alagoas, Brazil.

The sugarcane yield is reduced in agroforestry systems. This reduction in stalk weight and juice volume may be related to the morphophysiological adjustments, for example as a shade tolerance strategy. These adaptations were not able to compensate for the reduction of radiation in the understory of *Aleurites fordii*, which reduced overall yields. However, even under the influence of tree species, the 12 x 12 system showed satisfactory values with relation to the stalk weight (50.9 t ha^{-1}) and produced juice volume (26.8 m^3 ha^{-1}). This value is near the average stalk yield for the state of Rio Grande do Sul of 53.9 t ha^{-1} (Conab 2016). This result confirms the viability of the intercropping system for the production of sugarcane. Pinto et al. (2005), evaluating the yield of sugarcane in agroforestry systems with *Eucalyptus grandis*, found differences in sugarcane yields in different evaluation spacing. Plants spaced 11.6 m from the tree species obtained average yields of 64.1 t ha^{-1} in the state of São Paulo, Brazil.

The satisfactory yield values in the 12 X 12 system are related to greater availability of radiation within the system, which enabled a greater plant growth, confirmed by the elevated TDM and LAI (Fig. 4). In addition, the *Aleurites fordii* (deciduous species), displays leaf senescence in the colder seasons (winter-autumn). Senescence can increase the radiation intercepted by sugarcane, especially in the final stage of maturation, resulting in an increase of the stalk weight and produced juice (Fig. 8). This result highlights the importance of appropriate selection of tree species used in the composition of the agroforestry system.

These results are consistent with those obtained by Elli et al. (2016), who, evaluating the yield of sugarcane in different agroforestry systems, found higher stalk yields for intercropping with the species *Parapiptadenia rígida,* where the values of 61.9, 53.1, and 41.6 t ha^{-1} were obtained in three cultivation cycles. The greater yields observed by the authors is related to the characteristics of their forest species. Above all, because they enable greater radiation availability in the understory, an important characteristic of deciduous species.

The study of the growth variables, yield traits and dynamics of solar radiation in agroforestry systems are underfunded. Thus, the information generated in this study is relevant, as it provides information to farmers for the planning of more effective agroforestry arrangements. It also confirms the viability of the cultivation of sugarcane in agroforestry systems. Additionally, Brazilian law No. 12,651, May 25, 2012, which established a new Forest Code, allows small farmers to plant agroforestry systems in areas of permanent preservation (APP) and legal reserves (RL), provided that those systems are subject to a sustainable management plan.

3.6 CONCLUSIONS

The cultivation of sugarcane in agroforestry system did not present higher yields and radiation use efficiency, thus, the hypothesis of the study was rejected. However, even under the influence of the species *Aleurites fordii*, the cultivation of sugarcane in agroforestry systems showed satisfactory values of yield and radiation use efficiency and can be recommended for cultivation in alternative production systems. The use of agroforestry systems with 12 x 12m arrangements should be prioritized, because this enabled greater yields and radiation availability in the understory.

This study sought to provide new sustainable alternatives for farmers, in order to increase the diversification of rural properties and preserve existing agro-ecosystems. It is important that research is conducted in order to study the implementation of agroforestry systems in threatened ecosystems, such as in permanent preservation areas (APP's) and legal reserve (RL's). It is necessary to study the responses of these areas in with regard to environmental preservation, the maintenance of biodiversity, and economic return of agroforestry systems, and to do so while adapting to modern environmental legislation.

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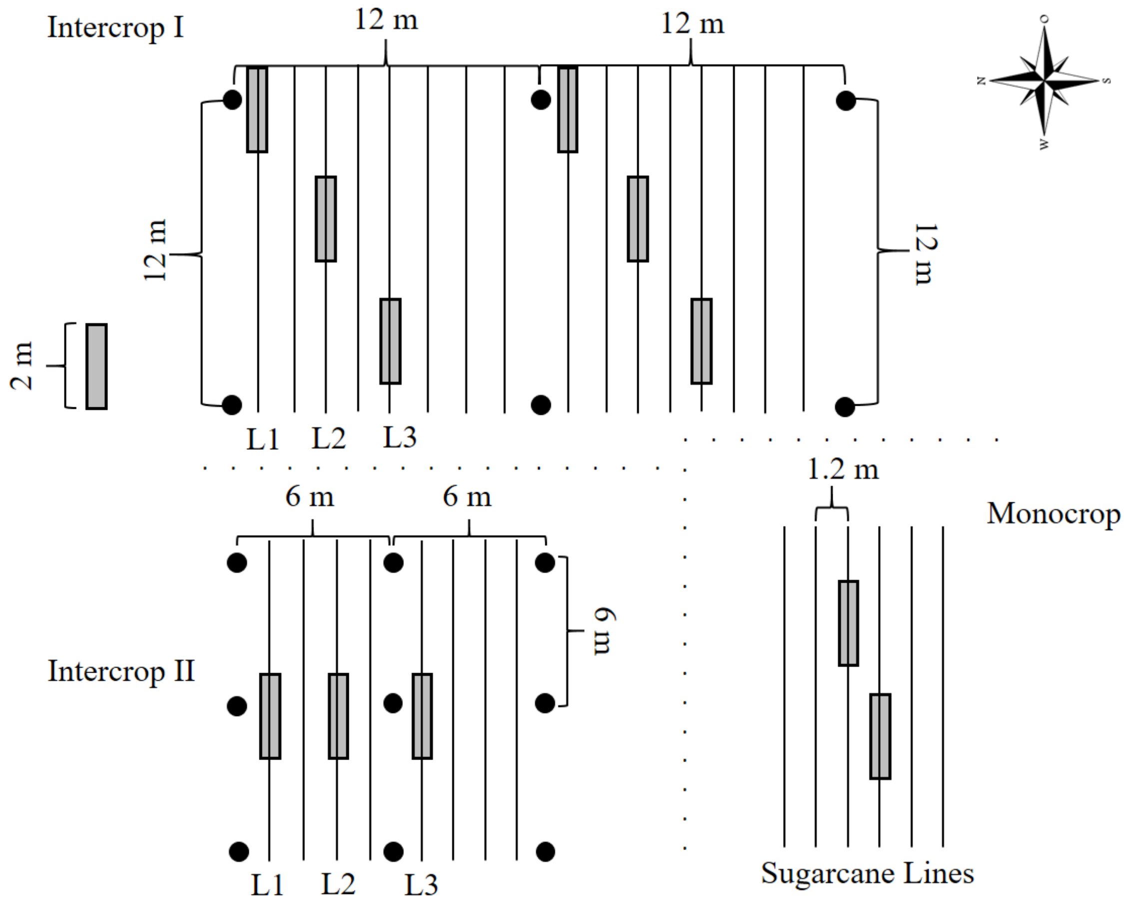

Figure 1 - A sketch of an experimental unit of the agroforestry systems (12 x 12 and 6 x 6) and the isolated system. Black circles represent the trees, continuous lines indicate where the sugarcane was planted, and the rectangles in grey represent the monthly evaluation plots of sugarcane.

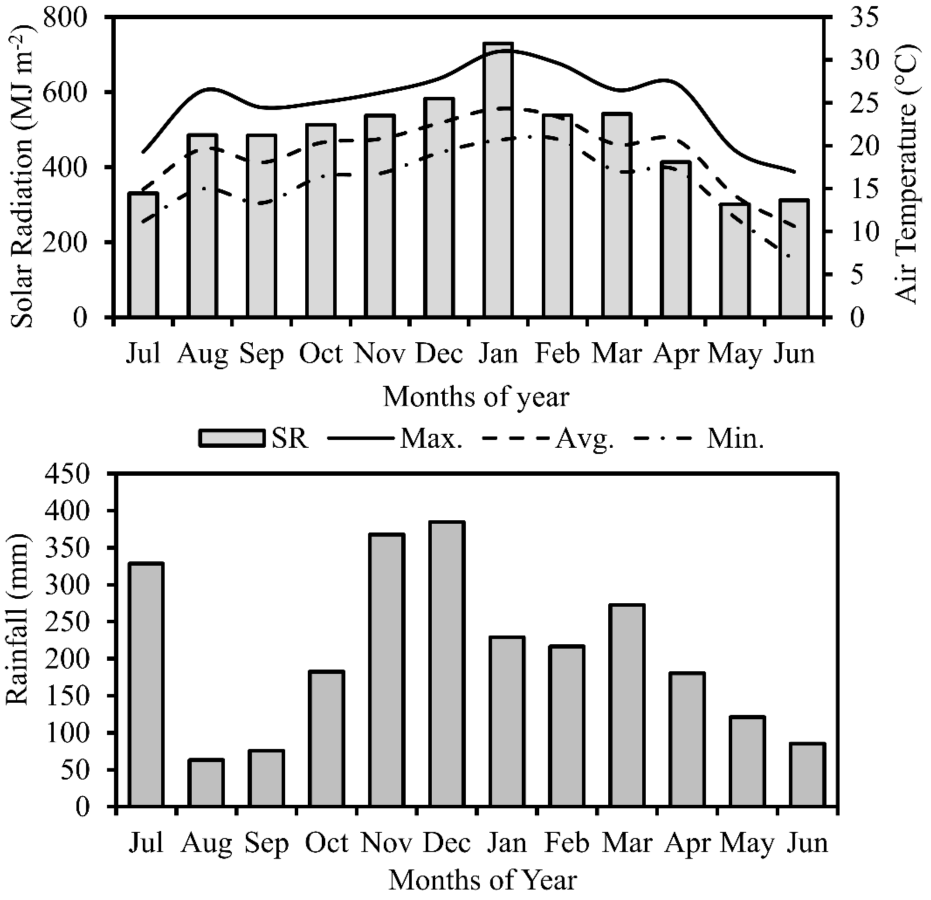

Figure 2 - Monthly average values of minimum, maximum and average temperature, accumulated incident solar radiation, and accumulated rainfall during the experimental period (07/02/2015 to 06/24/2016).

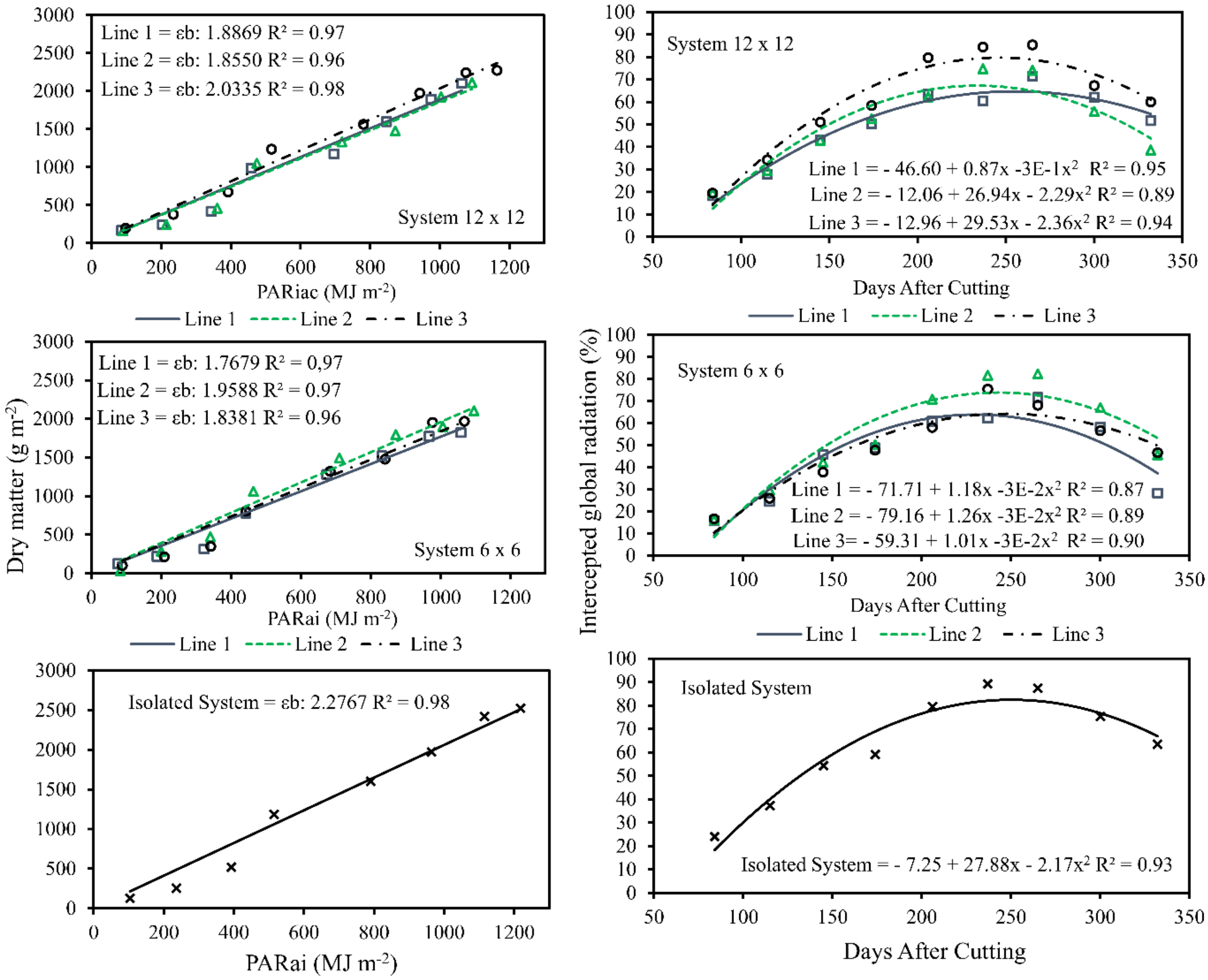

Figure 3 - Relationship between accumulated intercepted photosynthetically active radiation (PARiac) and dry matter produced (DM) (A); and intercepted global radiation of sugarcane in agroforestry and isolated systems in different lines of evaluation throughout the days after cutting (B).

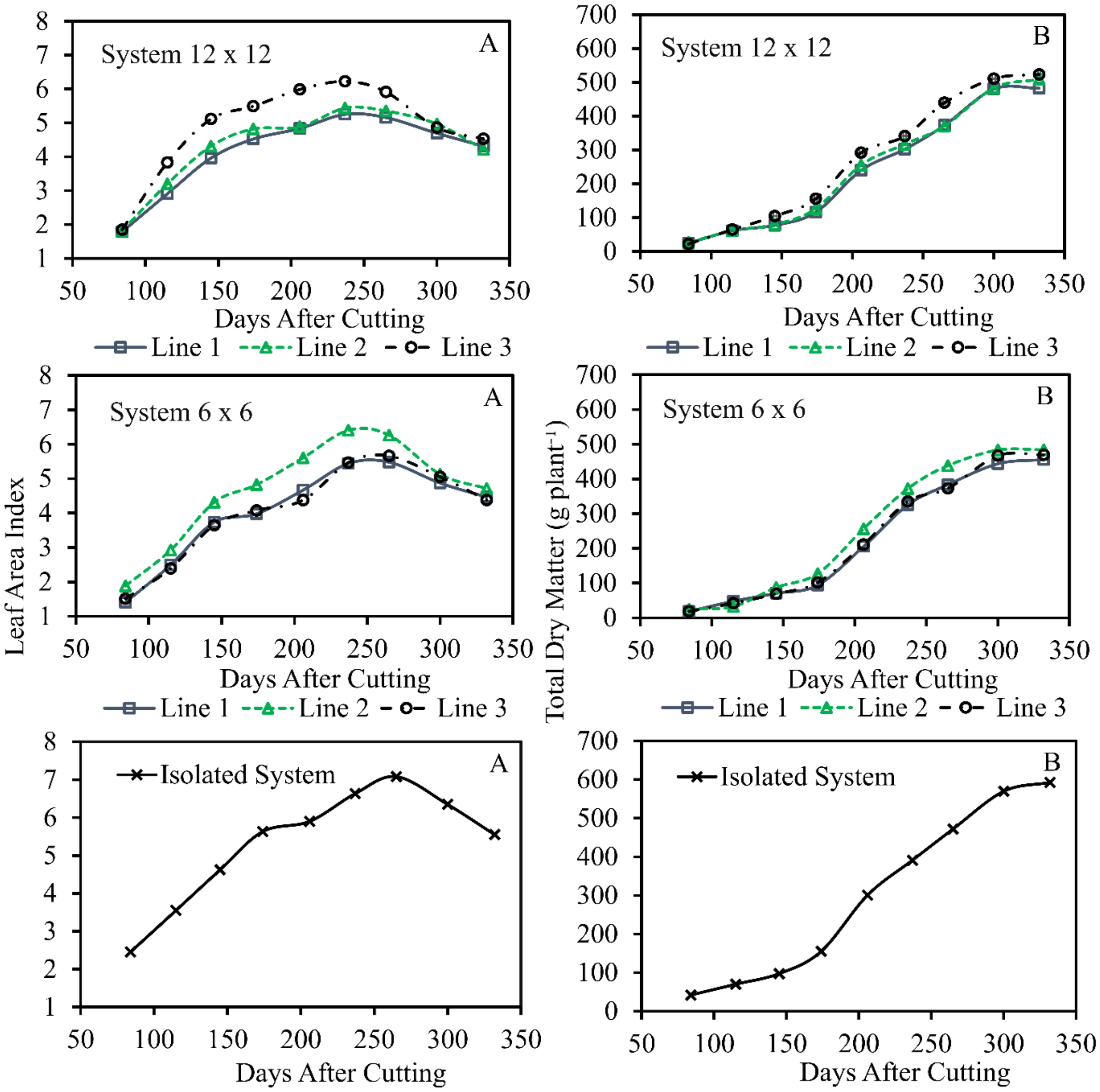

Figure 4 - Leaf area index (A) and total dry matter (B) of sugarcane in agroforestry and isolated systems in different lines of evaluation throughout the days after cutting.

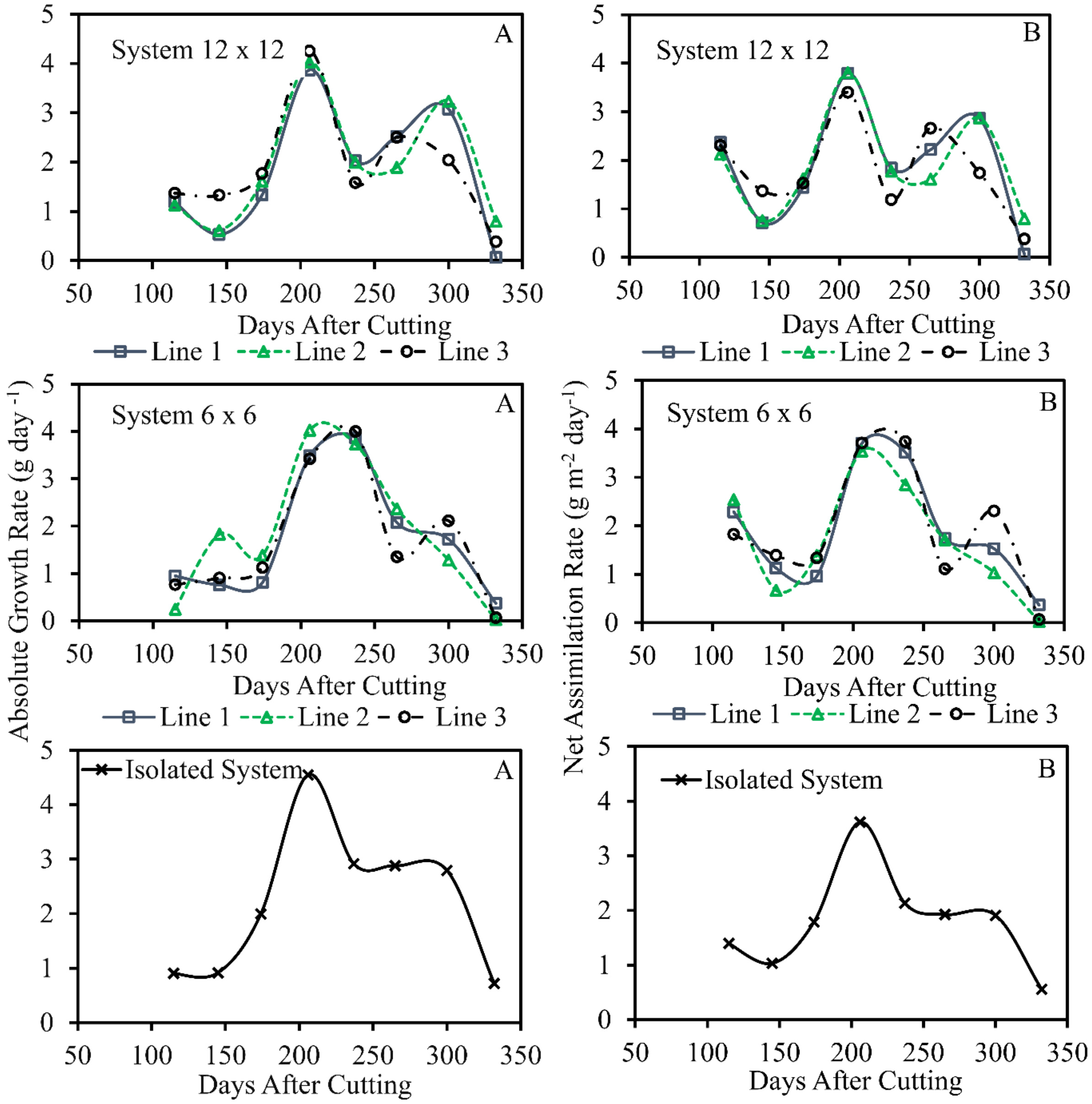

Figure 5 - Absolute growth rate (A) and net assimilation rate (B) of sugarcane in agroforestry and isolated systems in different lines of evaluation throughout the days after cutting.

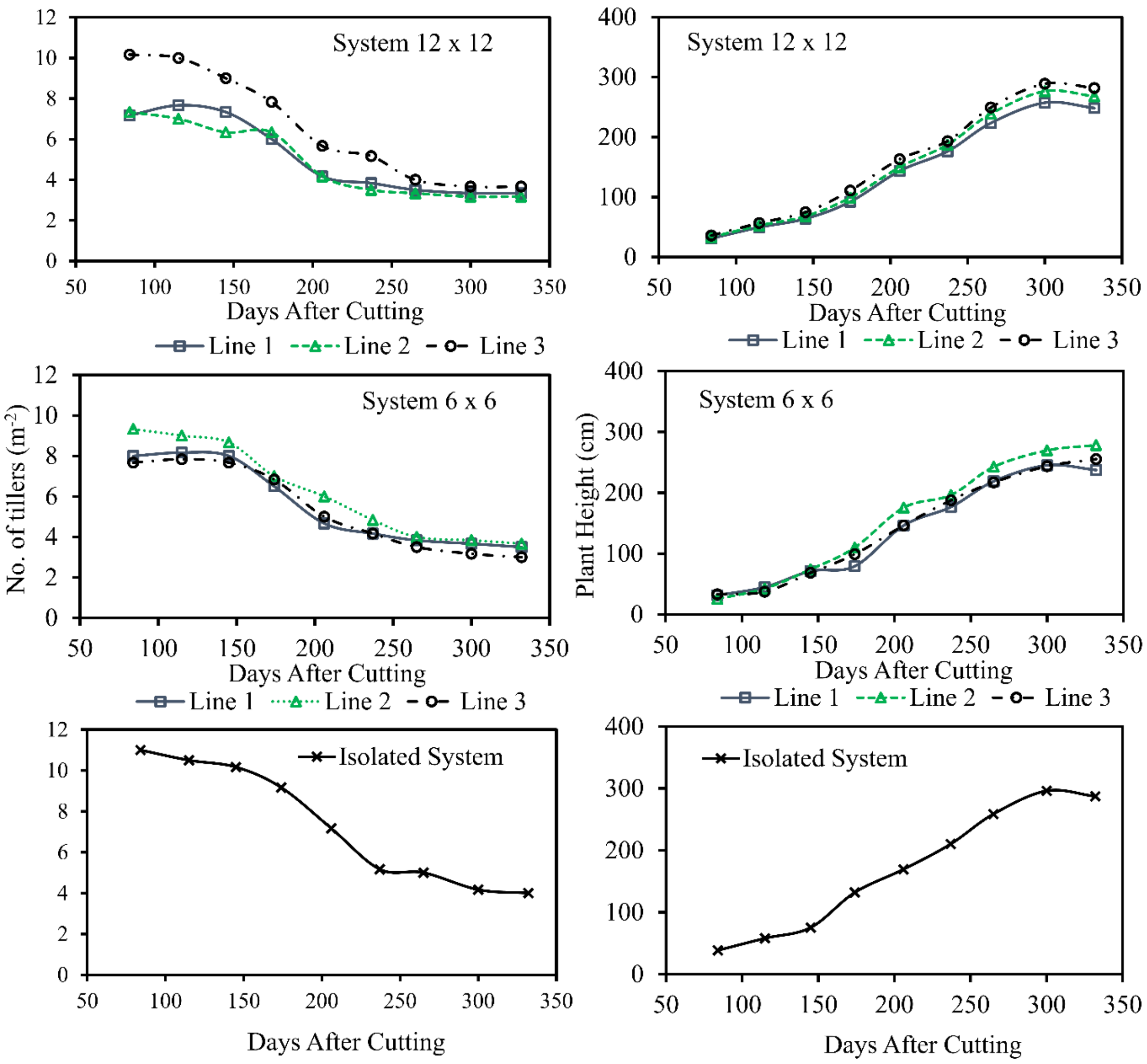

Figure 6 - Number of tillers (A) and plant height (B) of sugarcane in agroforestry and isolated systems in different lines of evaluation throughout the days after cutting.

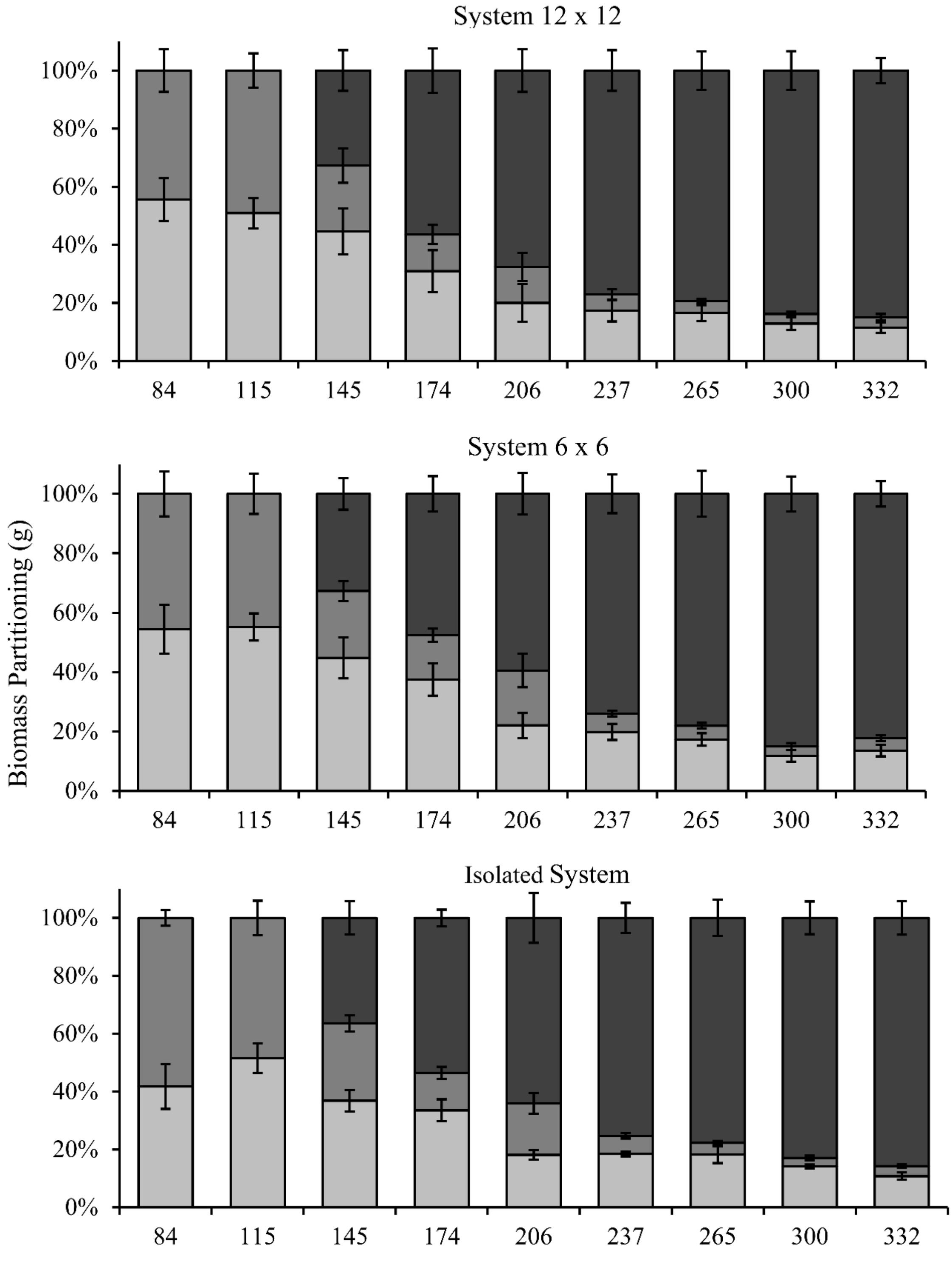

Figure 7 - Biomass partitioning in sugarcane plants in different cropping systems throughout the days after cutting. Each bar represents average values ± SE.

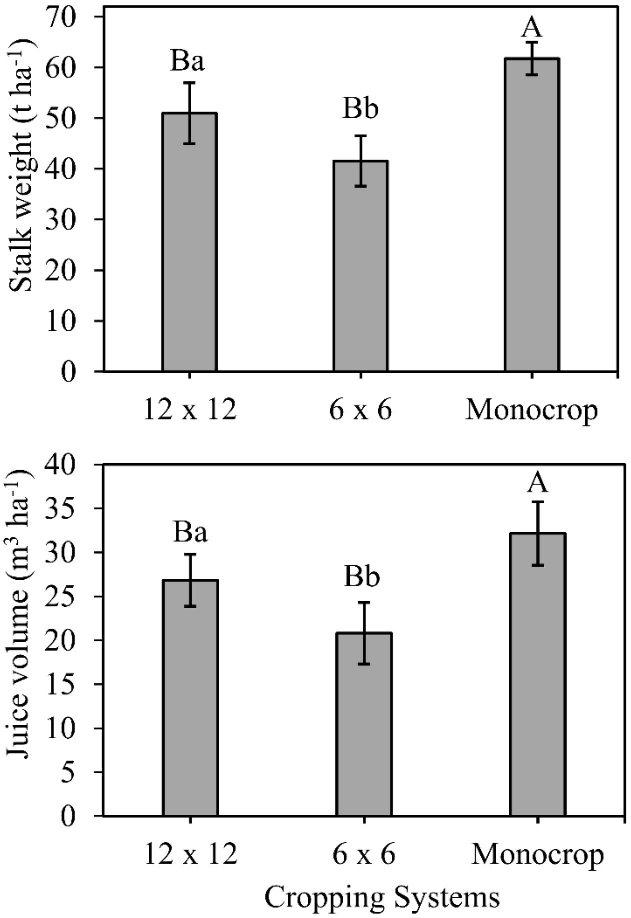

Figure 8 - Stalk weight and juice volume in sugarcane plants in different agroforestry and monocropping systems. Each bar represents average values ± SE. Means followed by the same letter do not differ among themselves. Uppercase compare the agroforestry systems with the control (Monocropping), by Dunnet test ($p > 0.05$); and lowercase compare the agroforestry systems (12 x 12m and 6 x 6m), by Tukey test ($p > 0.05$).

TABLE I

Height (H), stem diameter (SD), diameter at breast height (DBH) and mean diameter of crown (MDC) of *Aleurites fordii*, in agroforestry systems (12 x 12 and 6 x 6), the trees were five years old.

System	Allometric variables			
	H (m)	SD (cm)	DBH (cm)	MDC (m)
12 x 12	3.5	20.1	11.6	1.8
6 x 6	3.8	26.2	14.5	2.6

TABLE II

Light extinction coefficient with (± standard error) in different cropping systems of sugarcane cultivation throughout the days after cutting (DAC).

DAC	Cropping Systems		
	12 x 12	6 x 6	Monocrop
84	0.142 ± 0.038	0.124 ± 0.066	0.115 ± 0.047
115	0.158 ± 0.031	0.135 ± 0.092	0.136 ± 0.056
145	0.163 ± 0.039	0.169 ± 0.021	0.145 ± 0.037
174	0.190 ± 0.016	0.190 ± 0.029	0.159 ± 0.020
206	0.211 ± 0.038	0.275 ± 0.071	0.261 ± 0.019
237	0.302 ± 0.024	0.324 ± 0.066	0.337 ± 0.018
265	0.285 ± 0.067	0.296 ± 0.044	0.295 ± 0.026
300	0.207 ± 0.011	0.217 ± 0.033	0.228 ± 0.049
332	0.190 ± 0.026	0.145 ± 0.031	0.183 ± 0.023

4 ARTIGO III - YIELD AND QUALITATIVE TRAITS OF SUGARCANE CULTIVATED IN AGROFORESTRY SYSTEMS: TOWARDS SUSTAINABLE PRODUCTION SYSTEMS

Submetido para o periódico: Renewable Agriculture and Food Systems
Situação: Aceito

Yield and qualitative traits of sugarcane cultivated in agroforestry systems: Towards sustainable production systems

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4.1 Abstract

One of the greatest challenges in crop science worldwide is to generate a balance between crop production and environmental preservation. Agroforestry systems present promising strategies for balancing environmental health and crop production. The aim of this study was to evaluate yield components and the juice quality of five sugarcane crop years cultivated in the understory of *Aleurites fordii*, in two intercropping systems and a monocropping system. A field experiment was conducted from November 2011 to June 2016 in the city of Frederico Westphalen – Rio Grande do Sul, Brazil. Information generated in this study confirms the viability of the cultivation of sugarcane in agroforestry systems, and provides information for farmers which can be used to assist in the planning of more ideal agroforestry arrangements. Agroforestry systems should consider the benefits of forestry and cultivated plant species. In this study, *Aleurites fordii* trees had greater growth in the intercrop II system; however, this system promoted reductions in sugarcane yield components due to the lowest relative amount of solar radiation intercepted by sugarcane plants. For sugarcane production, the use of an intercropping system with 12x12m arrangements should be prioritized, because it promotes greater sugarcane yields when compared to a 6x6m intercropping systems; however, significant differences were not observed when the system (12x12m) was compared to the monocropping system for most of the analyzed variables. This study sought to provide new sustainable alternatives for farmers in order to increase the diversification of rural properties and maintain the preservation of existing agro-ecosystems.

Key words: Tree-crop interactions, *Sacharum officinarum* L., intercropping systems, tree arrangement, cane-ratoon.

4.2 Introduction

Rapid changes in agricultural environments are placing increased demands on farmers. In order to respond to these demands, farmers need to manage their crop systems by reducing risk, while increasing food production with a balance between crop production and environmental preservation, while still retaining management flexibility. In order to achieve this balance, it is necessary to meet the demands for food and energy without compromising existing agroecosystems (Godfray et al., 2010). Agroforestry systems have the potential to meet these objectives.

Agroforestry systems consist of integrated land use for forestry, crop, and/or livestock purposes; these factors provide clear agro-ecological advantages over conventional systems (Brooker et al., 2015). Advantages include higher production per unit of land (Zhang et al., 2007; Li et al., 2011), greater water and nutrient efficiency use (Vandermeer, 1989, 2011), greater carbon sequestration in the soil (Makumba et al., 2006; Cong et al., 2014), and an increased input of organic matter which has been shown to improve chemical, physical and the biological properties of soil (Tracy and Zhang, 2008; Salton et al., 2013). Agroforestry systems can provide continuous benefits or only benefits for a certain period of time; benefits depend on management practices, locations, and species included in the system.

Intercropping is the dominant agricultural strategy in many parts of the world, i.e. sub-Saharan Africa and large parts of Latin America, and intercropping systems provide an estimated 20% of the world’s food supply (Altieri, 2009; Chappell et al., 2013). Despite improvements in monocrop systems and the great potential of intercropping, little research has been carried out to determine the traits of cultivated species that drive the positive effects seen in intercropping systems; therefore, it can be seen that novel research involving intercropping systems in Brazil is especially relevant in the context of global food production.

Brazil is one of the primary sugarcane producing countries in the world, with estimates of 8.97 million hectares of planted area in 2015/2016 which produced 685 million Mg of sugarcane and resulted in an average yield of 76 Mg ha^{-1} (Conab, 2016). Sugarcane (*Sacharum officinarum* L.)

monocropping has had a great socio-economic and environmental impact in Brazil; agroforestry systems have been considered as an alternative for sustainable production in threatened ecosystems. In addition to a lack of research into intercropping systems described above, there has specifically been little work to assess yield traits and sugarcane juice quality in these systems.

In the planning of an agroforestry system, the choice of tree arrangement is essential to the success of a production system. Tree arrangements should consider tree use, future tree growth, and the resource requirements of the trees and crops to be incorporated in an intercropped system (Binkley et al., 2004; Kruschewsky et al., 2007; Rozados-Lorenzo et al., 2007; Prasad et al., 2010). In reduced tree arrangements, tree-spacing with greater relative proximity between trees (ie. higher number of trees per unit area); the tree interferes in the crops cultivated in the understory due greater interception of solar radiation by the tree canopy as well as due increased competition for water and nutrients. Competition is one of the major factors that has a negative impact on the yield of intercropping systems (Caballero et al., 1995; Li et al., 2011). Larger tree arrangements (those more widely spaced) encourage a healthy association with the crops (Dubè et al., 2002; Prasad et al., 2010). It is therefore that the production of the tree components and crops should be considered as a whole in order to define the most ideal tree arrangement and to provide greater yields and improve the quality of crops cultivated in the understory, as well as greater growth rates of the forest species.

To determine the sustainability of an agroforestry system, an understanding of environmental factors and plant interactions is essential (Berlyn and Cho, 2000; Ong et al., 2000). Tree–crop interactions can be regulated effectively and interspecies competition and can be minimized by employing efficient tree arrangements (Ghezehei et al., 2016) and by selecting compatible species (Bayala and Wallace, 2015; Ong and Kho, 2015).

In agroforestry systems, it is important to consider the characteristics and benefits of the two intercropped species. Tung trees (*Aleurites fordii*) are a good potential candidate for compose the agroforestry systems because of the species' unique growth characteristics which can lead to the improved cultivation of crops grown in its understory. The unique chemical properties of Tung seed oil make it one of the best known industrial ‘drying oils’. Phytochemical research into *Aleurites fordii* have led to the identification of various compounds including coumarins, diterpenoid esters, oils, sterols, and tannins as chemical constituents (Chen et al., 2010). In addition, Tung oil is currently used in paints, high quality printing, plasticisers, in certain types of medicines and chemical reagents (Park et al., 2008; Pei et al., 2012) and biodiesel production (Dyer et al., 2004; Chen et al., 2010).

Different tree arrangements in agroforestry systems can influence sugarcane traits such as yield and juice quality due the competition of existing resources (Muller et al., 2014) such as solar radiation (Elli et al., 2016). In the case of sugarcane (C4 metabolism), the response due to reduced radiation within the canopy can be maximized; in this context, the evaluation of yield components is an important step in understanding the response of plants under intercropped conditions. It is also necessary to analyze how many years of cultivation are possible in agroforestry and monocrop systems; in this case, the response of the productive capacity of sugarcane.

In addressing this lack of information, the following hypotheses were created: (1) sugarcane cultivated in intercropping systems presents a sugarcane yield and juice quality equal or greater to that of sugarcane produced in monocropping systems; and (2) the number of sugarcane harvests in intercropping or monocropping systems should not exceed five harvests. The aim of this study was to evaluate the yield components and juice quality of five sugarcane crop years cultivated in the understory of *Aleurites fordii*, in two intercropping systems and one monocropping system.

4.3 Materials and Methods

4.3.1 Study area

The field experiment was conducted from November 2011 to June 2016 in the city of Frederico Westphalen – Rio Grande do Sul, Brazil, at the coordinates 27º23'48 " S, 53º25'45 " and an altitude of 490m (Fig. 1). According to the Köppen climate classification, the climate is Cfa, i.e., humid subtropical with mean annual temperatures of 19.1°C and varying maximum and minimum temperatures of 38ºC and 0°C, respectively (Alvares et al., 2013). The soil of the experimental area was classified as typical Entisol Orthents. Fertilization was carried out according to a soil analysis and following recommendations for sugarcane crops (CCSF, 2004). The application of nitrogen was carried out 90 days after planting and after each cut (cane-ratoon) in amounts ranging from 100 to 140 kg ha^{-1} of N for each cane cycle.

4.3.2 Experimental design

The experimental design was a randomized complete block, characterized by a factorial arrangement of 3x5 defined by three cropping systems: Intercrop I (12 x 12m), Intercrop II (6 x 6m) and a monocrop system with sugarcane; five evaluation years (2012 to 2016) and three replications. In each marked rows (plots two meters in length), two representative stalks were collected which were taken to the laboratory for evaluation. In each evaluation year, a total of 84 stalks were collected and evaluated. The sample unit consisted of 16 stalks in the intercrop I system, 8 stalks in the intercrop II system and 4 stalks in the monocrop system. Each evaluated stalk was considered to be a repetition. The number of plants evaluated in each system was defined in order to identify the effect of the treatments; consideration was given to the inherent variability of each system following the assumptions described by Leite et al., (2009).

The sugarcane utilized for this study was developed by the Agronomic Institute of Campinas (IAC), cultivar IAC 87-3396, and is characterized by a high yield, high sucrose content, and excellent adaptation to soils with lower fertility. In the monocrop system, the sugarcane crop was distributed in six rows with 12 meters length. In the intercrop I system, trees were distributed in rows spaced at 12m; the sugarcane was distributed in eight rows and arranged corresponding with intervals between tree rows, with a total of 16 rows throughout the system. In the intercrop II system, trees were grown in rows spaced at 6m; the sugarcane was distributed in four rows arranged in correspondence to intervals between tree rows. A total of 15 trees were allocated for each experimental unit. Trees were planted in the experimental field in September and sugarcane in November of 2011. The seedlings and cuttings were manually planted after ploughing and harrowing the area.

In both systems, the sugarcane had a spacing of 1.20m and an initial density of 16 buds per meter with both tree and sugarcane oriented in rows towards the East and West. After the sugarcane was planted, plots were delineated by 2-m long sections marked with stakes and were distributed in three rows per treatment at different points in the understory of each experimental unit. Plot areas were chosen with the objective of representing the microclimate conditions of each cropping system. The arrangement of tree, sugarcane, and plot of evaluation are shown in Fig. 2.

4.3.3 Yield components and juice quality evaluations

The experiment was performed in five sugarcane cycles, one cane-plant (first cultivation year) and four cane-ratoon cycles (each cycle corresponding to a sugarcane regrowth) with a total of five years of evaluation (2012 to 2016). The 1st cut was performed on 07/26/2012, the 2nd on 07/25/2013, the 3rd on 06/16/2014, the 4th on 07/02/2015 and the last (5th cut) was performed on 06/23/2016. In collecting plants for evaluation, the harvest point was determined by the measurement and monitoring of sucrose levels and stalk humidity during the harvest season (Cardozo and Sentelhas, 2013).

On the day of plant collection, stalk numbers (SN) were counted in the field for each previously demarcated plot. Values were extrapolated per hectare (ha) for the existing population in each experimental unit. The number of stalks used to determine the stalk weight per ha for each evaluation year varied according to the sugarcane regrowth capacity. We utilized the following stalk numbers for each evaluation year: 20833, 46833, 62083, 49583 and 40416 stalk ha^{-1} for the years 2012, 2013, 2014, 2015 and 2016, respectively.

The yield components were analyzed in the laboratory. The stalk weight (SW, Mg ha^{-1}) was obtained by weighing each stalk on a digital scale; stalk length (SL, m) was measured from the first visible dewlap leaf to the stalk base, while stalk diameter (SD, mm) was determined by using the average of three measurements of stem diameter taken at the bottom, the middle and the top of the stalks. The number of nodes (NN) was obtained by a total count of nodes in each evaluation stem.

For the evaluations of sugarcane juice quality, juice volume (JV, m^3 ha^{-1}) was obtained by milling the stalk, and measured with the aid of a graduated cylinder with a capacity of 1 L. The JV samples were taken to determine the Brix degree by means of an automatic digital refractometer Acetec RDA 8600. Sucrose concentrations (SC, g L^{-1}) were determined using the equation proposed by Torres et al., (2006): SC = Brix degree x 10.13 + 1.445. Where, SC = sucrose concentration (g L^{-1}).

The total sucrose quantity (S, Mg ha^{-1}) was determined from the values of SC and JV, by the following equation: S = SC x JV/1000. Where, S = total sucrose quantity (Mg ha^{-1}), SC = sucrose concentration (g L^{-1}), and JV = juice volume (m^3 ha^{-1}).

4.3.4 Tree species used to compose the agroforestry systems and evaluated growth variables

The tree species Tung (*Aleurites fordii*), of the Euphorbiaceae family, an exotic deciduous species, was used to compose the agroforestry system. It was chosen due to its adaptability to environmental conditions and the high oil yield of its fruits. The productive evaluations (oil yield) was not performed due to the period of cultivation; the minimum period necessary for fruit production is five years with the peak production at ten years (Zhan et al., 2012).

After the transplanting of the seedlings to the field, quarterly evaluations were carried out from March 17, 2012, which corresponds to 176 days after the transplanting of the seedlings (DAT). The evaluations were carried out until June 21, 2016, resulting in total of 1736 DAT throughout 18 evaluation period. Evaluations were carried out on the days that marked the half of each season studied, but not necessarily on the same day or date between the different evaluation years. Evaluation dates were defined by their relative relation to the beginning of each season of the year: autumn 03/20, winter 06/21, spring 09/22 and summer 12/21.

The determination of height values (H), stem diameter (SD), diameter at breast height (DBH) and crown diameter (CD) of *Aleurites fordii* tree were evaluated during each season of the year. Tree height was measured from the ground level to the top leaf axils using a measuring tape until they reached 2.0 m, therafter a Vertex III Hypsometer was used. The stem diameter at ground level was measured using a tape measure at 5 cm above ground level, and the diameter at breast height was evaluated using a measure tape at a height of 130 cm. For crown diameter, evaluations were performed using a metric tape throughout vertical and horizontal measurements.

The values of meteorological variables during the experiment were obtained from a Climatological Station of the National Institute of Meteorology (INMET) linked to the Agroclimatology Laboratory (UFSM) located about 200m from the study site at coordinates 27° 39'S and 53° 43'W. The following meteorological variables were obtained: incident solar radiation (SR, MJ m^{-2}), rainfall (Rain, mm), minimum air temperature (T. Min, °C), maximum air temperature (T.Max, °C) and average air temperature (T. Ave, °C). Soil water availability was determined by a climatological water balance (Thornthwaite and Mather, 1955) on a month long time scale using a soil water holding capacity (SWHC) of 100 mm (Elli et al., 2016).

4.3.5 Solar radiation interception

The determination of intercepted solar radiation was carried out for the 5th cane-ratoon cycle. The amount of solar radiation intercepted by sugarcane was measured using a portable sensor pyranometer (LICOR PY32164) coupled to a Datalogger (LICOR 1400). The intercepted solar radiation values were measured monthly beginning in October 2015 (82 days after cutting) and finalized in June 2016 (332 days after cutting). Incident solar radiation was measured above and under the plant canopy (in the demarcated plots Fig. 2) with a portable pyranometer that recorded measurements in the period from 10 to 12h. The values of intercepted global radiation were obtained according to the following equation:

$$\% \text{ Intercepted} = [100 - (Rn \times 100 / Rt)]$$

Where: Rn = incident radiation under the canopy; Rt = incident radiation above the canopy.

4.3.6 Statistical analysis

The data were statistically analyzed with the software “Statistical Analysis System” (SAS, 2003). Data were initially examined for homogeneity of variance among years with the use of Bartlett's test, and then subjected to analysis of variance in order to determine treatment effects and possible interactions between cropping systems and years. The Dunnet test ($p<0.05$) was used to compare the intercrop I and intercrop II systems with the control (monocrop) system and Tukey test ($p<0.05$) to compare the difference between the systems intercrop I and intercrop II.

4.4 Results

According to variance analysis, we observed an interaction between evaluation years and cropping systems for the yield components number of nodes, stalk number, stalk weight, stalk diameter and stalk length. We did not observe an interaction between evaluation years and cropping systems for the variables: juice volume, sucrose concentration and total sucrose content, because of this, the main effects were analyzed.

The air temperature during the years of sugarcane evaluation ranged from -2.6 ºC to 37.0 ºC, with an average temperature of 18.8 ºC. The flux of global solar radiation was 17.35 MJ m^{-2} day^{-1} on average, with a variation of 0.49 to 38.46 MJ m^{-2} day^{-1}. In general, solar radiation had the highest values in the first and last month of the year (summer season) and diminished values during June and July (winter season). The water balance for each sugarcane cycle showed periods with water deficits and others with a water surplus (Fig. 3). The cane-plant cycle showed periods with accentuated water deficits (December to March), while for the cane-ratoon cycles significant water deficits were not observed.

4.4.1 Tree growth in two agroforestry systems

Aleurites fordii trees cultivated in the intercrop II system showed greater tree growth when compared to the intercrop I system (Table 1). All growth variables analyzed showed greater values for the intercrop II system. In general, considering all seasons and growth variables studied, we observed values 18% higher than those obtained for the intercrop II system. In relation to the seasons of the year, the summer season was responsible for the greater increase in the tree growth variables, while for the winter and spring season, a lower increment in the tree growth variables values were observed. When analyzing only the crown diameter in the last year (2016), the intercrop I system was 33.7 and 32.3% greater than the intercrop II system for the seasons of autumn and winter, respectively.

4.4.2 Solar radiation interception in agroforestry and monocrop systems

In evaluating the solar radiation intercepted by sugarcane in the cropping systems during the 5th cane-ratoon cycle (Fig. 4), we found variations in the amount of solar radiation intercepted by sugarcane plants during the cycle and in the different cropping systems. The greatest amount of solar radiation intercepted during the 5th cane-ratoon cycle was observed at 265 days after cutting where the monocrop, intercrop I and intercrop II systems intercepted 89.3, 78.1 and 73.9% of incident radiation, respectively. In general, sugarcane grown in the monocrop system intercepted greater amount of solar radiation (Fig. 4c) when compared to the agroforestry systems (Fig. 4a, b); however, when compared to the two agroforestry systems, the sugarcane grown in the intercrop I system showed greater amount of intercepted solar radiation which was approximately 12.2% higher than the intercrop II system. There observations were made considering mean values during the 5th cane-ratoon cycle.

4.4.3 Sugarcane yield components in agroforestry and monocrop systems

A significant difference for all variables were verified for sugarcane yield components when grown in the intercrop and monocrop systems throughout the evaluation years (Fig. 5). We saw a significant difference for the number of nodes between the cropping systems for only the 4th cane-ratoon cycle where the intercrop I and intercrop II system values were greater than the monocrop system (Fig. 5a). In relation to the evaluation years, the smallest number of nodes was verified for the cane-plant cycle with an average value of 5.3 nodes per plant. When compared to the other evaluation years, we observed an increase of 64.3% in the number of nodes with an average value for all cane-ratoon cycles of 14.9 nodes per plant.

We observe a pronounced response for the stalk number in the 2nd and 3rd cane-ratoon cycle (Fig. 5b). The greatest stalk number was seen for the monocrop and intercrop I systems, which were 35.2 and 41.0% greater than the intercrop II system in the 2nd and 3rd cane-ratoon cycles, respectively. Values for stalk number were observed to level-off for the 4th and 5th cane-ratoon cycle, with an average value of 10.6 stalks m^{-2} in the different cropping systems (Fig. 5b). For the cane-plant cycle, the lowest stalk number was seen with an average value of 5.7 stalks m^{-2}. The monocrop system showed a stalk weight 38.5, 26.0 and 23.7% greater than the intercrop II system for the 2nd, 3rd and 4th cane-ratoon cycle, respectively (Fig. 5c); while a significant difference was not observed when compared to the intercrop I system.

The greatest stalk yield, 85.3 Mg ha^{-1} was obtained for the monocrop system, followed by the intercrop I with 78.4 Mg ha^{-1} and lastly, the intercrop II sytem with 63.1 Mg ha^{-1} in the 3rd cane-ratoon cycle (Fig. 5c). For the 5th cane-ratoon cycle, the monocrop system showed greater values than either of the two agroforestry systems. In the first year, no difference was observed for the stalk yield for all cropping systems; this year had the lowest values for stalk yield. In relation to the evaluation years, the greatest stalk weight values were obtained in the 3rd cane-ratoon cycle with an average value of 75.6 Mg ha^{-1} and a subsequent decrease in the values reaching 52.1 Mg ha^{-1} in the 5th cane-ratoon cycle (Fig. 5c).

4.4.4 Sugarcane morphological traits in different cropping systems

Significant differences for the morphological traits of sugarcane when grown in intercrop and monocrop systems throughout the evaluation years were observed (Fig. 6). We saw a significant difference for the stem diameter between the cropping systems in the 2nd and 3rd cane-ratoon cycle, where the monocrop and intercrop I system showed the greatest values when compared to the intercrop II system (Fig. 6a). The greatest values of stem diameter were observed for the 4th cane-ratoon cycle with an average value of 29.8 mm, while the lowest values obtained for cane-plant cycle were seen with an average value of 20.0 mm.

The greatest stalk length values were found for the intercrop I system; these were greater than the monocrop and intercrop II systems for the 2nd and 3rd cane-ratoon cycle (Fig. 6b). The stalk length values for the monocrop system in the 5th cane-ratoon cycle were greater than the other agroforestry systems. Additionally, an increasing trend throughout the evaluation years was found independent of the cropping system; the greatest stalk length was observed in the 5th cane-ratoon cycle with an average value of 200 cm, which was 34.5% greater those obtained in the cane-plant cycle with a reported average value of 131 cm.

4.4.5 Sugarcane juice quality in intercrop and monocrop systems

When evaluating the effect of the cropping systems on the sugarcane quality (Fig. 7), a significant difference between the treatments for juice volume and total sucrose content were found; whereas for the sucrose content, no significant difference was observed. An average sucrose content of 174.4 g L^{-1} was obtained for all systems (Fig. 7b). The greatest values of juice volume were seen for the intercrop I and monocrop systems, which were 31.7 and 26.2% greater than the intercrop II system (Fig. 7a). The same response trend was seen for the variable total sucrose content, where the intercrop I and monocrop system were 32.1 and 26.1% greater than the intercrop II system (Fig. 7c).

In relation to the effect of cultivation years on sugarcane quality, all variables showed significant differences across years (Fig. 8). The cane-plant cycle presented the lowest values for all studied variables. Juice volume increased until the 4th cane-ratoon cycle at which point a subsequent decrease of 29.5% in the juice volume produced was seen in the 5th cane-ratoon cycle (Fig. 8a). The 3rd and 4th cane-ratoon cycles showed no significant difference with an average juice volume of 37.5 m^3 ha^{-1}. This same trend was observed for the total sucrose content (Fig. 8c). The greatest values were obtained for the 3rd and 4th cane-ratoon cycle with a subsequent decrease of 34.8% in the total amount of sucrose produced in the 5th cane-ratoon cycle.

The greatest sucrose content values were recorded in the 4th cane-ratoon cycle which differed significantly from the other evaluation years (Fig. 8b). It is important to highlight the low sucrose content in the first evaluation year which was only 69.1 g L^{-1}. In other years, considering an average value for all cane-ratoon cycles of 193.6 g L^{-1}, a difference of 64.3% was observed.

4.5 Discussion

4.5.1 Tree growth determines the amount of solar radiation intercepted by sugarcane in agroforestry systems

Aleurites fordii growth depends on tree spacing which determines the degree of intraspecific competition between other trees and interspecific competition between trees and sugarcane plants. This is especially relevant during the first year after tree planting due to sugarcane casting shade on the *Aleurites fordii* trees. The greater degree of competition seen in the intercrop II system led to greater tree growth, a development which can be associated with a strategy of the trees to acquire more resources (solar radiation, water, nutrients) through greater plasticity of the tree canopy (Schröter et al., 2012; Longuetaud et al., 2013; Van de Peer et al., 2017). The greater growth values of the trees cultivated in the intercrop II system resulted in a reduction of productive sugarcane responses. In this context, agroforestry systems should consider the benefits provided by both species in order to obtain a balance in the production system.

Aleurites fordii growth is influenced by the season of the year. In summer and autumn seasons, the tree growth is favored. A higher incidence of solar radiation and the occurrence of higher temperatures can benefits the photosynthetic rate of trees and result in an increase in the production of photoassimilates for tree growth. According to Boardman (1977), photosynthetic activity determines the growth of plants due to an increase or decrease in photoassimilates, a relationship which can be described as a function of meteorological conditions. On other hand, in the winter and spring seasons, the growth of *Aleurites fordii* trees was influenced by the occurrence of low air temperatures such as in days with frost, which can result in a reduction of photosynthetic activity as a consequence of cells freezing (Larcher, 2000). This response can reduce cell division and expansion, and affect tree growth (Table 1).

The growth and development of different species in the same area results in dynamic interactions between a community of plants which changes with time. These interactions influence the distribution of existing resources in the system (Muller et al., 2014), where solar radiation is the first to change. The lowest amount of radiation intercepted by the sugarcane in the intercrop I and intercrop II systems is explained due to the effects of the *Aleurites fordii* canopy which shades the sugarcane plants, especially those in the intercrop II system because the lower spacing between trees.

According to Leite et al. (2012), canopy dimensions interfere with the performance of physiological processes and are often used as indicators of a tree's ability to compete for resources. The results of the present study are similar to those of Hardy et al. (2004), whom reported that the amount of radiation intercepted by the trees and consequently the radiation that reaches the ground is determined by canopy characteristics such as crown diameter and the size of the existing gaps in the canopy, factors which can be determined by tree arrangement.

Our study highlights the importance of the choice of tree arrangement; considerations should be given to the height and crown diameter of a tree species over time and the requirements of the crops present in the understory. In this study, the lesser amount of solar radiation intercepted by sugarcane cultivated in the intercrop II system negatively influenced sugarcane yield components. It is therefore that a balance between crop and trees should be sought over time.

4.5.2 Yield components are influenced by cropping systems and evaluation years

The yield and quality components of sugarcane were influenced by different cropping systems and evaluation years. Changes in microclimate conditions of different cropping systems explains the variation of the yield components, and morphological and quality traits of cultivated sugarcane. A greater degree of interspecific competition for available natural resources was observed in the agroforestry systems but not the monocrop system, due to the presence of trees. Solar radiation and water availability were the primary meteorological variables that influenced yield components and the quality traits of sugarcane (Fig 3 and 4a, b). It can be affirmed that meteorological variables are the primary factors responsible for the yield and quality of sugarcane (Keating et al., 1999; Inman-Bamber et al., 2010; Cardozo and Sentelhas, 2013).

The cane-plant cycle was negatively affected by low water availability which occurred between the months of December 2011 to March 2012 (Fig. 3). This resulted in low values for yield and quality components, primarily of stalk weight and produced juice volume (Fig. 5c and Fig. 8a). Greater susceptibility of sugarcane to water stress occurs in the stalk elongation phase which results in a considerable reduction in the production of biomass and reduces the stalk weight and sucrose yield (Robertson et al., 1999; Silva and Costa, 2004; Inman-Bamber and Smith, 2005).

The monocrop and intercrop I systems showed similar responses for the number of stalks and stalk weight (Fig. 5b, c), stem diameter (Fig. 6a), juice volume and total sucrose yield (Fig. 7a, c). These responses are related to the greater availability of solar radiation in the understory of the *Aleurites fordii* trees in the intercrop I system, which allows for a greater amount of solar radiation to be intercepted by sugarcane plants (Figure 4a), as well as less competition for water and nutrients (Pinto et al., 2005; Zhang and Li, 2003; Nicodemo et al., 2016). A greater amount of intercepted solar radiation resulted in higher photosynthetic rates (Ribeiro et al., 2017), and consequently, greater production of assimilates which determines the productive responses of the sugarcane plants.

The low yield, morphological differences and quality of sugarcane cultivated in the intercrop II system are explained by the low amount of solar radiation intercepted by the sugarcane (Fig. 4b), when compared to the intercrop I system. The low amount of solar radiation intercepted is associated with the effects of the canopy of the *Aleurites fordii* trees which casts shade on the sugarcane plants, and led to a greater competition for water and nutrients.

The reduction in the productive responses of sugarcane cultivated in the intercrop II system may be related to the morphophysiological adjustments (Paciullo et al., 2011); for example, as a shade tolerance strategy, these adaptations were not able to compensate a reduction of radiation in the understory of *Aleurites fordii* and therefore influenced the productive sugarcane responses. According to Pinto et al., (2005) the main limiting factor in agroforestry systems is the availability of solar radiation, which together with the competition for water and nutrients limits sugarcane yields in plants near to the forest species.

The stalk yields in the agroforestry systems showed satisfactory values (78.4 Mg ha^{-1} and 63.1 Mg ha^{-1} for the intercrop systems I and II, respectively) for the 3rd cane-ratoon cycle when compared with the average stalk yield for the state of Rio Grande do Sul of 51.5 Mg ha^{-1} during the 2013/2014 sugarcane cycle (Conab, 2014). Additionally, these results are similar those obtained by Pinto et al., (2005), whom evaluated the yield of sugarcane in agroforestry systems with *Eucalyptus grandis* and found differences in sugarcane yields in different tree spacing. In the previously cited study, sugarcane grown among trees planted 11.6 m apart showed average yields of 64.1 Mg ha^{-1} in the state of São Paulo, Brazil. The yields seen in the present study were higher than those obtained by Elli et al., (2016) whom, evaluating the yield of sugarcane in different agroforestry systems with *Parapiptadenia rigida* species, found stalk yields of 61.9, 53.1 and 41.6 Mg ha^{-1} in three cultivation cycles. These results demonstrates the productive potential of sugarcane in intercropping conditions with forest species.

4.5.3 Number of sugarcane crops harvested

During the sugarcane cycle, it was possible to identify a period of greater production independent of the cropping systems. In the 3rd and 4th cane-ratoon cycles, the sugarcane reached its peak production resulting in the highest rate for produced stalks and juice volume. In the 5th cane-ratoon cycle a reduction of the productive capacity of the sugarcane was observed with a significant reduction in most of the analyzed variables. This may be explained by the lower number of plants per unit area, and due to the lower sugarcane tillering. This result was more evident for the intercropping systems because the higher levels of shading on the plants negatively influencing the tillering of the sugarcane. According to Singels and Smit (2009), the density of sugarcane plants tends to decrease with a reduction of solar radiation interception due the effects of shading resultant from the intercropping with the forest species.

Successive ratoon cycles resulted in the decline of productive sugarcane responses over time. Underground buds released from apical dominance successively emerged to produce another (ratoon) which grows to maturity. A general decline in sugarcane yields in successive ratoons is a phenomenon termed ratoon decline (Rumadan et al., 2013), and it limits the economic viability of sugarcane production due to the increasing frequency and necessity of costly replanting operations. Lower yields of older ratoons are generally associated with an increase in pests and diseases, increased competition between tillers and subsequent tiller mortality (Chapman et al., 1992), weed competition (Srivastava and Chauhan, 2006), and other crop management factors such as shading resultant from the growth of forest species in intercropping systems. The typical number of sugarcane crops harvested from a single plantation can range from three to seven cane-ratoon cycles (Ramburan et al., 2013).

4.5.4 Sugarcane juice production depends on the cropping system used

Changes in microclimatic conditions in different cropping systems led to variations in juice production and total sucrose yield, while variations for the sucrose content were not observed in the different cropping systems. Greater juice production and total sucrose yield observed for the monocrop and intercrop I systems, and this can explained by the lower degree of competition between sugarcane plants and trees for resources, particularly for solar radiation which was not limiting in these conditions. On other hand, for the intercrop II system, a greater degree of competition for resources resulted in a significant reduction in produced juice volume and in total sucrose yield. In addition, a lower number of obtained stalks and lower average stalk weight (Fig. 5b, c) resulted in a lower juice volume which highlights the relationship between the studied variables.

Total sucrose yield is a highly complex trait that depends on yield components, and morphological and quality traits, each having its own sensitivity to abiotic conditions (Rae et al., 2005). Interactions among sugarcane yield components and their effect on sucrose yields have been identified by others authors (Wang et al., 2008; Gouy et al., 2015). According to these authors, the stalk number was reported to be the most important component for sugarcane production, followed by stalk weight and stalk diameter, while plant height and sucrose content were considered to be of secondary importance (Wang et al., 2008; Gouy et al., 2015).

Our study demonstrated that intercropping systems did not significantly affect sucrose content in sugarcane juice. This response can be explained by microclimate variations in the cropping systems which was not sufficient to cause variation in sucrose content. In addition, due to the *Aleurites fordii* species' leaf senescence early in the winter season, this characteristic allows a greater availability of radiation during the sugarcane maturation period; this resulted in similar sucrose content between the different cropping systems. Variations in sucrose content were observed during the cane-ratoon cycles. These variations may be related to cane-ratoon age and the variation of the air temperature during each cane-ratoon cycle (Fig. 3) where low air temperatures during the ripening period may be responsible for a greater or lesser accumulation of sucrose.

The observed results corroborate with those of Cardozo and Sentelhas (2013), whom reported that in relation to the proximity of sugarcane harvest, the occurrence of low temperatures can hinder the growth of sugarcane, forcing a conversion of reduced sugars into sucrose. These results confirm that air temperature variation can influence sucrose content. The sucrose content in the stalk can vary by harvest time and crop age (Cardozo and Sentelhas, 2013), which was confirmed in the present study.

The study of the tree growth, solar radiation interception, sugarcane yield components, morphological traits, juice yield and quality of sugarcane cultivated in agroforestry systems are not a popular subject of research. Thus, the information generated in this study is relevant, as it provides information to farmers and can assist in the planning of more ideal agroforestry systems via more efficient arrangements, in addition to confirming the viability of sugarcane cultivated in agroforestry systems. This is especially relevant in the context of Brazilian law No. 12,651, May 25, 2012 which established a new Forest Code that allows farmers to plant agroforestry systems in areas of permanent preservation (APP) and legal reserves (RL), provided that said systems are subject to a sustainable management plan.

4.6 Conclusions

Agroforestry systems should consider the benefits of both forestry and cultivated species. In this study, *Aleurites fordii* trees had greater growth in the intercrop II system; however, this system promoted reductions in sugarcane yield components due to the lowest relative amount of solar radiation intercepted by sugarcane plants. For sugarcane production, the use of an intercropping system with 12x12m arrangements should be prioritized, because it promotes greater sugarcane yields when compared to a 6x6m intercropping systems; significant differences were not observed when the system (12x12m) was compared to the monocropping system for most of the analyzed variables, supporting the first hypothesis. We recommend the cultivation of sugarcane for up to a maximum of five cycles; after this period, economic evaluation and decision-making is necessary in order to plan a new sugarcane plantation which supports the second hypothesis.

The choice in agroforestry systems should consider the balance of a system; in this context, the intercrop I system should be prioritized because it presents higher sugarcane yields. In the future, from the moment that *Aleurites fordii* trees show a productive return, a new joint analysis of the data should be made in order to verify the suggested recommendations of the present research.

This study sought to provide new sustainable alternatives for farmers in order to increase the diversification of rural properties and maintain and/or improve the preservation of existing agro-ecosystems. It is important that new research is conducted in order to study the use of agroforestry systems in threatened ecosystems such as those in permanent preservation areas (APP's) and legal reserves (RL's).

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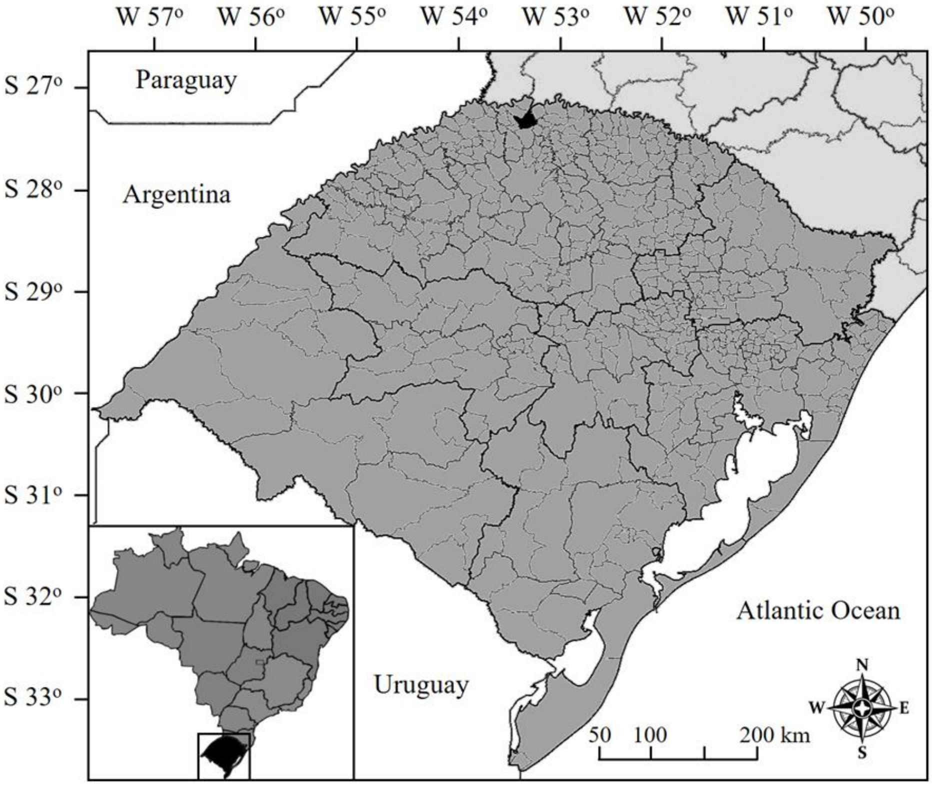

Figure 1. Geographical location of the experiment. The state of Rio Grande do Sul is highlighted in black on the bottom map, while the city of Frederico Westphalen is highlighted in black on the main map.

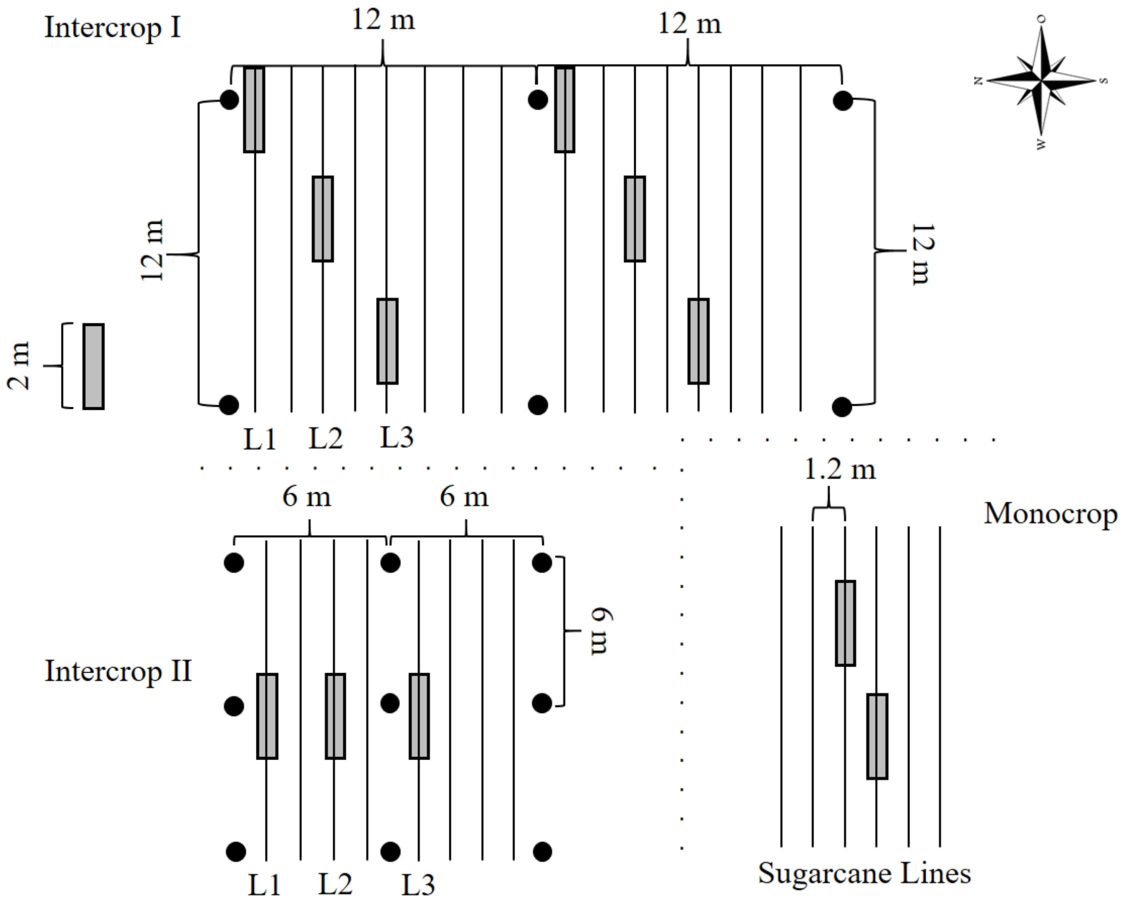

Figure 2. A sketch of the agroforestry system experimental units: Intercrop I: 12 × 12m, Intercrop II: 6 × 6m, and the monocrop system. Black circles represent trees, continuous lines indicate where the sugarcane was planted, and the rectangles in gray represent the year evaluation plots of sugarcane.

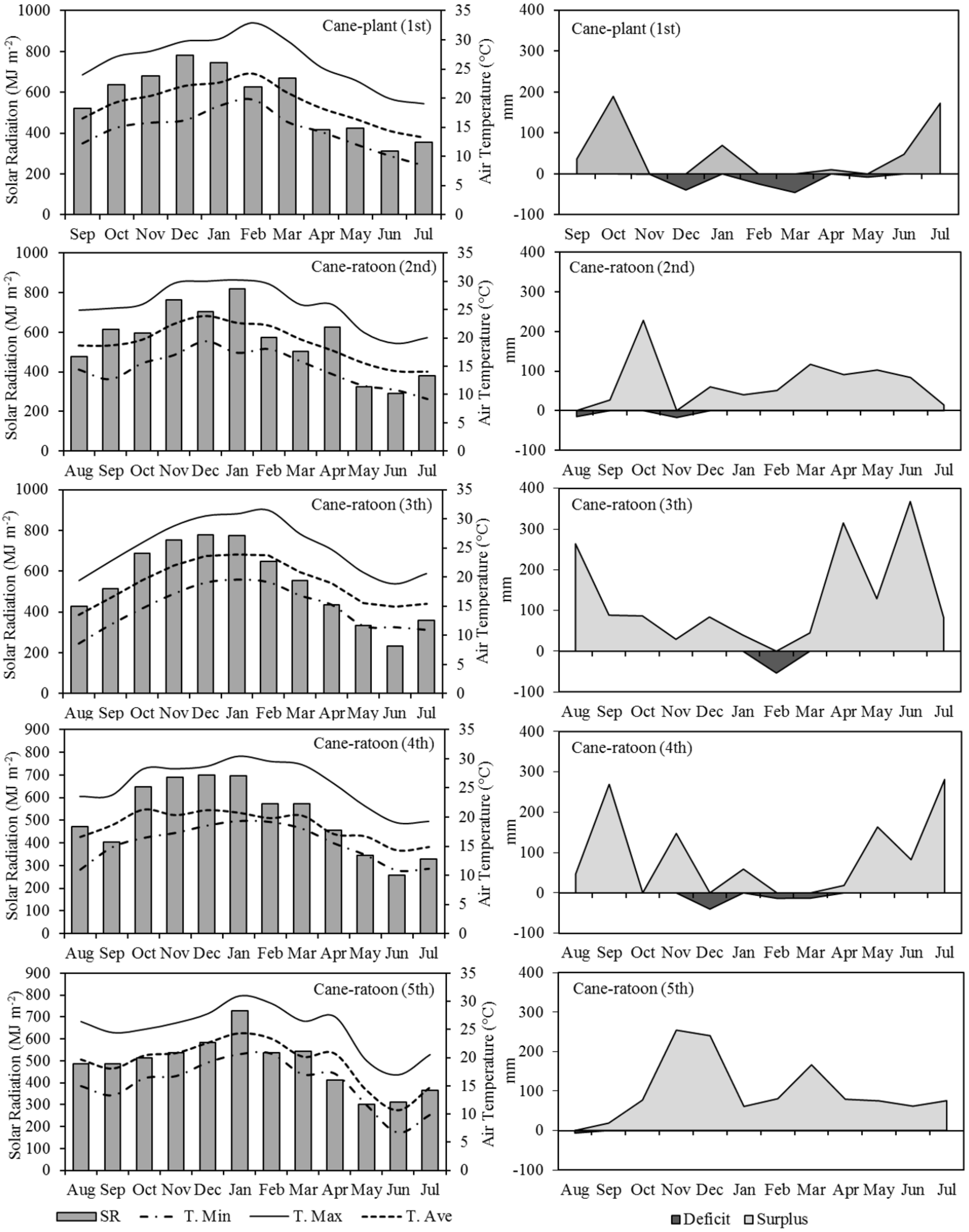

Figure 3. Average monthly values for minimum, maximum and average air temperature, accumulated incident solar radiation and water balance (Surplus = water surplus and Deficit = water deficit) during each sugarcane cycle in Frederico Westphalen, RS, Brazil.

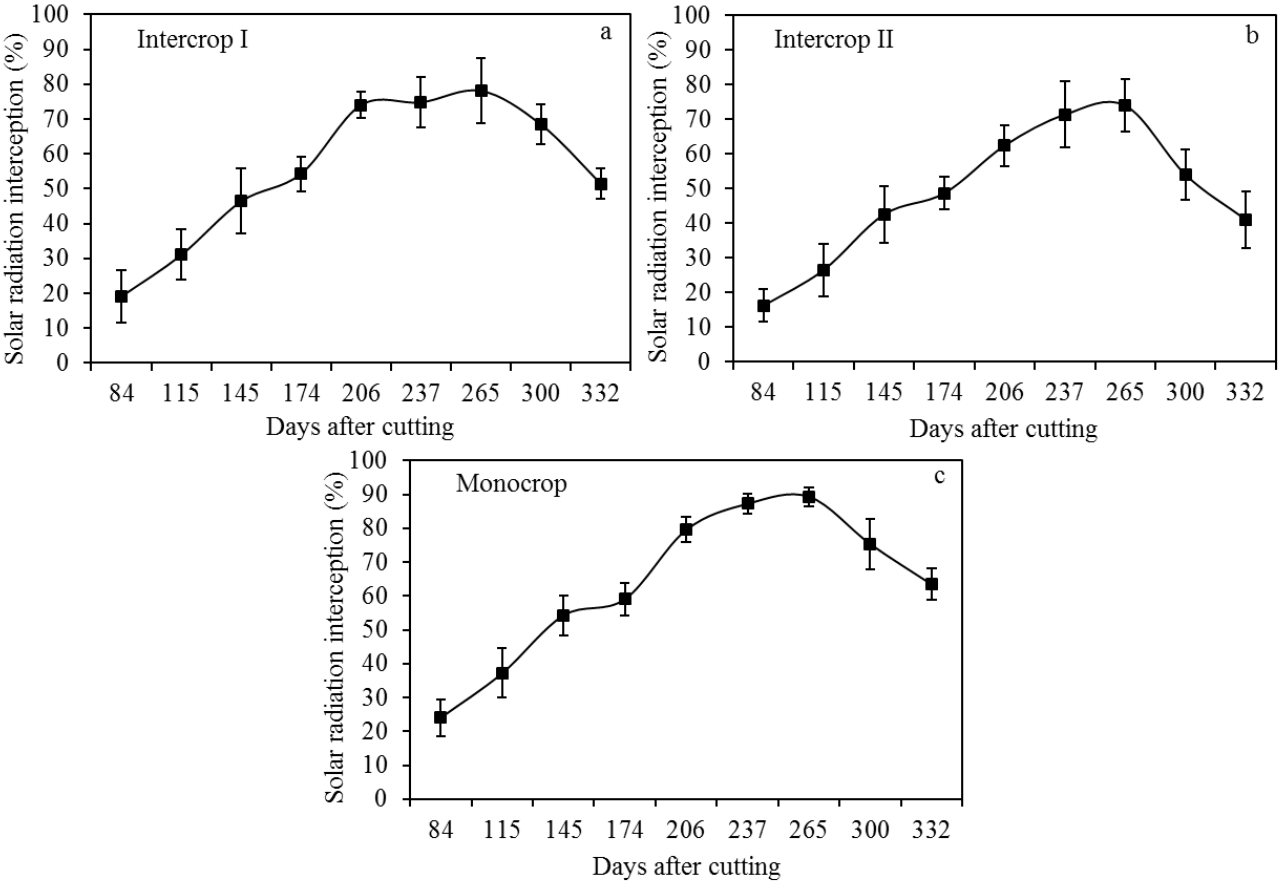

Figure 4. Solar radiation intercepted by sugarcane in intercrop and monocrop systems throughout the days after cutting in the 5th cane-ratoon cycle.

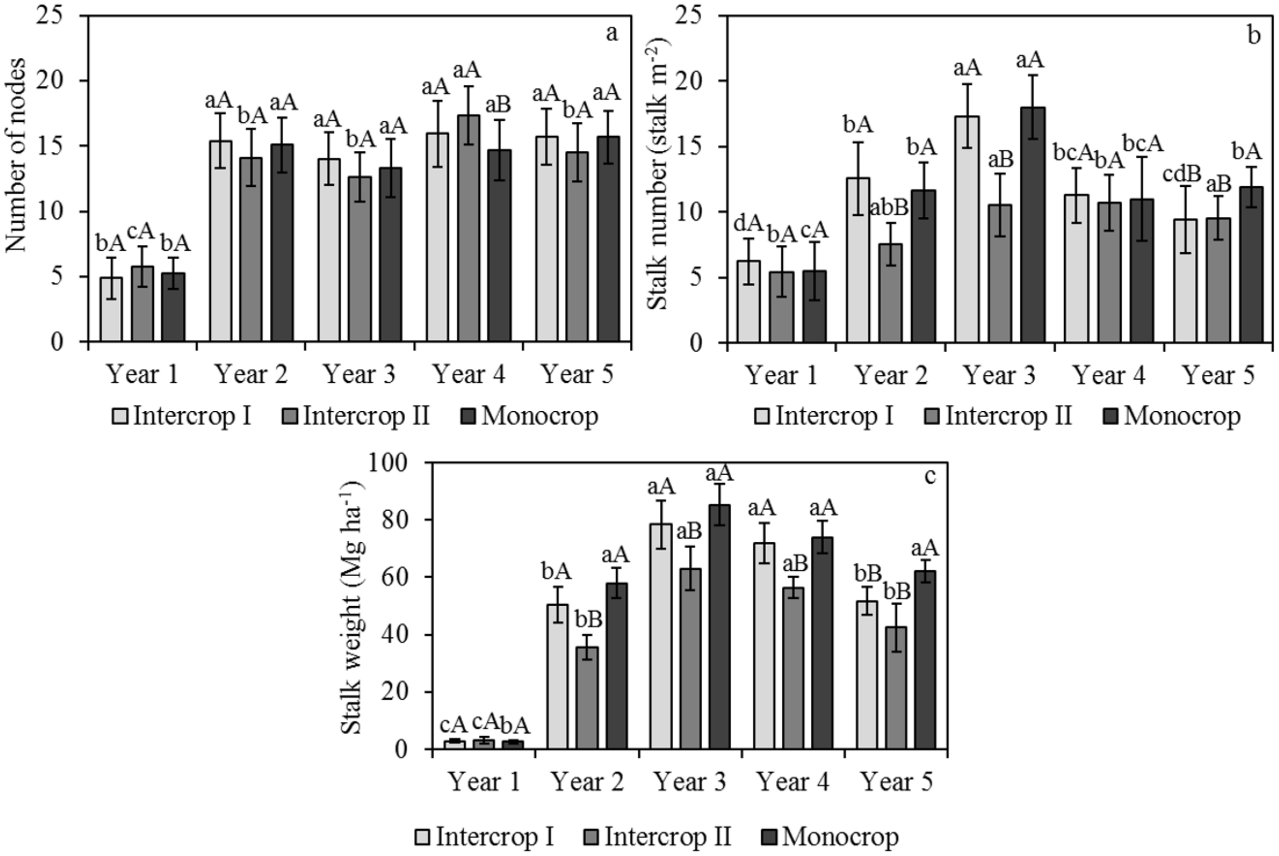

Figure 5. Yield components of sugarcane in intercrop and monocrop systems throughout the evaluation years. Each bar represents average values ± SE. Means followed by the same uppercase letter compare the agroforestry systems with the control (Monocrop), by Dunnet test ($p<0.05$); and lowercase letters compare the evaluation years for each cropping system, by Tukey test ($p<0.05$).

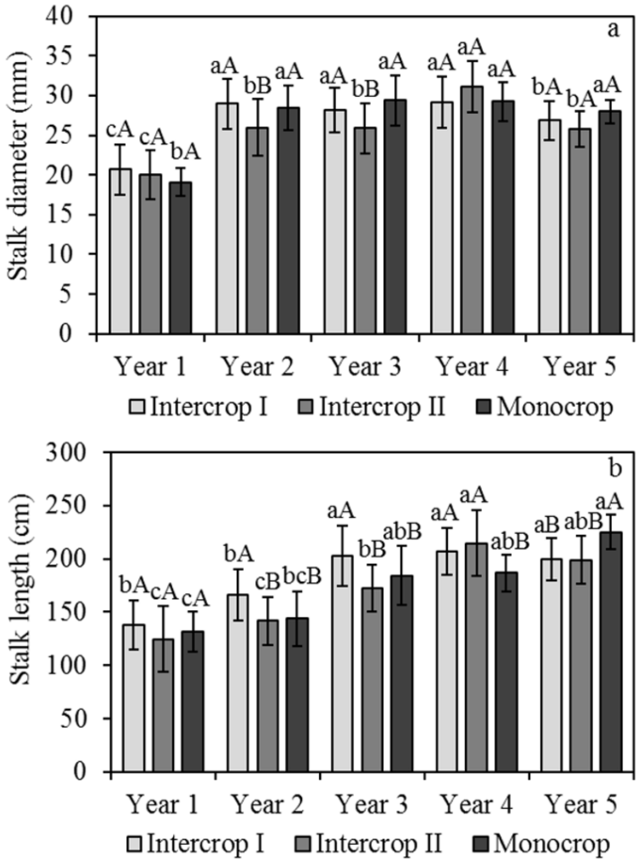

Figure 6. Morphological traits of sugarcane in intercrop and monocrop systems throughout the evaluation years. Means followed by the same uppercase letter compare the agroforestry systems with the control (Monocrop), by Dunnet test ($p<0.05$); and lowercase letters compare the evaluation years for each cropping system, by Tukey test ($p<0.05$).

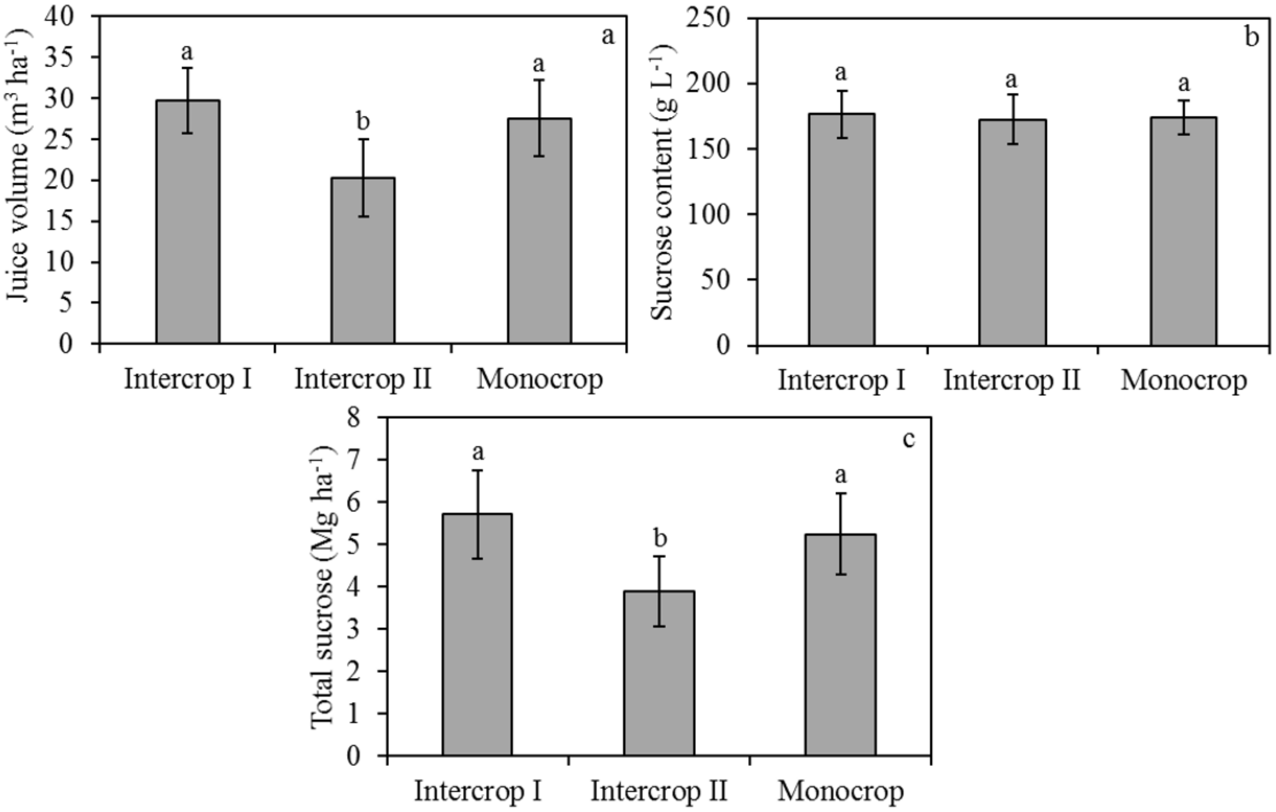

Figure 7. Quality traits of sugarcane in the different cropping systems. Each bars represent average values ± SE. Means followed by the same lowercase letter compare the agroforestry systems with the control (Monocrop), by Dunnet test ($p<0.05$).

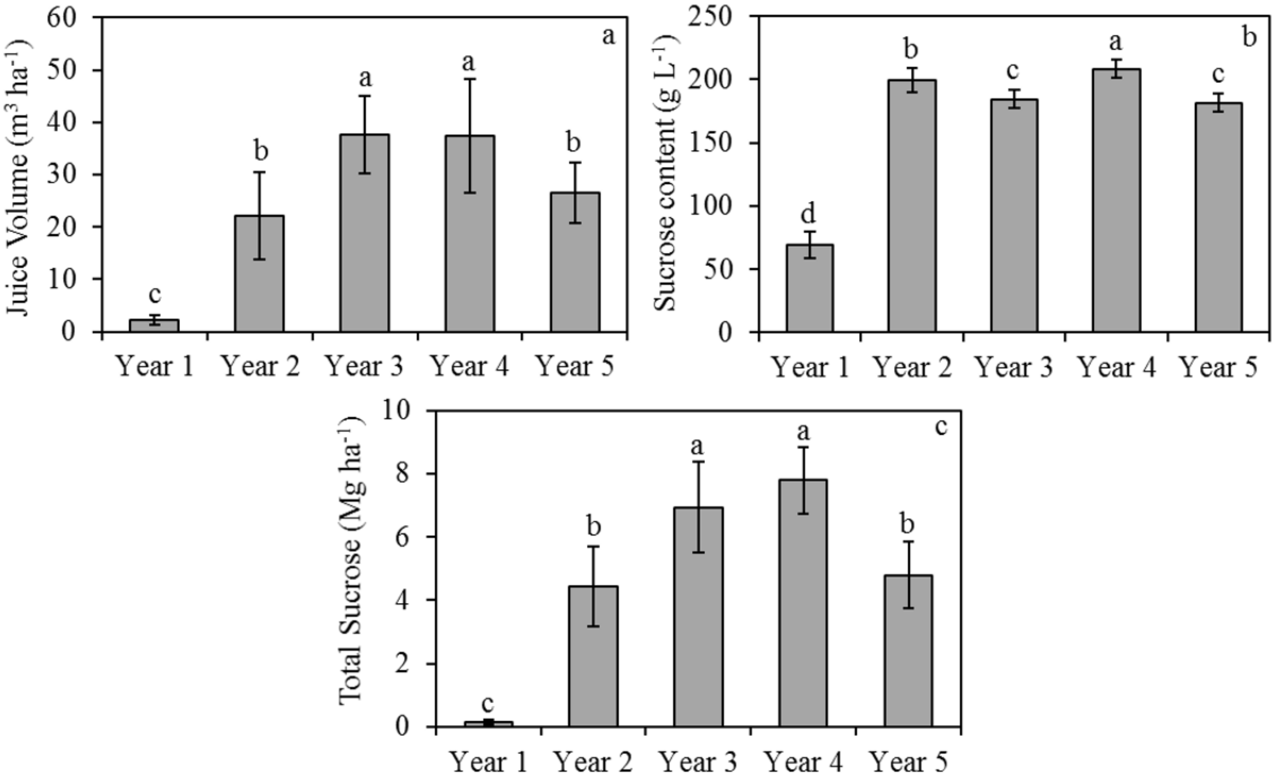

Figure 8. Quality traits of sugarcane between the different evaluation years. Each bars represent average values ± SE. Means followed by the same lowercase letter compare the evaluation years by Tukey test ($p<0.05$).

Table 1. Height (H), stem diameter (SD), diameter at breast height (DBH) and crown diameter (CD) of *Aleurites fordii* in two intercropping systems during the seasons of the year throughout the experimental period.

Year	Season	Intercrop	H (m)	SD (cm)	DBH (cm)	CD (m)
2012	Autumn	I	1.110	2.073	1.540	0.508
		II	1.117	2.189	1.520	0.556
	Winter	I	1.192	2.366	1.703	0.613
		II	1.148	2.535	1.770	0.645
	Spring	I	1.252	2.425	1.778	0.547
		II	1.175	2.583	1.810	0.512
	Summer	I	1.643	3.376	2.157	0.965
		II	2.002	4.046	1.738	1.534
2013	Autumn	I	1.605	6.090	2.476	0.901
		II	2.450	7.765	3.052	1.700
	Winter	I	1.591	6.135	2.970	0.815
		II	2.422	8.247	3.422	1.478
	Spring	I	1.887	6.600	3.220	0.901
		II	2.589	9.437	3.869	1.381
	Summer	I	2.357	13.857	4.041	1.231
		II	2.889	18.857	6.243	2.244
2014	Autumn	I	2.363	14.714	6.067	1.312
		II	3.024	19.743	8.086	2.061
	Winter	I	2.386	14.714	7.467	1.196
		II	2.926	19.900	8.829	1.851
	Spring	I	2.492	16.250	7.500	1.696
		II	3.060	19.843	7.914	2.301
	Summer	I	2.843	16.750	8.150	1.678
		II	3.351	22.714	10.014	2.714
2015	Autumn	I	2.937	16.915	8.200	1.740
		II	3.471	23.606	11.243	2.760
	Winter	I	3.055	16.850	9.033	1.843
		II	3.739	24.300	11.886	2.538
	Spring	I	2.977	16.683	8.917	1.612
		II	3.554	24.657	12.300	2.653
	Summer	I	3.356	19.100	11.000	1.564
		II	3.641	26.357	13.214	2.564
2016	Autumn	I	3.452	19.920	11.400	1.739
		II	3.766	26.286	13.971	2.624
	Winter	I	3.460	20.020	11.580	1.794
		II	3.781	26.186	14.500	2.598

5 DISCUSSÃO GERAL

O conhecimento das interações dinâmicas que ocorrem entre o crescimento da espécie florestal e as variáveis meteorológicas são de fundamental importância para que se obtenha sucesso na implantação dos sistemas agroflorestais. Tal fato é relevante considerando o cultivo de espécies no sub-bosque, bem como na definição de arranjos de árvores que possam beneficiar o crescimento das plantas presentes no sub-bosque como das próprias árvores. As árvores de Tungue cultivadas no sistema agroflorestal de 6x6m apresentaram maior crescimento quando comparado com aquelas crescidas em espaçamento de 12x12m. Esse resultado proporcionou uma maior interceptação da radiação solar pela copa das árvores, resultando em maior crescimento em diâmetro e altura.

As variáveis de crescimento do Tungue foram influenciadas pelas variáveis meteorológicas de forma diferenciada para cada estação do ano. A radiação solar incidente e a temperatura mínima do ar foram as variáveis meteorológicas que proporcionaram a maior influência no crescimento do Tungue, principalmente sobre as variáveis diâmetro do colo e diâmetro à altura do peito. Essas afirmações são confirmadas pela alta correlação, tanto positiva como negativa, observada para essas variáveis na análise de correlação canônica.

A ocorrência de geada (temperaturas mínimas extremas) no outono afetou significativamente os ramos apicais e a senescência precoce das folhas de Tungue. Além disso, o efeito do sombreamento proporcionado pela cana-de-açúcar nos períodos iniciais de estabelecimento do sistema agroflorestal influenciou as taxas fotossintéticas devido à redução na disponibilidade de radiação solar. Neste sentido, é possível afirmar que as interações dinâmicas existentes nos sistemas agroflorestais influenciam tanto a espécie florestal (principalmente nos estádios inicias de cultivo) como a cultura anual devido o sombreamento proporcionado pela copa das árvores.

A presença das árvores de Tungue no sistema agroflorestal resultaram em variações nas taxas de crescimento, eficiência do uso da radiação solar, bem como na produtividade da cana-de-açúcar cultivada no sub-bosque. Essa influência foi mais significativa para a cana-de-açúcar cultivada no sub-bosque do arranjo agroflorestal de 6x6m e sobre as linhas de cultivo próximas às árvores. Tal fato resultou na redução no índice de área foliar e, consequentemente, na radiação interceptada pelas plantas de cana-de-açúcar próximas das espécies arbóreas, resultando em uma menor eficiência do uso da radiação solar pelas plantas.

Além disso, os componentes de rendimento da cana-de-açúcar também foram influenciados pelos sistemas agroflorestais e anos de avaliação. As mudanças nas condições microclimáticas nos diferentes sistemas de cultivo explicam a variação dos componentes de rendimento, uma vez que a radiação solar e a disponibilidade de água foram as principais variáveis meteorológicas que influenciaram os componentes de rendimento da cana-de-açúcar. Por outro lado, a qualidade da cana-de-açúcar mensurada através do teor de sacarose não foi afetada pelos sistemas agroflorestais. Observou-se variação na qualidade apenas nos diferentes anos de avaliação. Essas variações podem estar relacionadas à idade da cana-soca e as variações na temperatura do ar durante cada ciclo, uma vez que a baixa temperatura do ar durante o período de amadurecimento é responsável pelo maior ou menor acúmulo de sacarose.

Durante os cinco anos de cultivo da cana-de-açúcar foi possível identificar um período de maior produção independente dos sistemas de cultivo estudados. O maior pico de produção foi obtido no 3º e 4º ciclos da cana-soca em função do maior número de colmos, peso de colmo e volume de suco produzido. No entanto, para o 5º ciclo de cana-soca, observou-se uma redução da capacidade produtiva da cana-de-açúcar com uma redução significativa na maioria dos componentes de produção estudados. Este resultado foi mais evidente para os sistemas agroflorestais, em função do sombreamento das árvores de Tungue sobre as plantas de cana-de-açúcar.

Os sistemas agroflorestais, por serem altamente dinâmicos, não modificam apenas a radiação solar em seu interior, mas sim um conjunto de variáveis. Portanto, o crescimento e a eficiência do uso da radiação pela 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 no crescimento e rendimento das plantas, principalmente em função da interação dinâmica existente nos sistemas agroflorestais.

Ambas as espécies Tungue e Cana-de-açúcar foram beneficiadas no cultivo em sistemas agroflorestais. A cana-de-açúcar foi beneficiada principalmente devido as características das árvores de Tungue, a qual apresenta a senescência das folhas na estação inverno e favorece a maturação da cana-de-açúcar. Para o Tungue o sombreamento inicial proporcionado pela cana-de-açúcar resultou em maior crescimento em altura e diâmetro devido maior plasticidade da copa das árvores. Com isso podemos inferir que, mesmo sob a influência das árvores de Tungue, o cultivo de cana-de-açúcar em sistemas agroflorestais mostrou valores satisfatórios de crescimento e produtividade podendo assim ser recomendados para o cultivo em sistemas alternativos de produção. Adicionalmente, o Tungue por apresentar altas taxas de crescimento no arranjo agroflorestal de 6x6m também pode ser recomendado para compor os sistemas agroflorestais. Assim, as informações geradas neste estudo são relevantes, pois auxiliam os agricultores no planejamento da implantação de novos sistemas agroflorestais.

O próximo passo deste estudo é realizar detalhadamente uma análise econômica dos diferentes componentes destes sistemas consorciados. Apesar da produtividade da cana-de-açúcar ser reduzida, devido a interferência da espécie florestal, deve-se levar em consideração o retorno econômico das árvores de Tungue, bem como a inserção de outras espécies sequenciais após o cultivo da cana-de-açúcar. Deve-se ressaltar que, além do retorno econômico, o uso destes sistemas é uma alternativa sustentável para o uso da terra, pois podem promover a preservação ambiental, manutenção da biodiversidade, bem como a diversificação da propriedade rural, auxiliando tanto pequenos como médios produtores rurais.

6 CONCLUSÃO GERAL

O crescimento das árvores de Tungue em sistema agroflorestal foi influenciado pelas variáveis meteorológicas de forma diferenciada em cada estação do ano. A estação do ano verão foi responsável pelo maior incremento em altura e diâmetro das árvores. As interações dinâmicas existentes entre as árvores de Tungue e as variáveis meteorológicas foram determinantes para o crescimento e produtividade da cana-de-açúcar cultivada no sub-bosque.

Os maiores valores de crescimento das árvores cultivadas no sistema agroflorestal de 6x6m resultaram em uma redução no crescimento, eficiência do uso da radiação e produtividade da cana-de-açúcar. Tal fato se deve a menor quantidade de radiação solar interceptada pela linhas de cana-de-açúcar crescidas próximas das árvores de Tungue.

Para a produção de cana-de-açúcar, deve-se priorizar o uso de um sistema agroflorestal com arranjos de 12x12m, pois promove maiores rendimentos de cana-de-açúcar quando comparados com um sistema agroflorestal de 6x6m, uma vez que a qualidade da cana-de-açúcar não foi afetada pelos sistemas de cultivo. No futuro, a partir do momento em que as árvores de Tungue apresentarem retorno produtivo, uma nova análise conjunta dos dados deve ser realizada a fim de verificar a recomendação sugerida na presente pesquisa.

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