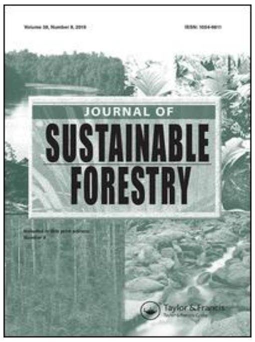

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Assessing Yield, Growth and Climate Traits in Agroforestry Systems in Southern Brazil

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ABSTRACT
The relationship between growth, yield and climate variables using multivariate analysis on agroforestry system has not been documented yet. Considering the potential of agroforestry systems as strategy to improve the balance of crop production and environmental health, the aims of this study were (i) to analyze the canonical correlations among groups of tree growth and climatic variables during four seasons of the year; and (ii) to characterize the relationships between sugarcane growth, yield, and quality variables in two agroforestry arrangements and sugarcane monocropping system. A field experiment was conducted from September 2011 to June 2016. The information generated in this study is relevant, as it provides information to farmers and can assist in the planning of new agroforestry systems due to the better knowledge of tree–crop interactions and climate effects in Southern Brazil. In this study, we demonstrated that crops and trees interact dynamically as a result of variations in the interception of solar radiation by trees in time due to the effect of tree age and arrangement, and we concluded that larger tree arrangements are suggested to benefit sugarcane growth and yield in agroforestry systems in Southern Brazil.

KEYWORDS
Agroforestry arrangements; environmental preservation; integrated land use; principal component analysis; sustainable systems; tree-crop interactions

Introduction

One of the biggest challenges in crop science worldwide is to improve the crop yield and the food production without compromise the environmental balance. In this context, the agroforestry systems gifts as an important tool for balancing environmental and crop production. To achieve this balance, the demand for food and energy needs to be met without damaging the agroecosystems (Godfray et al., 2010). In this paper, an agroforestry system was defined as a land use system in which trees are grown in combination with agricultural crops, and where both ecological and economic interactions occur between the components of the agroforestry system (Oelbermann et al., 2004; Pardon et al., 2017). Several authors have highlighted the potential beneficial effects of agroforestry systems

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such as carbon sequestration (Cardinael et al., 2015; Cong et al., 2014; Montagnini & Nair, 2004), increased input of organic matter, which improve physical, chemical, and biological properties of soil (Salton et al., 2013; Tracy & Zhang, 2008) and mitigation of soil erosion (Nair, 2007).

The sustainability of an agroforestry system is related to crop management and climatic dynamics, so it is essential to understand the environmental effects and plant interactions (Altieri, 2018; Ong et al., 2000). Tree–crop interactions can be adjusted since the competition can be reduced by employing efficient planting spacing (Ghezehei et al., 2016) and using compatible species (Bayala & Wallace, 2015; Ong & Kho, 2015). In this context, it is needed to study new alternative species to compose agroforestry systems and this study evaluates the insertion of Tung trees (*Aleurites fordii*) as an option for composing this system. This is particularly relevant due to the species' growth characteristics (deciduous characteristic) which can benefit the input of solar radiation into the understory on specific time of the year.

Studies with a several number of agricultural crops in agroforestry systems have been developed (Kumar & Nair, 2011; Nerlich et al., 2013). In this study, the authors proposed the insertion of sugarcane (*Sacharum officinarum* L.) intercropped with Tung trees. This approach is especially relevant, since Brazil is one of the largest sugarcane producers worldwide and the sugarcane monocropping has been promoting a great environmental and socio-economic impact, and the adoption of agroforestry systems to produce sugarcane can be a sustainable alternative. In this context, new studies should be developed to assess plant growth, yield traits, and the dynamics of resources available in these systems.

The basic structure of agroforestry systems is formed by their constituents and their arrangement in the cultivation area. In this context, the planting spacing should consider the resource requirements of trees and crops to be used in the system (Prasad et al., 2010). The benefits and advantages of both components of the agroforestry systems should be considered to define the most ideal planting spacing.

In agroforestry systems, there is a greater variability in the weather conditions in a temporal and spatial scale according to tree–crop interactions. 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.

One of the greatest challenges in promoting agroforestry is related to the decision-makers lack of reliable tools to accurately assess and predict crop traits and yields from both species growing in this system. Among the key challenges are the agroforestry systems complexity, which include interactions both above and below ground between system components, variations in the climate variables, especially the solar radiation, and the wide spatial and timescales which tree-crops interact (Luedeling et al., 2016). In this context, trees can also compete with crops for water and nutrients and reduce the land area available for crops, so that the net effect of agroforestry on crop yields over time will depend on attributes and interactions of the trees, crops, soil, climate, and management (Bayala et al., 2012; Smethurst et al., 2017).

Agricultural models are important tools and can be used to support decisions concerning the management, plant traits, and climate effects of food production systems (Luedeling et al., 2016; Webber et al., 2014). In order to understand tree–crop interactions over time and space, it is important to consider the use of a powerful method capable of providing an overview of complex multivariate data. In this context, the use of multivariate analyzes can be considered as a valuable tool to evaluate and understand complex multivariate data, which occurs in the agroforestry system. The basic principle of the use of multivariate analysis is related to the reduction of a large number of variables into a few dimensions with minimal information loss to allow the identification of essential associations, similarities, correlation, and finding and quantifying patterns among variables (Bro & Smilde, 2014; Wold et al., 1987). Such approaches as such as canonical correlation and principal component analysis can be used in studies regarding agroforestry systems.

Canonical correlation analysis (CCA) was proposed by Hotelling (1936) and developed in order 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. The use of this approach is a valuable tool for understanding the correlations between climatic variables and growth traits. In other hand, principal component analysis (PCA) is one of the most important and powerful methods capable of providing an overview of complex multivariate data (Bro & Smilde, 2014), as well as to identify patterns and characterize the crop systems studied. To the authors' knowledge, this is the first study to investigate the relationship between climatic variables and tree-crop variables using CCA and PCA to analyze agroforestry systems.

In this study, we hypothesized that the growth and yield of crops grown in agroforestry systems can be modified by the agroforestry arrangement and temporal scale, since in more densified arrangements the tree-crop competition for natural resources is greater, especially solar radiation. Therefore, the aims of this study were: (i) to analyze the canonical correlations among groups of tree growth and climatic variables during four seasons of the year; and (ii) to evaluate and characterize the relationships among sugarcane growth, yield, and quality variables in two agroforestry arrangements and sugarcane monocropping system in Southern Brazil.

Methods

Study area

A field study was conducted from September 2008 to September 2015 in the microregion of Frederico Westphalen in the state of Rio Grande do Sul, Brazil, at the coordinates 27º22'S, 53º25′W and an altitude of 480 m. According to the Köppen climate classification (Alvares et al., 2013), the climate is Cfa, i.e., humid subtropical with mean annual temperatures of 19.1°C, varying with maximum of 38ºC and minimum of 0°C. The soil of the experimental area was classified as typical Entisol Orthents. Tung seedlings were manually planted in the field in September and the sugarcane in November 2011. The rows of tree and sugarcane were oriented toward East and West.

Experimental design

The experimental design consisted in a randomized complete block, delineated by a factorial arrange of 3 × 5 defined by three cropping systems: intercrop I (12 × 12 m^2), intercrop II (6 × 6 m^2) and a monocrop system with sugarcane; five assessment years (2012–2016) and three replications. Each experimental unit was composed of 15 trees. In the intercrop I arrangement, trees were distributed in rows spaced at 12 m; 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 arrangement, trees were grown in rows spaced at 6 m; the sugarcane was distributed in four rows arranged in correspondence with intervals between tree rows. In both systems, the sugarcane had a spacing of 1.20 m and an initial density of 16 buds per meter. The arrangement of Tung tree, sugarcane plants, and assessment plots is shown in Figure 1.

Tree growth assessment

The Tung (*Aleurites fordii*) forest species was chosen to compose the agroforestry system. This tree belongs to the Euphorbiaceae family, which presents the deciduous characteristics (leaf senescence). The tree growth assessments started in March 17, 2012, corresponding to 176 days after transplanting the seedlings (DAT), and were concluded in June 21, 2016, resulting in 1736 DAT totalizing 18 assessment periods. Three trees were assessed in each block and each tree evaluated was considered as a repetition. The assessments were carried out for each season of the year, considering the beginning of each season the days: autumn 03/20, winter 06/21, spring 09/22 and summer 12/21.

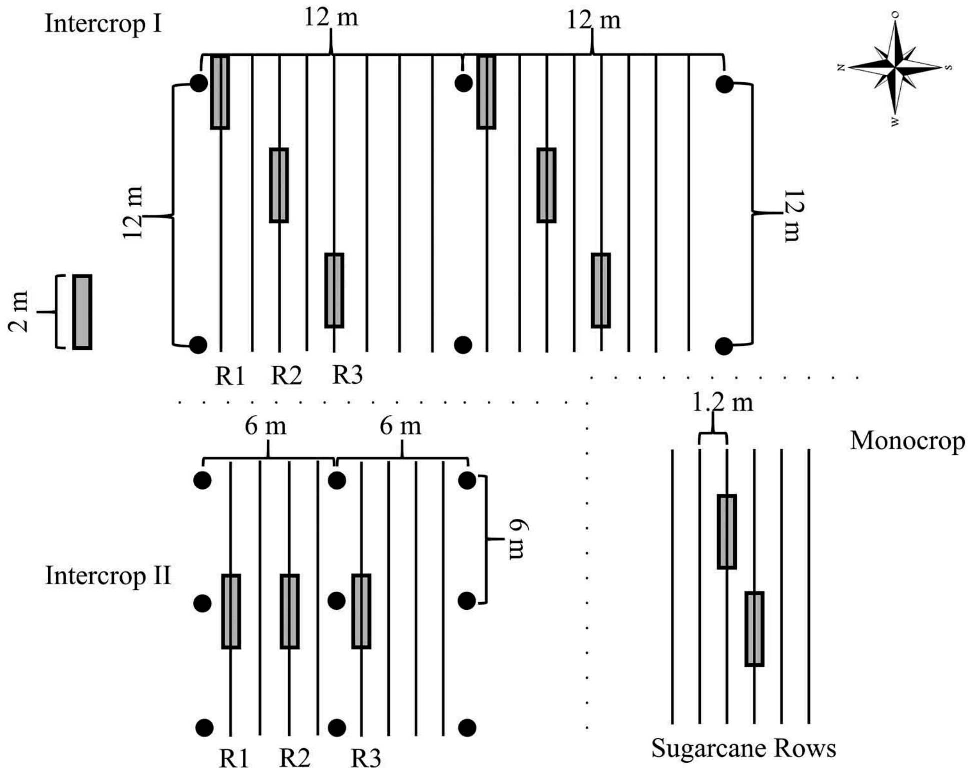

Figure 1. Representation of an experimental unit for each cropping systems: intercrop I: 12 × 12 m^2, intercrop II: 6 × 6 m^2, and sugarcane monocrop system. Continuous lines indicate sugarcane planting, gray rectangles represent the assessment plots, and black circles symbolize trees.

The following growth variables were measured: diameter at breast height (DBH), stem diameter (SD), height (H), and crown diameter (CD). For the measurements were utilized measuring tape, Vertex III Hypsometer, and metric tape. For the diameter at breast, height was evaluated at a height of 1.30 m, the stem diameter at 5 cm above ground level, the tree height was measured from ground level to the top leaf axils, and for the crown diameter, the assessments were performed taking vertical and horizontal measurements. All variables were assessed during each season of the years.

Climate variables

The climate data during the experiment were collected from a meteorological station vinculated to the Meteorology National Institute (INMET – Brazil), located approximately 200 m from the experiment. Climatic values were computed for each season of the year. The sum of the values for incident solar radiation (RAD, MJ m^{-2}) and rainfall (RAIN, mm) were recorded, while values for the minimum air temperature (TMIN, °C), maximum air temperature (TMAX, °C), and average air temperature (TAVE, °C) were computed using the average values for each season of the year.

The climatic conditions during the assessment years were: flux of global solar radiation ranged from 0.49 to 38.46 MJ m^{-2} day^{-1}, with an average of 17.35 MJ m^{-2} day^{-1}, for the air temperature we observed a variation from −2.6ºC to 37.0ºC, with an average temperature of 18.8ºC. The rain values showed a great variability during the experiment, in overall was observed a monthly average of 171.8 mm. Also, it was observed lower rainfall accumulated in 2012, with a monthly average of 129.2 mm.

Multivariate analysis of variance and canonical correlations

Multivariate analysis of variance (MANOVA) was used to produce an overall model and testing its effects for each variable and their interactions. The Box-Cox method was used to transform the data and MANOVA was performed using the PROC GLM procedure in SAS Institute Inc (2002). The statistics of Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace, and Roy's Greatest Root were obtained, they were translated into F statistics in order to test the null hypothesis. More information about the statistical tests may be seen in Morrison (2005).

Canonical correlation analysis was used to identify and quantify the relationship between two sets of traits, and to find their canonical weights (coefficients) by using the PROC CANCORR procedure (SAS Institute Inc, 2002). The reason for using canonical correlations is that, in an agroforestry system, because the continuous tree growth which is influenced by climatic 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 (Sherry & Henson, 2005; Wilks, 2011).

Two sets of traits were established: group 1 with predicted variables related to the trees (SD, H, DBH, and CD) and group 2 contained predictor variables related to the climatic variables (RAD, RAIN, TMIN, TMAX, and TAVE). The verification of the significance between the groups of variables was evaluated based on the statistic 'restricted maximum likelihood' (REML).

Sugarcane growth assessments

The sugarcane growth assessments were performed in ratoon sugarcane (4th cut, crop cycle 2015/2016). The first sugarcane growth assessment occurred in October 2015 and the last in May 2016. The cultivar used IAC 87-3396 was developed by the Agronomic Institute of Campinas (IAC). This cultivar is characterized by an excellent adaptation to soils with lower fertility and presents high yield and sucrose content.

The sugarcane assessments were performed every 30 days, with the last at 332 days after cutting (DAC), amounting to 8 months of plant collection. For each assessment period, a total of 42 plants were collected while two representative plants per assessment plot were evaluated, totalizing 332 analyzed plants. On the day of sample collection, the tiller numbers (TI) were counted.

The plant samples were sectioned and prepared the leaf discs to determine the leaf area. The total dry matter (TDM) was determined by taking the sum of the dry biomass of all components: leaf, pseudoculm+senescent, and stalk. The samples were gathered and placed in pre-identified individual paper sacks, which were allocated into a forced circulation oven at 60°C until they reach a constant mass. Lastly, the samples were weighed on a precision balance.

For the leaf area (LA) assessment, we utilized the disc method, following equation 1:

$$\mathrm{LA} = (\mathrm{n}^{\circ}\mathrm{discs} * \mathrm{punchdiscarea}) * \frac{(\mathrm{DMleaves} + \mathrm{discs})}{\mathrm{DMdiscs}} \tag{1}$$

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

With the data of dry matter and leaf area, the following growth variables were determined: specific leaf area (SLA, $\mathrm{m}^2\ \mathrm{g}^{-1}$), absolute growth rate (AGR, $\mathrm{g\ day}^{-1}$), relative growth rate (RGR, $\mathrm{g\ g}^{-1}\ \mathrm{day}^{-1}$), total dry matter (TDM, $\mathrm{g\ m}^{-2}$), and net assimilation rate (NAR, $\mathrm{g\ m}^{-2}\ \mathrm{day}^{-1}$) based on the methodology described in the literature (Thornley, 1976).

The values for solar radiation interception (SRI) and extinction coefficient (k) were measured monthly, where the incident solar radiation was measured above and under the plant canopy using a portable sensor pyranometer (LICOR PY32164, Lincoln, Nebraska, USA) coupled to a Datalogger (LICOR 1400, Lincoln, Nebraska, USA). The measurements were recorded in the period from 10 h to 12 h. The values of intercepted global radiation were obtained according to the following equation: % Intercepted = [100 – (Rn x 100/Rt)]. Where: Rn = incident radiation under the canopy; Rt = incident radiation above the canopy.

The light extinction coefficient (k) was obtained via a simple Beer's Law approach using the following equation: k = -ln(Rn/Rt)/LAI. Where k = extinction coefficient; Rn = incident radiation under tree canopy ($\mathrm{MJ\ m}^{-2}$); Rt = incident radiation above the canopy ($\mathrm{MJ\ m}^{-2}$) and LAI = leaf area index.

Sugarcane yield components and juice quality assessments

The yield and quality assessments were performed in five sugarcane cycles (2012–2016), represented by one cane-plant (first cultivation year) and four cane-ratoon cycles (each cycle corresponding to an individual sugarcane regrowth). The harvest was performed on the following dates: first cut 07/26/2012, second 07/25/2013, third 06/16/2014, fourth 07/02/2015 and the last (fifth cut) was performed on 06/23/2016. Two representative stalks were collected in each marked row (Figure 1), which were taken to the laboratory for assessment. For each assessment year, a total of 84 stalks were collected and evaluated. On the day of plant collection, stalk numbers (SN) and tiller number (TI) were counted in the field for each previously demarcated plot.

In the laboratory, the following yield and quality components were analyzed: stalk weight (SW, Mg ha^{-1}); stalk length (SL, m); stalk diameter (SD, mm); number of nodes (NN); internode length (IL, cm); juice volume (JV, m^3 ha^{-1}) and sucrose content (g L^{-1}). For these measurements were used a digital scale, metric tape graduated cylinder with a capacity of 1 L, and automatic digital refractometer Acetec RDA 8600.

Principal component analysis

To identify major patterns of variation and ordination of the sugarcane growth during one entire cycle and the yield variables for five crop cycles with respect to each agroforestry arrangement we conducted the principal component analysis. For the sugarcane growth, one PCA variable was performed and for the yield and quality sugarcane, another variable was performed. This technique is based on a change of the dimensional plane of the prospected data into a new data set that is representative of the original set whilst being smaller in terms of dimensionality.

The treatment evaluated in this study was coded as follows: X: intercrop system I (12 × 12 m^2), Y: intercrop system II (6 × 6 m^2), and M: sugarcane monocrop. For the first PCA, regarding the sugarcane growth variables, we analyze eight assessment times which were coded as follows: X1: October, X2: November, X3: December, X4: January, X5: February, X6: March, X7: April and X8: May 2016. This same assessment times were recorded for the Y and M treatments. For the second PCA, regarding the sugarcane yield and quality variables, we analyze five crop cycles which were coded as follows: X1: 2011–2012, X2: 2012–2013, X3: 2013–2014, X4: 2014–2015, and X5: 2015–2016 years. For these treatments, one cane-plant (first cultivation year) and four cane-ratoon cycles were considered, which each cycle corresponding to an individual sugarcane regrowth.

The data used for the PCA were standardized by dividing the difference between each data point and the arithmetic mean of the variable of interest by the standard deviation of the variable. The last PCA step was determining which principal component vectors to use. In this study, the obtained vectors are required to have a minimum cumulative variance of 70%, so two principal component vectors were used for the two PCA analysis. The normality distribution of all data was checked using the Shapiro–Wilk test. Additionally, paired variables with apparent collinearity were excluded from the PCA analysis. The principal components and biplot graphics were obtained by using the PROC PRINCOMP procedure (SAS Institute Inc, 2002).

Results

Multivariate analysis and canonical correlations

According to multivariate analysis, a significant effect in four seasons of the year and two agroforestry arrangements was observed (Table 1). The null hypothesis for all statistical tests Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace, and Roy's Greatest Root was rejected. These statistical tests show that the mean vectors represented in group 1 (tree growth variables) and group 2 (climatic variables) are independent.

The canonical correlation analysis and pair canonical significance for each season of the year and agroforestry arrangements can be seen in Table S1. 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, while for the summer season two significant canonical pairs were observed. The high magnitude of the canonical correlation coefficients indicated high dependence between the two groups of characters studied and reveals an association between these variates.

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 intercrop arrangements 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 2). For the winter season, one canonical pair was significant with correlation coefficient (r = 0.84 and r = 0.91) between groups 1 and 2 for the intercrop arrangements 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 2).

Regarding the spring season, the associations established through the first canonical pair presented correlations (r = 0.79 and r = 0.90) for the intercrop arrangements 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 in minimum and average air temperatures (group 2) (Table 3).

Table 1. Multivariate analysis of variance for each season of the year and agroforestry arrangements.

	Autumn				Winter			
	Intercrop I		Intercrop II		Intercrop I		Intercrop II	
Statistic	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**
	Spring				Summer			
	Intercrop I		Intercrop II		Intercrop I		Intercrop II	
Statistic	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.

Table 2. Canonical pairs estimated for Tung growth variables (group 1) and climatic variables (group 2) in the seasons of the year Autumn and Winter in two agroforestry arrangements.

	Autumn							
	Intercrop I				Intercrop II			
	Group 1				Group 1			
Variables	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 2				Group 2			
	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							
	Intercrop I				Intercrop II			
	Group 1				Group 1			
Variables	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 2				Group 2			
	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%; bold values represent the largest canonical weights (coefficients) that were considered in the discussion.

Two canonical pairs were significant for the summer season (Table 3). 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 intercrop arrangement I and II, respectively (Table 3). Regarding the first canonical pair (Table 3), 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). In other hand, for the second canonical pair, an inverse correlation between height and crown diameter with maximum air temperature was observed.

Principal component analysis of sugarcane growth

Main PCA results are presented in the following graphical analysis (Figures 2 and 3). The PCA analysis indicated that primary and secondary components were responsible for, respectively, 51.0% and 26.9% (total of 77.9%) of the cumulated variance for all

Table 3. Canonical pairs estimated for Tung growth variables (group 1) and climatic variables (group 2) for Spring and Summer seasons in two agroforestry arrangements.

	Spring							
	Intercrop I				Intercrop II			
	Group 1				Group 1			
Variables	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 2				Group 2			
	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							
	Intercrop I				Intercrop II			
	Group 1				Group 1			
Variables	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**	−0.520	0.326	0.013
CD	0.335	**−0.730**	0.812	0.477	0.410	**0.785**	0.862	0.254
	Group 2				Group 2			
	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%; bold values represent the largest canonical weights (coefficients) that were considered in the discussion.

investigated assessment times and cropping systems (Figure 2). For the growth and climate variables, PC1 was associated with LAI, SRI, k, and TDM in contrast with TI and SLA, while PC2 was associated especially with NAR, AGR, and RGR.

The assessment times for the cropping systems in the top right-side quadrant, related to the sugarcane growth on January, February, and March, were strongly associated with LAI, SRI, k, NAR, and AGR variables. In other hand, in the left-side quadrants are the groups composed of the first assessment times, which are represented by October, November, and December were associated with SLA, TI, and RGR variables. Also, the last assessment time (X8, Y8, and M8) was associated with TDM in contrast with the TI, SLA, and RGR variables, and the treatments related to the agroforestry arrangements (Y8 and X8) presented lower loadings than the monoculture (M8).

Principal component analysis of sugarcane yield and quality

The PCA analysis for the sugarcane yield and quality variables indicated that primary and secondary components were responsible for, respectively, 66.7% and 16.1% (total of

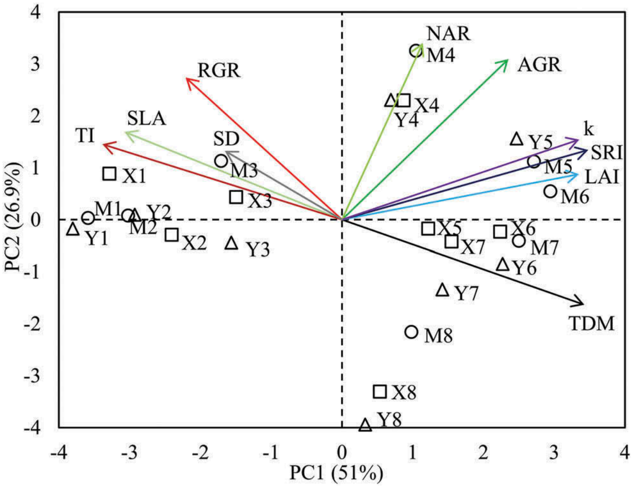

Figure 2. PCA with biplot showing the relationships between sugarcane growth and climatic variables during one crop cycle (2015 to 2016). The variables absolute growth rate (AGR), extinction coefficient (k), leaf area index (LAI), net assimilation rate (NAR), tiller number (TI), relative growth rate (RGR), solar radiation interception (SRI), specific leaf area (SLA), and total dry matter (TDM) are indicated by arrows, while the eight assessment times from two agroforestry arrangements and monocrop system are indicated as points X1 to X8 (12 × 12 m^2), Y1 to Y8 (6 × 6 m^2), and M1 to M8 (sugarcane monocrop).

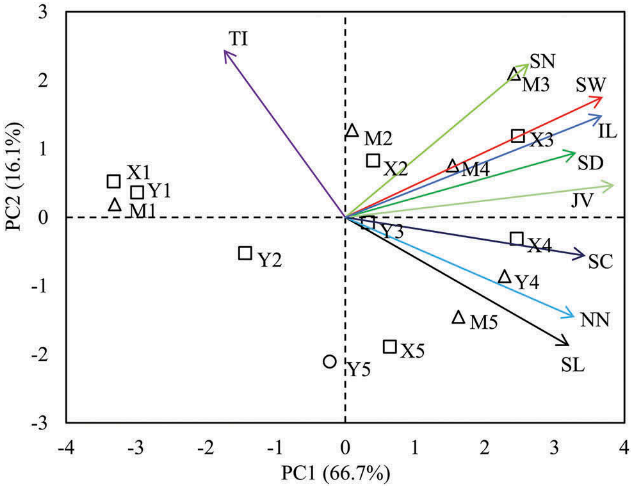

Figure 3. PCA with biplot showing the relationships between sugarcane yield and quality variables during five crop cycles (2012 to 2016). The variables internode length (IL), juice volume (JV), stalk length (SL), stalk number (SN), nodes number (NN), sucrose content (SC), stalk diameter (SD), stalk weight (SW), tiller number (TI) are indicated by arrows, while the five harvest times from two agroforestry arrangements and monocrop system are indicated as points X1 to X5 (12 × 12 m^2), Y1 to Y5 (6 × 6 m^2), and M1 to M5 (sugarcane monocrop).

82.8%) of the cumulated variance for the five sugarcane crop years and cropping systems (Figure 3). Regarding the variables, PC1 was especially associated with SW, JV, and IL, while PC2 was associated strongly with TI and SN in contrast with SL and NN.

The five sugarcane cycles were characterized in a different way according to the yield and quality variables for the different cropping systems (Figure 3). In the left-side quadrants are the groups composed of the first sugarcane cycles, which were associated especially with TI in contrast with SL, SC, and NN variables. In other hand, the treatments M3 and X3, which represent the 2nd cane-ratoon cycle showed higher association with SN, SW, IL, SD, and JV. Also, the last sugarcane cycle (X5, Y5, and M5) showed association with the reduction of NN, SL, and SC variables, and the treatment related to the agroforestry arrangement (Y5) presented lower loadings than the X5 and M5 treatments.

Discussion

To the best of our knowledge, this is the first study to examine the multivariate relationships between climate and tree-crop variables (plant growth, yield, and quality) in agroforestry system. Our study demonstrated that the use of multivariate approach was a valuable tool for understanding the correlations between climatic variables and tree growth traits for each season of the year, while the principal component analysis enables to identify sugarcane growth and yield patterns and characterize the crop systems studied.

Air temperature and solar radiation affects tree growth

Canonical correlation analysis demonstrated a strong influence of the climatic variables on diameter at breast height and stem diameter of Tung trees with magnitudes above 0.90 in most cases, independent of the season of the year and agroforestry arrangement. This result indicated that the climatic variables have greater influence especially in the secondary growth of Tung trees. Among the climatic variables, the air temperature and solar radiation were the main factors that affects tree growth while the water availability has greater effect, especially in the summer season. These results are confirmed by the high correlation, both positive and negative, for these variables in the canonical correlation analysis (Tables 2 and 3).

Tree growth is considered to be strongly influenced by air temperature worldwide (Bhattacharyya et al., 2006; Körner, 2003). Studies demonstrated a positive growth response to an increase in low temperature (Atkin & Tjoelker, 2003; Zanon & Finger, 2010). According to Gruber et al. (2009), the growth–temperature relationship is not a fixed constant. This response was observed in this study, where the Tung tree growth was affected according to the season of the year and as species' sensitivity to the impacts of increase and/or decrease the air temperature.

Other important role related to the air temperature is the induction of plant dormancy. For 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. Particularly for the Tung trees, the duration ranges from 350 to 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 in winter. 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 (Figure 4).

Figure 4. 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 damage observed on tree buds is explained by the date of frost occurrence and intensity of the minimum temperature. In this study, the occurrence of frost in the autumn season, specifically on 7th and 8th of June 2012 and 11th and 12th of June 2016, was observed with absolute extreme minimum air temperature of −2.2°C, −1.2°C, −2.3°C and −1.9°C, respectively. The frost occurrence in the autumn season was prejudicial because the tree, including branches and leaves, was in full activity during this season and the frost in these periods results in damages such as reduction of cell division/expansion, early leaf senescence, and consequently reduction in the net assimilation rate of the tree.

Our study demonstrated that the increase of minimum temperatures and greater solar radiation incidence can benefit Tung growth in an agroforestry system, especially in the autumn and winter seasons (Tables 2 and 3). These climatic variables are important in the formation of new buds, leaf area development, and interception of solar radiation by 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, air temperature and solar radiation with the growth variables. According to Li et al. (2016), photosynthetic activity determines plant growth through an increase or decrease in the production of photoassimilates as a function of climatic conditions.

The occurrence of high temperatures associated with periods of low water availability affects negatively Tung growth variables in the summer season. 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 et al., 2017).

In temperate climatic regions are common the occurrence of greater variability in the rain distribution and higher amounts of solar radiation incidence, especially in the months of January to March (summer season). In general, tree growth increases with rainfall (Dauber et al., 2005; Morales et al., 2004; Murphy & Lugo, 1986) and decreases in periods of drought (Lola da Costa et al., 2010; Nath et al., 2006). According to Sands and Mulligan (1990), Landsberg (2003), and Elli et al. (2017), 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.

The canonical correlation approach was essential to understanding the dynamics of the climatic conditions in the different seasons of the year on the growth of Tung trees cultivated in agroforestry system. With our findings, we can plan with better information on the implantation of crops in its understory. According to 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.

Sugarcane growth and yield patterns are modified by agroforestry arrangements

Associated with the importance that the forest tree provides to the agroforestry system; we should consider the benefits of the crop cultivated in its understory. In this context, the authors have performed an explanation about the sugarcane growth and yield throughout a principal component analysis for the sugarcane cultivated in two intercrop arrangements and monoculture systems.

The analysis of principal components for the sugarcane growth variables (Figure 2) indicated that the assessment times were not associated with the same variables during the crop cycle. Firstly, in the beginning of the cycle, there is a greater tillering and leaf emission which is associated with high specific leaf area. After this period, the plants showed intense vegetative development, which were related to the leaf area index, solar radiation interception, and net assimilation rate. Finally, a reduction in the tillering, specific leaf area, and relative growth rate was observed at the end of the cycle. This response was more pronounced for the sugarcane grown in the agroforestry arrangements.

Changes in the microclimatic conditions in different cropping systems explain the patterns of sugarcane growth during the cycle. The reduction in growth rates is explained by the effect of self-shading due to an increase in the leaf area index and solar radiation intercepted, 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, is 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.

In most cases, the sugarcane cultivated in monoculture showed PC loadings greater than the sugarcane cultivated in both agroforestry arrangements. This result can be explained due to the lowest amount of radiation intercepted by the sugarcane in these treatments which were associated with the effects of tree canopy, which shaded the sugarcane plants. In addition, due to sugarcane's high photosynthetic rate (C4 species), it needs a large amount of solar radiation to meet its photosynthetic demand. Thus, plants submitted to different levels of shading demonstrate changes in photosynthetic rate, which can reduce the total dry matter produced. According to Marchiori et al. (2014), excessive shading may affect growth traits causing decreases in tillering and photosynthetically active leaf area, as well as in the interception of solar radiation. This response is highlighted by Pinto et al. (2005), who reported that 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 close to the forest species.

The results obtained in the PCA for the sugarcane growth variables (Figure 2) aid to explain the results obtained in the PCA for the yield and quality variables (Figure 3), once that for most cases the sugarcane yield and quality for the sugarcane cultivated in both agroforestry arrangement showed lower PC loadings compared with the sugarcane in monoculture. This result can be better visualized in the last sugarcane cycle, in which the reduction in the stalk length, number of nodes, and sucrose content characterize the reduced tree arrangement (Y5).

Regarding the patterns of sugarcane yield and quality variables during the five crop cycles, the PCA indicated that the first cycle was characterized by reduced stalk length and number of nodes. This response can be explained due to a water deficit that occurs during the cycle of 2011–2012. For this cycle was observed an accumulated of 1,093 mm, with water deficits more pronounced during December to March, period that corresponds with an intense vegetative development. 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 (Inman-Bamber & Smith, 2005; Robertson et al., 1996; Silva & Costa, 2004).

For the other crop years, we can emphasize that the treatments M3, X3, and Y3, which represents the 2nd cane-ratoon cycle showed greater PC loadings, which were associated especially with the stalk weight, juice volume, and internode length. Also, we can highlight that the monocrop system (M3) showed higher PC loading when compared to the other agroforestry arrangements (X3 and Y3).

In agroforestry systems, crops and trees interact dynamically as a result of variations in the interception of solar radiation by trees in time due to the effect of tree age and arrangement because of the spacing between trees. In this context, for the last crop cycle (2015–2016), reduced PC loadings for the cropping systems was observed, especially for the reduced tree arrangement, due to the higher tree–crop interactions, mainly due to the shading that the tree canopy promotes in the sugarcane plants. These results can be related to the greater degree of interspecific competition for available natural resources which occurs in the agroforestry arrangements due to the presence of trees while in the monocrop system, this response was not observed. In this context, the competition by solar radiation and water availability was the primary meteorological variables that influenced yield and quality traits of sugarcane (Cardozo & Sentelhas, 2013; Inman-Bamber et al., 2010).

The study has generated information which is relevant to agroforestry managers and producers. However, it could have been interesting to evaluate the economic viability of this system, as well as social and environmental impacts. Further studies should address this important aspect that will contribute to sustainability in agroforestry system management.

The information generated in this study is relevant, as it provides information to farmers and can assist in the planning of new agroforestry systems due to the better knowledge of tree–crop interactions and climate effects in Southern Brazil. According to the context of Brazilian law No. 12,651, May 25, 2012, which established a new Forest Code, permitting the implantation of agroforestry systems, provided these systems are subject to a sustainable management plan, in areas of permanent preservation (APP) and legal reserves (RL). This is relevant and can contribute to the increase in the food and energy production.

Conclusion

In this study, we demonstrated that crops and trees interact dynamically as a result of variations in the interception of solar radiation by trees in time due to the effect of tree age and arrangement. With the canonical correlation analysis, the groups of climatic variables and tree growth variables are not interdependent, since the incident solar radiation and minimum air temperature were the main climatic variables that affected tree growth. During the winter season, Tung trees were affected by frost occurrence. This information is relevant for the establishment of agroforestry systems and especially through the selection of suitable species combinations.

The patterns of sugarcane growth and yield were influenced by the temporal scale and agroforestry arrangements. The second cane-ratoon cycle resulted in higher sugarcane yield while the reduced tree arrangement provided a greater competition for resources, which affected sugarcane growth and yield. So, larger tree arrangements are suggested to benefit sugarcane growth and yield in agroforestry systems in southern Brazil.

It is essential to understand the biophysical interactions existing in an agroforestry system. Such knowledge may enable people to employ and manage such systems more successfully, achieving satisfactory outputs. The multivariate analysis can be used as a valuable tool and versatile method to analyze and understanding tree–crop interactions in agroforestry system. This multivariate approach enabled to evaluate the effects of climate variables on tree growth and elucidate the sugarcane growth and yield pattern in agroforestry system and monoculture.

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Disclosure of interest

The authors declare that they have no conflict of interest.

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