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Sensitivity of newly transplanted coffee plants to climatic conditions at altitudes of Minas Gerais, Brazil

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Abstract

The influence of climate on the early development of newly transplanted coffee plants is poorly known. Good initial development is important for the sustainability of longevity and yield. We determined the climatic sensitivity of five-month-old coffee seedlings transplanted under climatic conditions at high altitude during the first two years of development in the state of Minas Gerais in Brazil. Plant height (PLH), orthotropic stem diameter (SDI), and plagiotropic branch number (PBN) were recorded every three months, and the effects of the climatic variables degree days (DD), potential evapotranspiration (PET), actual evapotranspiration (AET), global radiation (Qg), and water deficit (WD) rate in conventionally tilled, furrowed, and untilled systems were determined. The data were analysed with sigmoidal and peak models adjusted by least squares fitting. The development of the coffee crop was sensitive to the climatic conditions. Plant height, stem diameter, and plagiotropic branch number were logistic functions of DD, PET, AET, and Qg and had a parabolic relationship with WD. The coffee plants transplanted in the untilled system had larger SDIs and higher PBNs. The furrowed system produced the tallest plants. Water deficit was the most important meteorological variable during the study period. Water deficits of 0.5-0.7 mm d^{-1} promoted the development of PLH, SDI, and PBN by 0.19 cm d^{-1}, 0.06 cm d^{-1} and 0.10 d^{-1}, respectively.

Keywords: agrometeorological modelling; multivariate analysis, growth analysis; water budget.
Abbreviations: PLH_plant height; SDI_orthotropic stem diameter; PBN_plagiotropic branch number; DD_degree days; PET_ potential evapotranspiration; AET_actual evapotranspiration; Qg_global radiation; WD_water deficit; CT_ conventional Tillage; FU_furrow; NT_ no tillage; PLH_{CT}_plant height in the conventional system; PBN_{NT}_plagiotropic branch number in the untilled system; PBN_{FU}_plagiotropic branch number in the furrowed system; PBN_{CT}_ plagiotropic branch number in the conventional system.

Introduction

Coffee is the most consumed drink in the world and is a major Brazilian export product (Rodrigues et al., 2014), but few studies have examined the influence of climate on the early development of coffee plants (Resende et al., 2009; Rodríguez et al., 2013). The juvenile period in coffee plants is approximately three years during which production is low. Caffeine, amino acids, and phenolic compounds are some of the important functional properties contributing to the quality of coffee grains (Butt and Sultan, 2011; Kitzberger et al., 2013). Coffee is a perennial plant belonging to the family Rubiaceae. Two species, *Coffea arabica* L. and *C. canephora* Pierre ex A.Froehner, are commonly grown for commercial production (Cubry et al., 2013), producing 74.92 and 25.08%, respectively, of the world's coffee. The state of Minas Gerais has the largest area of production in Brazil, with 1,245,710 hectares (CONAB, 2014), predominantly with *C. arabica* (Barbosa et al., 2012). The coffee grown in Minas Gerais above 900 m has a slower production cycle that promotes good grain formation and high quality and yields (Bardin-Camparotto et al., 2012).

Climatic variability has a major impact on agricultural activities, such as planting and harvesting (Sá Junior et al., 2012). Air temperature, solar radiation, and rainfall are critical meteorological variables in agricultural production (Hoogenboom 2000) and have large phenological influences on coffee plants (Camargo 2010). Solar radiation provides the energy for photosynthesis (Oliveira et al., 2012) and affects the partitioning and accumulation of biomass (Angelocci et al., 2008). The air temperature regulates the rates of vegetative and reproductive development, but high air temperatures associated with water deficits during flowering can kill the flowers (Pereira et al., 2008), and continuous exposure to temperatures above 30 °C leads to leaf yellowing and even growth reduction (Damatta and Ramalho, 2006). Drought affects evapotranspiration, moisture extraction by roots, the distribution of the root system, canopy size, fruit growth, and the developmental rates of crops (Camargo 2010). Reductions in coffee yield are mostly due to water deficits (Carvalho et al., 2011). The interaction among meteorological, physiological, soil, and management factors can be efficiently simulated by crop models (Rolim et al., 2008). A model is a mathematical representation of a system, and modelling is the process of development of this representation (Jones et al., 1987). Models can examine the effects of meteorological variables on crops (Nunes et al., 2010), can incorporate information from various scientific

Table 1. Estimates of parameters Logistic and Lorentz models adjusted of plant height (PLH) of coffee arabica in the different types of planting in relation to weather conditions (DD = degree days; PET = potential evapotranspiration; AET = actual evapotranspiration; Qg = global radiation; WD = water deficit; PLH = plant height; CT = conventional; FU = furrow; NT = no-tillage; α =amplitude; k = average rate; x_c = central point; A = area below the curve; y_0 = offset; W = midpoint standart deviation).

Logistic model								
		α	*k*	X_C	A	Y_0	R^2_{adj}	p-valor
DD	PLH_{CT}	2.12	0.11	35.61	-	-	0.79	0.0043
	PLH_{NT}	4.64	0.16	33.5	-	-	0.86	0.0014
	PLH_{FU}	5.19	0.17	35.61	-	-	0.89	0.0007
PET	PLH_{CT}	7.53	0.26	18.29	-	-	0.78	0.0050
	PLH_{NT}	11.08	0.41	13.60	-	-	0.86	0.0016
	PLH_{FU}	13.50	0.46	12.99	-	-	0.88	0.0010
AET	PLH_{CT}	6.95	0.20	21.76	-	-	0.77	0.0050
	PLH_{NT}	9.28	0.35	14.24	-	-	0.85	0.0010
	PLH_{FU}	9.38	0.36	13.85	-	-	0.86	0.0014
Qg	PLH_{CT}	4.35	0.18	28.01	-	-	0.83	0.0024
	PLH_{NT}	6.92	0.20	28.04	-	-	0.86	0.0015
	PLH_{FU}	19.44	0.24	28.85	-	-	0.92	0.0003
Lorentz model								
		α	*w*	X_C	A	Y_0	R^2_{adj}	p-valor
WD	PLH_{CT}	-	0.04	0.59	0.04	0.1	0.83	0.0020
	PLH_{NT}	-	0.06	0.60	0.04	0.1	0.87	0.0010
	PLH_{FU}	-	0.07	0.61	0.04	0.1	0.90	0.0005

disciplines (Jame and Cutforth, 1996), and can help decision makers to plan management strategies (Santos and Camargo, 2006). Nonlinear models are commonly used in agricultural research. For example, Salomão et al. (2006) estimated the development of lychee fruit with a simple sigmoidal model, Matarazzo et al. (2013) adjusted simple sigmoidal models to determine the rate of lulo (*Solanum quitoense*) fruit development, and Alves et al. (2013) used nonlinear models to estimate the development of passionfruit.This study determined the sensitivity of newly transplanted coffee plants to the climatic conditions at high altitude by correlating growth with air temperature, potential evapotranspiration, actual evapotranspiration, global radiation, and water deficit.

Results and Discussion

Meteorological analysis

The average temperature in the region during the study period ranged from 19 to 25 ºC (Fig. 1B), Qg from 12 to 26 MJ m^{-2} d^{-1}, PET from 40 to 135 mm mo^{-1}, and AET from 25 to 130 mm mo^{-1}. These values were similar to the normal climatological conditions of 16-23 ºC for temperature, 41-103 mm mo^{-1} for PET, and 40-101 mm mo^{-1} for AET (INMET, 2014). The WD occurred from June to August, reaching an intensity of 27 mm (Fig. 1A). PLH varied from 18 to 100 cm, SDI from 3 to 35 mm, and PBN from 1 to 45 unit (Fig. 1B, C, D).

Analysis combining plant and meteorological data

The early development of the coffee plants in the various treatments was dependent on the climatic conditions. The first two components (PC_1 and PC_2) of the PCA of all variables of growth and meteorological conditions together explained 78.32% of the total variability of the data. The development of the plants was most influenced by WD, followed by Qg.

Model analysis

Increases in WD and Qg decreased PET, AET, and DD. These results were similar to those reported by Fioreze et al.

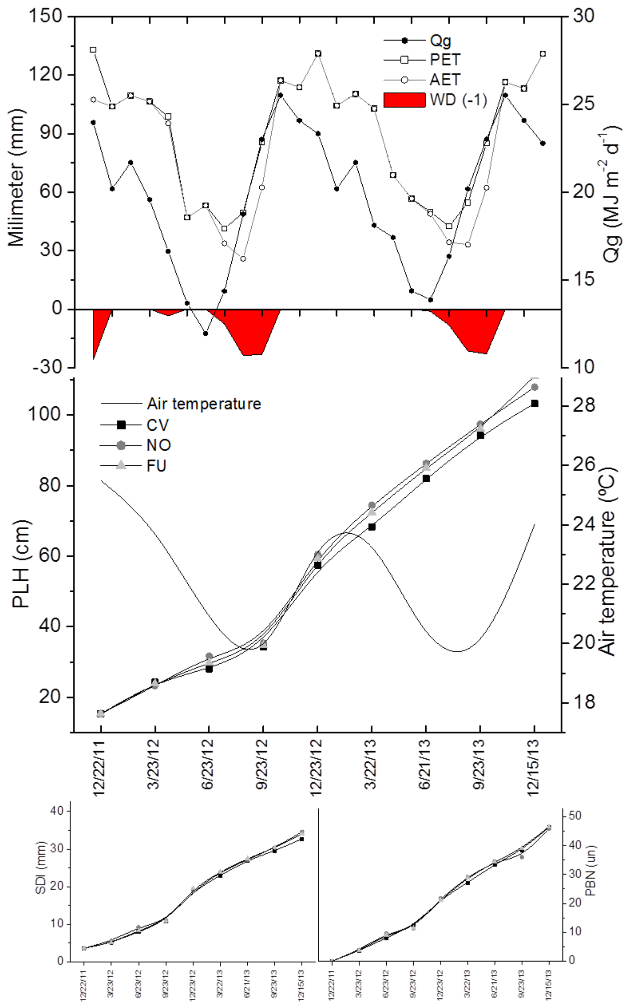

Fig 1. Air temperature (T), potential evapotranspiration (PET), actual evapotranspiration (AET), global radiation (Qg), water deficit (WD), plant height (PLH), orthotropic stem diameter (SDI) and plagiotropic branch number (PBN) in period of coffee arabica implantation.

Table 2. Estimates of parameters Logistic and Lorentz models adjusted of stem diameter (SDI) of coffee arabica in the different types of planting in relation to weather conditions (DD = degree days; PET = potential evapotranspiration; AET = actual evapotranspiration; Qg = global radiation; WD = water deficit; SDI = orthotropic stem diameter; CT = conventional; FU = furrow; NT = no-tillage; α =amplitude; k = average rate; x_c = central point; A = area below the curve; y_0 = offset; W = midpoint standart deviation).

Logistic model								
		α	*k*	X_C	A	Y_0	R^2_{adj}	p-valor
DD	SDI_{CT}	2.56	0.12	44.27	-	-	0.87	0.0010
	SDI_{NT}	4.61	0.17	38.92	-	-	0.93	0.0002
	SDI_{FU}	3.61	0.15	40.58	-	-	0.88	0.0009
PET	SDI_{CT}	8.73	0.32	19.53	-	-	0.86	0.0010
	SDI_{NT}	14.98	0.45	15.95	-	-	0.93	0.0002
	SDI_{FU}	12.27	0.40	17.08	-	-	0.88	0.0009
AET	SDI_{CT}	7.13	0.27	21.30	-	-	0.86	0.0010
	SDI_{NT}	11.58	0.39	16.52	-	-	0.93	0.0002
	SDI_{FU}	10.00	0.33	18.67	-	-	0.87	0.0010
Qg	SDI_{CT}	9.12	0.17	40.95	-	-	0.87	0.0010
	SDI_{NT}	7.79	0.20	34.24	-	-	0.91	0.0004
	SDI_{FU}	5.48	0.20	32.82	-	-	0.89	0.0008
Lorentz model								
		α	*w*	X_C	A	Y_0	R^2_{adj}	p-valor
WD	SDI_{CT}	-	0.01	0.660	0	0.04	0.84	0.0020
	SDI_{NT}	-	0.02	0.660	0	0.04	0.87	0.0010
	SDI_{FU}	-	0.03	0.660	0	0.04	0.87	0.0010

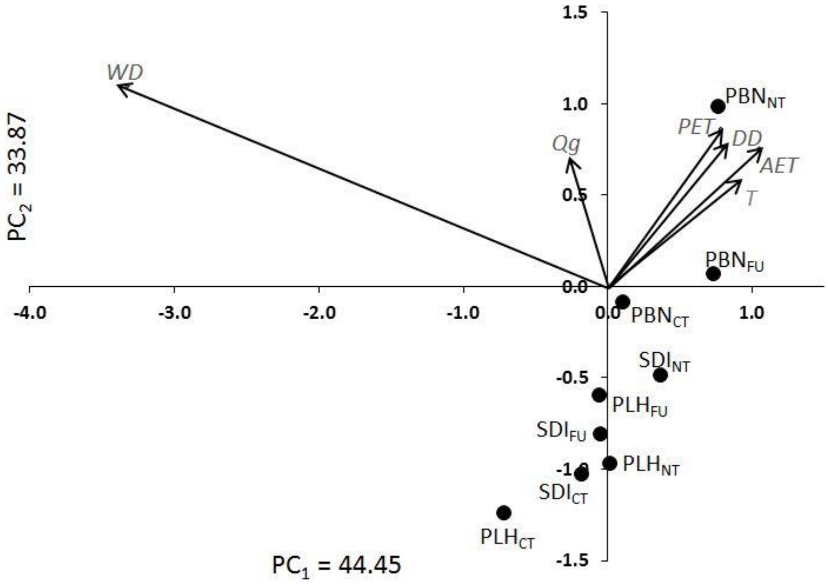

Fig 2. Biplot PC1 vs PC2 of dependent and independent variables (DD = degree days; PET = potential evapotranspiration; AET = actual evapotranspiration; Qg = global radiation; WD = water deficit; T = Air temperature; PLH = plant height; SDI = orthotropic stem diameter; PBN = plagiotropic branch number; CT = conventional; FU = furrow; NT = no-tillage).

(2013) in soybeans under shade and water deficit. DD was highly correlated positively with PET and AET (Fig. 2). Plant height in the conventional system (PLH_{CT}) was negatively correlated with the development of the plagiotropic branch number (PBN) in the untilled (PBN_{NT}) and furrowed (PBN_{FU}) systems. PBN in the conventionally tilled system (PBN_{CT}) was less sensitive to the climatic conditions. We used logistic and Lorentz models adjusted for correlated growth rates with the variability of the meteorological conditions. The rates of increase in PLH, SDI, and PBN were logistically associated with DD, PET, AET, and Qg rates. For example, 12 DD d^{-1} (Fig. 3A), 3.3 mm d^{-1} of PET (Fig. 3B), 2.6 mm d^{-1} of AET (Fig. 3C), or 10 MJ m^{-2} d^{-1} of Qg (Fig. 3D) is required to obtain a growth rate of 0.15 cm d^{-1} in the PLH_{FU} system. The average rate response growth of increases in PLH as a function of DD was 0.11, 0.16, and 0.17 cm DD^{-1} for the CT, NT, and FU systems, respectively. PLH as a function of WD followed a Gaussian curve. For example, a WD rate of approximately 0.6 mm d^{-1} maximised the average development of PLH at 0.19 cm d^{-1} (Fig. 3E). WD rates >0.9 mm d^{-1} decrease the PLH rate, probably due to lower stomatal conductance and transpiration (Taiz and Zeiger, 2009) that consequently lower the photosynthetic rate of plants (Ferraz et al., 2012). The NT and FU systems promoted higher PLHs compared to CT. The CT system showed intense plowing of the upper soil layer, causing surface compaction (Llanillo et al., 2006), soil degradation, and loss of structural quality (Ros et al., 2014). PLH was highly sensitive to variations of PET. The FU system had the highest rates of PLH as a function of all meteorological

Table 3. Estimates of parameters Logistic and Lorentz models adjusted for the plagiothropic branches number (PBN) of coffee arabica in the different types of planting systems in relation to weather conditions (DD = degree days; PET = potential evapotranspiration; AET = actual evapotranspiration; Qg = global radiation; WD = water deficit; PBN = plagiotropic branch number; CT = conventional; FU = furrow; NT = no-tillage; α =amplitude; k = average rate; x_c = central point; A = area below the curve; y_0 = offset; W = midpoint standart deviation).

Logistic model								
		α	*k*	X_C	A	Y_0	R^2_{adj}	p-valor
DD	PBN_{CT}	1.77	0.12	39.45	-	-	0.95	0.0008
	PBN_{NT}	16.77	0.29	30.79	-	-	0.91	0.0004
	PBN_{FU}	3.85	0.16	36.18	-	-	0.97	0.0001
PET	PBN_{CT}	15.23	0.29	21.79	-	-	0.95	0.0001
	PBN_{NT}	38.94	0.71	12.06	-	-	0.93	0.0002
	PBN_{FU}	33.56	0.43	17.52	-	-	0.97	0.0002
AET	PBN_{CT}	11.74	0.23	24.71	-	-	0.94	0.0001
	PBN_{NT}	29.89	0.63	12.13	-	-	0.89	0.0008
	PBN_{FU}	16.51	0.38	16.88	-	-	0.97	0.0002
Qg	PBN_{CT}	0.09	0.16	1.32	-	-	0.91	0.0004
	PBN_{NT}	15.86	0.41	22.80	-	-	0.89	0.0008
	PBN_{FU}	3.07	0.19	28.61	-	-	0.94	0.0001
Lorentz model								
		α	*w*	X_C	A	Y_0	R^2_{adj}	p-valor
WD	PBN_{CT}	-	0.01	0.6	0.09	0	0.65	0.0100
	PBN_{NT}	-	0.44	0.6	0.09	0	0.91	0.0004
	PBN_{FU}	-	0.62	0.6	0.09	0	0.94	0.0001

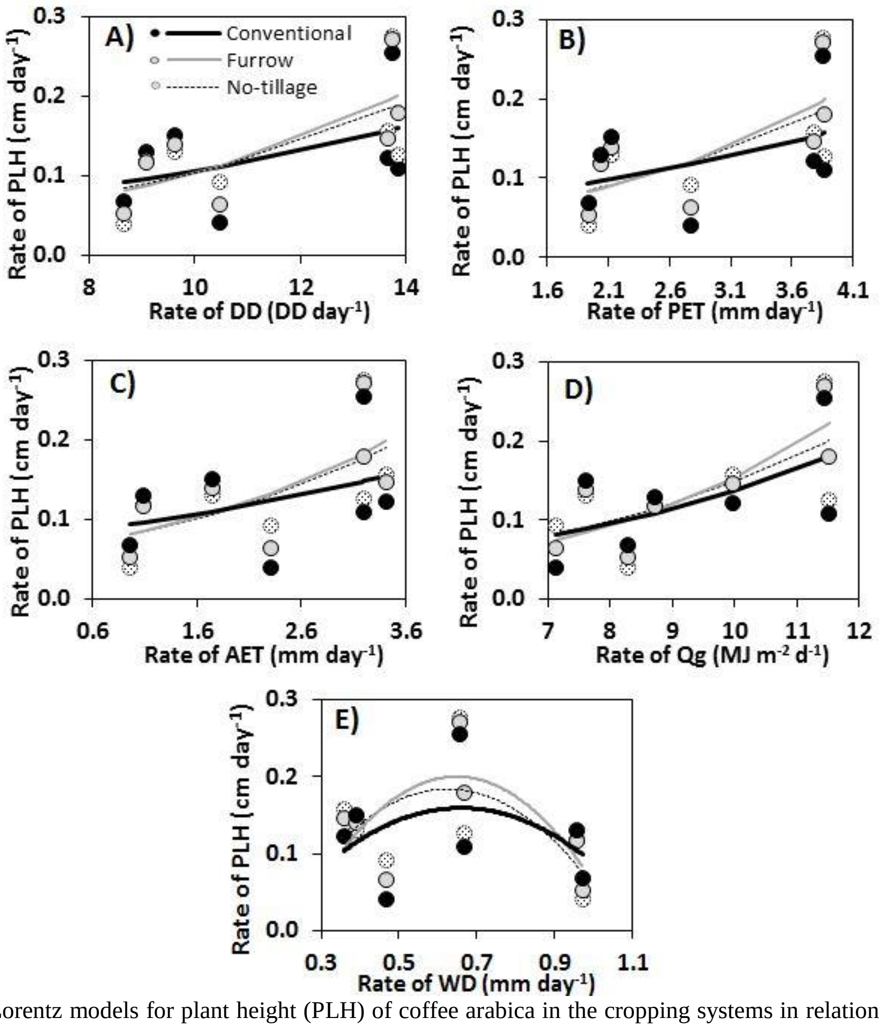

Fig 3. Logistic and Lorentz models for plant height (PLH) of coffee arabica in the cropping systems in relation to A) rate of degree days (DD), B) potential evapotranspiration (PET), C) actual evapotranspiration (AET), D) global radiation (Qg) and E) water deficit (WD).

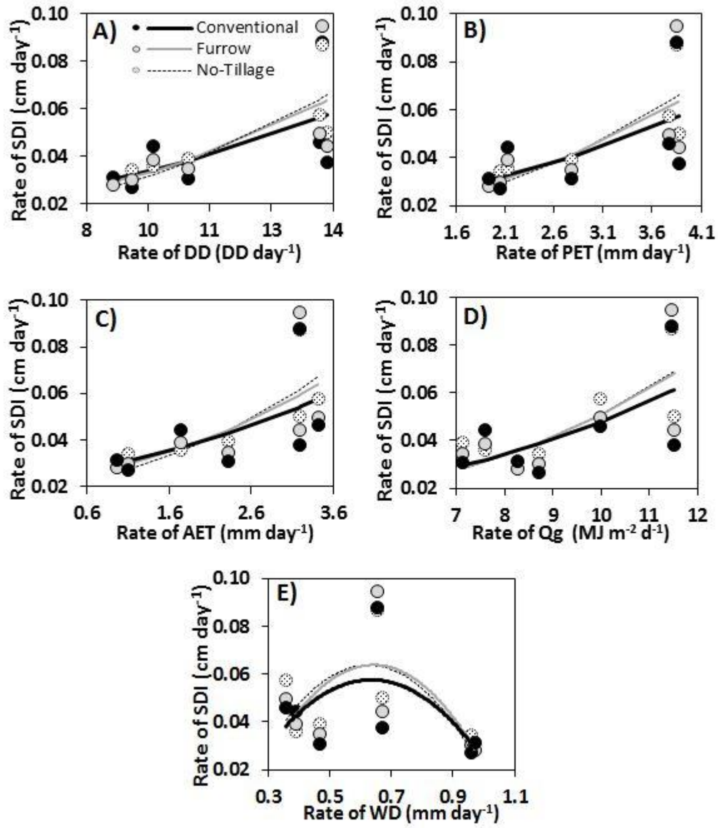

Fig 4. Logistic and Lorentz models for orthotropic stem diameter (SDI) of coffee arabica in the cropping systems in relation to rate of A) degree days (DD), B) potential evapotranspiration (PET), C) actual evapotranspiration (AET), D) global radiation (Qg) and E) water deficit (WD).

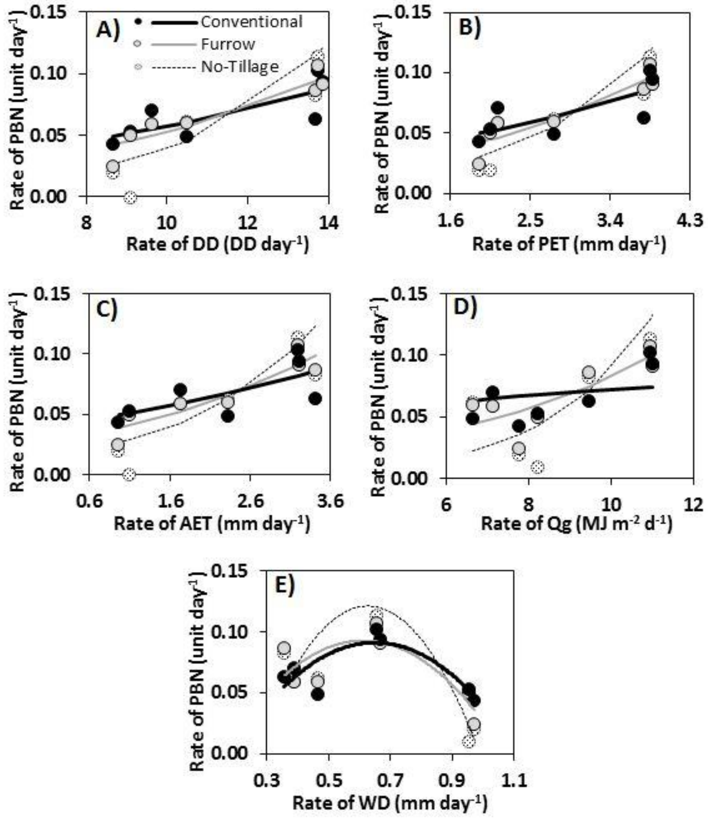

Fig 5. Logistic and Lorentz models for plagiotropic branch number (PBN) of coffee arabica in the cropping systems in relation to rate of A) degree days (DD), B) potential evapotranspiration (PET), C) actual evapotranspiration (AET), D) global radiation (Qg) and E) water deficit (WD).

variables, with a k of 0.46 as a function of PET. The CT system had low k, the lowest of which was 0.11 as a function of DD.The adjusted models were all significant ($p < 0.01$), with high values of R^2adj near 1.0, indicating that the growth rates of newly transplanted coffee plants in the various tillage systems could be correlated with the meteorological variables. For example, the logistic model verified the growth rate of PLH_{FU} as a function of Qg with high precision (R^2adj = 0.92) and statistical significance (p = 0.0003) (Table 1).

An SDI growth rate of 0.04 cm d^{-1} for recently transplanted coffee plants in the NT system required 10.7 DD d^{-1} (Fig. 4A), 2.8 mm d^{-1} of PET (Fig. 4B), 1.9 mm d^{-1} of AET (Fig. 4C), or 8.7 MJ m^{-2} d^{-1} of Qg (Fig. 4D). The average rates of increase in SDI as a function of Qg were 0.18, 0.20, and 0.24 cm MJ m^{-2} for the CT, NT, and FU systems, respectively. A WD rate of approximately 0.62 mm d^{-1} maximised the average rate of development of SDI at 0.06 cm d^{-1} in the CT system. WD rates >1 mm d^{-1} decreased the growth rate of SDI (Fig. 4E). A high WD decreases sucrose levels and yield (Silva et al., 2010; Silva et al., 2013). SDI growth was higher in the NT and FU systems than in the CT system. SDI was most sensitive to PET, with values of k of 0.32; 0.45, and 0.40 for the CT, NT, and FU systems, respectively. SDI, however, was least sensitive to DD, with values of k of 0.12; 0.17, and 0.15 for the CT, NT, and FU systems, respectively (Table 2). For a growth rate of 0.1 unit d^{-1}, the PBN of recently transplanted coffee plants in the NT system required 13 DD d^{-1} (Fig. 5A), 3.5 mm d^{-1} of PET (Fig. 5B), 2.9 mm d^{-1} of AET (Fig. 5C), or 10 MJ m^{-2} d^{-1} of Qg (Fig. 5D). The growth of one PBN thus needs 130 DD, 35 mm of PET, 29 mm of AET, or 100 MJ m^{-2} d^{-1} of Qg. The average rates of increase in PBN as a function of AET were 0.23, 0.63, and 0.38 cm mm^{-1} in the CT, NT, and FU systems, respectively. A WD of approximately 0.6 mm d^{-1} maximised the average developmental rate of PBN at 0.12 unit d^{-1} in the NT system (Fig. 5E). Rates of WD >1 mm d^{-1} reduced growth. PBN was most sensitive to PET, with values of k of 0.29, 0.71, and 0.43 for the CT, NT, and FU systems, respectively. PBN was least sensitive to DD, with values of k of 0.12, 0.29, and 0.16 for the CT, NT, and FU systems, respectively (Table 3). The growth of PBN was higher in the NT system than in the FU and CT systems. A high PBN provides higher yields, because the PBN represents the number of productive branches. This higher PBN occurred in the NT system likely due to its higher availability of soil water (Stone and Silveira, 1999; Stone and Moreira, 2000), ensuring a greater preservation of the physical properties (Ros et al., 2014) while reducing erosion losses and increasing soil organic-matter content (Leite et al., 2003).

Materials and Methods

Plant materials and experimental conditions

The experiment was conducted in Muzambinho, Minas Gerais, Brazil (21°22′33″S, 46°31′ 32″W, 1050 m a.s.l.), an important region of coffee production at high altitude. The classification of the predominant climate of the region is $B_4rB'_2a$ (humid with low water deficit) (Thornthwaite 1948). The experimental area was 25 × 80 m at a slope of 15% with rhodic Haplustox soil (EMBRAPA 2006). Plants with 5-6 pairs of true leaves of the *C. arabica* cultivar Catucaí 2-SL were transplanted on 17 December 2011. The experiment had a randomised block design with four replicates of three tillage systems: conventional tillage (CT), furrowed (FU), and no tillage (NT). CT scarified the soil with a plough followed by levelling, the FU system cultivated only along the rows, and NT was not tilled. The seedlings were transplanted to the field at five months of age and were grown for two years under unshaded conditions and without irrigation. The seedlings were spaced at 3.00 × 1.0 m, with a total of 3333 plants per hectare. The agricultural practices were established in accordance with those normally employed in the region for Arabica coffee. The plants were evaluated approximately every three months until their reproductive phenological cycle had stabilised (December 2011 to December 2013), for a total of nine evaluations in two productive cycles. Plant height (PLH) was measured using a graduated ruler, orthotropic stem diameter (SDI) was measured using digital callipers with a precision of 0.1 mm, and plagiotropic branch number (PBN) was counted directly.

Meteorological data

Data for maximum and minimum air temperature (°C) and rainfall (mm) were measured by 107-L and TB4-L sensors (Campbell Scientific, Logan USA), respectively. The data were collected using a 21X data logger (Campbell Scientific). The daily average air temperature was calculated as the average of the maximum and minimum temperatures. The sequential daily water balance was calculated as proposed by Thornthwaite and Mather (1955), using the available water capacity of 100 mm. The potential evapotranspiration was estimated using the Thornthwaite (1948) method. These estimates were calculated with an Excel spreadsheet developed by Rolim et al. (1998).

Using a lower base temperature of 10.2 °C as proposed by Nunes et al., (2010), the summation of degree days, ∑GD, was calculated as:

$$\sum GD = \left[\frac{Tmax - Tmin}{2}\right] - Tbase \tag{1}$$

where Tmax is the absolute daily maximum air temperature (ºC), Tmin is the absolute daily minimum air temperature (ºC), and Tbase is the lower base temperature of the crop. The global radiation (Qg) was estimated using the Hargreaves-Samani (HS) model (1982):

$$Qg = K_r \times (T_{max} - T_{\min})^{0.5} \times Q_0 \tag{2}$$

where Qo is the extraterrestrial solar radiation (MJ m^{-2} d^{-1}) and K_r is a calibration coefficient (0.16). The daily rate of vegetative growth (Tx) in the treatments and the meteorological variables were calculated as:

$$Tx = \frac{dv}{ND} \tag{3}$$

Where; dv is the variation of the measured variable (actual value - previous value), and ND is the number of days between assessments.

Data analysis

A principal components analysis (PCA) was used to verify the general interdependence of all growth and climatic variables, following the Manly (2004) method. The sensitivity of the newly transplanted plants to the meteorological variables were analysed using sigmoidal (Logistic, Eq. 4) and peak (Lorentz, Eq. 5) nonlinear regression models, both with four parameters:

$$y = \frac{\alpha}{1 + e^{[-k(x - xc)]}} \tag{4}$$

$$y = yo + \frac{2A}{\pi}\frac{w}{4(x - xc)^2 + w^2} \tag{5}$$

Where; α is the amplitude, k is the average rate, x_c is the central point, A is the area below the curve, y_0 is the offset, and W is the midpoint standard deviation.

We used degree days (DD), potential evapotranspiration (PET), actual evapotranspiration (AET), water deficit (WD), and global radiation (Qg) rates as independent variables in the models and PLH, SDI and PBN rates as dependent variables. The normal distribution of the data and errors were verified by Kolmogorov-Smirnov tests.

The estimation of the parameters in nonlinear models used the method of ordinary least squares, which minimises the sum of the squared errors of the model, employing the generalised reduced gradient (GRG2) optimisation system (Lasdon and Waren, 1982). The models were selected by evaluating the precision by the adjusted coefficient of determination (R^2) (Cornell and Berger, 1987) (equation 6) and the statistical significance of the models ($p < 0.05$):

$$R^2\ adj = \left[1 - \frac{(1-R^2)\times(n-1)}{n-\varepsilon-1}\right] \quad (6)$$

where n is the number of data points, and ε is the number of independent variables in the regression. The coefficient of determination (R^2) was calculated by:

$$R^2 = \left(\frac{SQR+SQE}{SQR}\right) \quad (7)$$

where SQR is the regression sum of squares ($\sum(y_{est} - \bar{y}_{obs})^2$), and SQE is the sum of squared errors ($\sum(y_{obs} - y_{est})^2$).

Conclusions

The development of newly transplanted arabica coffee plants was sensitive to meteorological conditions. Water deficit was the most important meteorological variable during the study period in this high region. A water deficit of 0.5-0.7 mm d^{-1} promoted the development of plant height, orthotropic stem diameter, and plagiotropic branch number. The plants transplanted in the untilled system promoted the development of orthotropic stem diameter and plagiotropic branch number. The furrowed system produced the tallest plants.

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